Cape Peninsula
University of Technology

COMPUTATIONAL MODELING OF A SMART IMPELLER ACTUATED BY SHAPE MEMORY ALLOYS.

by

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Bellville
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DECLARATION

I, Godwin Fonguh Fuhnwi here, declare that the contents of this thesis represent my own unaided work, and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

03/03/2011

Signed **Date**

ABSTRACT

Smart (SMA-Shape Memory Alloy) Technology continues to advance rapidly as engineers move closer to and understand better the industrial and commercial needs for SMA. As a matter of fact, all types of products, which exercise some type of control over their function, are rapidly making their way into the marketplace [36] Nonetheless, nowhere has been evidence in the development of a SMA impeller.

Unlike traditional impellers with no control over their function and sometimes fixed angle of attack, this paper demonstrates numerical investigations using analytical algorithms (Matrix laboratory programming and excel spread sheet) and advanced computer simulation package, Engineering Fluid dynamics (EFD) into the feasibility of using a smart impeller to study the performance of a pumping system and the best angle of attack for a Shape Memory Impeller.

Primarily, Bench mark data and dimensions are obtained from a standard centrifugal pump run on a FM21 demonstration unit. Using the same standard centrifugal pump, and keeping all other dimensions the same but altering the angle of attack, EFD simulations where made.

From analytical algorithm and EFD comparison, it was evident that the best angle of attack is 12 degree at the outlet angle with respect to the inlet angle.

From EFD results, it is palpable that, by increasing the angle of attack from 35 degree to 45 degree at the outlet there will be huge increase in flow rate by 63.47%

There is also a slight decrease in the impeller Torque from 35 degrees to 42 degrees by 0.72%.

It is economically feasible to work at an outlet angle of 42 degrees due to increase in efficiency of 62.1% and a drop in torque of 0.72% by varying the outlet angle from 35 degrees to 42 degree.

Understanding how critical actuator design is, it should be suggested that any shape memory impeller should never be used in critical components without a prior history of thermal and mechanical loading.

Therefore, a NiTi impeller constitutive model can be designed, with impeller blades made from NiTi plates, trained to remember its best angle of attack (Martensitic phase). NiTi shape memory metal alloy (plates-blades) can exist in a two different temperature-dependent crystal structures (phases) called *martensite* [9](lower temperature-normal pumping condition) and *austenite* [9] (higher temperature or parent phase-trained best angle of attack.)

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- A special word of thanks to my family, my mother, my late father, my wife, my sister and my brothers. You have supported me since the start of my academic career and played a very important role to my studies and my life.

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MAY GOD BLESS YOU ALL.

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CHAPTER ONE

OVERVIEW OF THE PROJECT

1.1 Introduction

One of the major parameters used to analyse the performance of a pump is the mass flow rate of fluid through the pump. For incompressible flow, it is more common to use Volume flow rate rather than mass flow rate. [36][42]

The type of pumping system (technical design) determines its efficiency as it relates to the torque on the system, power at pump inlet relative to outlet power and also inlet flow velocity and outlet flow velocity comparatively.

A smart impeller is one that should change its configuration to match its system's working conditions depending on the temperatures or loading condition in which it is working.[36]

On the commercial side there are smart automobiles and more recently, smart appliances have also begun to appear. On the industrial side there is smart instrumentation, smart control valves and smart motors. The pump industry is behind the times in incorporating the use of computer technology to operate, control and protect pumps and their systems. Certainly over the past few decades, significant progress has been made in the areas of pump hydraulics, mechanical design and applications through the use of computerized tools such as computational fluid dynamics (CFD) and finite element analysis (FEA). However, only recently have manufacturers begun to develop “smart” pumps which incorporate microprocessors as part of their normal function. [36]

A smart pumping system by definition must be capable of knowing when to adjust itself to system changes without manual intervention. The system must also be fault tolerant. Fault tolerance enables the system to recognize and safeguard itself from operating under conditions that may reduce its life.[36] Adverse conditions such as dry running, operating against a closed suction or discharge valve and cavitations must all be recognized and reacted to before damage occurs. The system must also be capable of understanding when the system transient or unusual operating condition has cleared; thereby allowing normal pump operation to resume.

1.2 Background

A typical example, a “smart” pumping system consists of a pump, variable speed drive, instrumentation, microprocessor and special software [36]. The pump can be any standard centrifugal pump (See figure 1.21 and 1.22 below) fitted with instrumentation to measure suction pressure, suction temperature, discharge pressure and pump flow.

All of the hydraulic characteristics of the pump, fluid characteristics, user control parameters, alarm settings and pump control software reside on the microprocessor of the smart controller. The pump control software enables the controller to sense pump and process conditions and react accordingly. These systems can be designed to maintain constant values of speed, capacity, pressure, level or pH and can be controlled either locally or through a distributed control system (DCS). [36]

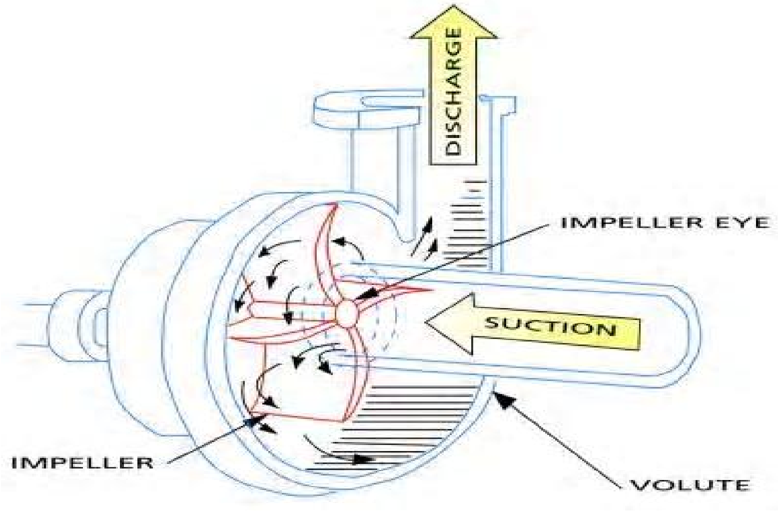

Figure 1.21: Pump in pumping mode showing impeller

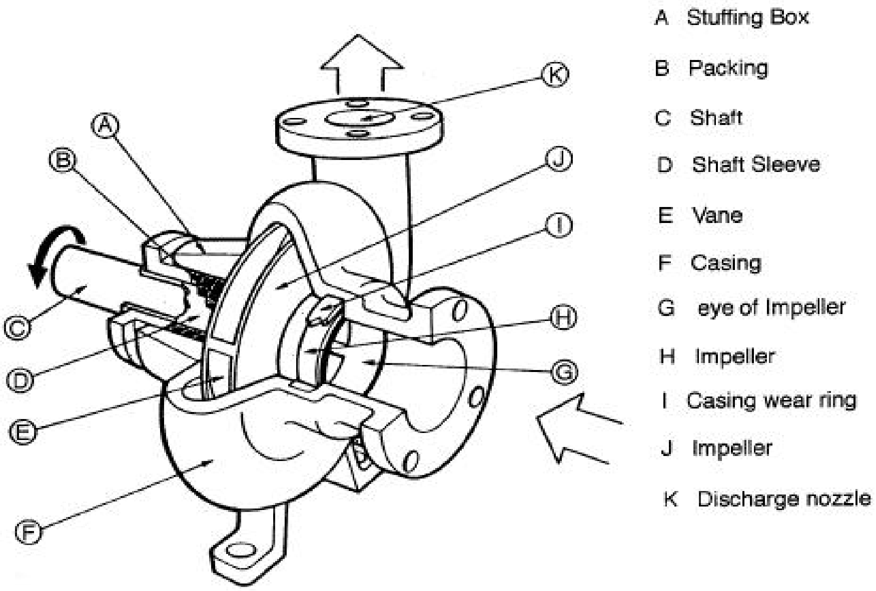

Figure1.22: A cross section of a centrifugal pump

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Numerous pump and impeller designs have been conceptualised to match the different applications in industries. See figure 1.23 to figure 1.28 below for some design configurations. Despite all the differences in configuration, blade angle, size, shape and impeller variation, more and more impellers are being designed everyday to perform specific applications.

Figure: 1.23

Figure: 1.24

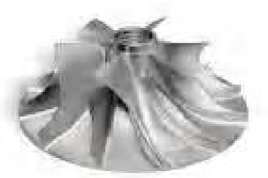


Figure: 1.25

Figure: 1.26

Figure: 1.27

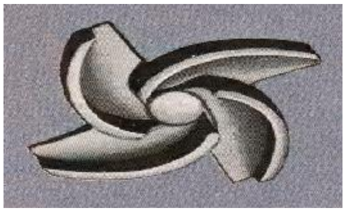
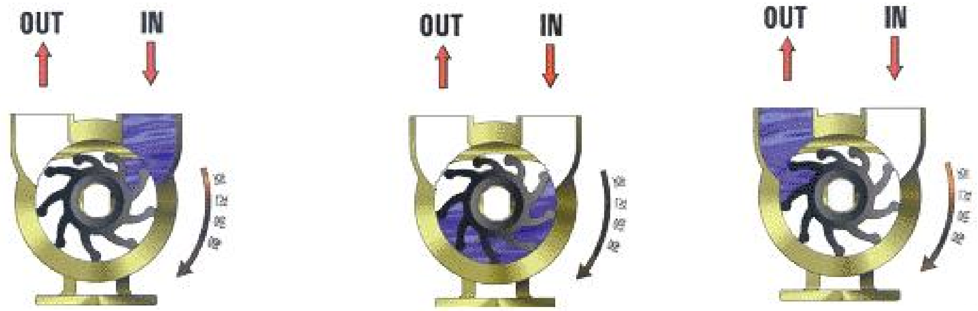


Figure: 1.28

Flexible impeller pumps have been widely used in the marine industry and provide an efficient solution to most marine pumping needs. The primary advantage of a flexible impeller pump is its self-priming capability.[42] As the vanes of the impeller are depressed and rebound, they create their own vacuum drawing fluid into the pumps (See operating principle in figure 1.29 below).

A dry pump can lift water up to as much as 3 meters. Thus a flexible impeller pump being used in bilge, deck wash, or engine cooling need not be located below the water line or be manually primed [42]. An added feature of flexible impeller pumps is that they can pass large particles without clogging or damaging the pump. This reduces the need for filtering the incoming fluid. [42]

Figure 1.29: Operating principle



After the blades leave the cam, the blades pop up. The action creates a vacuum, which draws liquid into the pump

Each blade draws in liquid and carries it to the outlet port

When the blades compress, they expel the remainder of the liquid. The flow is continuous and uniform.

1.3 Statement of problem

One of the major challenges faced by pump manufacturers is the manufacture of a pump that can match pump outputs exactly to system conditions and can detect, protect the pump and system against unusual operating conditions.

This thesis thus seeks to investigate numerically the feasibility of developing a Shape Memory Smart Impeller, i.e. using Shape Memory Materials as impeller vanes/blades or inserts. The investigation will study the performance of a pumping system and the best angle of attack for a Shape Memory Impeller. By knowing the best angle of attack, shape memory Alloy plates can then be trained and imbedded in an impeller to remember the best angle of attack. This will be a smart impeller, i.e change its configuration to increase or slow its pumping rate by simply changing its blade angles as a function of fluid temperature. (Angle of attack)

1.4 Objectives of the Study

1.4.1 Primary Objective

The primary objective of this study is the conceptualisation a Shape Memory Smart Centrifugal Impeller for use in conditions where a slight fluctuation in the environmental temperature conditions may lead to detrimental consequences to the entire closed system. An example of such a system could include that of the cooling system in a nuclear reactor.

1.4.2 Sub-Objectives

In order to achieve the primary objective, a few sub-objectives have to be realized. These include:

- To understand the operation and corresponding analytical solution for a given pumping situation,
  - The system studied and investigated is the FM21 centrifugal pump demonstration unit. See figure 3.11 (Top view) and figure 3.12 (side view) below **[40]**. This system was used because of its variable control advantages as will be seen in chapter 4.
  - Investigate and determine the performance of the FM21 centrifugal pump demonstration unit system in (i) above as will be seen in Appendix A13 and A14
- To determine analytically and numerically the optimum conditions for a specific pumping condition, i.e.
  - Optimum impeller blade inlet angle with corresponding outlet angle and efficiency
  - Optimum impeller blade inlet angle with corresponding outlet angle and impeller outlet velocity
  - Optimum impeller blade inlet angle with corresponding outlet angle and fluid flow rate through the impeller

    - Optimum impeller blade inlet angle with corresponding outlet angle and impeller shaft torque
    - Optimum impeller blade inlet angle with corresponding outlet angle with least eddy formation in the impeller system.
- To conceptualize a Shape Memory Smart Impeller using NiTi Shape Memory Alloys
- To use CFD analyses in order to validate analytical solutions.

1.5 Research Methodology

A numerical investigation into the feasibility of using a smart impeller to study the performance of a pumping system and the best angle of attack for a Shape Memory Impeller.

By using advanced computer simulation software, Engineering Fluid Dynamics (EFD), a system will be designed using Solid works in which the flow rate (efficiency) of the outlet fluid pumped by the variable outlet angle of the impeller will be measured. The outlet angle is gradually increased while the flow rate (efficiency) is captured at each outlet angle. All other configurations will be kept constant (e.g., inlet angle, flow velocity at inlet, etc) A graph of variable outlet angle versus efficiency will be drawn. Analytical results will be compared with simulation results from EFD. The goal will be realisation of an optimum angle of attack, with increased efficiency with decrease in power or torque on the impeller. Perceptibly, a decrease in the angle of attack should decrease efficiency and an increase in the angle of attack, should increase efficiency.

In real time pumping systems, this variation can then be achieved by the variation in the trained memory plates imbedded in our impeller reacting according to temperature changes in the pumping system.

This smart pumping system will be capable of knowing when to adjust itself to temperature changes without manual intervention. The system will also be capable of responding when the system transient or unusual operating condition has cleared; thereby allowing normal pump operation to resume.

i) Experimental analysis:

The initial step was to study the pumping Fm21 rig and performing 100 tests. Data was captured, inlet flow, power in, power out etc and tabulated on a table as seen in Appendix A13 and A14.

This was done using a series of configurations so that only one impeller was functional.

The rig was then dismantled carefully and the impeller was removed and studied.

All dimensions of this impeller were measured to two decimal places and drawn in 3D view using Solid works.

ii) Analytical algorithms:

Using the dimensions measured in (i) above and data collected in (i) above to perform, analytical calculations to determine the performance of the impeller.

At the same time analytical calculations were also made while varying the outlet angle and keeping the inlet constant.

The above analytical algorithms were supported by MATLAB and Microsoft Excel.

MATLAB is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include Math and computation Algorithm development Data acquisition Modelling, simulation, and prototyping Data analysis, exploration, and visualization Scientific and engineering graphics Application development, including graphical user interface building MATLAB is an interactive system whose basic data element is an array that does not require dimensioning. This allows you to solve many technical computing problems, especially those with matrix and vector formulations, in a fraction of the time it would take to write a program in a scalar noninteractive language such as C or Fortran. The name MATLAB stands for matrix laboratory. MATLAB was originally written to provide easy access to matrix software developed by the LINPACK and EISPACK projects. Today, MATLAB engines incorporate the LAPACK and BLAS libraries, embedding the state of the art in software for matrix computation. MATLAB has evolved over a period of years with input from many users. In university environments, it is the standard instructional tool for introductory and advanced courses in mathematics, engineering, and science. In industry, MATLAB is the tool of choice for high-productivity research, development, and analysis. MATLAB features a family of add-on application-specific solutions called toolboxes. Very important to most users of MATLAB, toolboxes allow you to learn and apply specialized technology. Toolboxes are comprehensive collections of MATLAB functions (M-files) that extend the MATLAB environment to solve particular classes of problems. Areas in which toolboxes are available include signal processing, control systems, neural networks, fuzzy logic, wavelets, simulation, and many others.

Performance graphs were plotted for both Excel and MATLAB algorithms.

iii) Solid works

Solid Works software provides part and assembly configuration management capabilities, which can accelerate the entire product design process. Configuration management allows you to:

- Store information about a part or assembly and its components in a particular state.
- Create multiple design variations of a part or assembly model within a single document.
- Develop and manage families of models with different dimensions, components, properties or other parameters

The impeller, extracted from the FM21 unit was drawn to scale in this 3D software. While keeping the inlet angle constant, the outlet angle was varied for each different impeller. A constant interval of 5 degrees was used for the first simulation, then 2 degrees and lastly 0.5 degrees.

Each of the varied impeller configurations were made into a completely separate assembly and saved while waiting to be simulated separately in EFD

iv) Engineering fluid Dynamics (EFD)

The assemblies compiled in iii) above are then imported into EFD and simulated using the simulation algorithms.

Obtaining reliable early findings about flow and heat transfer processes is often a crucial criterion for the success of a development project. In some cases, concrete information about the physical flow and heat transfer functions in a future design or method is required right from the definition phase. In the age of Product Lifecycle Management (PLM) strategies, there is no longer any viable alternative to computer-based simulation.

Flow calculations that are not able to keep pace with the general progress of a project are less useful as development tools. As a result, the efficiency of simulation calculations – not only flow simulations – is determined to a large extent by the total processing time required. This begins with the provision of 3D CAD data for the design to be analysed and ends with the presentation of results and conclusions to the decision-making bodies. Under practical conditions in development and design departments, this challenge can only be met using specially tailored calculation tools. These tools must be designed in such a way as to free the project engineer as far as possible from specific calculation activities and allow him to concentrate exclusively on the actual resolution of the physical and technical issues. Crucial elements here include handling of the CAD data for generation of the geometric model to achieve the maximum possible integration, automatic grid technology, stability and reliability of the mathematical algorithms through intelligent solution control and efficient evaluation and documentation of results.

The initial version of the geometry to be analysed normally exists as a 3D CAD data file. This data can be most easily used for a simulation if the simulation program is integrated into the CAD system and can directly use the system's geometry functions. The Engineering Fluid Dynamics (EFD) software from NIKA for flow and heat transfer simulation is integrated into solid works as a workbench as an additional module and uses these systems' respective user interfaces to access the same features as are available for the geometry model itself. Changes and optimisations to the geometry based on findings from the simulation calculations can be made directly in the CAD system using the familiar modeling functions. However, there are also various areas where more universal handling of 3D geometry data is required. For example, many system suppliers and engineering service providers process geometry data for simulations in a range of data formats and expect the data to be seamlessly transferred using import interfaces for original data from all major 3D CAD systems and using interfaces for universal standard formats such as STEP, IGES and VDAFS. It is important that the parameters of the initial version of the imported components and assemblies are changed or supplemented for subsequent analyses and can be returned to their original format for direct processing in the original system. To meet these requirements, NIKA has developed the EFD.Lab program system, which combines the Engineering Fluid Dynamics technology for flow calculations and a latest generation parametric volume modeler with a full range of interfaces. EFD.Lab thus provides comprehensive CAD links for almost all important 3D CAD systems.

a) Automatic Grid Generation

The finite volume method has established itself as the fundamental calculation method for simulating flow, heat and material transfer. This method requires a calculation grid in the area to be analysed. It is crucial that this grid is of high quality in terms of flow calculations. The criteria include automatic generation of hexahedron cells over the entire calculation area and a sufficient grid density in areas that are critical in terms of the fluid mechanics, without allowing the calculation to become inefficient due to unnecessarily large models. If the 3D CAD models created for the mechanical design and production are now used for grid generation, a problem occurs: the area to be calculated – the space filled with liquid or gas – is not normally modelled as a separate solid and is not therefore available for grid generation. To overcome this, the EFD programs can automatically identify both the enclosed internal flow space and the outer flow area, as well as the solid areas of different materials involved in heat transfer. A grid of hexahedron elements is then automatically generated for the entire calculation area using RAM (Rectangular Adaptive Mesh) technology, and the grid density is automatically adjusted at geometrically and physically critical areas.

b) Automated Evaluation of Results Using Standard Software

Efficient evaluation and documentation of the calculation results is another important factor in the total processing time and thus in the total costs of a flow simulation. With MS Office, the PC platform provides a standard for creating documents or presentations and evaluating numerical material. The combination of MS Office with a flow simulation program integrately into a CAD system or a volume modeller opens up new possibilities when it comes to providing effective and practical access to the calculation results. For example, result data along a CAD curve can be extracted and automatically presented and evaluated as a chart or table in MS Excel. Users can adapt the templates used to meet their own individual corporate Identity, allowing presentation-ready documents to be created.

The performance of each impeller is determined and plotted.

v) Feasibility:

The feasibility study is done with graphical representation. Comparing the different algorithms and contrasting.

1.6 Overview of Thesis

Chapter 2 provides an overview of pumping systems and specifically centrifugal pumping systems. Chapter 3 gives an overview of the centrifugal pumping system used to develop the specific pumping scenario used to develop the Shape Memory Smart Impeller, while Chapter 4 provides a background to Shape Memory Alloys as well as the mechanisms or phenomenon used in the conceptualisation of the Shape Memory Alloy Smart Impeller. Chapter 5 provides an analytical description of the pumping system and introduces the concepts used to conceptualise the Shape Memory Smart Impeller. It further describes analytically the operation of the impeller and draws conclusions on its feasibility. Chapter 6 provides a description of the CFD software used, and Chapter 7 provides a discussion of CFD results obtained. Chapter 8 provides conclusions and makes recommendations for future studies of the Shape Memory Smart Impeller.

CHAPTER TWO

LITERATURE REVIEW ON PUMPS

2.1 Choice of Pump

Pumping may be defined as the addition of energy to a fluid to move it from one point to another. It is not, as frequently thought, the addition of pressure. Energy is the capacity to do work, and adding it to a fluid causes the fluid to do work. By definition, a centrifugal pump is a device whose primary purpose is to produce pressure by accelerating fluid particles to high velocity providing them with velocity energy [3]

The design will focus on centrifugal pumps because they are commonly used. They can be found around our home-in dishwashers, hot tubs, clothes washers and dryers, fluid dryers, vacuum cleaners, kitchen exhaust hoods, bathroom exhaust pumps, leaf blowers, furnaces, etc. They are also used in cars –water pump in engine, the are blower in heater/fluid condition. Centrifugal pumps are ubiquitous in industry as well; they are used in building ventilation systems, washing operations, and in numerous other industrial operations in which fluid is pumped. [3]

2.2 Functionality of the centrifugal pump

A centrifugal pump briefly, is a machine consisting of rotating vanes enclosed within a housing. In a centrifugal flow pump, fluid enters axially (in the same direction as the axis of the rotating shaft.) in the centre of the pump, after which it encounters the rotating blades. The vanes impart energy to a fluid through centrifugal force. It acquires tangential and radial velocity by momentum transfer with the impeller blades, and additional radial velocity by centrifugal forces, which are actually a lack of sufficient centripetal forces to sustain circular motion. The fluid leaves the impeller after gaining both speed and pressure as it is flung radially outward into a scroll (also called volute) and is discharged radially (or tangentially) along the outer radius of the pump casing. The scroll is a snail-shape diffuser whose purpose is to decelerate the fast moving fluid leaving the trailing edges of the impeller blades, thereby further increasing the fluid's pressure, and to combine and direct the flow from all the blade passages toward a common outlet. [37]

2.3 Inlet and outlet diameter of a centrifugal pump.

If the inlet and outlet diameters are the same the average flow speed at the outlet is identical to that at the inlet. Thus, it is not necessarily the speed, but the pressure that increases from inlet to outlet through a centrifugal pump [37].

2.4 Blade Geometry

There are three types of centrifugal pump that warrant discussion, based on the impeller geometry;[37]

1. Backward-inclined blades
2. Radial blades(Straight blades)
3. Forward inclined blades

2.4.1 Backward inclined blades

Centrifugal pumps with backward inclined angles are the most common. This yields the highest efficiency of the three because fluid flows into and out of the blade passages with the least amount of turning. Fluid foil shaped blades; will yield similar performance but even higher efficiency. The pressure rise is intermediate between the two types of centrifugal pumps [37].

2.4.2 Straight blades

Centrifugal pumps with radial blades (also called straight blades), have the simplest geometry and produce the largest pressure rise of the three for a wide range of volume flow rates, but the pressure rise decreases rapidly after the point of maximum efficiency[37].

2.4.3 Forward inclined blades.

Forward inclined blades produce a pressure rise that is nearly constant, albeit lower than that of radial or backward-inclined blades, over a wide range of volume flow rates. Centrifugal pumps with forward inclined blades generally have more blades, but the blades are smaller. Centrifugal pumps with forward inclined blades generally have a lower maximum efficiency than do straight blade- pumps [37].

Radial and backward are preferred for applications where one needs to provide volume flow rate and pressure rise within a narrow range of values. If a wider range volume flow rates and/or pressure rises are desired, the performance of radial and backward-inclined pumps may not be able to satisfy the new requirements; these types of pumps are less forgiving(less robust) the performance of forward-inclined pumps is more forgiving and accommodates a wider variation, at the cost of lower efficiency and less pressure per unit of power input. If a pump is needed to produce large pressure rise over a wide range of volume flow rates, the forward-inclined centrifugal pump is attractive.

Net head and brake horsepower performance curves for these three types of centrifugal pump are compared below. The curves have been adjusted such that each pump achieves the .same free delivery (maximum volume flow rate at zero net head). These are quantitative sketches for comparison only. Actual measured performance curves may differ significantly in shape, depending on details of the pump design.

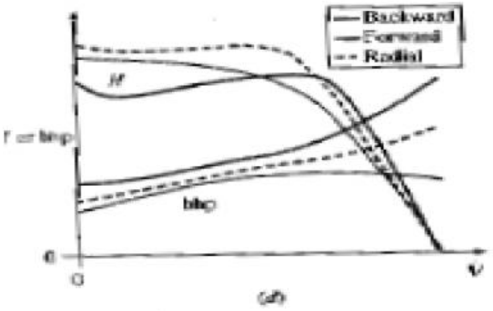


Figure 2.41: Horse power performance curves

2.5 Velocity vectors through the blades

The inclination of the impeller blades (backward, radial or forward) the velocity vectors can be analyse mathematically and using Matrix Laboratory.(analytical algorithm)

Normally the actual flow may be unsteady, fully three-dimensional, and perhaps compressible. But for simplicity, the research will consider steady flow rate in both absolute reference frame and in relative reference rotating with the impeller. Only incompressible flow will be considered. In addition, only radial or normal velocity component and the circumferential or tangential velocity from blade inlet to outlet will be considered. We do not consider the axial velocity component, in order words, although there is a nonzero axial component of velocity through the impeller, it does not enter our analysis.

2.6 Variation in impeller diameter

The performance of a pump changes if the impeller is reduced in diameter (within a limit dependent upon the impeller design) from the characteristics of a larger impeller.

The diameter of an average impeller can be cut down by 20 per cent of its original maximum value without adverse effect. Cutting it down to less than 80 per cent will generally result to a lower efficiency. Its has been documented

that if a impeller is cut in diameter, the flow rate varies as the impeller diameter and at the same time the head varies as the square of the impeller diameter and the power varies as the cube of the of the impeller diameter. That is;

$Q = Q_1(D/D_1)$

$H = H_1(D/D_1)^2$

$P = P_1(D/D_1)^3$

D_1= Original diameter

D = Cut down diameter

Q_1= Flowrate with D_1 impeller.

Q= Flowrate with D impeller.

H_1= Head with D_1 impeller at Q_1

H= Head with D impeller at Q

P_1= Power with corresponding $D_{1,}$ H_1 and Q_1

P= Power with corresponding $D_,$ H and Q

Experiments conducted by Karassik and Carter, a pump was tested at 1800 rpm (with impeller diameter of 14.75 inch), if the diameter is reduce to 14 inch in diameter, results were as follows [38]

Table 2.61: Results from Karassik and Carter

Flowrate (gpm)	Head (ft)	Power (bhp)	Efficiency (%)
3.797	141.5	162	83.7
3.322	165.3	158.2	87.6
2.847	180.7	149.2	87.0
1.898	199	121.6	78.4
949	206	91.5	54.0
0	207.4	65.4	0

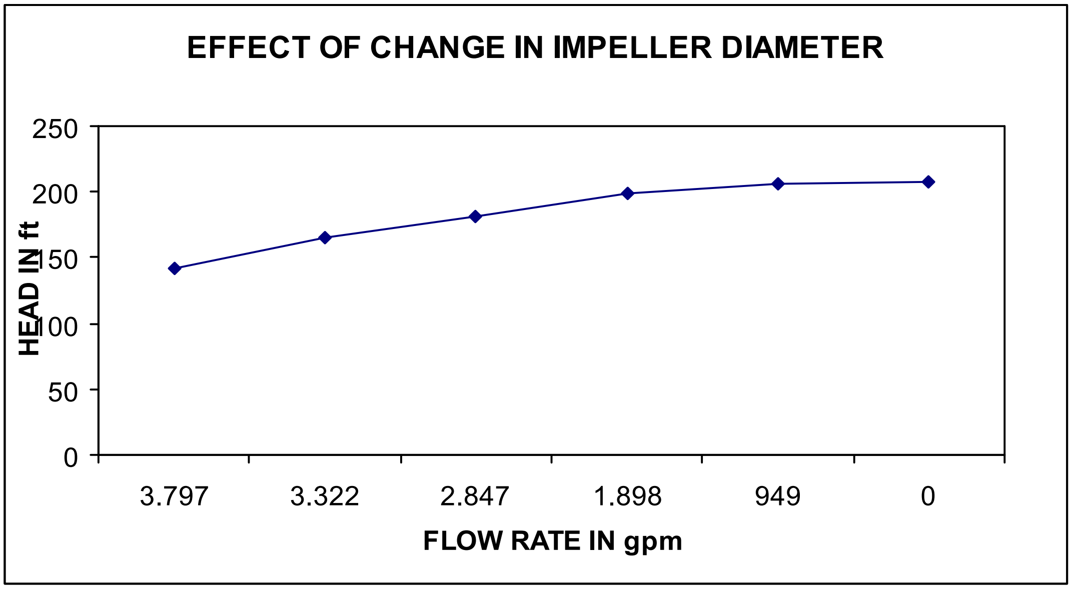


Figure 2.61: Graph of head versus flow rate

2.7 Blade aerodynamic design.

As mentioned previously the choice of correct twist and of special fluid foil sections to reduce compressibility losses are of major importance in modern blades design [30]. However other considerations still remain to be studied with care if the efficiency of the blade is to be kept at its maximum under severe operating conditions.

2.8 Centrifugal and aerodynamic twisting

In a variable-pitch impeller as described later, the blades are turned in the hub about their longitudinal or pitch-change axis. Clearly the mechanism provided to produce this pitch change must be capable of exerting sufficient force to overcome any mechanical or aerodynamic opposing force set up by the blades themselves [30].

The “mechanical force” involved is known as Centrifugal Twisting Moment (C.T.M). This force is closely allied to the normal centrifugal force acting on the blades when the impeller is rotating about the shaft. It is the turning couple produced due to the inclination of the blade section at an angle to the SMA of rotation and results in the natural tendency for any blade, when rotating turned about its longitudinal axis towards zero pitch so that the blades section are turned in to the SMA blade rotation[30] .

2.9 Thrust and torque forces.

The main factor that determines the force developed by an aerofoil section is the angle at which it is inclined to the relative flow, i.e. the angle of attack. Thus, for the blade section to develop the requisite aerodynamic force for propulsion, each section along the blade must be inclined at the appropriate angle of attack to the relative flow direction pertaining to the section hence knowing angle of attack is a simple mater to indicate the force developed [37].

CHAPTER THREE

PUMPING SYSTEM

3.1 The pumping system.

The system used is the FM21 centrifugal pump demonstration unit. This system is utilised in the Department of Mechanical Engineering of the Cape Peninsula University of Technology as a demonstration unit for undergraduate students. See figure 3.11 (Top view) and figure 3.12 (side view) below **[40]**.

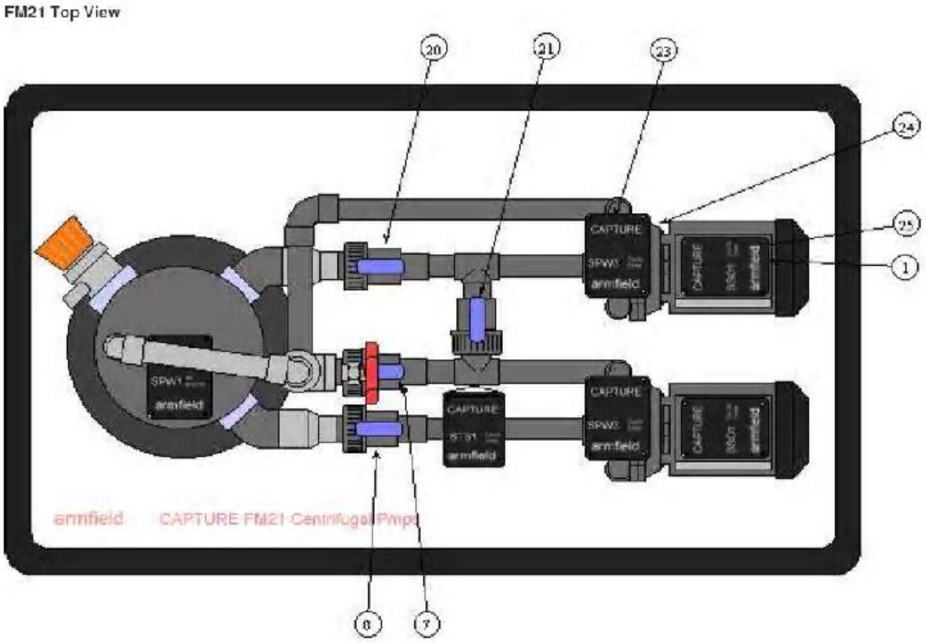


Figure: 3.11: FM21 centrifugal pump testing unit (top view)

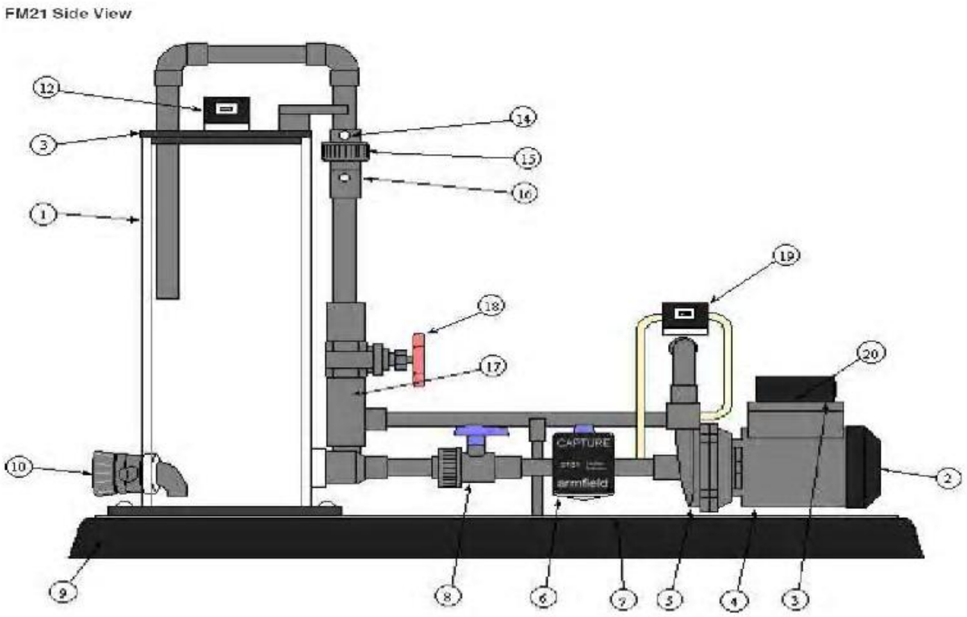


Figure: 3.12: FM21 centrifugal pump testing unit (side view)

The equipment comprises two identical centrifugal water pumps (5 and 23) driven by electric motors (4 and 25) which are mounted on a support plinth (9) together with a clear acrylic reservoir (11) and associated interconnecting pipework for continuous circulation. Configurations of either series, parallel or single pump operation can be set using the appropriate valves (7, 8, 20 and 21). Clean water is used as the operating fluid and a drain valve (10) at the base of the reservoir allows the water to be drained after use.

Appropriate sensors are incorporated on the unit to facilitate analysis of the pump performance when connected to a suitable computer via an IFD Interface Console. In addition to the tappings lines required by the pressure sensors, additional tappings are included in the pipework at the pressure tapping points to allow appropriate calibration instruments to be connected.

The flow of water through the centrifugal pumps is regulated by a flow control valve (18) installed in the discharge pipework of the unit. Adjustment of this valve allows the head/flow produced by the pumps, either separately of combined, to be varied.

The following sensors are used to monitor the performance of the pumps:-

3.2 Differential pressure sensor SPW1:

This comprises of a pressure sensitive device with appropriate signal conditioning all contained in a protective case (12) and used to measure pressure developed across the orifice plate (15) installed in the discharge pipework of the pump(s). The volume flow rate of water for either series, parallel or single pump operation can be calculated using this measurement.

The sensor is connected to the appropriate tappings in the pipework using flexible tubing. Additional tappings (14 and 16) are provided for the connection of appropriate instrumentation to facilitate calibration of the differential pressure sensor.

3.3 Differential pressure sensor SPW3 (2 off):

This comprises of a pressure sensitive piezoresistive device with appropriate signal conditioning all contained in a protective case (19 and 22) and is used to measure the difference in pressure between the inlet and outlet of each centrifugal pump. The head developed by the pumps can be calculated from this measurement.

The sensors are connected to the appropriate tappings in the ducts using flexible tubing.

3.4 Rotational speed sensor SSO1 (2 off):

This comprises of a reflective infra-red opto switch (1 and 2) on a remote lead with appropriate signal conditioning in a protective case (3 and 24). They are used to measure the rotational speed of each motor/impeller.

Each opto switch is mounted on a bracket adjacent to the end of each motor shaft which incorporates a reflective strip to facilitate measurement of the rotational speed.

3.5 A temperature sensor STS1:

This comprises of a temperature sensitive semiconductor device on a remote lead with appropriate signal conditioning in a protective case (6) and is used to measure the temperature of the water entering the first centrifugal pump.

The sensor is inserted through the wall of the pipe using a waterproof gland. The sensor may be removed from the gland for the purpose of calibration using appropriate equipment.

3.6 SWA1 Wattmeter

In addition to the above sensors, which are all permanently attached to the FM21 unit, an Integrating Wattmeter (SWA1) (See Figure 3.61: SWA1 integrated wattmeter) may be connected to the power line of each pump:

The wattmeters are connected between the mains lead from each pump and a suitable power supply. This facilitates the measurement of the electrical power supplied to each motor.

The Armfield SWA1 Integrating Wattmeter provides power of between 0 and 500W, continuously variable using the Variac Dial.

The meter signal is available on a ‘phone’ connector, giving a 0 to 5V output.
The Wattmeter is connected between the mains lead from the pump and a suitable power supply to facilitate measurement of the electrical power supplied to the motor.

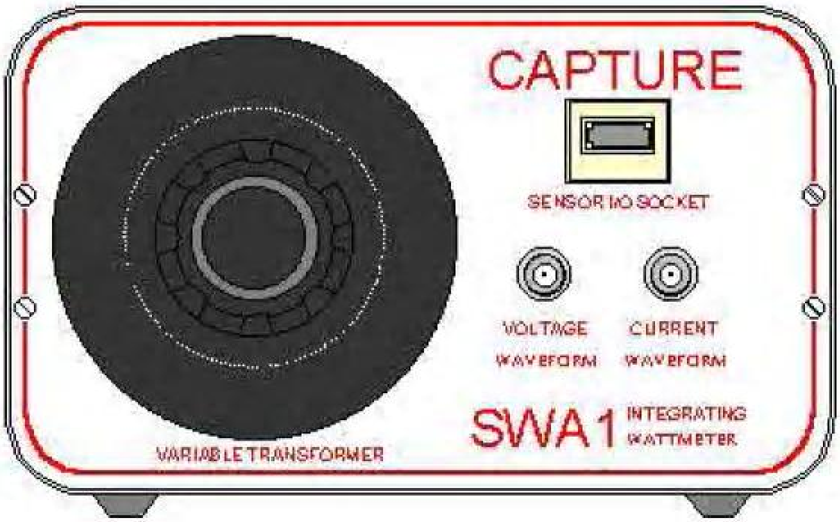


Figure 3.61: SWA1 integrated wattmeter

3.7 The IFD6 Interface

The IFD6 interface is used to transfer data from the heat exchanger under test to a computer.

It connects to the computer's USB port.

The sensors on the FM21 are connected using special phone sockets.

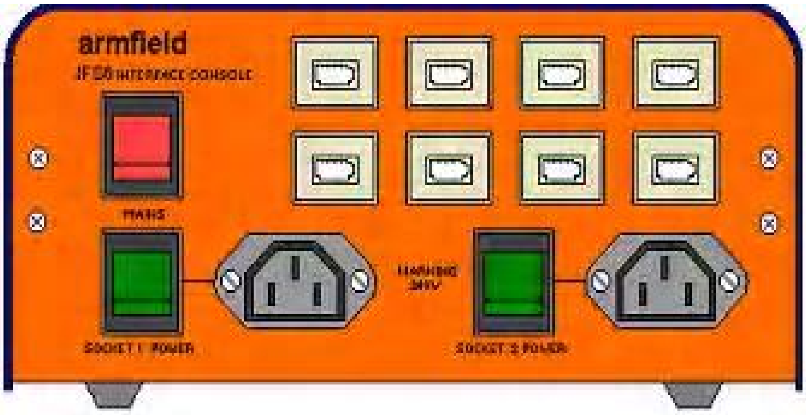


Figure 3.71: IFD6 interface

3.8 Operation of the pump

For the pump operation, only a single pump operation was considered. All tappings lines in the pipework of the FM21 are connected to appropriate sensors or blanked. The differential pressure sensor SPW1 (12) should be connected directly across the orifice plate assembly (15) and the differential pressure sensor SPW3 (19) should be connected between the inlet and outlet of the first pump (5).

Open the inlet valve (8) and close the outlet control valve (18). Ensure that the unit configuration valves (20 and 21) are closed and (7) is open.

Ensure the drain valve (10) at the base of the reservoir is fully closed then fill the reservoir with clean, cold water.

Connect the mains lead from the motor of the first centrifugal pump to the Integrating Wattmeter SWA1. Connect the SWA1 to the MAINS OUTPUT on IFD.

Switch on the mains supply. Check that the pump operates. Open the outlet flow control valve fully and allow water to circulate until all air bubbles are expelled. Switch off pump.

Connect each of the sensor conditioning boxes to the appropriate sensor sockets on the IFD, using the numbered connecting leads, as follows:-

- Channel 1 to sensor SPW1 (12)
- Channel 2 to sensor STS1 (6)
- Channel 3 to sensor SPW3 (19)
- Channel 4 to sensor SSO1 (3)
- Channel 5 to Integrating Wattmeter SWA1

3.9 Practical Sampling.

The picture below (See FM21 laboratory demonstration unit) was taken before sampling.

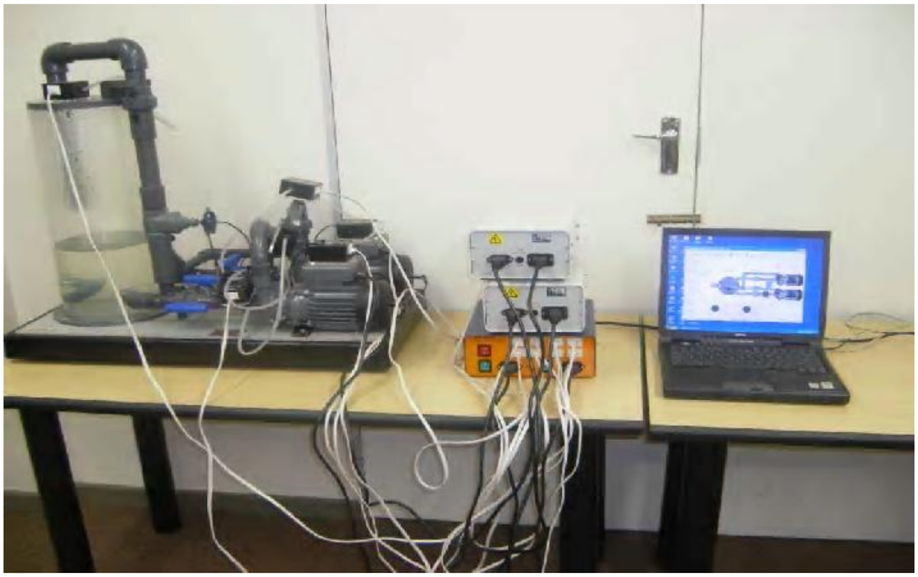
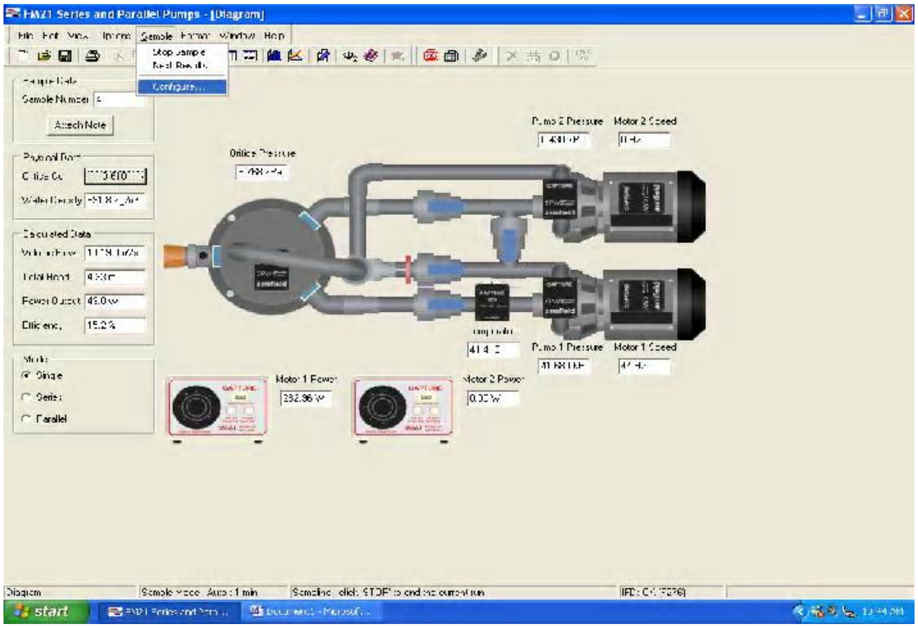


Figure 3.91: FM21 laboratory demonstration unit

This single pump operation is a closed loop system. Using the Armfield software, configuration was made to capture data for an hour. See Armfield operating window figure 3.92 to Figure 3.94 below



Sample Number 4

Power Output 45.0 W

Efficiency 15.2 %

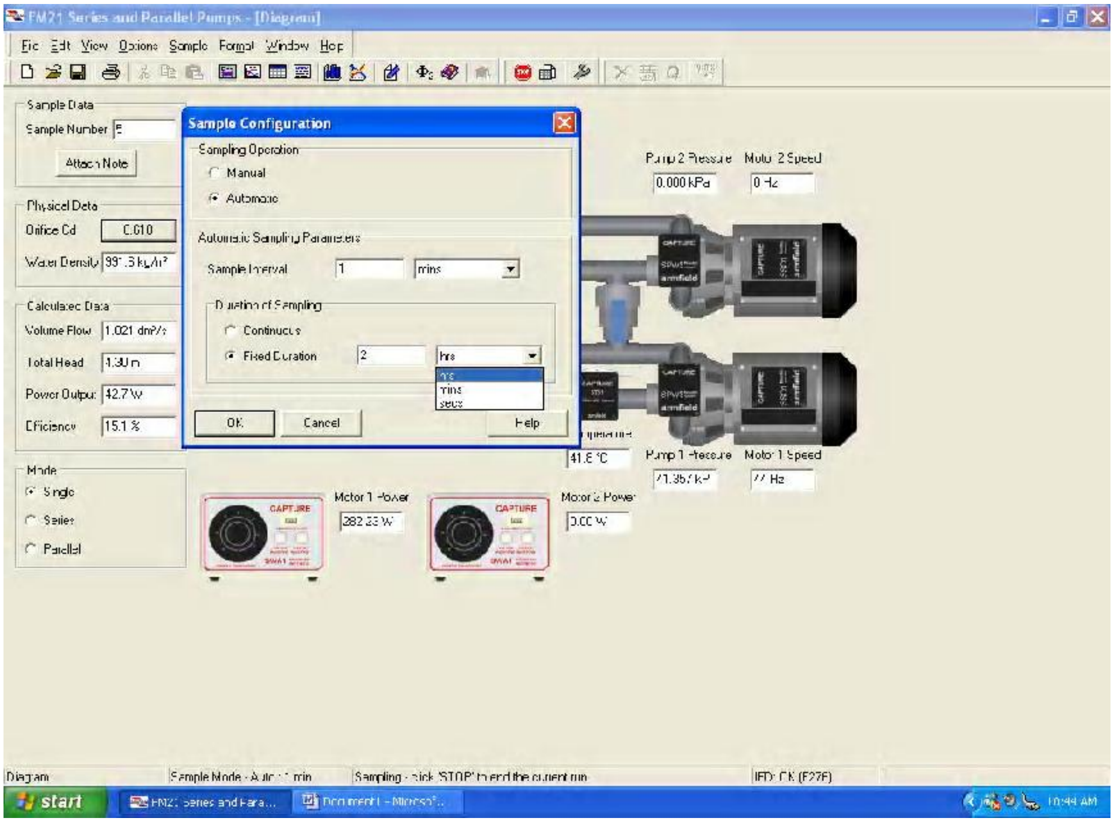
Mode: ● Single ○ Series ○ Parallel

Motor 1 Power 232.96 W

Motor 2 Power 0.00 W

Sample Mode: Auto : 1 min

Figure 3.92: Armfield software window during sampling



Sample Number: 5

Orifice Cd: 0.610

Water Density: 991.3 kg/m³

Volume Flow: 1.021 dm³/s

Total Head: 4.30 m

Power Output: 42.7 W

Efficiency: 15.1 %

Mode: ○ Single ● ○ Series ○ Parallel

Sampling Operation: ○ Manual ● Automatic

Automatic Sampling Parameters: Sample Interval 1 mins

Duration of Sampling: ○ Continuous ● Fixed Duration 2 hrs

Pump 2 Pressure: 0.000 kPa

Motor 2 Speed: 0 Hz

Temperature: 41.8 °C

Pump 1 Pressure: 71.357 kPa

Motor 1 Speed: 77 Hz

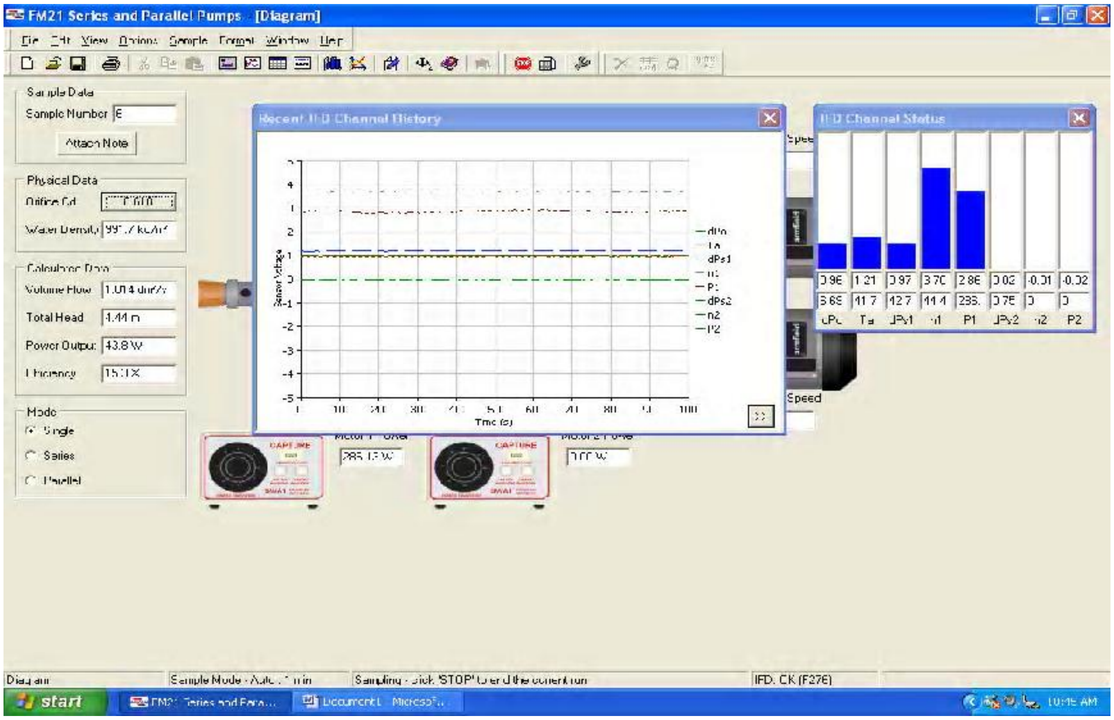
Motor 1 Power: 282.33 W

Motor 2 Power: 0.00 W

Diagram | Sample Mode - Auto - 1 min | Sampling - click 'STOP' to end the current run | IFD: OK (F27E)

10:44 AM

Figure 3.93: Armfield software sample configuration window during sampling.



Sample Number: 6

Orifice Cd: 0.610

Water Density: 991.7 kg/m³

Volume Flow: 1.014 dm³/s

Total Head: 4.44 m

Power Output: 43.8 W

Efficiency: 15.1 %

Mode: ● Single ○ Series ○ Parallel

Motor 1 Power: 285.13 W

Motor 2 Power: 0.00 W

0.96	1.21	0.97	3.70	2.86	0.02	-0.01	-0.02
3.69	41.7	42.7	44.4	236.	0.76	0	0
dPo	Ta	dPs1	n1	P1	dPs2	n2	P2

Diagram | Sample Mode - Auto - 1 min | Sampling - click 'STOP' to end the current run | IFD: OK (F27E)

10:46 AM

Figure 3.94: Armfield software IFD channel status and history window during sampling.

3.10 Nomenclature and Practical Calculations

The variables obtained from the sensors on the equipment are:-

Symbol	Term	Units
dpo	Pressure drop across the orifice plate	Pa (Pascals)(1Pa=1N/m2)
dps	Pressure drop across the pump	Pa (Pascals)
Ta	Water temperature at pump inlet	°C (Celsius)
Pe	Input power to the motor	W (Watts)

Constants used in the calculations:-

Symbol	Term Value	Units
d	Orifice plate diameter	0.024 m
Cd	Orifice discharge coefficient	0.61
g	Gravitational acceleration	9.81 m/s^2
A1	Cross sectional area of the pump inlet	0.00029865 m^2
A2	Cross sectional area of the pump outlet	0.00029865 m^2
n	Rotational speed of the pump	Hz=45=2700rpm=282.74rad/s

Calculated variables:-

Symbol	Term	Units
Qv	Volume flow rate	m^3/s
v1	Velocity in the duct at pump inlet	m/s
v2	Velocity in the duct at pump outlet	m/s

H	Pump total head	m
Pu	Pump power output	W
Egr	Overall efficiency	%

Formula Used

$$Q_v = \frac{C_d \times \pi \times d^2 \times \sqrt{2 \times \rho \times dp_o}}{4 \times \rho}$$

$$V_1 = \frac{Q_v}{A_1}$$

$$V_2 = \frac{Q_v}{A_2}$$

$$H = \frac{(V_2^2 - V_1^2)}{2g} + \frac{p_2 - p_1}{\rho g} + (z_2 - z_1)$$

$$P_u = Q_v \times \rho g H$$

$$E_{gr} = \frac{P_u}{P_e} \times 100$$

100 sample data was capture at interval of one minute. See Appendix A13 and A14 for laboratory results.

The Euler Head and the velocity head was cancelled out so that only the pressure head can be measure. That is, only the impeller efficiency.

The below equations were used and it confirm those with Laboratory result as seen in Appendix A13 and A14

E = (Pressure at outlet - Pressure at inlet) x Q/torque/Angular velocity

OR

E = (Pressure at outlet - Pressure at inlet) / Density/gravity

CHAPTER FOUR

LITERATURE REVIEW ON NiTi SHAPE MEMORY ALLOYS

4.1 General Principles of Shape Memory Alloy

Shape memory alloys (SMA) such as Nickel-Titanium (NiTi) are distinguished by two unusual characteristics, i.e. the shape memory effect and pseudo-elasticity. The shape memory effect is one in which the material can be mechanically deformed (seemingly permanently) at a temperature below a certain transition temperature, but will revert to its original shape upon heating above the transition temperature. Pseudo elasticity refers to the material's ability (at temperatures somewhat above the transition temperature) to be strained significantly (to strains higher than 6% for nearly equiatomic NiTi.) and return to its unstrained configuration upon loading via a hysteresis loop. A diffusionless transformation between two solid state metallurgical phases called Austenite and Martensite is responsible for both effects and can be induced by either changes in stress or temperature [39].

4.2 General Characteristics of Nickel Titanium

NiTi shape memory metal alloy can exist in a two different temperature-dependent crystal structures (phases) called *martensite* (lower temperature) and *austenite* (higher temperature or parent phase). Several properties of austenite NiTi and martensite NiTi are notably different.[39]

When martensite NiTi is heated, it begins to change into austenite (Figure 4.31-A). The temperature at which this phenomenon starts is called *austenite start temperature* (A_s). The temperature at which this transformation is complete is called *austenite finish temperature* (A_f). When austenite NiTi is cooled, it begins to transform into martensite. The temperature at which this transformation starts is called *martensite start temperature* (M_s). The temperature at which martensite is again completely reverted is called *martensite finish temperature* (M_f) [39]

Composition and metallurgical treatments have dramatic impacts on the above *transition temperatures*. From the point of view of practical applications, NiTi can have three different forms: martensite (at temperatures below A_s), stress-induced martensite (at temperatures above A_f), and austenite (at temperatures above A_f). When the material is in its martensite form, it is soft and ductile and can be easily deformed (somewhat like soft pewter). *Superelastic* NiTi is highly elastic (rubber-like), while austenitic NiTi is quite strong and hard (similar to titanium) (Figure 4.31-B). The NiTi material has all these properties, their specific expression depending on the temperature in which it is used.[39]

4.3 Hysteresis

The temperature range for the martensite-to-austenite transformation, i.e. soft-to-hard transition, which takes place upon heating, is somewhat higher than that for the reverse transformation upon cooling (Figure 4.31-A). The difference between the transition temperatures upon heating and cooling is called *hysteresis*. Hysteresis is generally defined as the difference between the temperatures at which the material is 50 % transformed to austenite upon heating and 50 % transformed to martensite upon cooling. This difference can be up to 20-30 °C (Buehler *et al.* 1967, Funakubo 1987). In practice, this means that an alloy designed to be completely transformed by body temperature upon heating ($A_f < 37$ °C) would require cooling to about +5 °C to fully retransform into martensite (M_f).

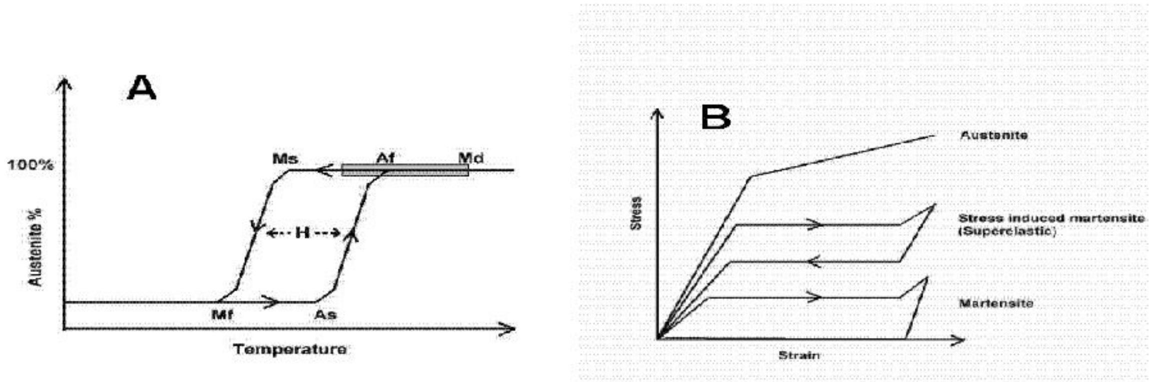


Figure 4.31 A) Martensitic transformation and hysteresis (= H) upon a change of temperature. As = austenite start, Af = austenite finish, Ms = martensite start, Mf = martensite finish and Md = Highest temperature to strain-induced martensite. Gray area = area of optimal super elasticity, and **B)** Stress-strain behaviour of different phases of NiTi at constant temperature.

4.4 Thermoelastic martensitic transformation

The unique behaviour of NiTi is based on the temperature-dependent austenite-to-martensite phase transformation on an atomic scale, which is also called *thermoelastic martensitic transformation*. The thermoelastic martensitic transformation causing the shape recovery is a result of the need of the crystal lattice structure to accommodate to the minimum energy state for a given temperature (Otsuka & Wayman 1998).[39]

In NiTi, the relative symmetries between the two phases lead to a highly ordered transformation, where the displacements of individual atoms can be accurately predicted and eventually lead to a shape change on a macroscopic scale. The crystal structure of martensite is relatively less symmetric compared to that of the parent phase.

If a single crystal of the parent phase is cooled below M_f, then martensite variants with a total of 24 crystallographically equivalent habit planes are generally created. There is, however, only one possible parent phase (austenite) orientation, and all martensitic configurations revert to that single defined structure and shape upon heating above A_f. The mechanism by which single martensite variants deform is called *twinning,* and it can be described as a mirror symmetry displacement of atoms across a particular atom plane, i.e. the twinning plane [39]

While most metals deform by slip or dislocation, NiTi responds to stress by simply changing the orientation of its crystal structure through the movement of twin boundaries.

A NiTi specimen will deform until it consists only of the corresponding variant which produces maximum strain. However, deformation beyond this will result in classical plastic deformation by slip, which is irrecoverable and therefore has no “memory effect”. If the deformation is halted midway, the specimen will contain several different corresponding variants. If such a specimen is heated above A_f, a parent phase with an orientation identical to that existing prior to the deformation is created from the correspondence variants in accordance with the lattice correspondences between the original parent phase and each variant (Figure 4.41). The austenite crystal structure is a simple cubic structure, while martensite has a more complex rhombic structure. This phenomenon causes the specimen to revert completely to the shape it had before the deformation (Andreasen *et al.* 1987, Gil *et al.* 1998).

The above phenomenon is the basis of such special properties as the shape memory effect and superelasticity.

4.5 Shape memory effect

NiTi senses a change in ambient temperature and is able to convert its shape to a pre-programmed structure. While NiTi is soft and easily deformable in its lower temperature form (martensite), it resumes its original shape and rigidity when heated to its higher temperature form (austenite) (Figure 4.41). This is called the *one-way shape memory effect.* The ability of shape memory alloys to recover a preset shape upon heating above the transformation temperatures and to return to a certain alternate shape upon cooling is known as the *two-way shape memory effect*. Two-way memory is exceptional. There is also an *all-round shape memory effect*, which is a special case of the two-way shape memory effect.[39]

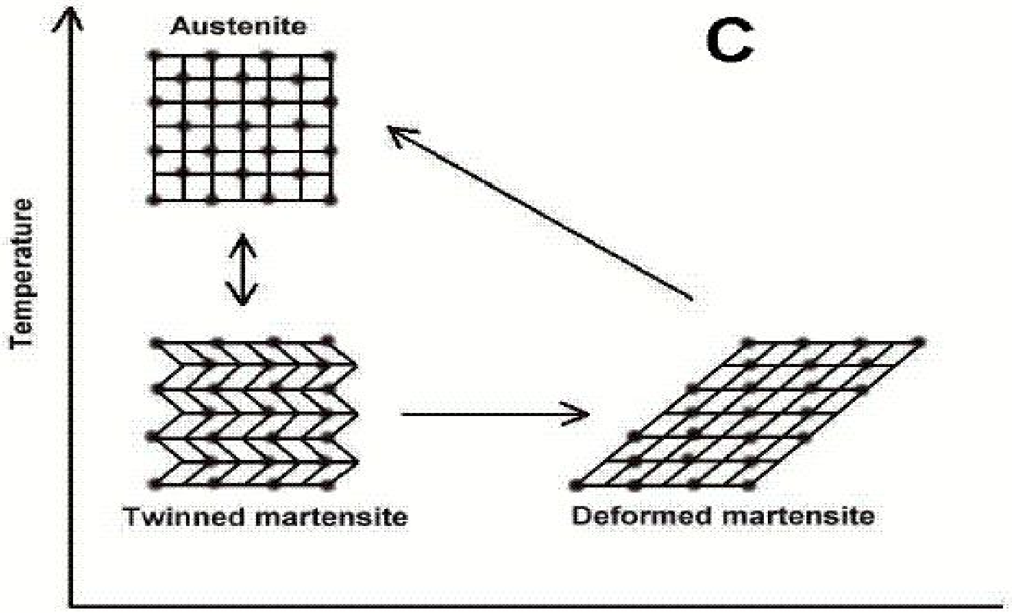


Figure 4.41: Transformation from the austenite to the martensite phase and shape memory effect. The high-temperature austenitic structure undergoes twinning as the temperature is lowered. This twinned structure is called martensite. The martensitic structure is easily deformed by outer stress into a particular shape, and the crystal structure undergoes parallel registry. When heated, the deformed martensite resumes its austenitic form, and the macroscopic shape memory phenomenon is seen.

4.6 Superelasticity

Super-elasticity (or pseudo- elasticity) refers to the ability of NiTi to return to its original shape upon unloading after a substantial deformation. This is based on stress-induced martensite formation. The application of an outer stress causes martensite to form at temperatures higher than Ms. The macroscopic deformation is accommodated by the formation of martensite. When the stress is released, the martensite transforms back into austenite and the specimen returns back to its original shape (Figure 4.61). Super-elastic NiTi can be strained several times more than ordinary metal alloys without being plastically deformed, which reflects its rubber-like behaviour. It is, however, only observed over a specific temperature area. The highest temperature at which martensite can no longer stress induced is called M_d. Above M_d NiTi alloy is deformed like ordinary materials by slipping. Below A_s, the material is martensitic and does not recover. Thus, super-elasticity appears in a temperature range from near A_f and up to M_d. The largest ability to recover occurs close to A_f (Duerig *et al.* 1996).

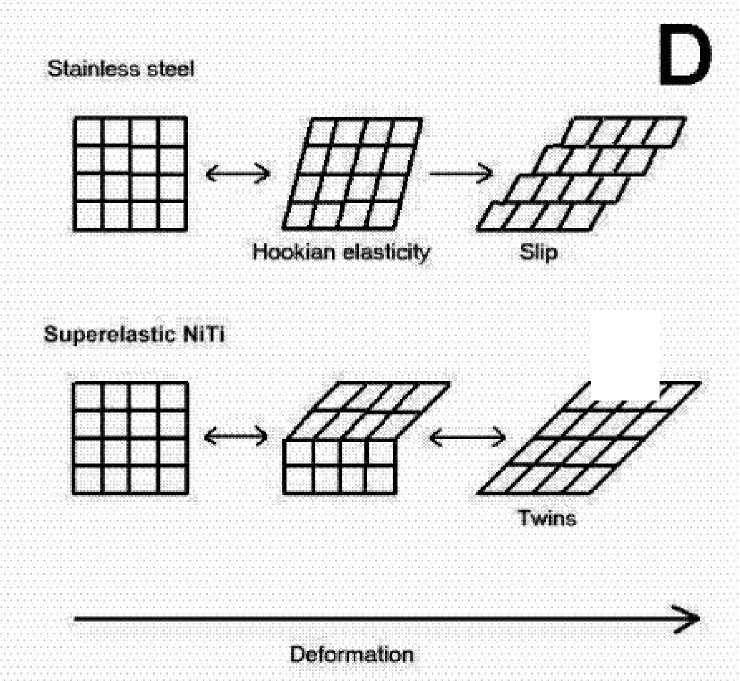


Figure: 4.61: Schematic presentation of lattice structure changes caused by outer stress in stainless steel or superelastic NiTi alloy. In stainless steel, outer stress first causes reversible Hookian type changes in the elastic area. In the plastic area, deformation takes place via a mechanism called slip. This deformation is irreversible. In superelastic NiTi alloy, outer stress causes a twinning type of accommodation which is recovered when outer stress is removed.

4.7 Limitations of shape memory and superelastic behavior

About 8% strain can be recovered by unloading and heating. Strain above the limiting value will remain as a permanent plastic deformation. The operating temperature for shape memory devices must not move significantly away from the transformation range, or else the shape memory characteristics may be altered. A shape memory NiTi implant must be deformed at a temperature below A_s (usually < +5 °C). Moreover, the deformation limit determined by distinctive implant design (sharp angles, etc.) and the intrinsic strain tolerance of NiTi material must not be disregarded (Otsuka & Wayman 1998).

4.8 Mechanical properties of NiTi

For orthopedic biomaterial applications, the two properties of major importance are strength (mechanical) and reactivity (chemical). Generally, there are two basic mechanical demands for the material and design of the implant. Service stresses must be safely below the yield strength of the material, and in cyclic loads the service stress must be kept below the fatigue limit (Figure 4.81).

The mechanical properties of NiTi depend on its phase state at a certain temperature (Buehler *et al.* 1967, Van Humbeeck *et al.* 1998) (Figure 4.41). Fully austenitic NiTi material generally has suitable properties for surgical implantation. The common mechanical properties of martensitic and austenitic NiTi are presented in Table 4.81. There are some exceptional properties that might be useful in surgery. NiTi has an ability to be highly damping and vibration-attenuating below A_s. For example, when a martensic NiTi ball is dropped from a constant height, it bounces only slightly over half the height reached by a similar ball dropped above the A_f temperature. From the orthopedic point of view, this property could be useful in, for example, dampening the peak stress between the bone and the articular prosthesis. The low elastic modulus of NiTi (which is much closer to the bone elastic modulus than that of any other implant metal) might provide benefits in specific applications. NiTi has unique high fatigue and ductile properties, which are also related to its martensitic transformation. These properties are usually favorable in orthopedic implants. Also, very high wear resistance has been reported compared to the CoCrMo alloy (Sekiguchi 1987). NiTi is a non-magnetic alloy. MRI imaging is thus possible. Electrical resistance and acoustic damping also change when the temperature changes.

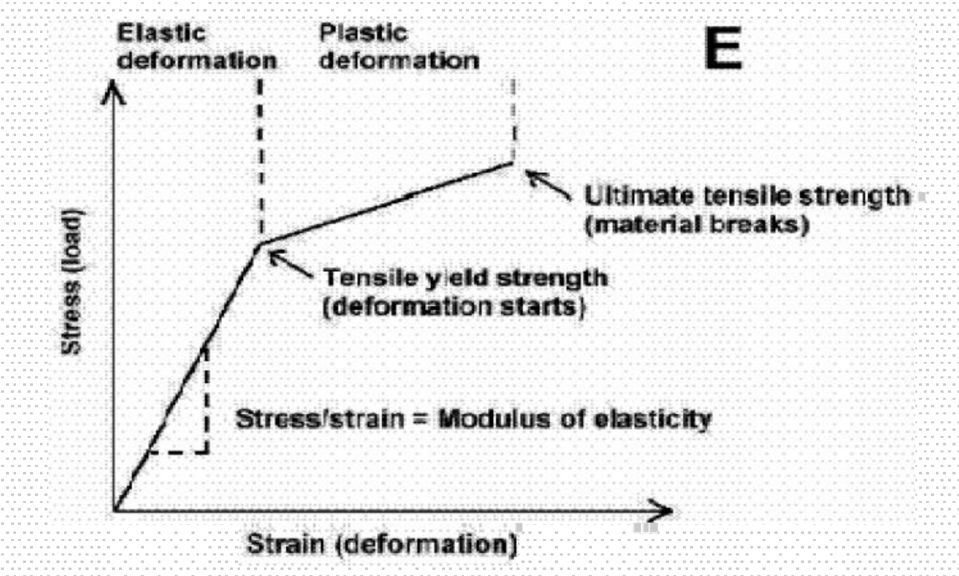


Figure: 4.81: E) Schematic presentation of the stress-strain behavior ordinary implant metals. The material exhibits elastic behavior until sufficient stress is applied to reach the tensile yield strength, at which point permanent deformation occurs. In the elastic range, the stress-strain ratio determines the elastic modulus. The metal breaks when the applied stress exceeds the ultimate tensile strength of the particular material

Table 4.81: Selected mechanical properties of NiTi, implant stainless steel (316LVM), titanium (cp-Ti, grade IV) and Ti-6Al-4V alloy.

	NiTi		**Stainless Steel**	**Titanium**	**Ti-6Al-4V**
	Austenitic	**Martensitic**			
Ultimate tensile strength (Mpa)	800 - 1500	103 - 1100	483 - 1850	540 - 740	920 - 1140
Tensile yield strength (Mpa)	100 - 800	50 - 300	190 - 1213	390	830 - 1070
Modulus of elasticity (GPa)	70 - 110	21 - 69	190 - 200	105 - 110	100 - 110
Elongation at failure (%)	1 - 20	up to 60	12 - 40	16	8

* **Lowest and highest values have been compiled from picked references (Buehler I. 1967, Funakubo 1987, Breme *et al*. 1998, Van Humbeeck *et al*. 1998).**

4.9 Effect of alloy composition, heat treatment and mechanical working on NiTi properties

It is feasible to vary the critical transition temperatures either by small variations of the Ti/Ni composition or by substituting metallic cobalt for nickel. Lowering of A_f is possible by adding nickel. If nickel is added above 55.6 Wt%, a stable second phase (Ti-Ni3) forms and the NiTi properties are lost. To avoid this problem, the cobalt substitution can be used to lower the TTR. The properties of NiTi can also be greatly modified by mechanical working and through heat treatment (time and temperature) (Buehler *et al.* 1967).

4.10 Fabrication

Solid NiTi alloys are manufactured by a double vacuum melting process, to ensure the quality, purity and properties of the material. After the formulation of raw materials, the alloy is vacuum induction melted (1400°C). After the initial melting, the alloy transition temperature must be controlled due to the sensitivity of the transition temperature to small changes in the alloy chemistry. This is followed by vacuum arc re-melting to improve the chemistry, homogeneity and structure of the alloy. Double-melted ingots can be hot-worked (800°C) and cold-worked to a wide range of product sizes and shapes (Andreasen *et al.* 1987).

Porous NiTi can be made by sintering or using self-propagating high temperature synthesis, also called ignition synthesis. The possibility to make composite SMA products (combination with polymers) is under investigation (Brailovski *et al.* 1996).

4.11 Programming (Training)

The use of the one-way shape memory or superelastic property of NiTi for a specific application requires a piece of NiTi to be molded into the desired shape. The characteristic heat treatment is then done to set the specimen to its final shape. The heat treatment methods used to set shapes in both the shape memory and the superelastic forms of NiTi are similar. Adequate heat treatment parameters (temperature and suitable time) are needed to set the shape and the properties of the item (Otsuka & Wayman 1998). They must usually be determined experimentally for the requirements of each desired part. Rapid cooling of some kind is preferred, such as water quenching or rapid fluid cooling.

The two-way shape memory training procedure can be made by SME training or SIM training. In *SME training,* the specimen is cooled below M_f and bent to the desired shape. It is then heated to a temperature above A_f and allowed freely to take its austenite shape. The procedure is repeated 20-30 times, which completes the training. The sample now assumes its programmed shape upon cooling under M_f and to another shape when heated above A_f.

In *SIM training,* the specimen is bent just above Ms to produce the preferred variants of stress-induced martensite and then cooled below the Mf temperature. Upon subsequent heating above the A_f temperature, the specimen takes its original austenitic shape. This procedure is repeated 20-30 times.

4.12 Use of NiTi SMA's for a Shape Memory Smart Impeller

In this particular study the shape memory effect exhibited by NiTi shape memory alloys will be utilized in the description of the Shape Memory Smart Impeller. It is thus believed that as the temperature of the fluid being pumped through the system is increased, the change in temperature will induce a phase transformation in the NiTi blade from Martensite to the parent phase, Austenite. The parent phase will have the shape and geometry of an optimal blade inlet angle thus increasing the flow rate through the system. Once the fluid temperature has decreased to its normal operating conditions the blades will revert to their normal operating shape and geometry.

CHAPTER FIVE

DEVELOPMENT OF A SHAPE MEMORY SMART IMPELLER

5.1 Analytical Approach to determine hydro-dynamic loading on centrifugal pump impellers

As discussed earlier, the centrifugal pump work on the principle of force vortex flow, i.e. when a mass of fluid is rotated due to an external torque, a rise in the fluid pressure head occurs. This rise in pressure head is proportional to the square of the tangential velocity of the liquid and is given at each point of the rotating fluid [43] as:

Rise in Pressure = $\frac{V^2}{2g} = \frac{\omega^2 r^2}{2g}$ or $\left[\frac{\omega^2}{2g}\right] r^2$

If we consider a centrifugal pump impeller rotating at a constant angular velocity of 1200rpm, the pressure within the system increases as the impeller radius increases (see Fig. 5.11 below), thus delivering the fluid to a higher level (increase in fluid head).

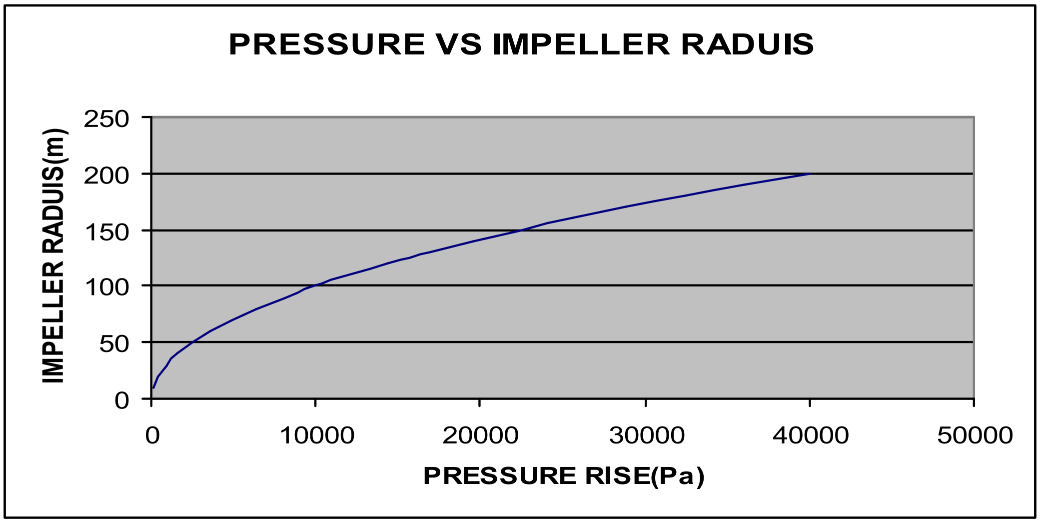


Figure 5.11: Impeller radius versus pressure rise.

In a similar way the work done by the impeller can be calculated using velocity triangles (see Fig. 5.12 below) at both the inlet and outlet of the centrifugal pump impeller blades. Fluid enters the impeller radially and to obtain optimal efficiency of the system the absolute inlet velocity should enter the blades at 90^0 to the direction of motion of the impeller.

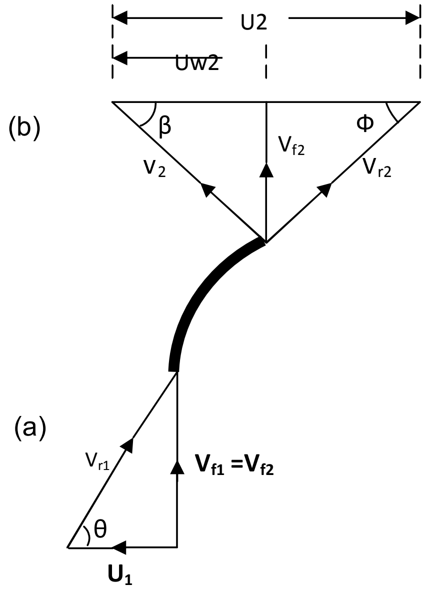


Figure 5.12: Velocity triangles – a) at blade inlet, and b) at blade outlet

Where,

N = speed of impeller in rpm

D = diameter of impeller at inlet.

U_1 = tangential velocity of impeller at inlet.

$$U_1 = \frac{\pi D_1 N}{60}$$

D_2 = diameter of impeller at outlet.

U_2 = tangential velocity of impeller at outlet

$$U_2 = \frac{\pi D_2 N}{60}$$ [41]

V_1 = Absolute velocity of water at inlet

Vr_1 = Relative velocity of water at inlet

α = angel made by the absolute velocity (V_1) at inlet with the direction of motion of vane

θ = Angle made by relative velocity (Vr_1) at inlet with the direction of motion of vane, and V_2 Vr_2 $\beta \& \phi$ are corresponding values at values at outlet.

As the water enters the impeller radially which means the absolute velocity of water at inlet is in the radial direction and hence $\alpha = 90^0$ and $V_{w_1} = 0$

Work done by impeller on water per second per unit weight of water sticking per second

$$= \frac{1}{g}\left[Vw_2U_2 - Vw_1U_1\right]$$ [41]

Since $V_{w_1} = 0$ $\Rightarrow \frac{1}{g}Vw_2U_2$

If W = weight of water = $\rho g Q$

where

Q = Flow rate, and

Work done by impeller on water per second = $\frac{W}{g}.Vw_2U_2$

Q = Area x Velocity of flow

= $\pi D_1 B_1 \times Vf_1$

= $\pi D_2 B_2 \times Vf_2$

B_1 and B_2 are width of impeller at inlet and outlet

Vf_1 and Vf_2 are velocity of flow at inlet and outlet

If we now consider a centrifugal pump impeller rotating at 1500rpm with inside and outside diameters of 100mm and 200mm respectively. If the fluid enters the impeller radially, and the impeller blade inlet and outlet angles are 20^0 and 30^0 respectively we may determine the workdone by the impeller on the fluid per unit weight of fluid as 17, 23 Nm/N. If we now vary the impeller outlet blade angle from 5^0 to 90^0 with increments of 5^0 and holding all other terms constant we obtain relationships for

- outlet blade angle versus relative inlet velocity (for constant inlet angle of 20^0); see Fig 5.13

- outlet blade angle versus relative outlet velocity (for constant inlet angle of 20^0); see Fig 5.14
- outlet blade angle versus Work Done (for constant inlet angle of 20^0); see Fig 5.15

From Figs. 5.13 – 5.14 it is clear that increases in the outlet angle (while keeping the inlet angle constant) will increase the relative inlet velocity, the relative outlet velocity, and Work Done on the fluid.

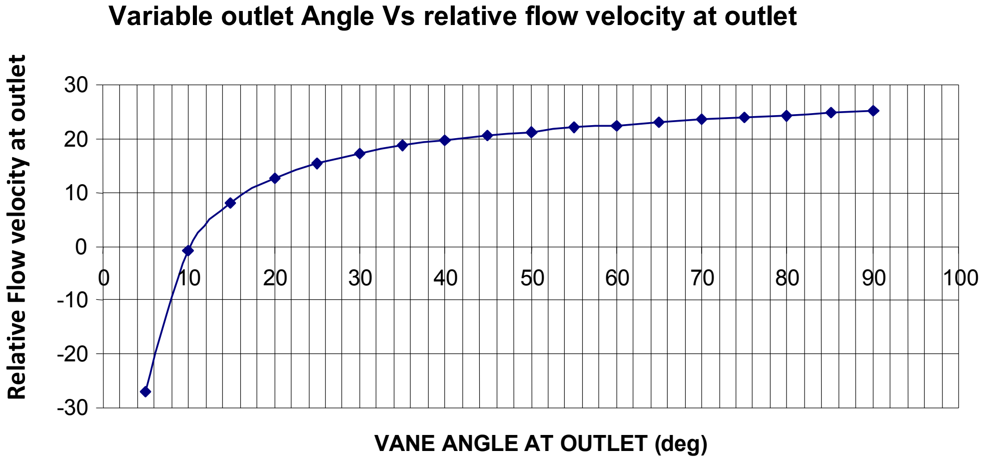


Figure: 5.13: A graph of Variable outlet angle versus relative flow velocity for a constant vane inlet angle of 20 degrees.

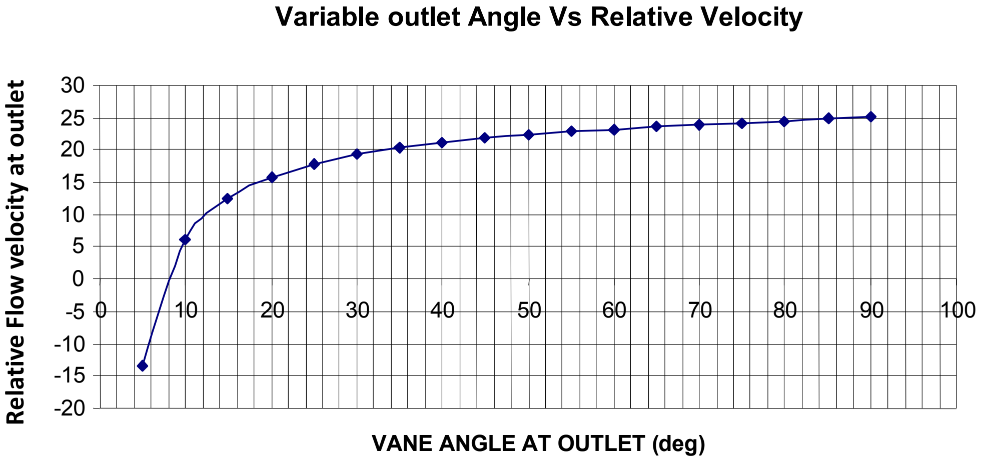


Figure 5.14: A graph of Variable outlet angle versus relative velocity at outlet for a constant vane inlet angle of 15 degrees.

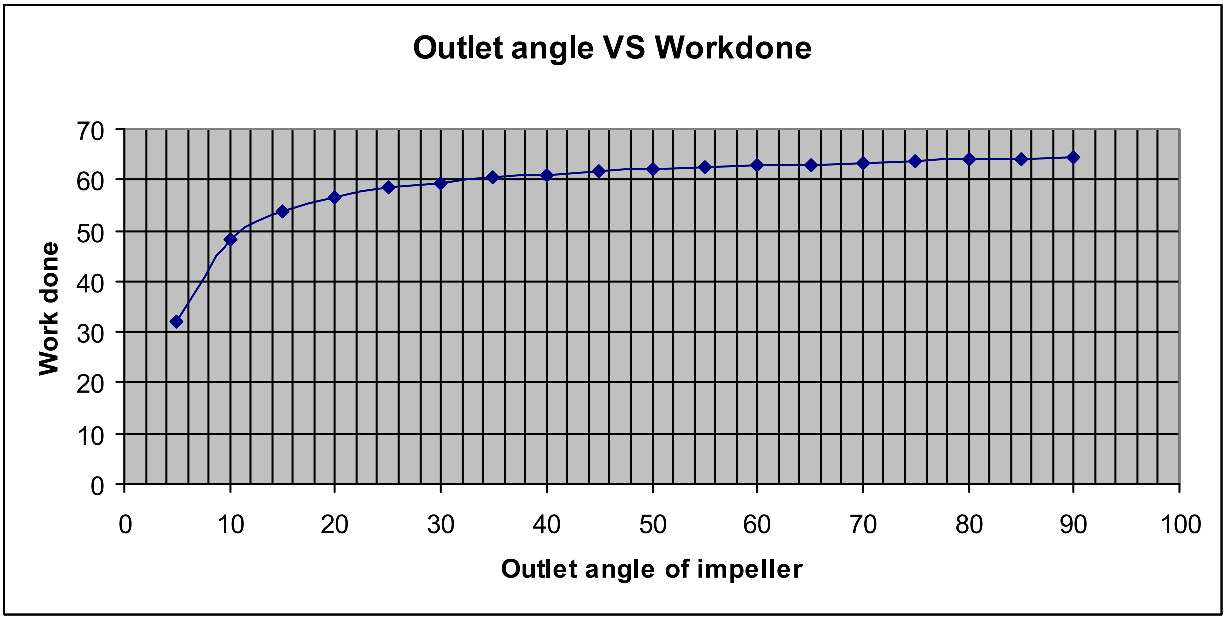


Figure 5.15: A graphs of Variable outlet angle versus work done for a constant vane inlet angle of 5 degrees.

5.2 Using MATLAB to determine the optimal centrifugal impeller blade inlet and outlet angles for a specific application.

Water flows through a centrifugal pump having a rotating impeller (see Fig 5.21 below). This pump has a stationary axial inlet (the eye), a pipe section with a central body of circular arc contour, which turns the flow by 90 degrees from the axial direction. At the inlet's exit the radial water flow is sucked by a rotating impeller, which has seven untwisted constant-thickness backswept blades. Each blade is cambered from 30 degrees at the impeller inlet of 16 mm radius to range of 0 to 90 degrees at the impeller exit of 42 mm radius, both with respect to the radial direction. All variables were kept constant except for the impeller outlet which was varied from 30 to 55 degrees (see Fig 5.22, 5.23, 5.24 and 5.25). The inlet angle for the impeller was 30 degrees. These blades are confined between the impeller shrouding disks (see Fig 5.26) rotating with the same angular speed of 2000 rpm.

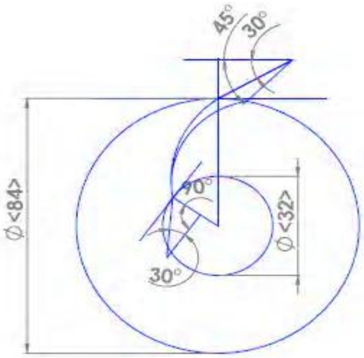


Figure 5.21: Basic construction of impeller

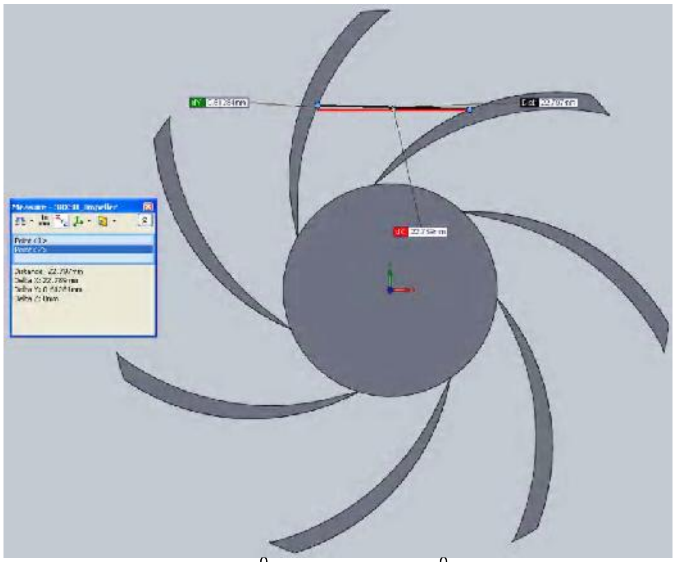


Figure 5.22: 30^0 Inlet Angle - 30^0 Outlet Angle

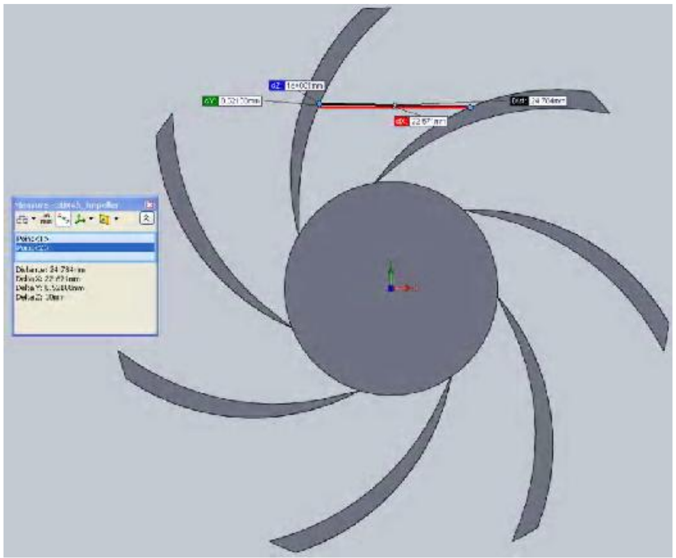


Figure 5.23: 30^0 Inlet Angle - 45^0 Outlet Angle

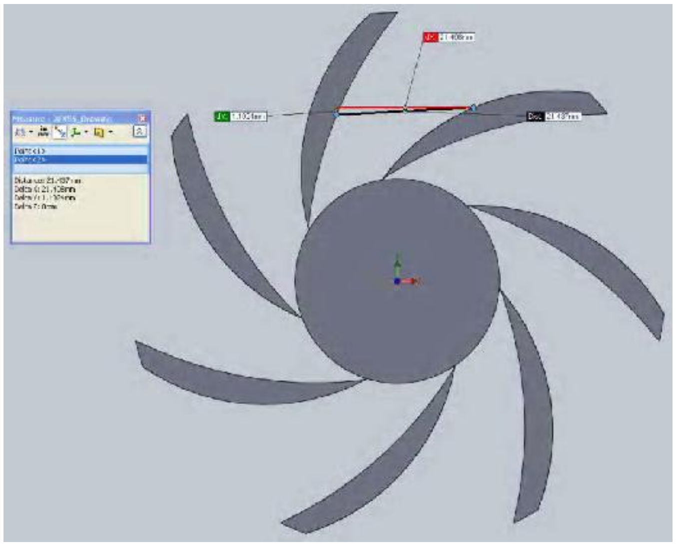


Figure 5.24: 30^0 Inlet Angle - 50^0 Outlet Angle

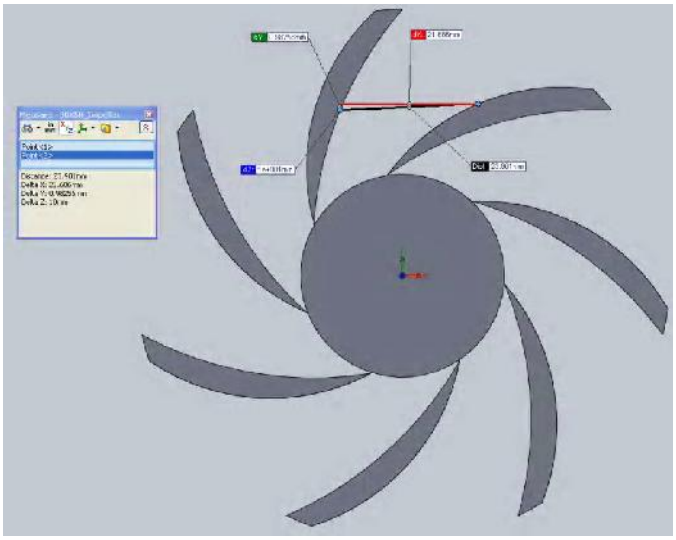


Figure 5.25: 30^0 Inlet Angle - 55^0 Outlet Angle

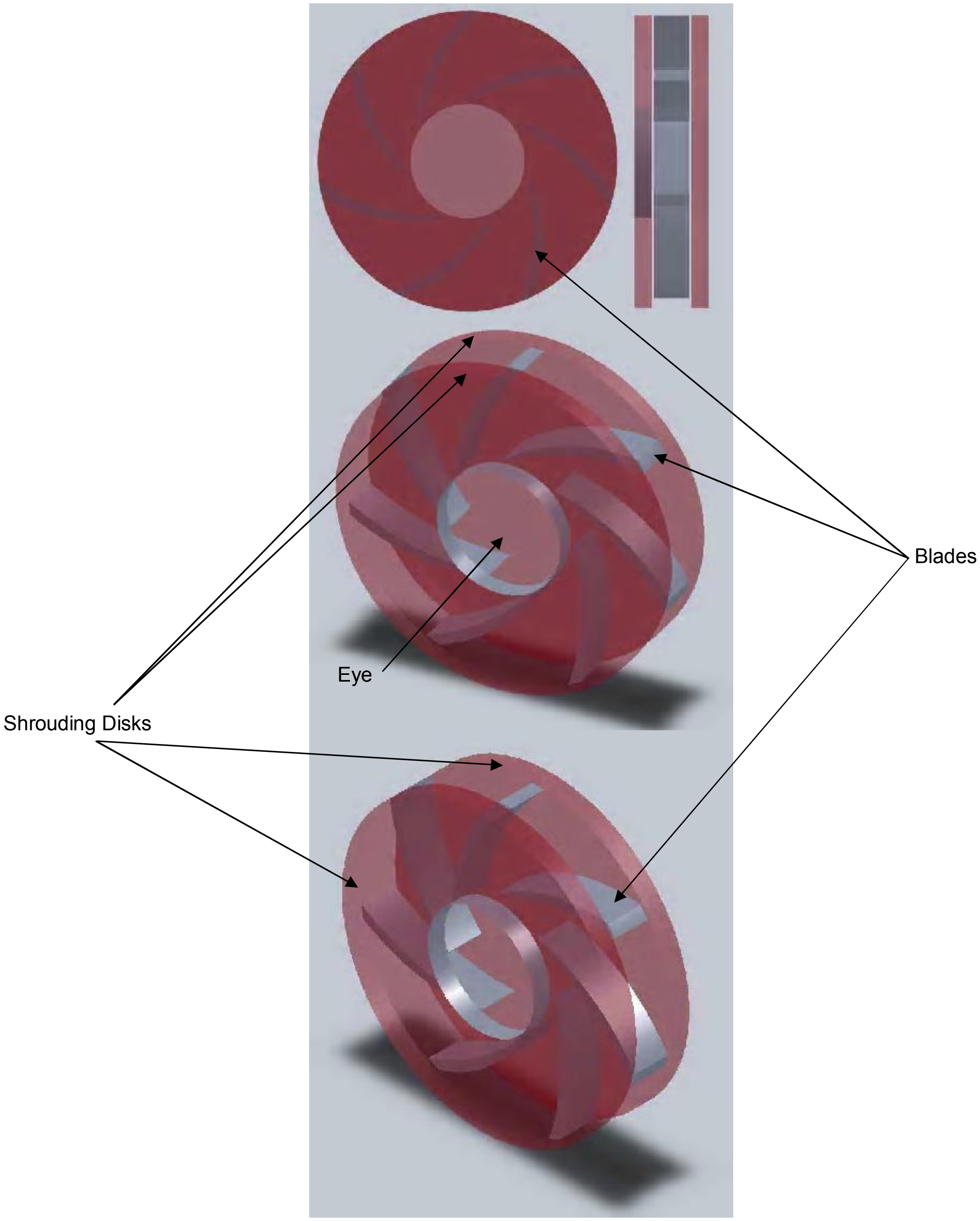


Figure 5.26: 3D Solid Model of Centrifugal Pump Impeller showing blades, eye, shrouding disks

5.2.1 MATLAB Solution Algorithm

The Matrix Laboratory routine within MatLab was used as a tool to aid the calculation process since conventional methods for calculations, i.e. small increments in the outlet angle, would be cumbersome. The proposed situation is that of a constant impeller inlet blade angle of attack of 30^0 while the impeller outlet angle varied from 30^0 to 55^0 with increments of 0.1^0. The results obtained looked at optimal angle of attack, velocity at outlet, and the work done for each specific angle of attack. The solution algorithm used here was that of the velocity triangle approach described above. The results obtained here will also be used to compare with results obtained from computational fluid dynamics as discussed in Chapter 6 & 7. The input and output request to Matrix Laboratory is provided the figures listed below.

Fig. 5.28 shows the work done by the impeller on the fluid for each increment in the impeller blade outlet angle, i.e. the blue line. The curve shows the results using the velocity triangle approach while the solid “straight” red line shows the “mean” value for the work done versus outlet angle of attack. The “mean” divides the graph (in Fig. 5.28) in three regions, i.e. regions 1, 2, and 3. Both regions 1 and 3 are below the mean line while region 2 lies above it. Using Matrix Laboratory we identify the optimum work done with its corresponding angle of attack, i.e. the green vertical line. This optimum point is also considered to give the best work done with corresponding angle of attack for this specific situation even though the angle of attack is increased. The best outlet angle for the situation described was obtained to be 43.3^0. Fig. 5.28 also shows that if we considers these operating conditions for our Shape Memory Smart Impeller, region 2 would be the ideal area for the angle of attack to vary. From pump theory it is also evident that increasing the angle of attack beyond 43.3^0 would have adverse performance on the efficiency of the systems as well as introduce an increase in the torque of the impeller shaft.

INPUT

INPUT NAMES

D_1 = Internal diameter of impeller in mm

D_2 = external Diameter of impeller in mm

N = speed of motor in rpm

a_1 = vane angle at inlet

a_2 = vane angle at outlet

V_{f1} = velocity of flow at inlet

V_{f2} = velocity of flow at outlet

U_1 = tangential velocity of impeller at inlet

U_2 = tangential velocity of impeller at outlet

& = angle made by absolute velocity at inlet with the direction of motion of vane.

Water enters radially & = 90 deg $V_{w1} = 0$

Where, vw = velocity of whirl at inlet.

$V_{f1} = V_{f2}$

INPUT DATA

$d_1 = 32$

$d_2 = 84$

n = 2000

$a_1 = 30$

$a_2 = 45$

OUTPUT

PRIMARY OUTPUT

$U_1 = p_i*d_1*N / 60$

$U_2 = p_i*d_2*N / 60$

$V_{f1} = U_1*\tan(p_i*a_1 / 180)$

$V_{f1} = V_{f2}$

$V_{f2} = U_1*\tan(p_i*a_1 / 180)$

a_2_rad = tan ($p_i * a_2 / 180$)

Ratio = V_{f2} / a_2_rad

$V_{w2} = U_2 - (V_{f2} / \tan(p_i * a_2 / 180))$

Work Done = $Y = V_{w2} * U_2 / 9.81$

SECONDARY OUTPUT

From inlet velocity triangle

$\tan(a_1) = V_{f1} / U_1$

From out velocity triangle

$\tan(a_2) = V_{f1} / (U_2 - V_{w2})$

END

OUTPUT REQUEST: RESULTS

Function w = graph (a_2)

Allow plotting of variables

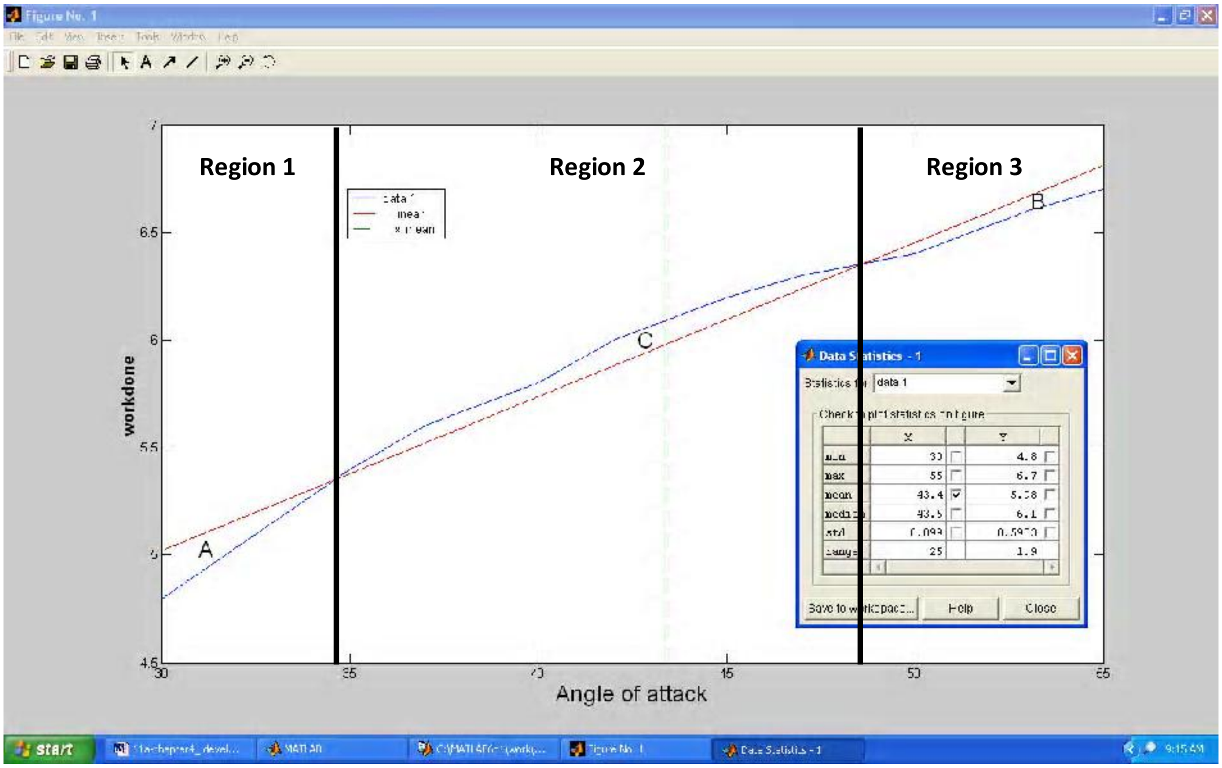
w=[4.8,5.4,5.6,5.8,6.0,6.2,6.3,6.4,6.6,6.7]

a2=[30,35,37,40,42,45,47,50,53,55]

Plot (a_2, w)

End

Figure 5.27: Input and Output request for MatrixLaboratory within Matlab



Statistics for: data 1

Check to plot statistics on figure

	X		Y	
min	30	☐	4.8	☐
max	55	☐	6.7	☐
mean	43.4	☑	5.78	☐
median	43.5	☐	6.1	☐
std	7.093	☐	0.5970	☐
range	25		1.9	

Figure 5.28: MATLAB work done versus outlet angle

5.3 Conceptualization of Shape Memory Smart Impeller

From discussions in sections 5.1 and 5.2, it is clear that changing the centrifugal impeller blade outlet angle increases outlet velocity and in turn the pressure head, as well as the work done by the impeller on the fluid passing through the system. The impellers presented above (see Figs. 5.22 – 5.25) were designed to have their outside blade sections remain identical while the inside blade section changes as the blade outlet angle is increased. If we now superimpose the 3D solid models of the 4 impellers, i.e. outlet blade angles from 30, 45, 50, and 55 degrees, we see that the fluid flow passage (horizontal measurement) is decreased as the outlet blade angle is increased (see Fig 5.31 below). This is also graphically presented in Fig 5.32. These measurements were taken using the 3D Solid Modeling software package, SolidWorks, and were measured from the middle of the inside blade to the center of rotation. For impeller blade outlet angles 45, 50, and 55 degrees the percentage decrease in the horizontal measure of fluid flow passage was determined as 1.086, 10.15, and 12.71 respectively.

From the discussion above it is clear that if we consider the entire blade or a section of it to be constituted of NiTi shape memory alloys and utilizing the shape memory effect it will be possible to change the blade outlet angle if the temperature of the fluid is increased above the NiTi specific A_s transition temperature, thus decreasing the fluid flow passage and increasing outlet velocity, pressure and work done by the impeller on the fluid.

Under normal operating conditions, the NiTi SMA will be in its softer martensitic phase. Any increase in the temperature of the fluid will then lead to the thermo-elastic phase transformation from martensite to austenite. The NiTi SMA should thus be trained to transform to the predefined shape of the 55 degree blade outlet angle on heating and revert back to the 30 degree outlet angle upon cooling (see Fig 5.34).

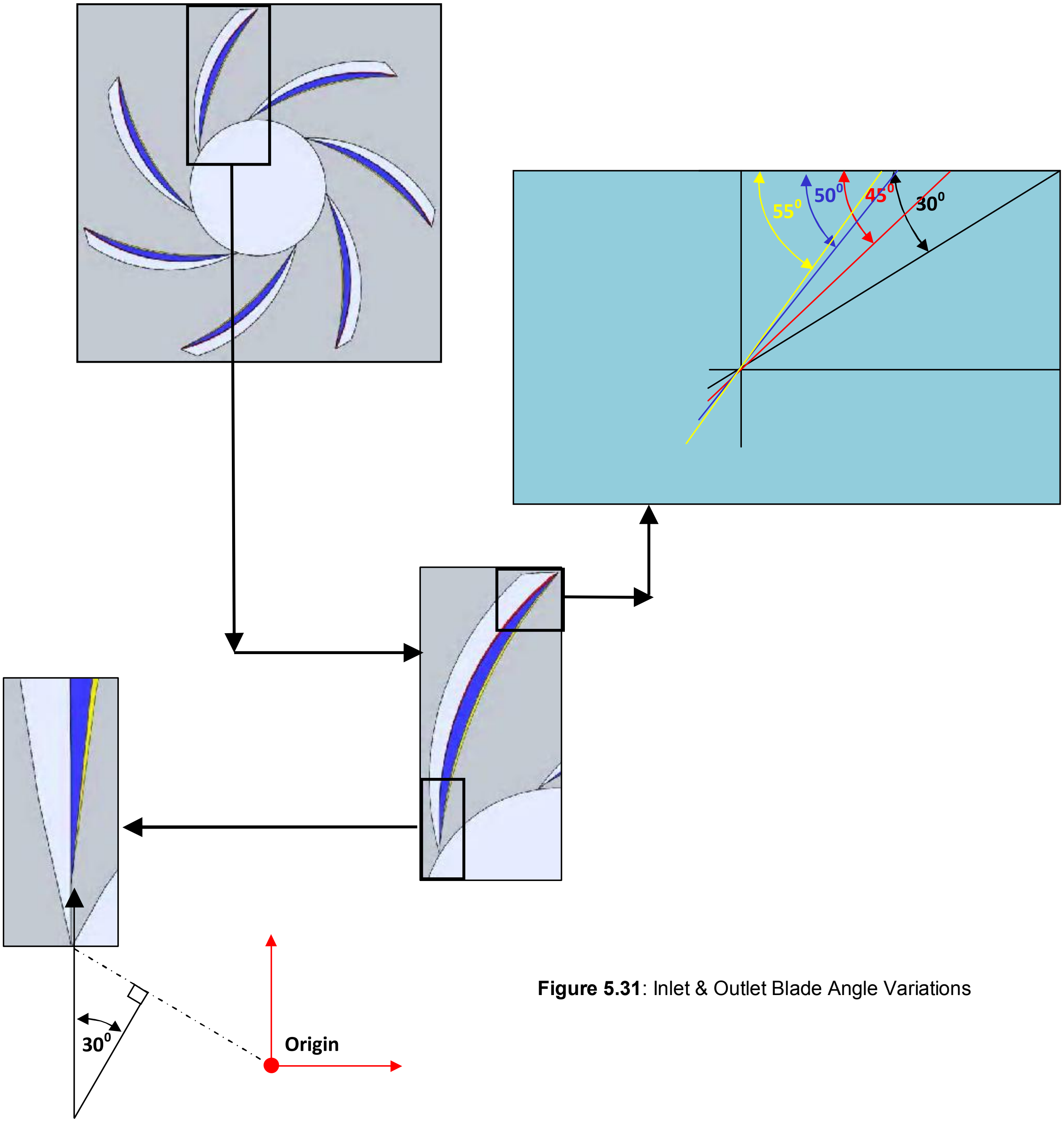


Figure 5.31: Inlet & Outlet Blade Angle Variations

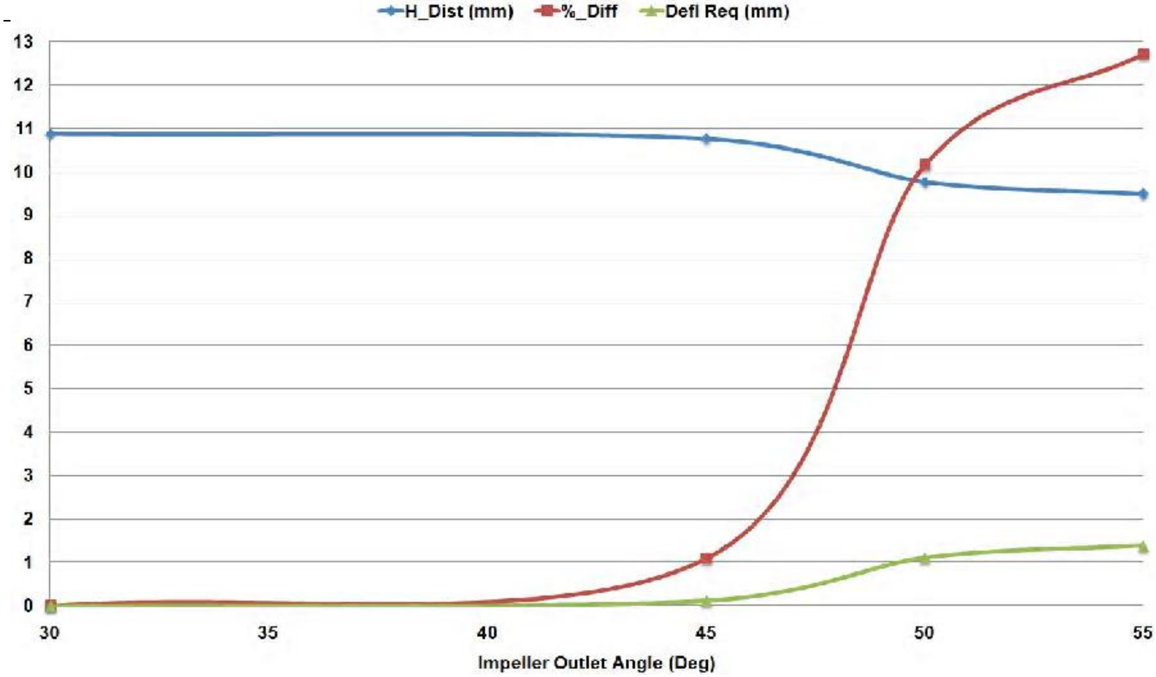
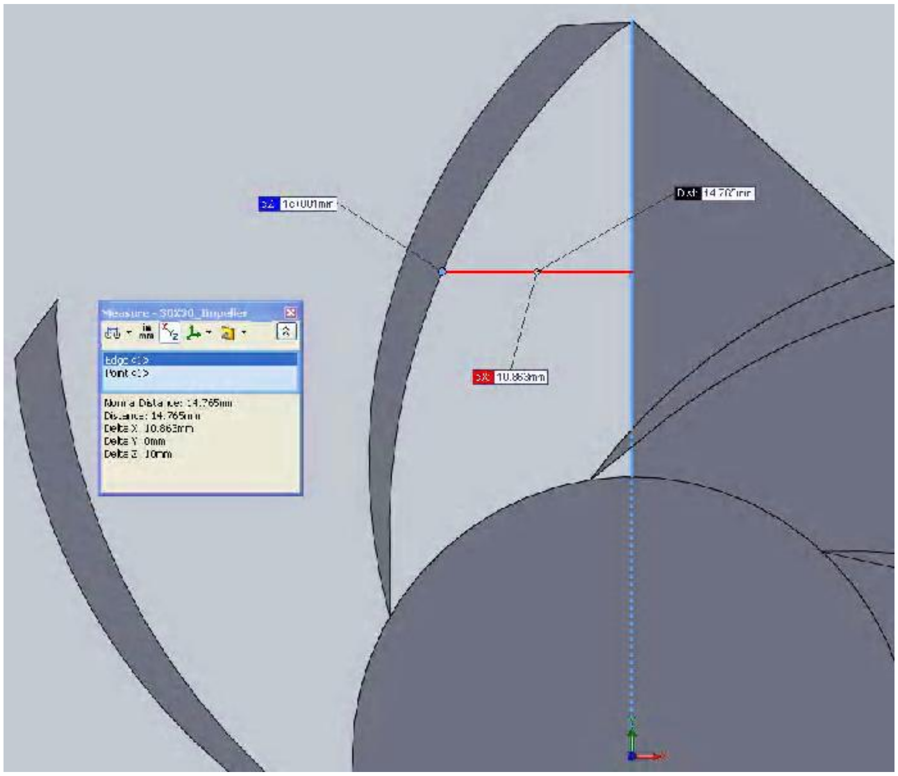


Figure 5.32: Dimensional Blade Angle Variations



Normal Distance: 14.765mm
Distance: 14.765mm
Delta X: 10.863mm
Delta Y: 0mm
Delta Z: 10mm

Figure 5.33: Horizontal measurement from Blade Angle Center to Center of Impeller Rotation

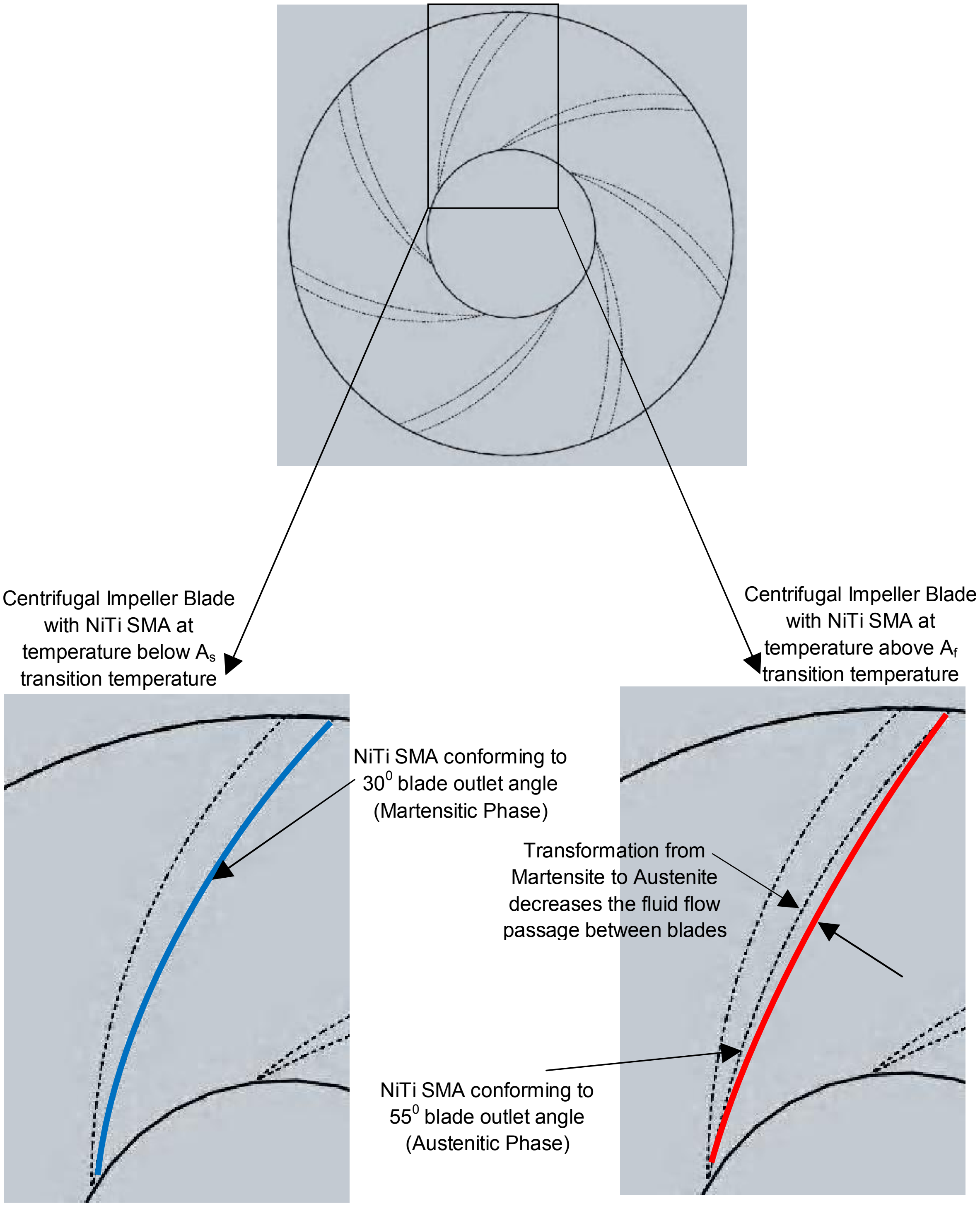


Figure 5.34: 1st Conceptual representation of the operating mechanism of the Shape Memory Smart Impeller

5.4 Structural Model

Considering the discussion above and now assuming that the NiTi strip is treated as a thin beam we find a possible solution to the operating mechanism of the Shape Memory Smart Impeller (see Fig 5.41 below). At normal operating conditions, i.e. temperatures below A_s temperature, the NiTi thin beam assumes the inner shape of the impeller blade, i.e. 30^0 inlet angle and 30^0 outlet angle. Any change in the fluid temperature to above A_s and A_f will result in the NiTi SMA transforming from its low temperature martensitic state to the high temperature austenitic state. The latter state would be set to conform to the blade angle for 30^0 inlet angle and 55^0 outlet angle. Furthermore it will be assumed that the free end (see Fig 5.41) moves within a guide until the final state is achieved.

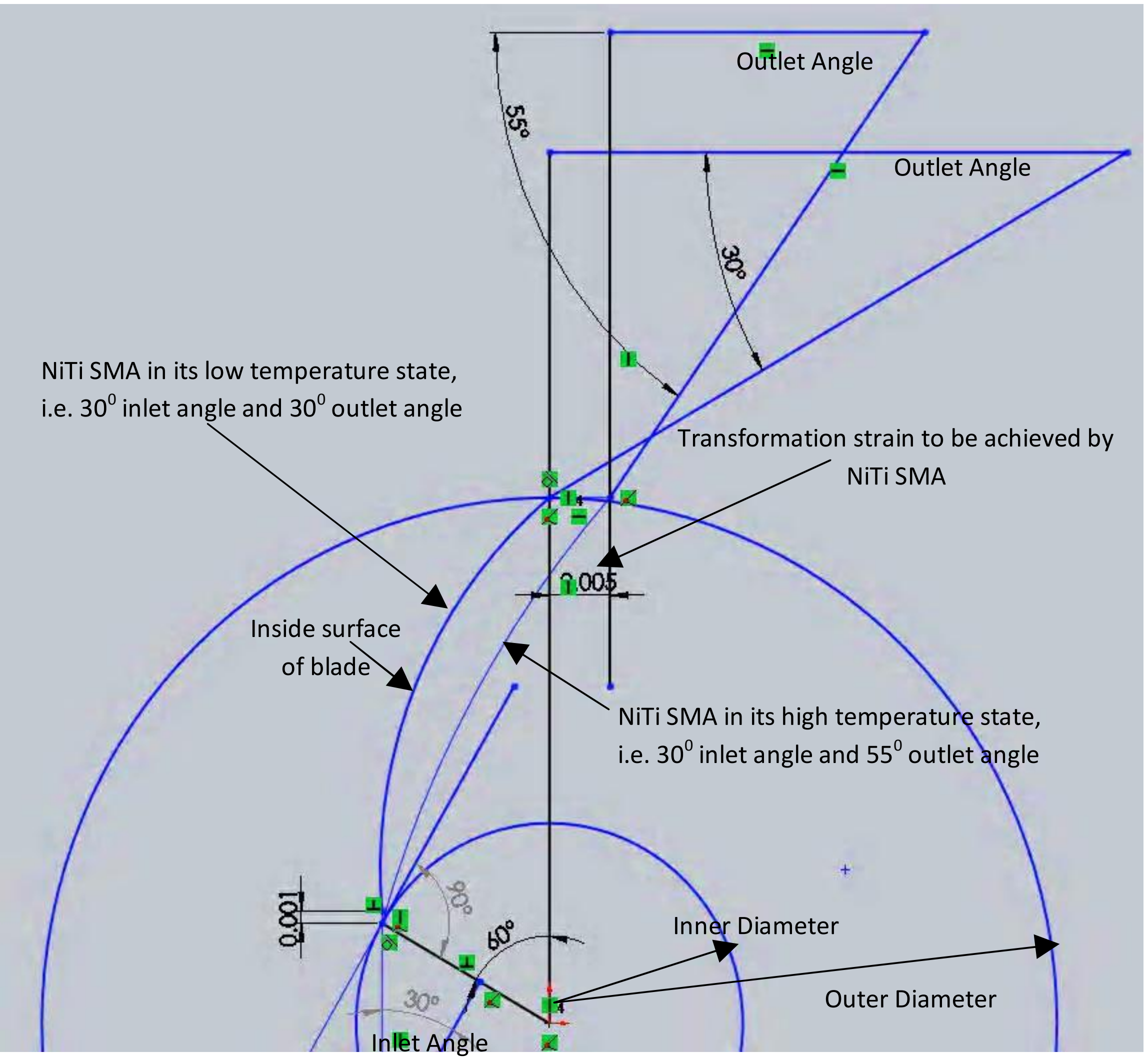


Figure 5.41: Operating mechanism of the Shape Memory Smart Impeller

The above assumptions place the solution to this particular in the area of thin beam theory with an initial curvature. We can then assume end conditions for the particular problem to be one end (at inlet) of the thin beam is fixed and the other end (at outlet) is restrained against rotation (see Fig 5.42).

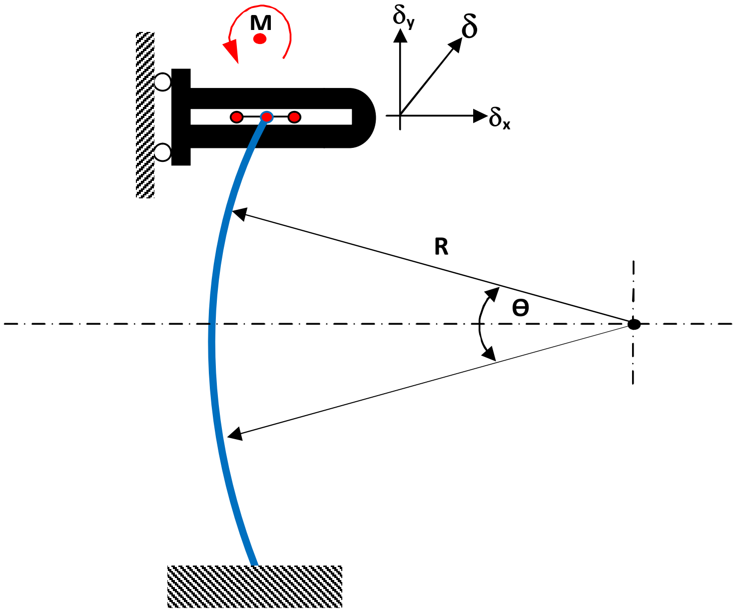


Figure 5.42: Idealized model of operating mechanism of the Shape Memory Smart Impeller

The configuration presented in Fig 5.42 gives the circumferential normal stress as

$$\sigma = \frac{My}{Aer}$$ [46] (5.41)

Where M is the applied bending moment, A is the area of the cross section, e is the centroidal distance of the specific area's to the neutral axis, and y and r locate the radial position of the desired stress from the neutral axis and the center of the curvature (see Fig 5.43).

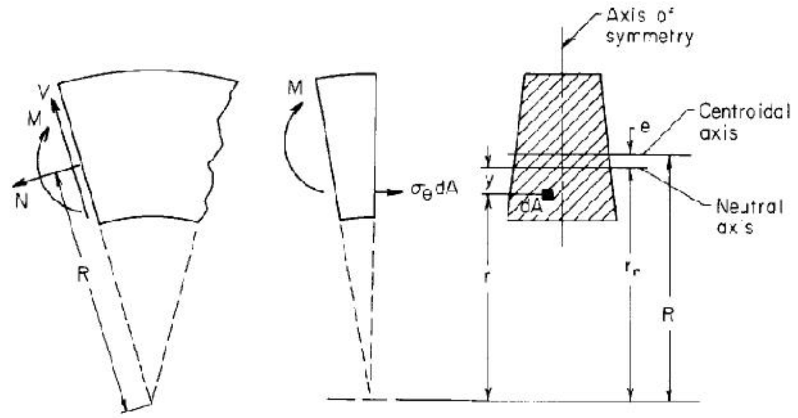


Figure 5.43: Internal loading present in a loaded curved beam

If we further assume that for our specific beam problem, $\frac{R}{d} > 8$, then

$$\mathbf{e} \approx \frac{\mathbf{I}}{\mathbf{RA}} \tag{5.4.2}$$

where, d is the width of the beam, I area moment of inertia of the cross section about the centroidal axis. Since the angular distortion, horizontal and vertical reactions are zero at the movable end of our beam presented in Fig 5.42, the analytical formulations for reactions and deformations for the configuration described in Fig 5.42 is given as [46]

$$\frac{\mathbf{M}}{\mathbf{R}} = \frac{\mathbf{LF_M}}{\mathbf{B_{MM}}} \tag{5.4.3}$$

$$\delta_{\mathbf{H}} = \frac{\mathbf{R^3}}{\mathbf{EI}}\left(\mathbf{B_{HM}}\frac{\mathbf{M}}{\mathbf{R}} - \mathbf{LF_H}\right) \tag{5.4.4}$$

$$\delta_{\mathbf{V}} = \frac{\mathbf{R^3}}{\mathbf{EI}}\left(\mathbf{B_{VM}}\frac{\mathbf{M}}{\mathbf{R}} - \mathbf{LF_V}\right) \tag{5.4.5}$$

where $(\mathbf{LF_M})$, $(\mathbf{LF_E})$ and $(\mathbf{LF_V})$ are loading terms to be evaluated for a given situation.

$$B_{HM} = -2\theta c + k_2 2s \tag{5.4.6}$$

$$B_{VM} = 2\theta s \tag{5.4.7}$$

and

$$c = \cos\theta \tag{5.4.8}$$

$$s = \sin\theta \tag{5.4.9}$$

$$k_2 = 1 - \frac{I}{AR^2} \tag{5.4.10}$$

5.5 Constitutive Modeling of NiTi Shape Memory Alloys.

As discussed in section 5.4, the shape memory effect exhibited by shape memory alloys will be utilized to affect actuation of the Shape Memory Smart Impeller. At normal operating conditions, i.e. fluid temperatures below austenite start temperature, the NiTi insert will conform to the shape of a blade with 30^0 inlet angle and 30^0 outlet angle. If the temperature of the water increases to above the austenite start temperature and continues to rise to austenite finish temperature thus fully transforming martensite to austenite, the NiTi insert will take the form of a blade with 30^0 inlet angle and 50^0 outlet angle. Considering the configuration presented in Fig 5.42, the transformation strain is thus equal to the displacement, δ, of the curved beam. This shape change due to the temperature increase causes an internal stress to be developed in the NiTi insert equal to the circumferential stress, $\sigma = \frac{My}{A_e r}$, discussed in section 5.4.

Constitutive models developed for shape memory alloys have followed different approaches [ ]. In this study however, the Brinson model [ ] will be used. This model uses constant material functions and offers the advantage of capturing the thermomechanical behavior of SMA's at any temperature and includes in its expression quantifyable engineering quantities and material properties. Based on the energy balance law, the constitutive relation for SMA's according to the Brinson model [45] is given as:

$$\sigma - \sigma^{0} = \mathbf{E}(\xi)\varepsilon - \mathbf{E}(\xi^{0})\varepsilon^{0} + \Omega(\xi)\xi - \Omega(\xi^{0})\xi^{0} + \Theta(T - T^{0}) \qquad (5.5.1)$$

where the quantities in the initial state is given by the suffix ^{0}, and the actual quantities without the suffix. The terms or quantities in equ. 5.5.1 is given as follows:

- $\mathbf{E}$ is the Young's modulus, and is given in terms of a linear function of the martensite phase as $\mathbf{E} = \mathbf{E_A} + \xi(\mathbf{E_M} - \mathbf{E_A})$ with E_A and E_M representing the 100% austenite and 100% martensite Young's Moduli respectively.
- ξ represent the martensite phase fraction present in the material and is composed of two types, i.e. thermally transformed and stress induced, given as $\xi = \xi_T + \xi_S$.
- Ω represent a so called transformation tensor, related to Young's Modulus, and is given in the form $\Omega\left(\xi\right) = -\varepsilon_{\mathbf{T_r}}\mathbf{E}(\xi)$. $\varepsilon_{\mathbf{T_r}}$ is the maximum transformation strain and for this particular situation assumed to be related to the displacement, δ , of the curved beam.
- The final term in equ 5.5.1, $\Theta(\mathbf{T} - \mathbf{T^{0}})$ is related to the thermal strain generated in the SMA due to the rise in temperature and Θ is equivalent to the thermal expansion of the SMA.

If we now assume that when the material is in its initial state it is free from stress, in a fully twinned mareinsitic state, and that the elastic strain components are negligible compared to the transformation strain, then equ 5.5.1 is dependant only on thermal and transformation strains and is reduced to

$$\sigma = \Omega\{\xi\}\xi + \Theta(T - T^0) \qquad (5.5.2)$$

The mechanism of actuation for our smart impeller is driven purely by thermal changes, i.e. increases in temperature from A_s to A_f will transform the twinned martensite to austenite, thus causing the shape change from a 30^0 inlet angle and 30^0 outlet angle to 30^0 inlet angle and 55^0 outlet angle. In the reverse transformation, i.e. a decrease in temperature from M_s to M_f, will transform the austenite back to twinned martensite and the SMA reverts back to the 30^0 inlet angle and 30^0 outlet angle.

If we assume that the transformation is not dependant on stress, Brinson [45] proposed the following relations associated ξ and $\mathbf{T}$ for equ 5.5.2.

For the conversion to Austenite

$$\xi_{M\rightarrow A} = \frac{\xi}{2}[\cos[a_A(T - A_s)]+1] \qquad (5.5.3)$$

where $a_A = \frac{\pi}{(A_f - A_s)}$ and holds for $T > A_s$

For the conversion to Martensite

$$\xi_{A\rightarrow M} = \frac{1-\xi}{2}[\cos[a_M(T - M_f)]+1] \qquad (5.5.4)$$

where $a_M = \frac{\pi}{(M_s - M_f)}$ and holds for $M_f < T < M_s$ and $T < T^0$, else $\xi_{A\rightarrow M} = 0$

The total transformation displacement [ ] is further given as

$$\delta = \delta_A + \xi_{A\_M}(\delta_M - \delta_A) \qquad \text{for transformation to austenite} \qquad (5.5.5)$$

and

$$\delta = \delta_A + \xi_{M\_A}(\delta_M - \delta_A) \qquad \text{for transformation to martensite} \qquad (5.5.6)$$

with

$$\delta = \sqrt{(\delta_x)^2 + (\delta_y)^2} \qquad (5.5.7)$$

In equs 5.5.5 and 5.5.6, Δ_A and Δ_M represents the transformation deformation of each phase. The components of displacement in equ 5.5.7, i.e. Δ_x and Δ_y, represent the horizontal and vertical movement at the free end of the curved SMA insert.

5.6 Numerical Illustration

Consider the diagrams in Fig 5.61 (a) and (b). It shows the Shape Memory Smart Impeller at low temperature, Fig 5.61 (a), and high temperature, Fig 5.61 (b) conditions. At low temperature conditions, the span of the NiTi SMA blade insert is given as $S_1 = R_1\theta_1$ and at high temperature it is given as $S_2 = R_2\theta_2$, i.e. phase transformation changes the blade from state 1 to state 2. The NiTi SMA blade insert is displace through both vertical, (δ_y), and horizontal, (δ_x), directions to produce the total displacement, (δ), of the insert (see Fig 5.62). The transformation strain is thus given as $\varepsilon_{Tr} = \frac{S_2\theta_2 - S_1\theta_1}{(S_1\theta_1)}$. Equs 5.55 – 5.57 is then used to determine the displacement and its components at different temperatures and phase fractions. Figs 5.63 and 5.64 shows the solution algorithms used to solve for martensite phase fraction, Young’s Modulus, transformation strain, bending stress, and loading terms as functions of temperature and martensite phase fraction.

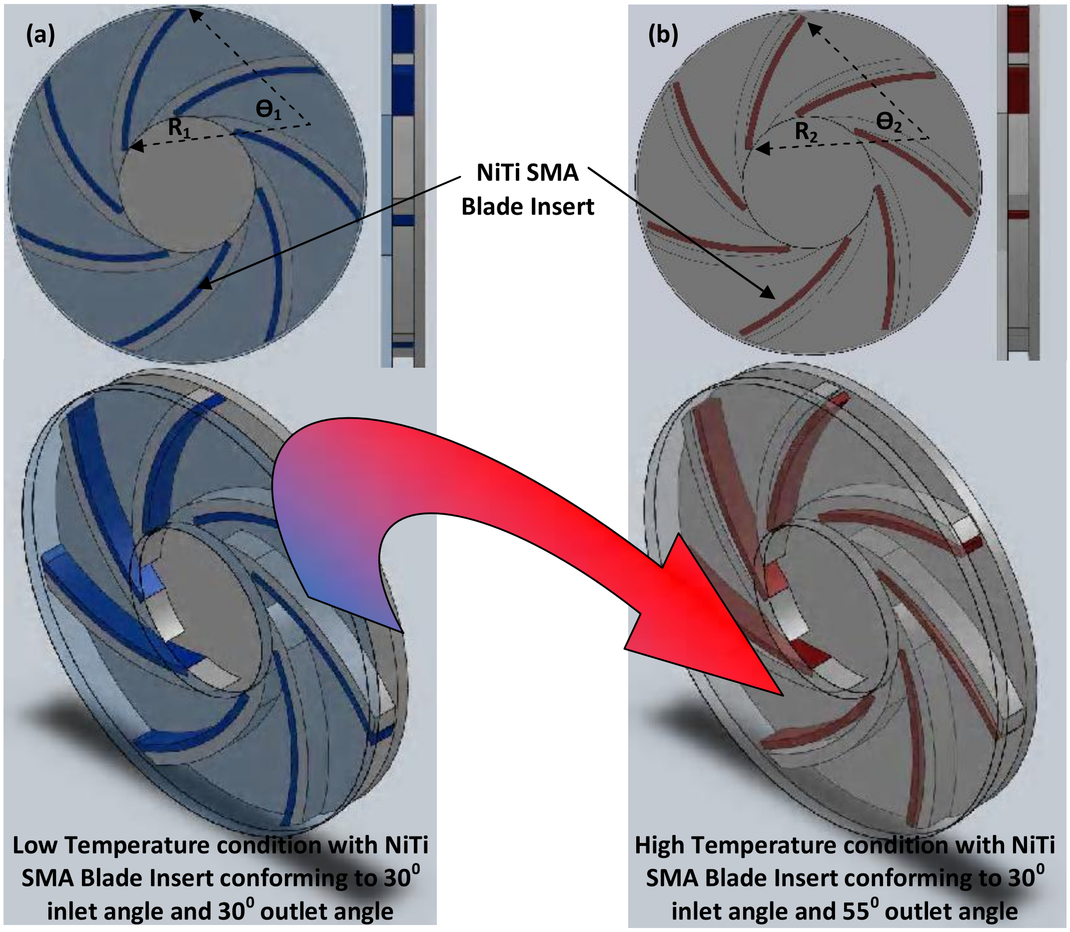


Figure 5.61: Idealized model of the Shape Memory Smart Impeller with (a) showing low temperature configuration and (b) showing high temperature configuration.

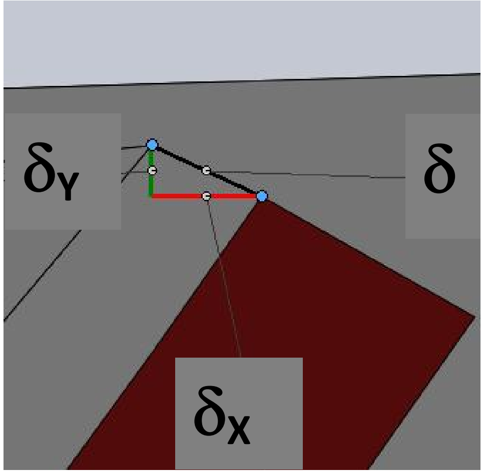
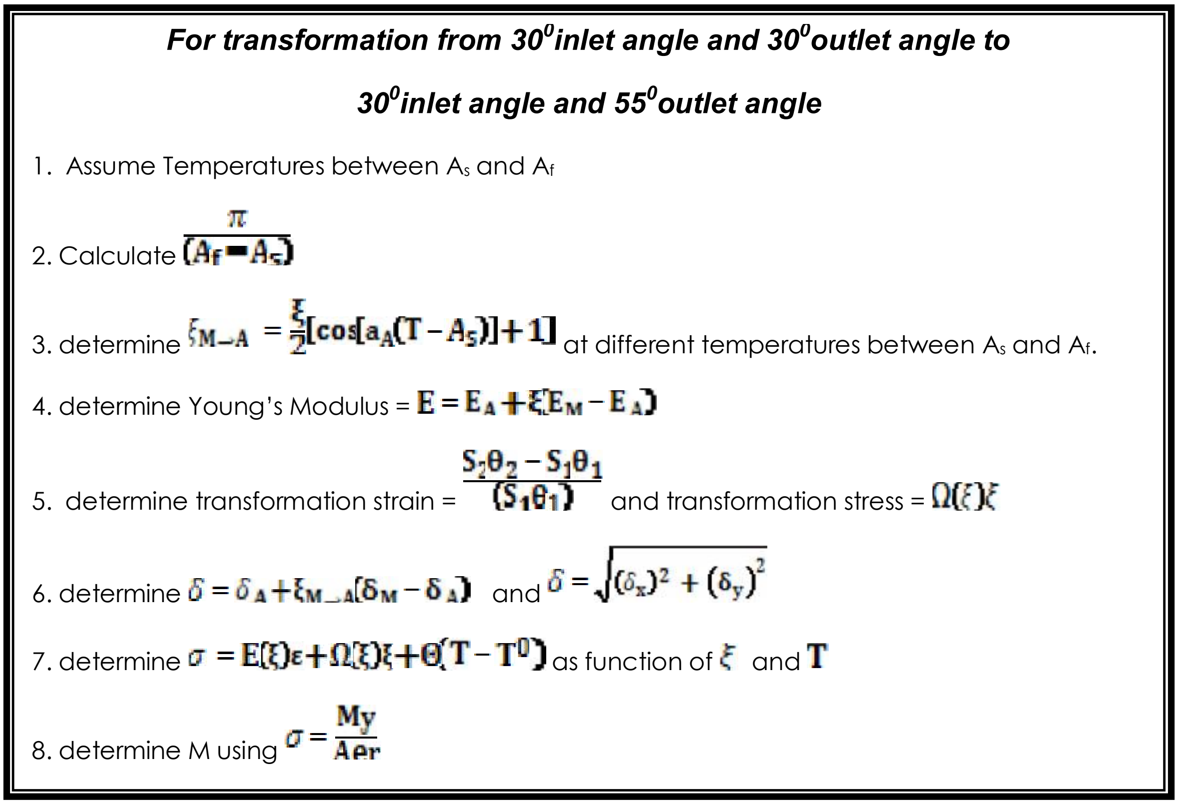


Figure 5.62: Illustration showing total displacement, the horizontal component of displacement and the vertical component of displacement.



For transformation from 30^0inlet angle and 30^0outlet angle to

30^0inlet angle and 55^0outlet angle

1. Assume Temperatures between A_s and A_f

2. Calculate $\frac{\pi}{(A_f - A_s)}$

3. determine $\xi_{M-A} = \frac{\xi}{2}[\cos[a_A(T - A_s)] + 1]$ at different temperatures between A_s and A_f.

4. determine Young's Modulus = $E = E_A + \xi(E_M - E_A)$

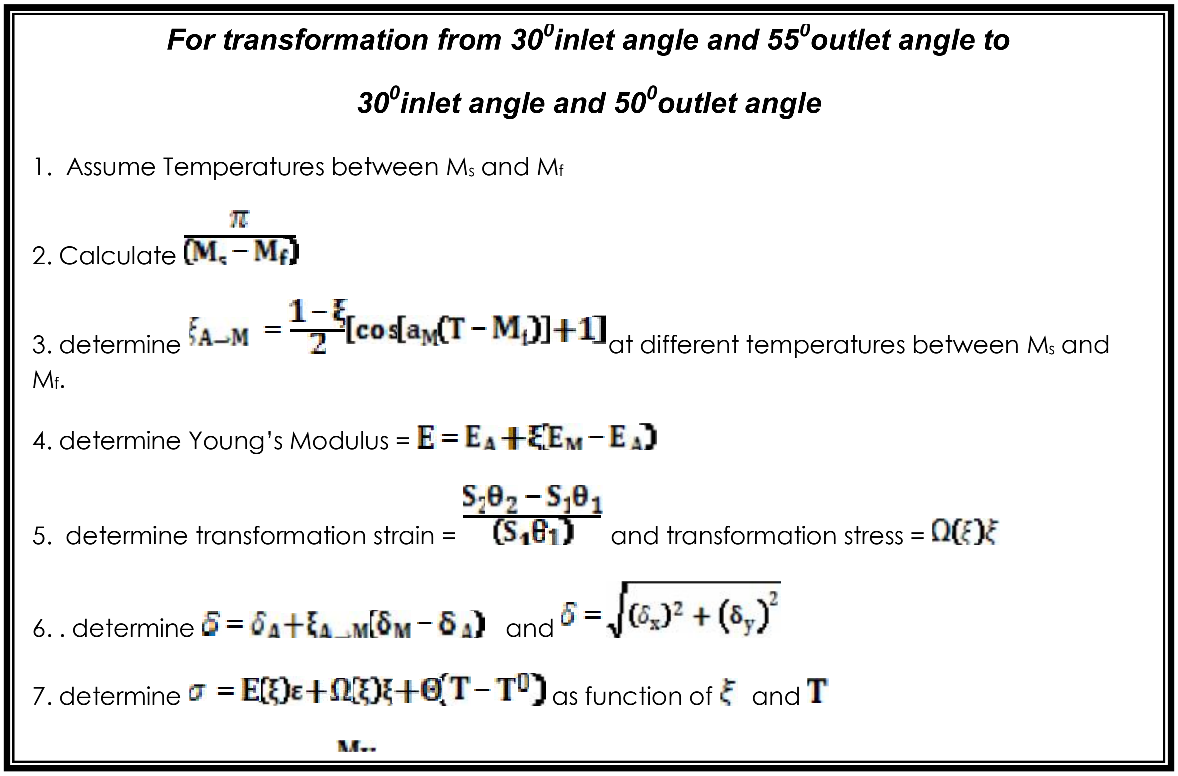
5. determine transformation strain = $\frac{S_2\theta_2 - S_1\theta_1}{(S_1\theta_1)}$ and transformation stress = $\Omega(\xi)\xi$

6. determine $\delta = \delta_A + \xi_{M-A}(\delta_M - \delta_A)$ and $\delta = \sqrt{(\delta_x)^2 + (\delta_y)^2}$

7. determine $\sigma = E(\xi)\varepsilon + \Omega(\xi)\xi + \Theta(T - T^0)$ as function of ξ and T

8. determine M using $\sigma = \frac{My}{A\theta r}$

Figure 5.63: Solution algorithm used for heating condition..



For transformation from 30^0inlet angle and 55^0outlet angle to

30^0inlet angle and 50^0outlet angle

1. Assume Temperatures between M_s and M_f

2. Calculate $\frac{\pi}{(M_s - M_f)}$

3. determine $\xi_{A-M} = \frac{1-\xi}{2}[\cos[a_M(T - M_f)] + 1]$ at different temperatures between M_s and M_f.

4. determine Young's Modulus = $E = E_A + \xi(E_M - E_A)$

5. determine transformation strain = $\frac{S_2\theta_2 - S_1\theta_1}{(S_1\theta_1)}$ and transformation stress = $\Omega(\xi)\xi$

6. . determine $\delta = \delta_A + \xi_{A-M}(\delta_M - \delta_A)$ and $\delta = \sqrt{(\delta_x)^2 + (\delta_y)^2}$

7. determine $\sigma = E(\xi)\varepsilon + \Omega(\xi)\xi + \Theta(T - T^0)$ as function of ξ and T

Figure 5.64: Solution algorithm used for cooling condition..

All constants used in the algorithm have been defined previously [45] and will given in Table 5.61.

Table 5.61: Constants used in the Solution Algorithms

Symbol	Description	Value
A_s	Austenite Start Temperature	44.65^0C
A_f	Austenite Finish Temperature	52.04^0C
M_s	Martensite Start Temperature	39.63^0C
M_f	Martensite Finish Temperature	32.54^0C
E_M	Martensite Young's Modulus	34GPa
E_M	Austenite Young's Modulus	89GPa
Θ	NiTi Thermal Expansion Coefficient	10e-5/^{0}C
ρ	Density of NiTi SMA	6450 kg/m^3
T^0	Reference Temperature	40^0C
D_I	Diameter of Impeller	84mm
D_E	Diameter of Eye	32mm
R_1	Radius of SMA Blade insert at low temperature state	45.7mm
θ_1	Angle forming Span of SMA Blade insert at low temperature state	44.165^0 = 0.77082rad
θ_2	Angle forming Span of SMA Blade insert at high temperature state	30.524^0 = 0.53274rad
R_2	Radius of SMA Blade insert at high temperature state	63.1mm
A	SMA Insert Area	1.5e-3 x 5e-3 m^2
I	SMA Insert Second Moment of Area	$(1.5e-3)^3$ x (5e-3) / 12m^3

The results of the solution is provided in the tables below, i.e. Table 5.62 – 5.64 shows results for heating and Table 5.65 – 5.67 shows results for cooling. Fig 5.65 graphically shows the martensitic phase fraction for both heating and cooling. Fig 5.66 graphically shows the displacements with its components for both heating and cooling.

Table 5.62: Results of Martensite Phase Fraction versus Displacements and its Components

HEATING: M → A

TEMP (^{0}C)	$\xi_{M\text{-}A}$	Δ(mm)	Δ_X(mm)	Δ_Y(mm)
4.00E+01	1.00E+00	0.00E+00	0.00E+00	0.00E+00
4.10E+01	1.00E+00	0.00E+00	0.00E+00	0.00E+00
4.20E+01	1.00E+00	0.00E+00	0.00E+00	0.00E+00
4.30E+01	1.00E+00	0.00E+00	0.00E+00	0.00E+00
4.40E+01	1.00E+00	0.00E+00	0.00E+00	0.00E+00
4.47E+01	1.00E+00	0.00E+00	0.00E+00	0.00E+00
4.57E+01	9.56E-01	3.32E-02	3.02E-02	1.40E-02
4.67E+01	8.30E-01	1.27E-01	1.15E-01	5.34E-02
4.77E+01	6.46E-01	2.65E-01	2.40E-01	1.11E-01
4.87E+01	4.35E-01	4.22E-01	3.83E-01	1.77E-01
4.97E+01	2.37E-01	5.70E-01	5.17E-01	2.40E-01
5.00E+01	1.77E-01	6.15E-01	5.58E-01	2.59E-01
5.05E+01	1.03E-01	6.70E-01	6.08E-01	2.82E-01
5.10E+01	4.81E-02	7.11E-01	6.45E-01	2.99E-01
5.15E+01	1.31E-02	7.37E-01	6.69E-01	3.10E-01
5.20E+01	1.00E-04	7.47E-01	6.78E-01	3.14E-01
5.20E+01	0.00E+00	7.47E-01	6.78E-01	3.14E-01

Table 5.63: Results of Martensite Phase Fraction versus Young's Modulus and Strains

HEATING: M → A

TEMP (^{0}C)	$\xi_{M\text{-}A}$	E (Pa)	ε_{Th}	ε_{Tr}
4.00E+01	1.00E+00	3.40E+10	0.00E+00	0.00E+00
4.10E+01	1.00E+00	3.40E+10	0.00E+00	0.00E+00
4.20E+01	1.00E+00	3.40E+10	0.00E+00	0.00E+00
4.30E+01	1.00E+00	3.40E+10	0.00E+00	0.00E+00
4.40E+01	1.00E+00	3.40E+10	0.00E+00	0.00E+00
4.47E+01	1.00E+00	3.40E+10	0.00E+00	0.00E+00
4.57E+01	9.56E-01	3.65E+10	-2.03E-03	1.00E-06
4.67E+01	8.30E-01	4.34E+10	-7.77E-03	2.00E-06
4.77E+01	6.46E-01	5.35E+10	-1.62E-02	3.00E-06
4.87E+01	4.35E-01	6.51E+10	-2.58E-02	4.00E-06
4.97E+01	2.37E-01	7.60E+10	-3.49E-02	5.00E-06
5.00E+01	1.77E-01	7.93E+10	-3.76E-02	5.35E-06
5.05E+01	1.03E-01	8.33E+10	-4.10E-02	5.85E-06
5.10E+01	4.81E-02	8.64E+10	-4.35E-02	6.35E-06
5.15E+01	1.31E-02	8.83E+10	-4.51E-02	6.85E-06
5.20E+01	1.00E-04	8.90E+10	-4.57E-02	7.35E-06
5.20E+01	0.00E+00	8.90E+10	-4.57E-02	7.39E-06

Table 5.64: Results of Martensite Phase Fraction versus Young's Modulus and Stresses

HEATING: M → A

TEMP (^{0}C)	ξ_{M-A}	E (Pa)	σ_{Th}(Pa)	σ_{Tr}(Pa)	σ(Pa)
4.00E+01	1.00E+00	3.40E+10	0.00E+00	0.00E+00	0.00E+00
4.10E+01	1.00E+00	3.40E+10	0.00E+00	0.00E+00	0.00E+00
4.20E+01	1.00E+00	3.40E+10	0.00E+00	0.00E+00	0.00E+00
4.30E+01	1.00E+00	3.40E+10	0.00E+00	0.00E+00	0.00E+00
4.40E+01	1.00E+00	3.40E+10	0.00E+00	0.00E+00	0.00E+00
4.47E+01	1.00E+00	3.40E+10	0.00E+00	0.00E+00	0.00E+00
4.57E+01	9.56E-01	3.65E+10	-7.41E+07	3.65E+04	-7.41E+07
4.67E+01	8.30E-01	4.34E+10	-3.37E+08	8.67E+04	-3.37E+08
4.77E+01	6.46E-01	5.35E+10	-8.66E+08	1.61E+05	-8.66E+08
4.87E+01	4.35E-01	6.51E+10	-1.68E+09	2.60E+05	-1.68E+09
4.97E+01	2.37E-01	7.60E+10	-2.65E+09	3.80E+05	-2.65E+09
5.00E+01	1.77E-01	7.93E+10	-2.98E+09	4.24E+05	-2.98E+09
5.05E+01	1.03E-01	8.33E+10	-3.41E+09	4.87E+05	-3.41E+09
5.10E+01	4.81E-02	8.64E+10	-3.76E+09	5.48E+05	-3.76E+09
5.15E+01	1.31E-02	8.83E+10	-3.98E+09	6.05E+05	-3.98E+09
5.20E+01	1.00E-04	8.90E+10	-4.07E+09	6.54E+05	-4.07E+09
5.20E+01	0.00E+00	8.90E+10	-4.07E+09	6.58E+05	-4.07E+09

Table 5.65: Results of Martensite Phase Fraction versus Displacements and its Components

COOLING: A → M

TEMP (^{0}C)	ξ_{A-M}	Δ(mm)	Δ_X(mm)	Δ_Y(mm)
5.20E+01	0.00E+00	7.47E-01	6.78E-01	3.14E-01
4.50E+01	0.00E+00	7.47E-01	6.78E-01	3.14E-01
4.00E+01	0.00E+00	7.47E-01	6.78E-01	3.14E-01
3.96E+01	0.00E+00	7.47E-01	6.78E-01	3.14E-01
3.86E+01	4.83E-02	7.11E-01	6.45E-01	2.99E-01
3.76E+01	1.84E-01	6.10E-01	5.53E-01	2.56E-01
3.66E+01	3.80E-01	4.63E-01	4.20E-01	1.95E-01
3.56E+01	6.00E-01	2.99E-01	2.71E-01	1.26E-01
3.46E+01	8.00E-01	1.49E-01	1.36E-01	6.28E-02
3.40E+01	8.99E-01	7.54E-02	6.85E-02	3.17E-02
3.35E+01	9.55E-01	3.36E-02	3.05E-02	1.41E-02
3.30E+01	9.89E-01	8.22E-03	7.46E-03	3.45E-03
3.28E+01	9.97E-01	2.24E-03	2.03E-03	9.42E-04
3.25E+01	1.00E+00	0.00E+00	0.00E+00	0.00E+00
3.00E+01	1.00E+00	0.00E+00	0.00E+00	0.00E+00
2.90E+01	1.00E+00	0.00E+00	0.00E+00	0.00E+00
2.50E+01	1.00E+00	0.00E+00	0.00E+00	0.00E+00

Table 5.66: Results of Martensite Phase Fraction versus Young's Modulus and Strains

COOLING: A $\rightarrow$ M

TEMP (^{0}C)	$\xi_{M\text{-}A}$	E (Pa)	ε_{Th}	ε_{Tr}
5.20E+01	0.00E+00	8.90E+10	-4.57E-02	0.00E+00
4.50E+01	0.00E+00	8.90E+10	-4.57E-02	-7.04E-06
4.00E+01	0.00E+00	8.90E+10	-4.57E-02	-1.20E-05
3.96E+01	0.00E+00	8.90E+10	-4.57E-02	-1.24E-05
3.86E+01	4.83E-02	8.63E+10	-4.35E-02	-1.34E-05
3.76E+01	1.84E-01	7.89E+10	-3.73E-02	-1.44E-05
3.66E+01	3.80E-01	6.81E+10	-2.83E-02	-1.54E-05
3.56E+01	6.00E-01	5.60E+10	-1.83E-02	-1.64E-05
3.46E+01	8.00E-01	4.50E+10	-9.14E-03	-1.74E-05
3.40E+01	8.99E-01	3.96E+10	-4.62E-03	-1.80E-05
3.35E+01	9.55E-01	3.65E+10	-2.06E-03	-1.85E-05
3.30E+01	9.89E-01	3.46E+10	-5.03E-04	-1.90E-05
3.28E+01	9.97E-01	3.42E+10	-1.37E-04	-1.92E-05
3.25E+01	1.00E+00	3.40E+10	0.00E+00	0.00E+00
3.00E+01	1.00E+00	3.40E+10	0.00E+00	0.00E+00
2.90E+01	1.00E+00	3.40E+10	0.00E+00	0.00E+00
2.50E+01	1.00E+00	3.40E+10	0.00E+00	0.00E+00

Table 5.67: Results of Martensite Phase Fraction versus Young's Modulus and Stresses

COOLING: A $\rightarrow$ M

TEMP (^{0}C)	$\xi_{M\text{-}A}$	E (Pa)	σ_{Th}(Pa)	σ_{Tr}(Pa)	σ(Pa)
5.20E+01	0.00E+00	8.90E+10	-4.07E+09	0.00E+00	-4.07E+09
4.50E+01	0.00E+00	8.90E+10	-4.07E+09	-6.27E+05	-4.07E+09
4.00E+01	0.00E+00	8.90E+10	-4.07E+09	-1.07E+06	-4.07E+09
3.96E+01	0.00E+00	8.90E+10	-4.07E+09	-1.10E+06	-4.07E+09
3.86E+01	4.83E-02	8.63E+10	-3.76E+09	-1.16E+06	-3.76E+09
3.76E+01	1.84E-01	7.89E+10	-2.94E+09	-1.14E+06	-2.94E+09
3.66E+01	3.80E-01	6.81E+10	-1.93E+09	-1.05E+06	-1.93E+09
3.56E+01	6.00E-01	5.60E+10	-1.02E+09	-9.19E+05	-1.02E+09
3.46E+01	8.00E-01	4.50E+10	-4.11E+08	-7.83E+05	-4.12E+08
3.40E+01	8.99E-01	3.96E+10	-1.83E+08	-7.14E+05	-1.83E+08
3.35E+01	9.55E-01	3.65E+10	-7.50E+07	-6.76E+05	-7.57E+07
3.30E+01	9.89E-01	3.46E+10	-1.74E+07	-6.59E+05	-1.81E+07
3.28E+01	9.97E-01	3.42E+10	-4.68E+06	-6.57E+05	-5.34E+06
3.25E+01	1.00E+00	3.40E+10	0.00E+00	0.00E+00	0.00E+00
3.00E+01	1.00E+00	3.40E+10	0.00E+00	0.00E+00	0.00E+00
2.90E+01	1.00E+00	3.40E+10	0.00E+00	0.00E+00	0.00E+00
2.50E+01	1.00E+00	3.40E+10	0.00E+00	0.00E+00	0.00E+00

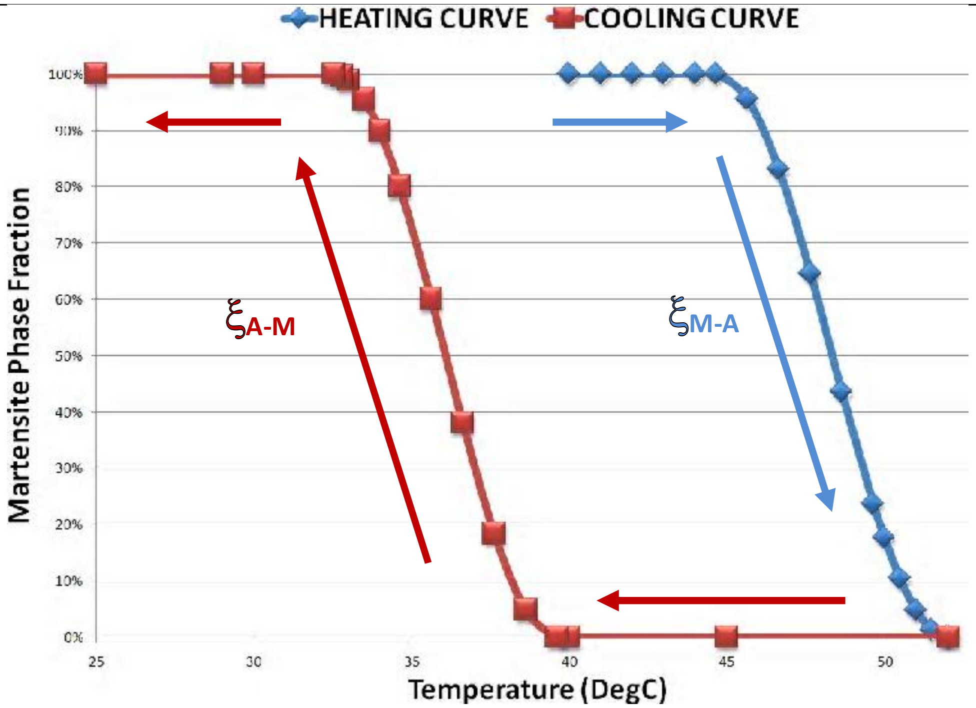


Figure 5.65: Martensite Phase Fraction for Heating and Cooling versus Temperature

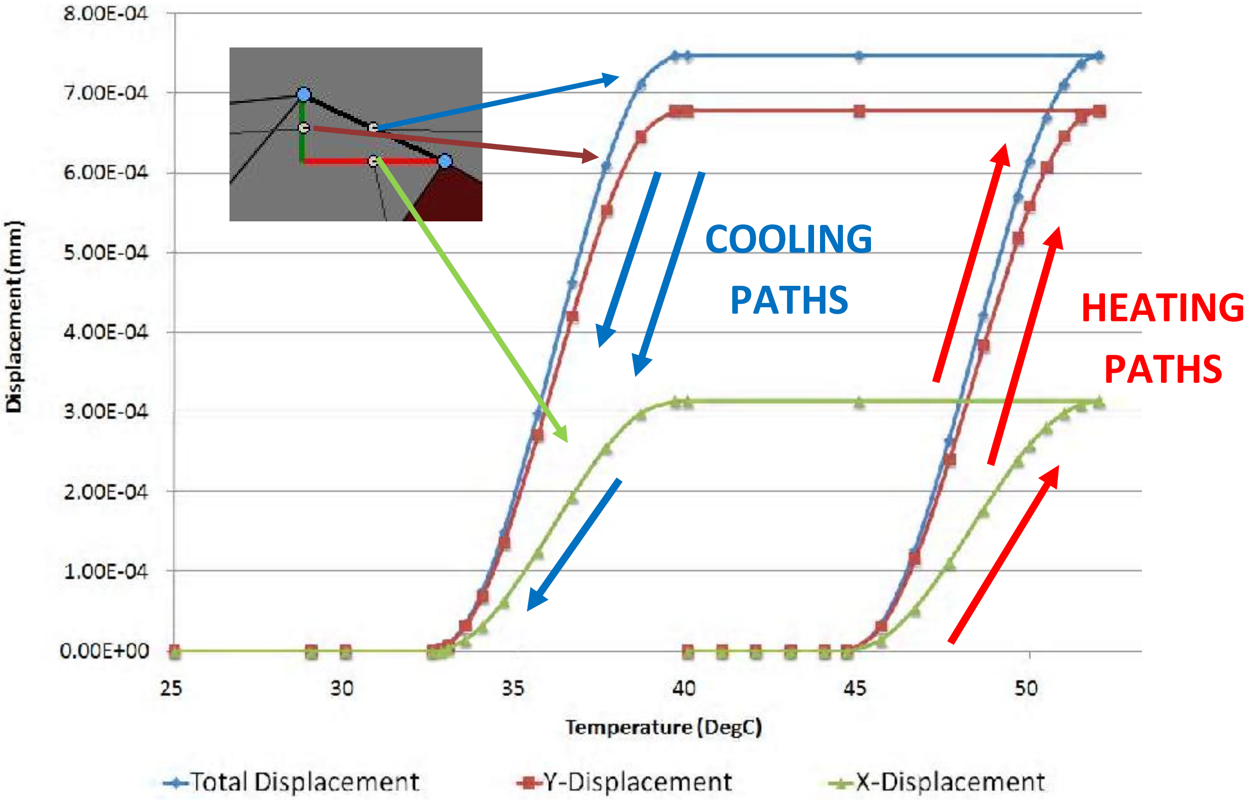


Figure 5.66: Total Displacements and its components versus Temperature

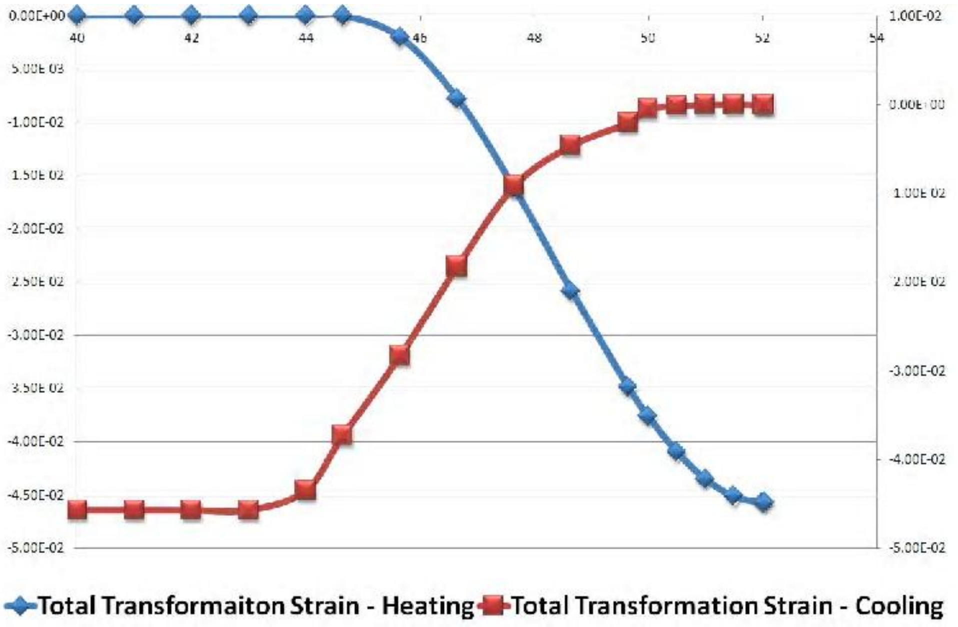


Figure 5.67: Transformation Strain versus Temperature

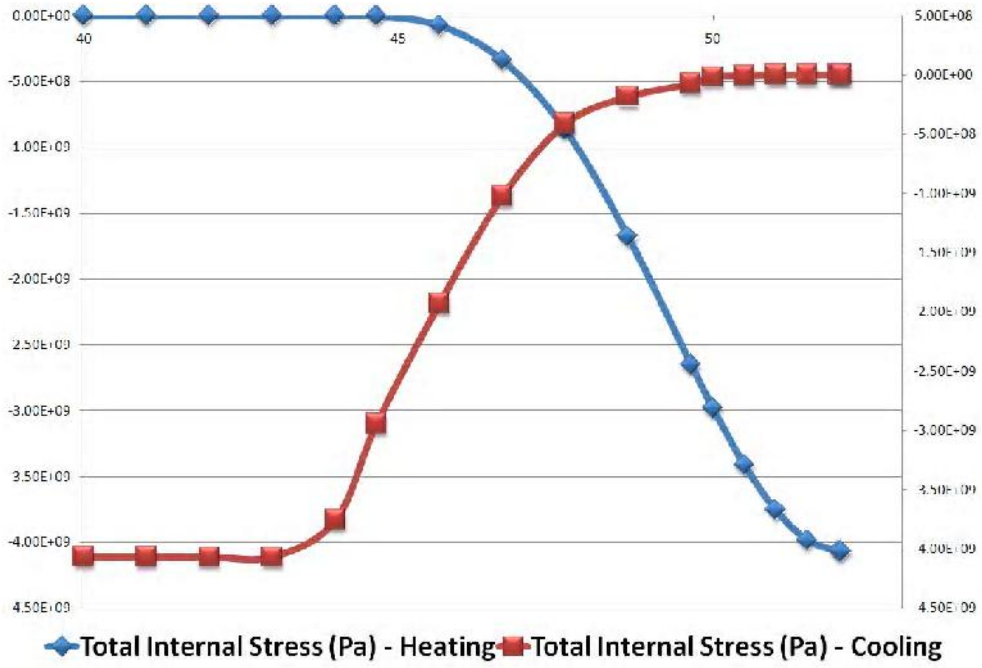


Figure 5.68: Total Internal Stress versus Temperature

From the 3D solid modeling software package, SolidWorks, the maximum total displacement, δ ,was measured as 0.747mm with its components, i.e. vertical, δ_v ,and horizontal, δ_v , being 0.678mm and 0.314mm respectively. Fig 5.66 graphically shows these values as they change with temperature for both heating and cooling.

The maximum transformation strain, i.e. $\varepsilon_{Tr} = \frac{S_2\theta_2 - S_1\theta_1}{(S_1\theta_1)}$, was determined at 4.57e-2 compressive, and Fig 5.67 shows how it transforms for both heating and cooling. The maximum total circumferential stress was determined at 4.09GPa – compressive and is shown graphically in Fig 5.68 for both heating and cooling cycles. The internal moment due to the phase transformation was determined as 7.63Nm while the loading terms of Equ 5.43 – 5.45, i.e. (LF_M) , (LF_H) and (LF_V) , were determined as 128.837N, 11.5026N, and 11.5026N respectively.

5.7 Discussion of Results

The method shown above shows the feasibility of using the approach to solve for the displacements, i.e. total, vertical and horizontal, at all instances of temperature and martensite phase fraction. It thus indicates that a Shape Memory Smart Impeller is conceptualized. The displacements, although small, changes the outlet angle of the blade from 30^0 to 55^0, thus theoretically increasing the velocity at the outlet and increasing the head of the centrifugal impeller. It should be noted though that for this specific situation, an optimum anlge of attack of 43.3^0 would produce the optimum work done and efficiency as described in section 5.2. This indecates that the shape memory insert be trained to conform to this outlet angle and thus actuate within region 2 of Fig. 5.28.

The moment at the free end is small and under normal operating conditions the force of flow would overcome this moment thus not affecting the transformation. The internal stress is high and further investigation into the shape and geometry of the blade and or insert should be conducted to improve the internal stress.

CHAPTER SIX

EFD ANALYSES

6.1 Background to ENGINEERING FLUID DYNAMICS (EFD)

Computers these days play a major role in design of aerodynamic and hydro-dynamic structures. CAD embedded fluid flow simulation software have redefined the design process by allowing for effective design optimization with little cost and in less time.

EFD.Lab is a full-featured general purpose CAD-embedded finite volume fluid flow and heat transfer simulation tool that encompasses the following features:

- Rectangular adaptive meshing (with manual or automatic refinement).
- Partial cells technology to accurately simulate near wall boundary conditions.
- Laminar, transitional and turbulent flow regimes, all automatically generated and within the same model.
- Turbulent flow modelled using the Favre-Averaged Navier Stokes equation.
- Automatic convergence control

EFD was developed by Flomerics, who are world-leading developers of engineering simulation software and services for analysis of fluid flow, heat transfer and electromagnetic radiation. Flomerics' software is designed to be embedded deeply into the design process and used by mainstream design engineers, not just by analysis specialists.

6.1.1 Rectangular adaptive meshing

EFD calculations are performed in a rectangular parallelepiped-shaped computational domain whose boundaries are orthogonal to the axes of the Cartesian Global coordinate system. A computational mesh splits the computational domain with a set of planes orthogonal to the Cartesian Global Coordinate System's axes to form rectangular parallelepipeds called cells. The resulting mesh consists of cells of the following three types (shown in figure 6.1):

- Fluid cells are the cells located entirely in the fluid
- Solid cells are the cells located entirely in the solid
- Partial cells are the cells which are partly in the solid and partly in the fluid. For each partial cell the following information is kept: coordinates of intersections of the cell edges with the solid surface and normal to the solid surface within the cell.

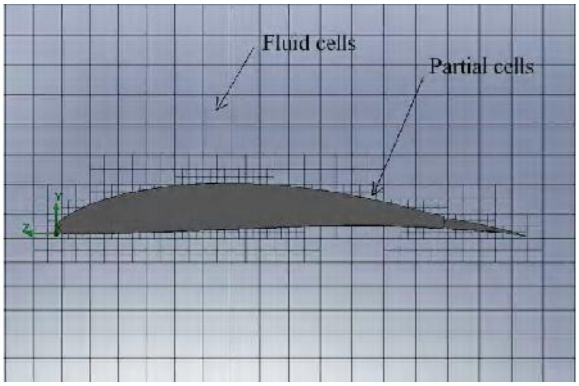


Figure 6.1: Mesh cell types.

The mesh is constructed in the following steps:

- Construction of basic mesh taking into account the control planes and respective values of cell number and cell size ratios.
- Resolving of the interface between substances, including refinement of the basic mesh at the solid/fluid and solid/solid boundaries to resolve the relatively small solid features and solid/solid interface, tolerance and curvature refinement of the mesh at a solid/fluid, solid/porous and fluid/porous boundaries to resolve the interface curvature.
- Narrow channels refinement, which is the refinement of the mesh in narrow channels taking into account the respective user-specified settings.
- Refinement of all fluid, and or solid, and or partial mesh cells up to the user-specified level.
- Mesh conservation. i.e. a set of control procedures, including check for the difference in area of cell facets common for the adjacent cells of different levels.

6.2 Simulation algorithm for Engineering Fluid Dynamics

Water flows through a centrifugal pump having a rotating impeller (see below). This pump has a stationary axial inlet (an eye), a pipe section with a central body of circular arc contour, which turns the flow by 90 degrees from the axial direction. At the inlet's exit the radial water flow is sucked by a rotating impeller, which has seven untwisted constant-thickness backswept blades. Each blade is cambered from 30 degrees at the impeller inlet of 16 mm radius to range of 0 to 90 degrees at the impeller exit of 42 mm radius, both with respect to the radial direction. While keeping all configurations the same, only the impeller outlet angle was increase for each in impeller by 5 degree. The inlet angle for all impeller was 30 degrees. These blades are confined between the impeller shrouding disks rotating with the same (as the blades) angular speed of 2000 rpm

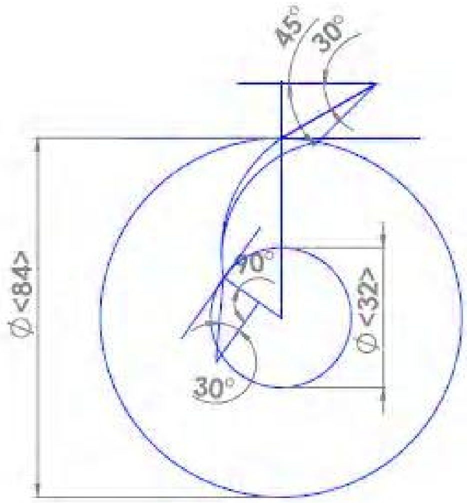


Figure 6.12: Basic construction of impeller

To complete the problem statement, let us specify the following inlet and outlet boundary conditions: inlet water of 0.3 m^3s^{-1} volume flow rate having uniform velocity profile with vectors parallel to the pump's axis; at the radial-directed outlet a static pressure of 1 atmosphere is specified.

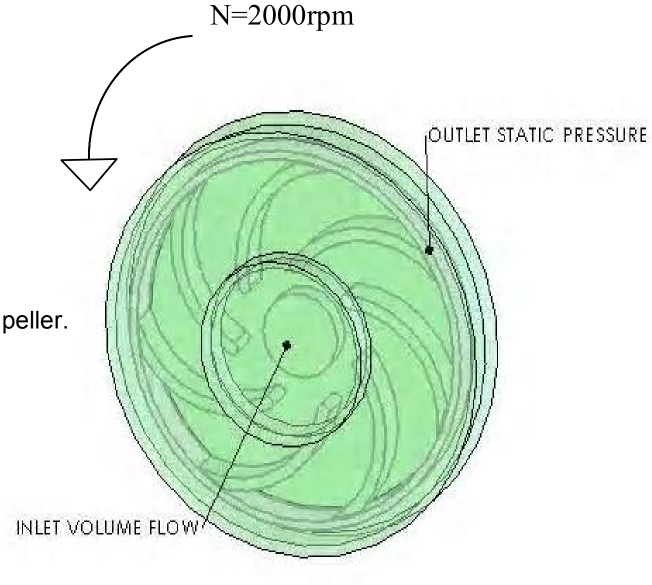


Figure 6.13: Centrifugal pumps with rotating impeller.

6.2.1Project Definition: A new project was created using the wizard

Table 6.2: Project definition table

Project name	*Use current: Impeller Efficiency*
Unit system	*SI*
Analysis type	*Internal; Exclude cavities without flow conditions*
Physical features	*Rotation: Type - Global rotating, Rotation axis - Z axis of Global Coordinate system, Angular velocity=2000 RPM (209.43951 rad/s)*
Default fluid	Water
Wall Conditions	*Adiabatic wall, default smooth walls*
Initial Conditions	*Default conditions*
Result and Geometry Resolution	*Set the Result resolution level* 5 *Minimum gap size =* `0.04` *m, minimum wall thickness =* `0.01`*, other options are default*

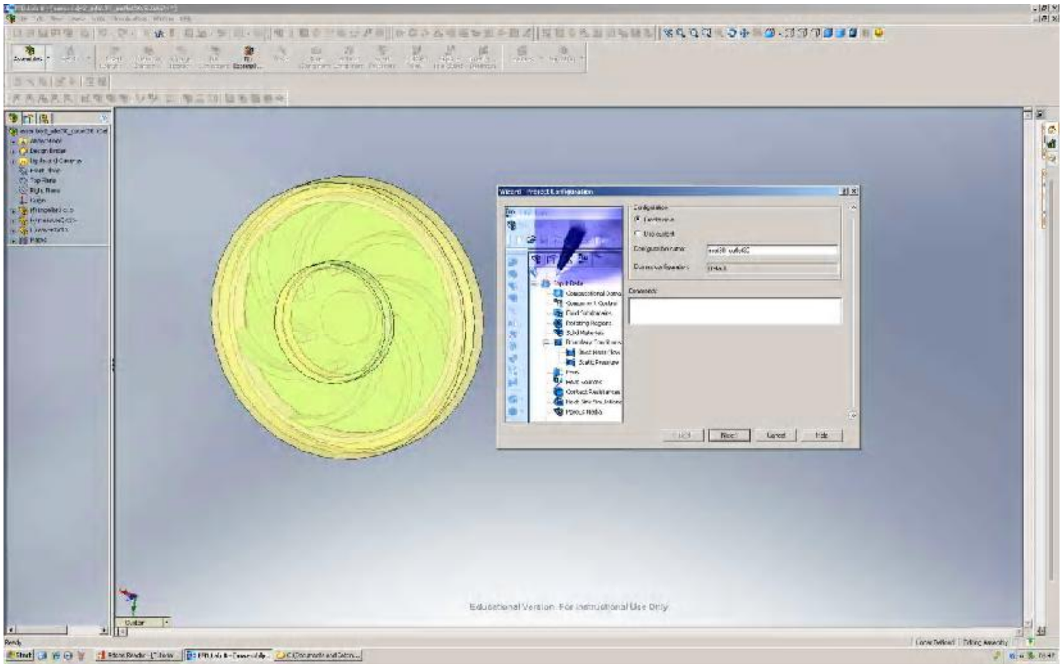


Figure 6.21: Creating a new wizard

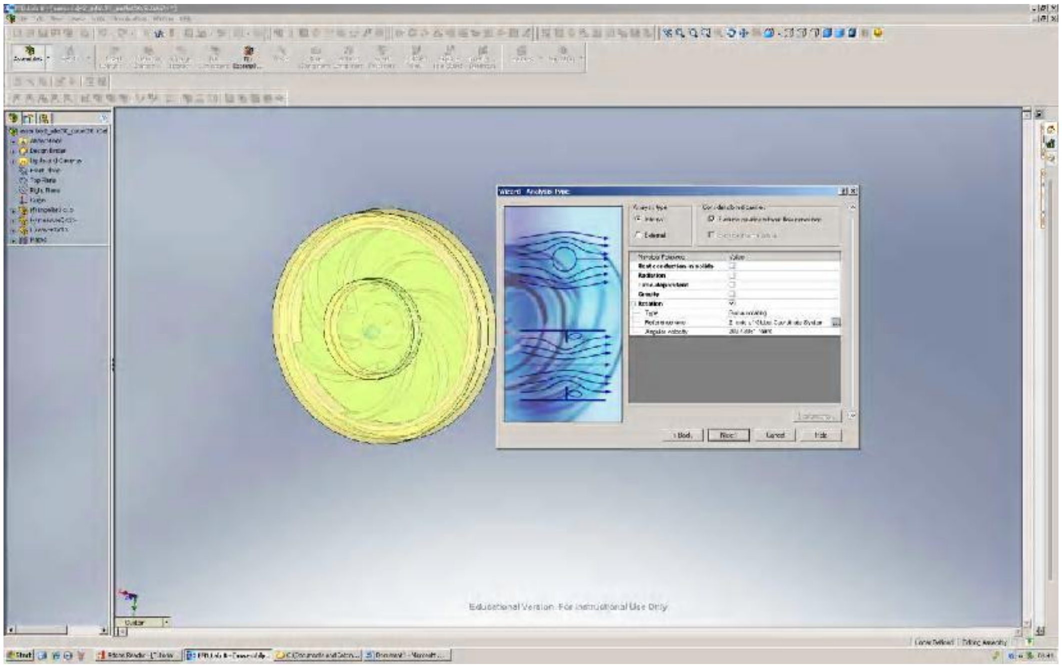


Figure 6.22: Creating analysis type

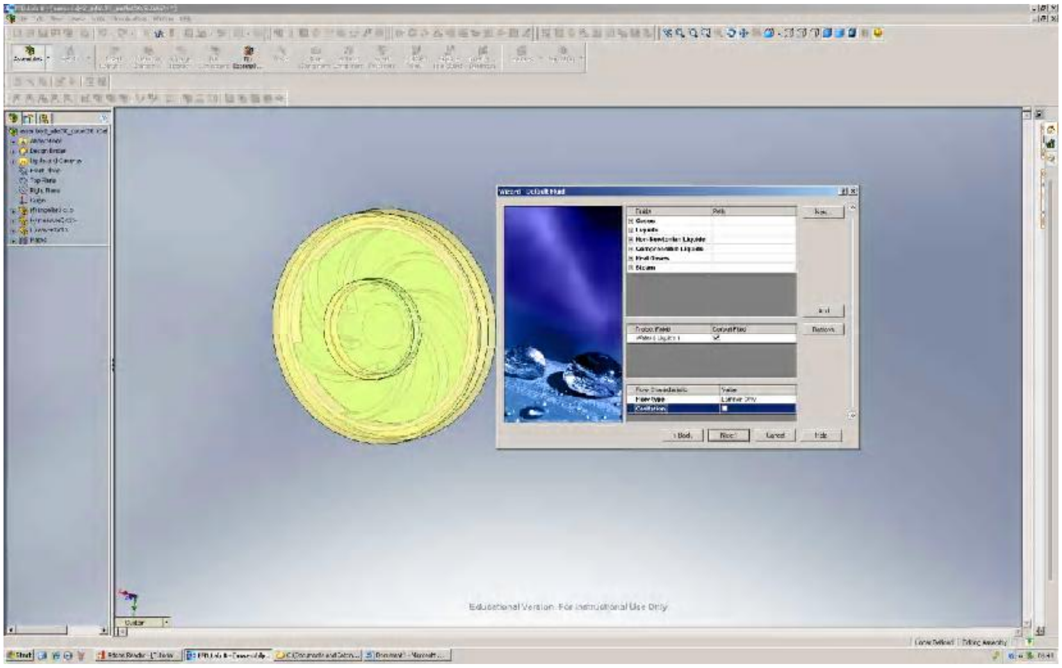


Figure 6.23: Creating physical features

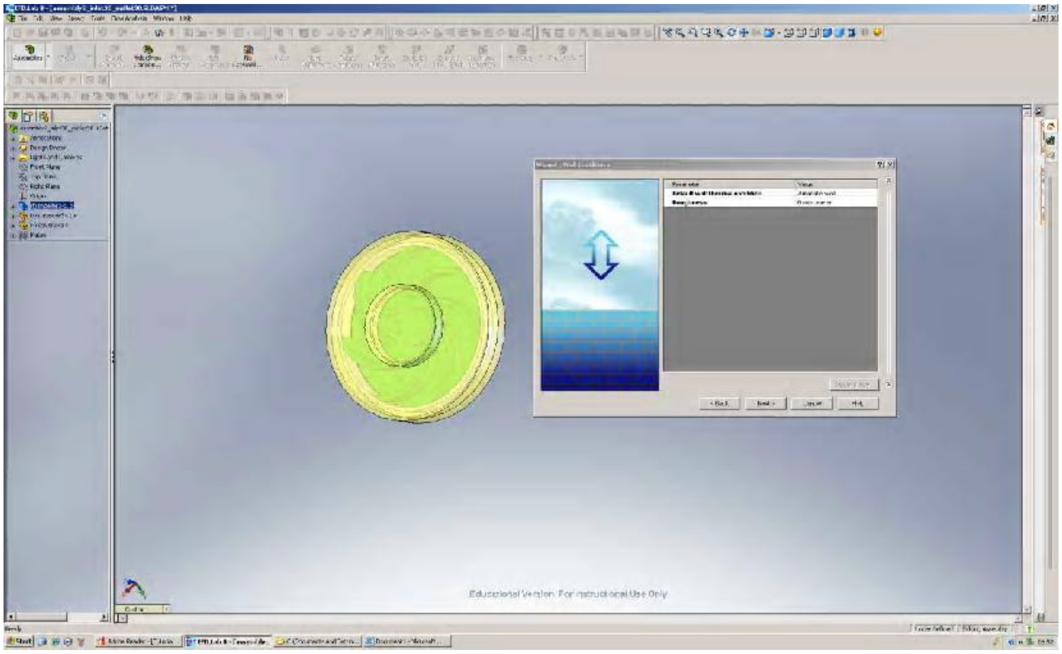


Figure: 6.24: Creating wall conditions

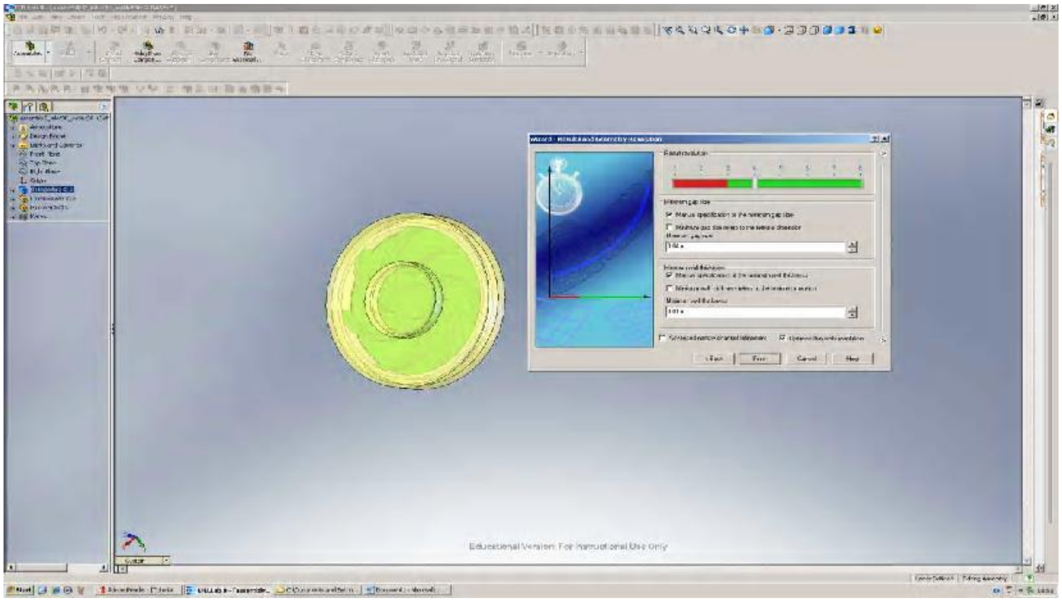


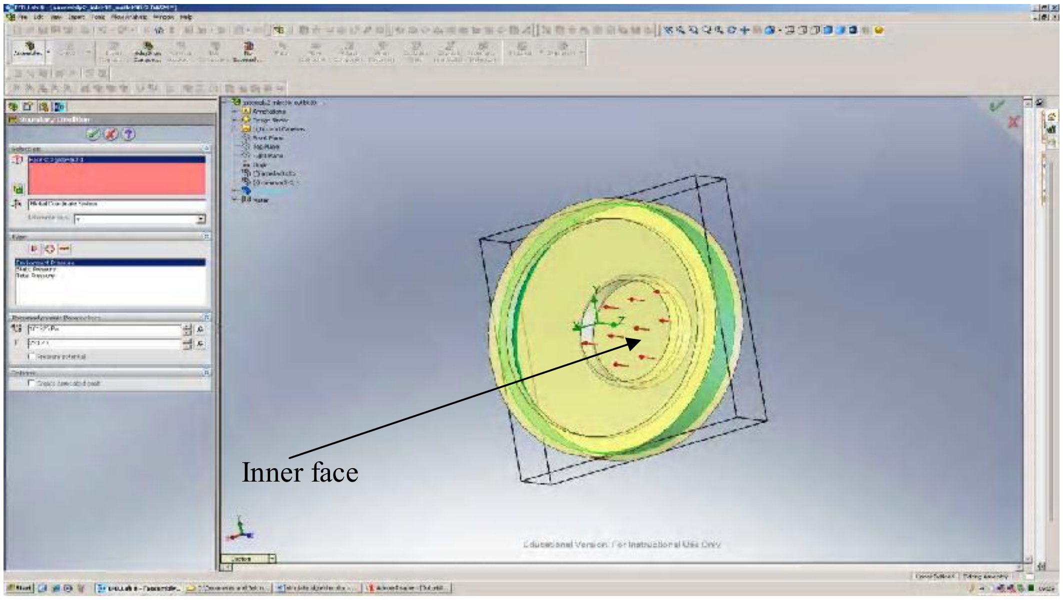
Figure 6.25: Geometry Resolution. The resolution was set to level 5

6.3 Boundary Conditions

6.31 Inlet boundary condition.

Inlet Volume Flow: Volume flow rate of 0.3 m^3/s (uniform velocity profile) normal to the inner face of the Cover in the absolute frame of reference (the Relative to rotating frame option is disabled);

The inlet boundary is specified as shown below



6.32 Outlet boundary condition:

Outlet Environment Pressure: Default value (101325 Pa) for the Environment pressure (in the absolute frame of reference - the Pressure potential is disabled) at the radial outlet face.

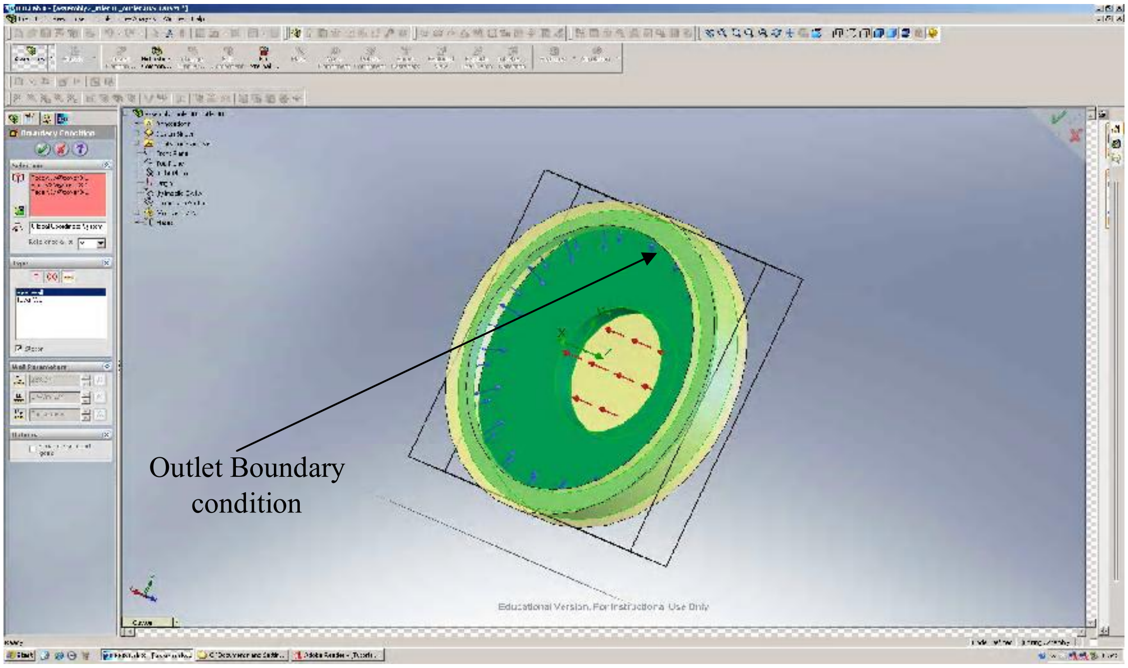


Figure: 6.32: Outlet boundary condition

6.4 Specifying Stationary Walls

The stator condition at the corresponding walls of the pump's cover was specify

1. Select the inner cover's faces except for the outlet and inlet faces.
2. Click **Flow Analysis**, **Insert**, **Boundary Condition**.
3. Click **Wall**, keep the default **Real Wall** condition type and go to the **Moving Wall Settings** tab.
4. On the **Moving Wall Settings** tab, click **Stator**.
5. Click **OK** and rename the new **Real Wal l1** condition to Stator Walls.

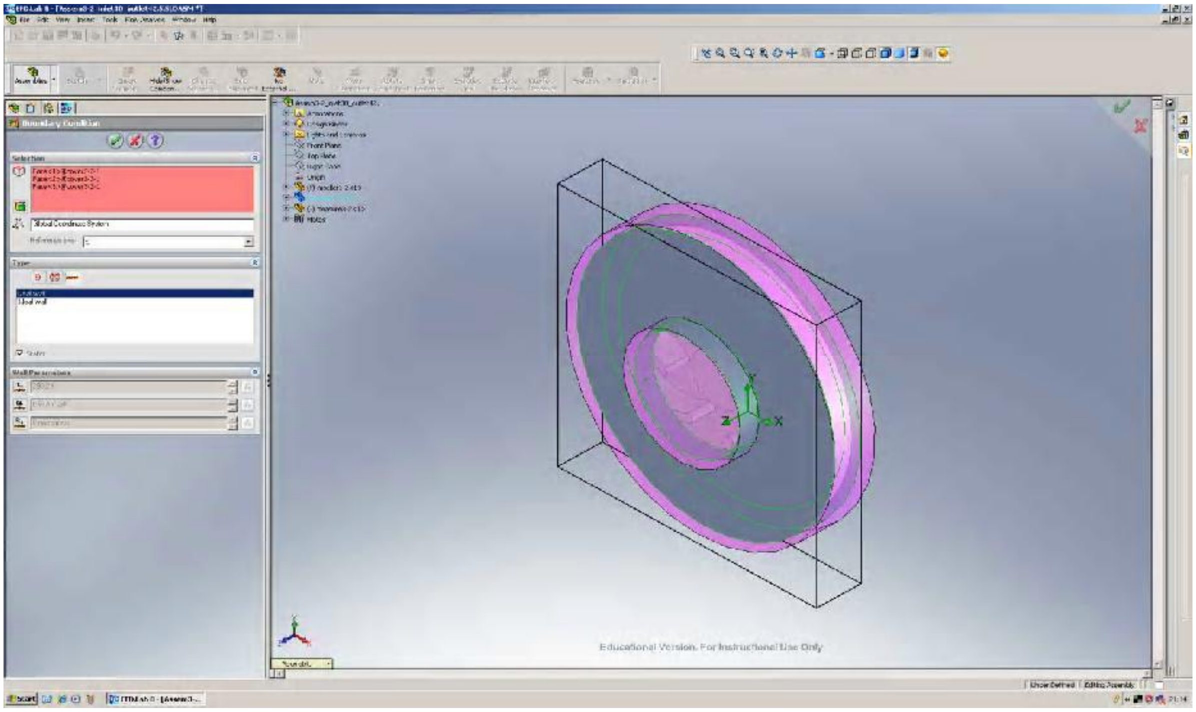


Figure: 6.41: Selecting stationary walls

6.5 Impeller efficiency

Engineers dealing with pump equipment are interested in the pump efficiency. For the pump under consideration the efficiency (η) can be calculated in the following way

$$\eta = \left| \frac{(P_{outlet} - P_{inlet}) \cdot Q}{\Omega \cdot M} \right|$$

where *Pinlet* is the static pressure at the pump's inlet, *Poutlet* is the bulk-average static pressures at the impeller's outlet (Pa), *Q* is the volume flow rate (m3/s), Ω is the impeller rotation angular velocity (rad/s), and M is the impeller torque (N·m). To obtain *Poutlet,* an auxiliary **measure** component was placed where the flow exits the impeller. The **measure** component is only used for the pressure measurement (the corresponding goal will be specified at the inner face of the **measure** thin ring), thus it should be disabled in the **Component Control** dialog box.

6.5.1 Click **Flow Analysis**, **Component Control**.

6.5.2 Select the **Measure** item and click **Disable**.

6.5.3 Click **OK** to close the dialog.

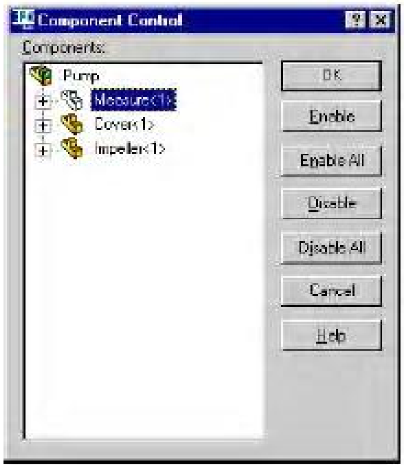


Figure 6.51: Component control window

6.6 Specifying project goals

First, since the pressure and volume flow rate boundary condition are specified, it makes sense to set the mass flow rate surface goal at the pump's inlet and outlet to inspect the mass balance as an additional criterion for converging the calculation.

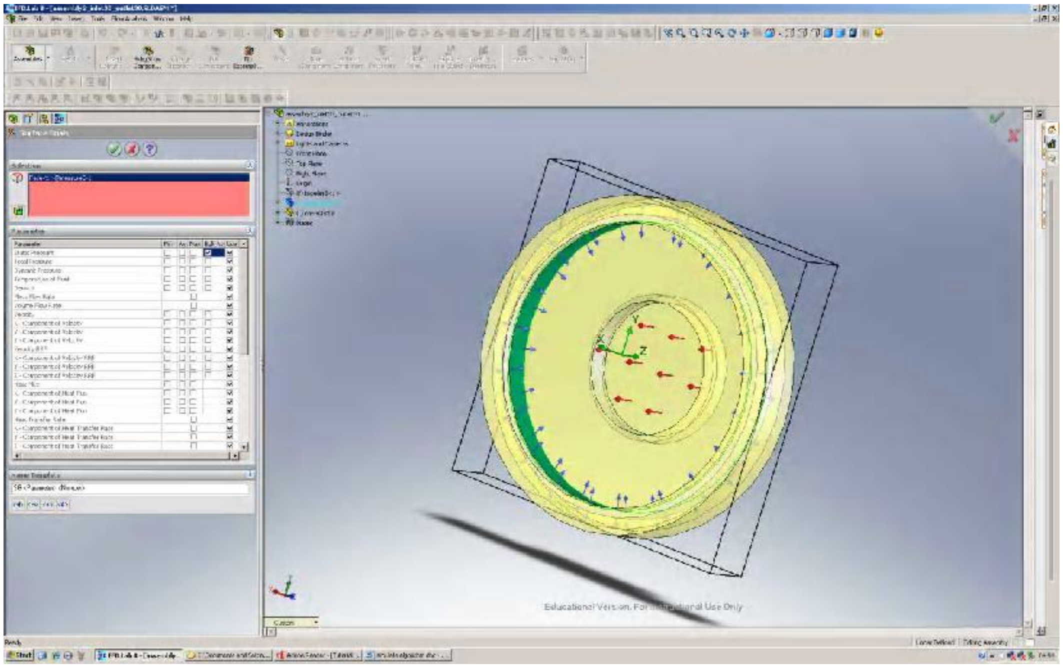
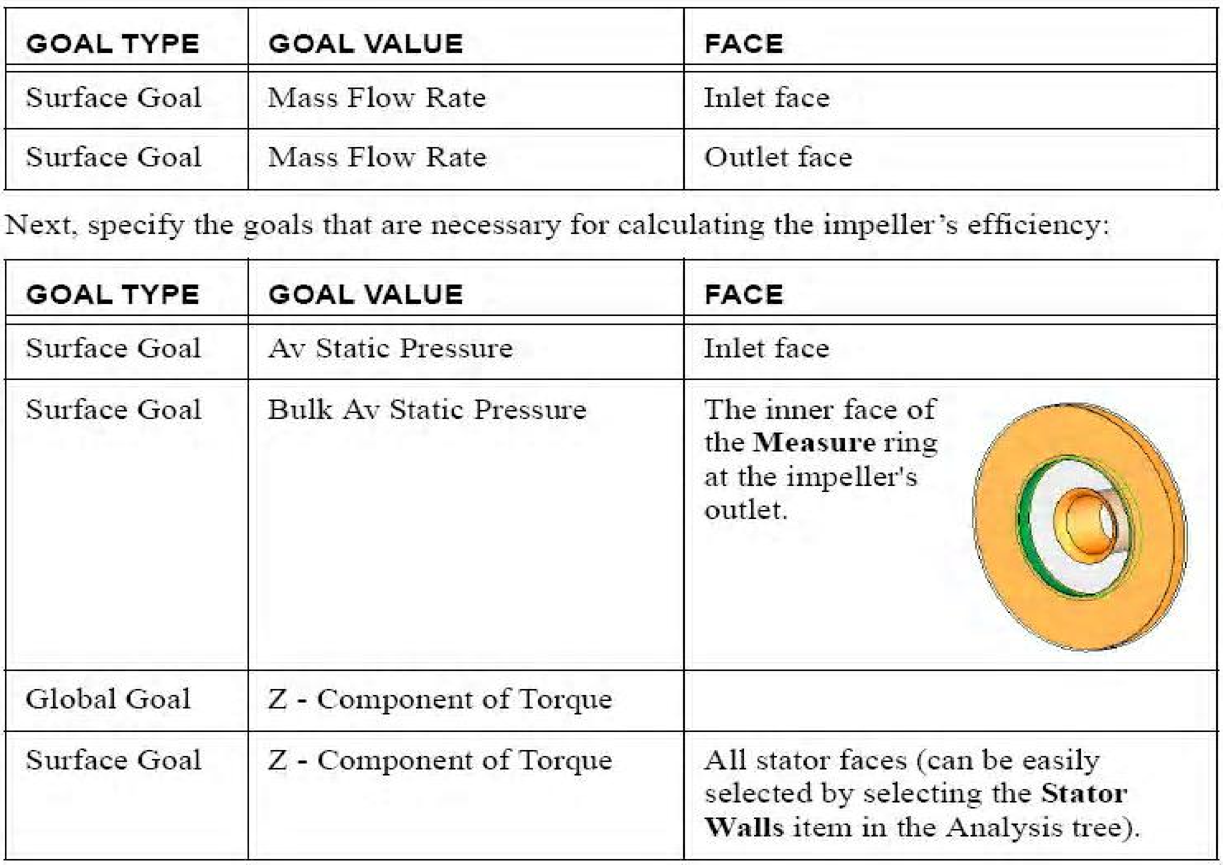


Figure 6.61: Creating surface Goals

Table 6.6: Specifying project goals



GOAL TYPE	GOAL VALUE	FACE
Surface Goal	Mass Flow Rate	Inlet face
Surface Goal	Mass Flow Rate	Outlet face

Next, specify the goals that are necessary for calculating the impeller's efficiency:

GOAL TYPE	GOAL VALUE	FACE
Surface Goal	Av Static Pressure	Inlet face
Surface Goal	Bulk Av Static Pressure	The inner face of the **Measure** ring at the impeller's outlet.
Global Goal	Z - Component of Torque	
Surface Goal	Z - Component of Torque	All stator faces (can be easily selected by selecting the **Stator Walls** item in the Analysis tree).

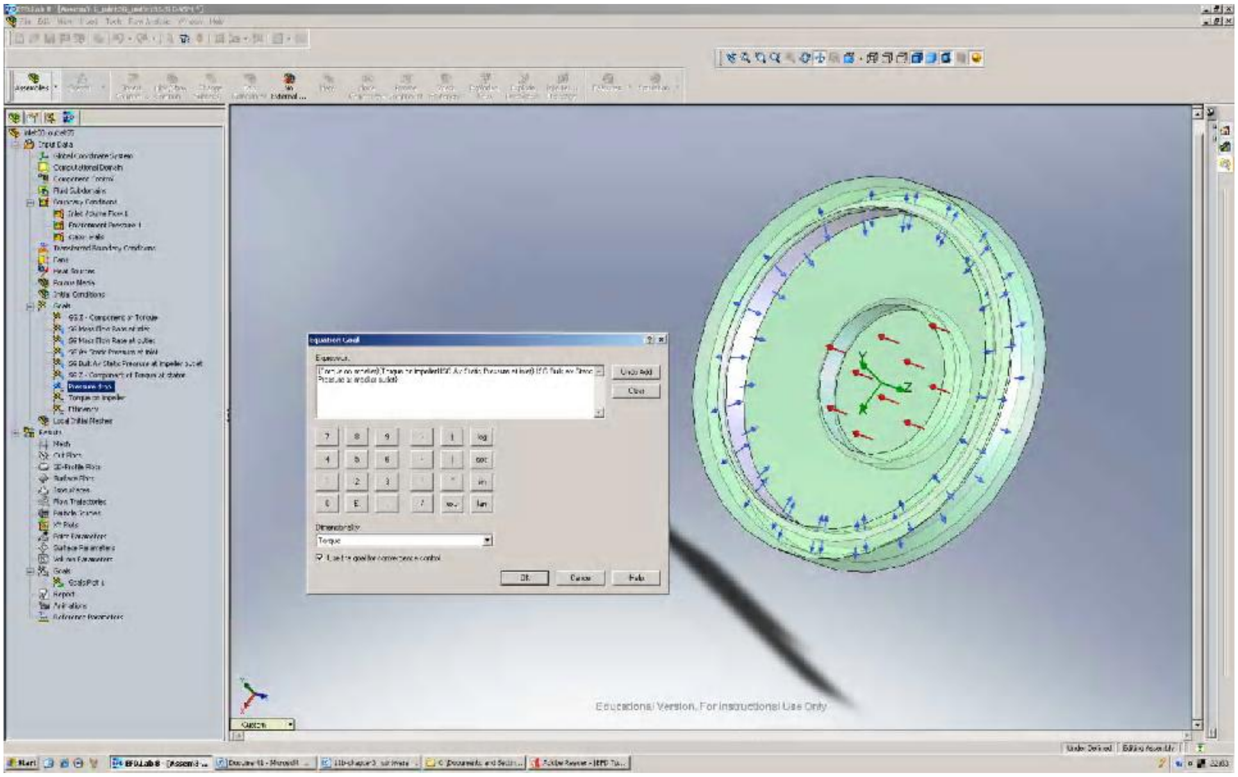
Rename the created goals as shown below:

- Goals
  - GG Z - Component of Torque
  - SG Mass Flow Rate Inlet
  - SG Mass Flow Rate Outlet
  - SG Average Static Pressure Inlet
  - SG Bulk Average Static Pressure Impeller's Outlet
  - SG Z - Component of Torque at Stator
- Results

Figure 6.62: Naming Goals' tree

6.7 Specifying equation goals

To avoid manual selecting of all impeller's faces in contact with water (more than 150) we will calculate impeller torque as the difference between the global torque (calculated over all faces in contact with water) and the stator torque (calculated over the stator faces in contact with water)



Dimensionality: Torque

☑ Use this goal for convergence control

Figure 6.71: Creating equation Goals

Table 6.7: Specifying equation goals

EQUATION GOAL NAME	FORMULA	DIMENSIONALITY
Pressure Drop	{SG Av Static Pressure Inlet}-{SG Bulk Av Static Pressure Impeller's Outlet}	Pressure & stress
Torque on Impeller	{GG Z - Component of Torque}-{SG Z - Component of Torque at Stator}	Torque
EFFICIENCY	{Pressure Drop}*{Inlet Volume Flow 1:Volume flow rate normal to face:3.000e-001}/209.44/ {Torque on Impeller}	No units

Figure 6.72: Naming equations' tree

Save the model and run the calculations

6.8 Results.

The velocity vectors and static pressure distribution are shown below. To display vectors in the rotating reference frame, in the **View Settings** open the **Parameter List** dialog box and select **Velocity RRF** parameter. Then select the **Velocity RRF** parameter under the **Vectors** tab of the **View Settings** dialog box.

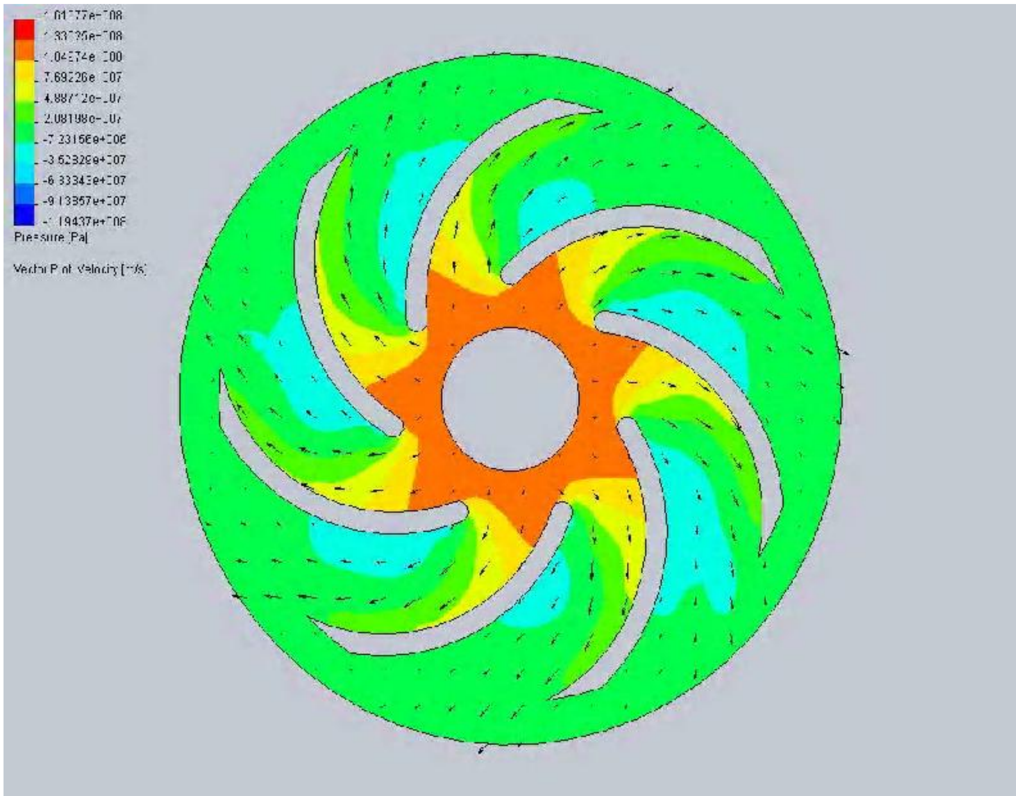


Figure 6.81: Pressure plot

CHAPTER SEVEN

RESULTS & DISCUSSION OF CFD ANALYSES

7.1 Results of Engineering Fluid Dynamics

If we consider the situation described in section 5.2, Chapter 5 and considering the inputs described in Chapter 6 we construct 6 solid models of our impeller, each having an inlet blade angle 30^0 but outlet angles varying from 30^0 to 55^0 with increments of 5^0. It is clear that the efficiency of the impeller drops drastically from 30 degrees inlet and 30 degrees outlet, but increases gradually as the outlet angle increase from this point. The graph also shows a characteristic optimum increase up to 45 degrees outlet where it starts to flatten out. This will allow us to have an angle of attack of 15 degrees from an inlet angle of 30 degrees.

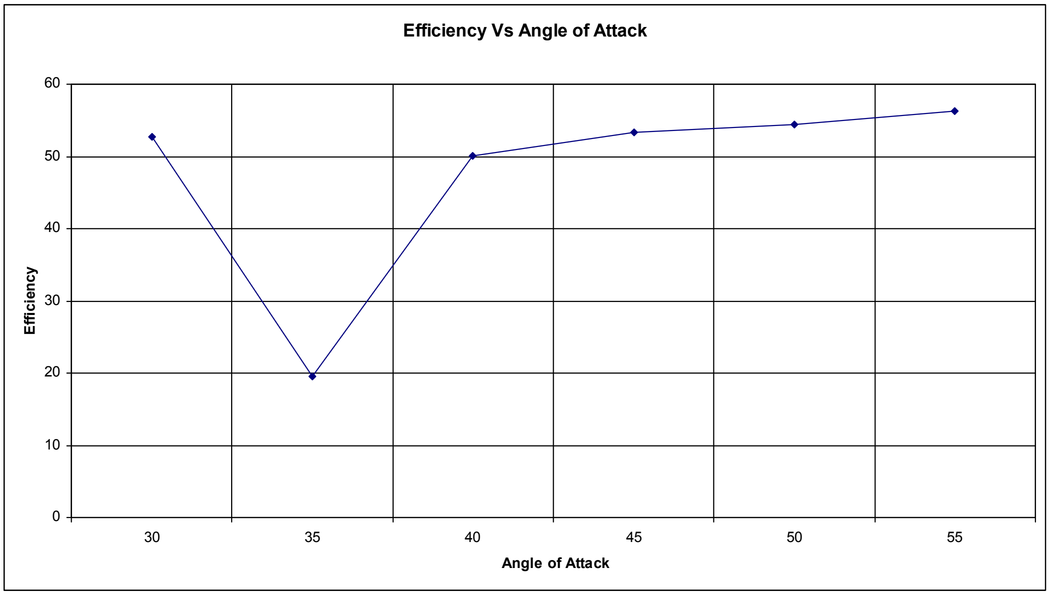


Figure 7.31: efficiency versus angle of attack in steps of 5 degrees

A Detail investigation reveals that there is a jump from 42 degrees to 45 degrees. Secondly there is a decrease from 45degrees to 46 before increasing slowing onward.

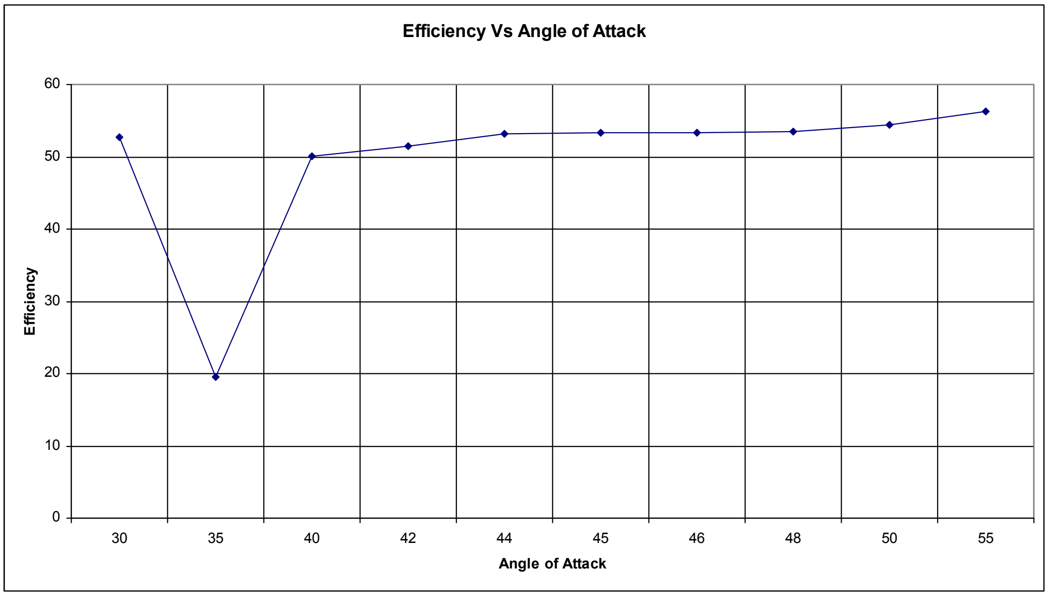


Figure 7.32: Detail investigation of efficiency versus angle of attack

Investigating the torque on the system, it was revealed that despite an increase in the efficiency from 40 degrees to 42 degrees at the outlet, there is surprisingly a decrease in the torque in this section. See figure 7.33 below.

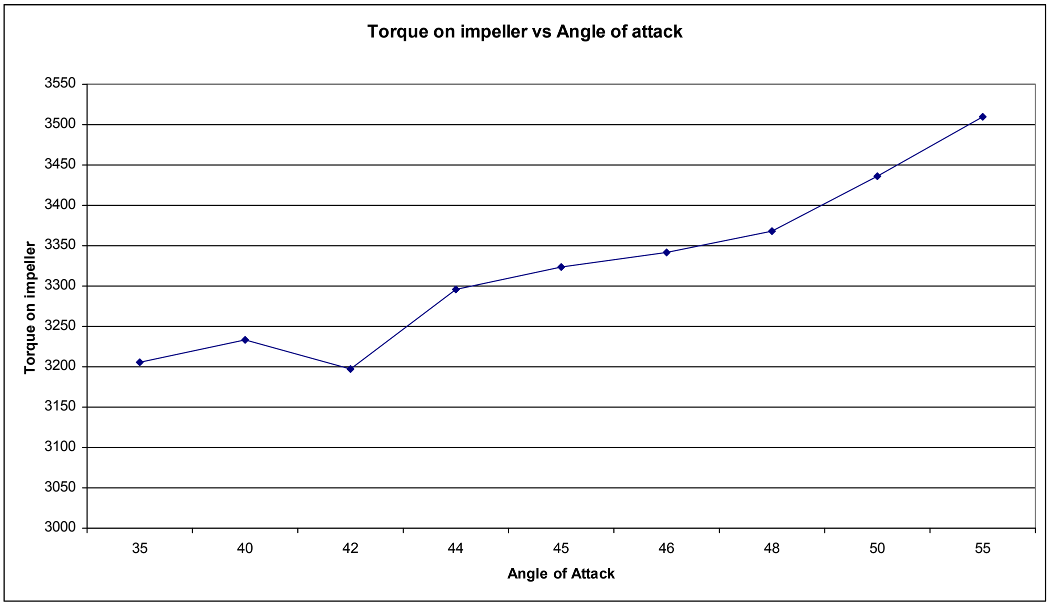


Figure 7.33: Detail investigation of impeller torque versus angle of attack.

A closer look at the torque alone on both sides of 42 degrees (where there is a drop) confirms our V-shape. (See Figure 7.34)

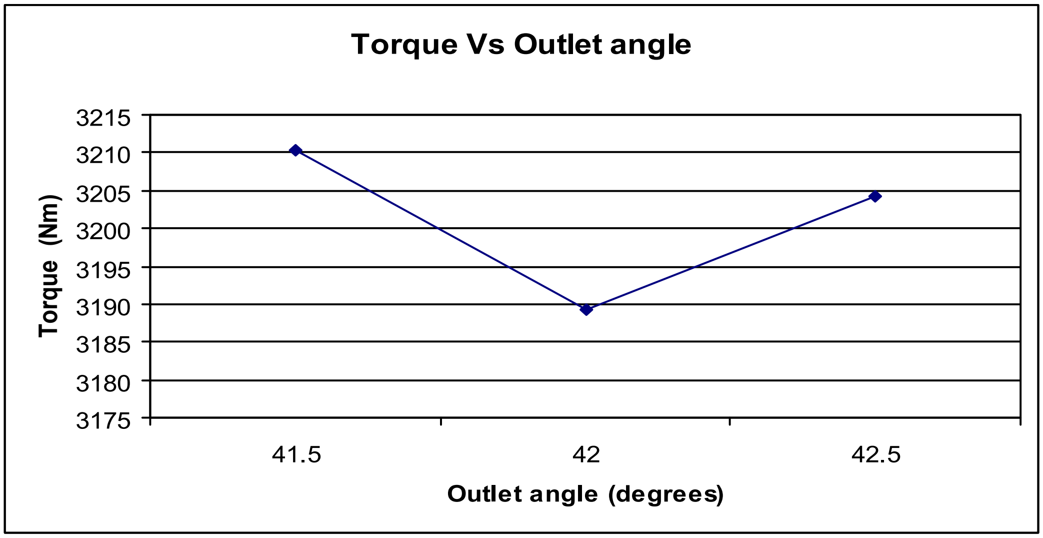


Figure 7.34: Torque vs. outlet angle

A trend in the between 40 degrees and 44 degrees confirms and reveals a polynomial gutter curve with the lowest torque still at 42 degrees. See figure 7.35

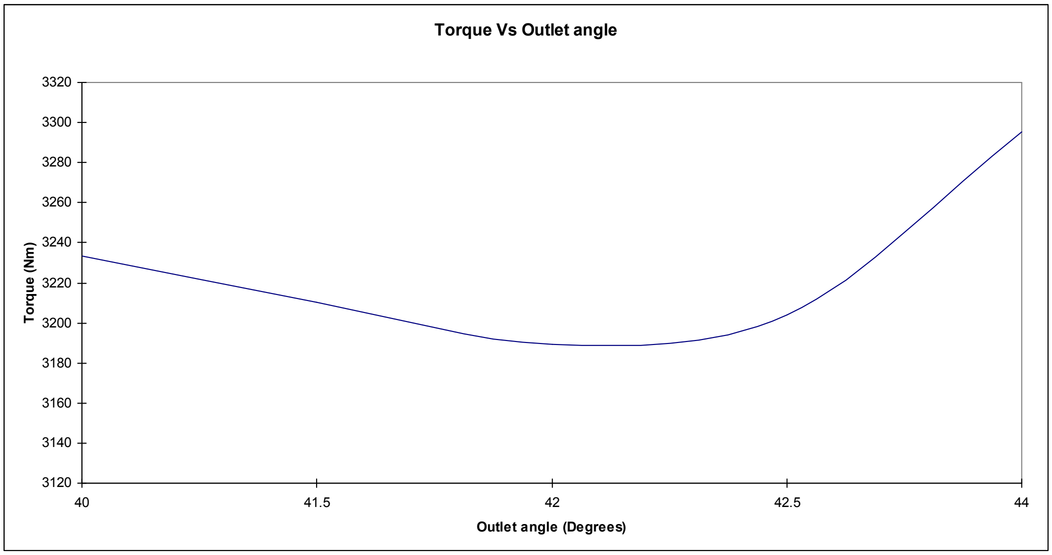


Figure 7.35: Polynomial gutter curve

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7.2 Investigation of results.

i) Passage area

Looking at the blade to blade orientation, (see figure below) and investigating the blade passage area ABCD (see figure below) and the passage outlet length for variable angle of attack, the following results were obtained.

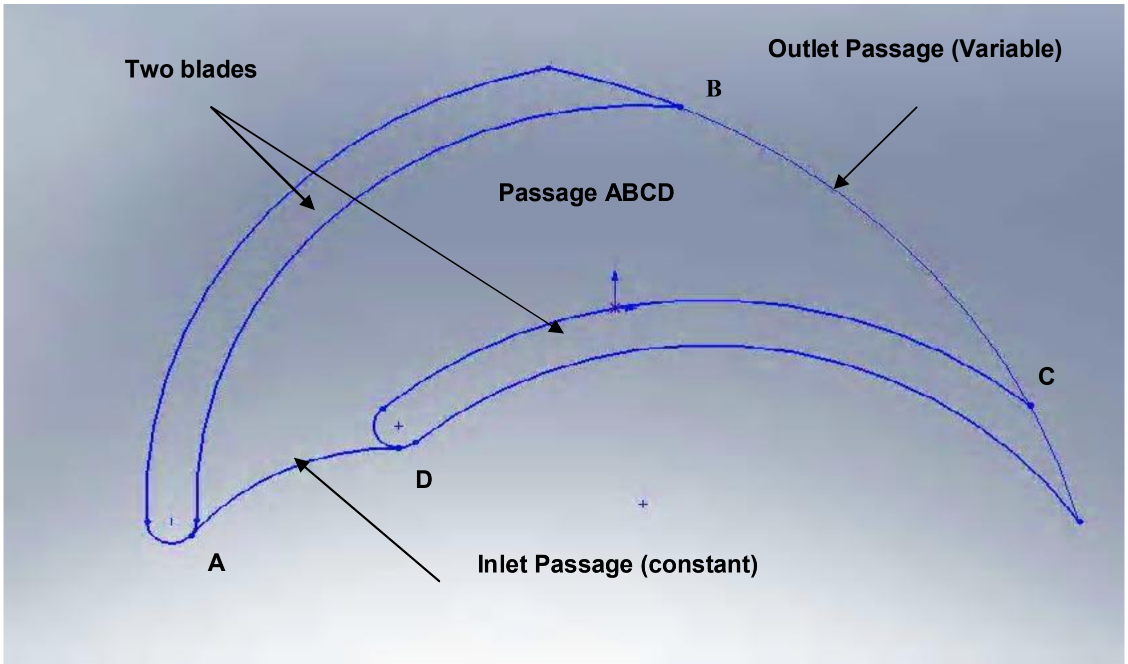

Figure 7.36: Passage area obtained from Blade to Blade setup

The passage areas demonstrate continues decrease with increase in outlet angle. See figure 7.37 below.

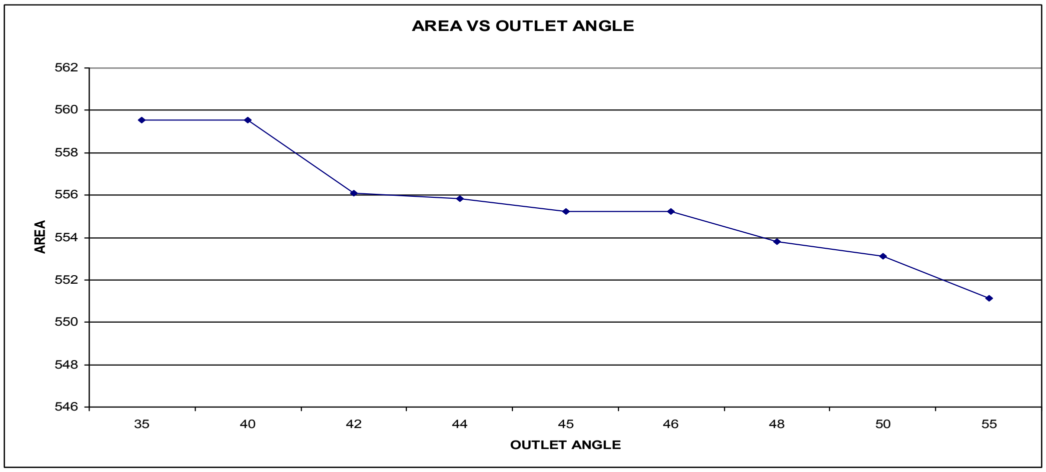

Figure 7.37: Detail investigation on passage area versus outlet angle.

ii) Passage length

Quiet amazingly, the passage length is erratic, but with outlet angle 42 degrees at the minimum and 45 degrees at the maximum. See figure 7.38 below

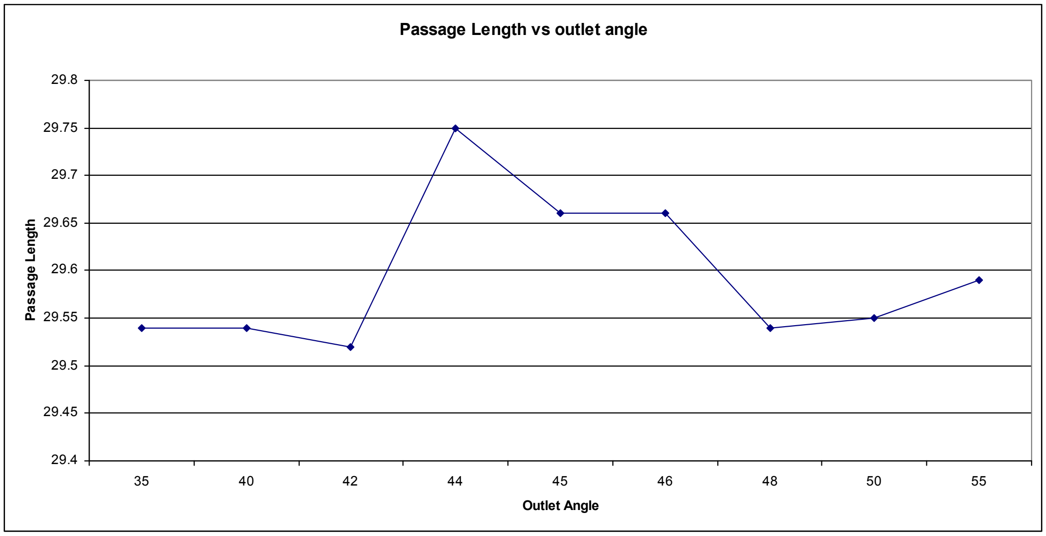

Figure 7.38: Detail investigation on outlet passage length versus outlet angle.

7.3 Discussion of Results.

From analytical algorithm and EFD comparison, it was evident that the best angle of attack is 12 degree at the outlet angle with respect to the inlet angle.

From EFD results, it is palpable that, by increasing the angle of attack from 35 degree to 45 degree at the outlet there will be huge increase in flow rate by 63.47%

There is also a slight decrease in the in the impeller Torque from 35 degrees to 42 degrees by 0.72%.

It is economically feasible to work at an outlet angle of 42 degrees due to increase in efficiency of 62.1% and a drop in torque of 0.72% by varying the outlet angle from 35 degrees to 42 degree.

Looking at the particle inspection for each angle of attack in EFD, it was revealed that there were fewer eddies at the outlet angle of 42 degrees as opposed to the other outlet angles.

According to Bansal [41] more eddies indicate

More friction,
Less flow
Lower fluid velocity
Lower efficiency

The increase in efficiency with increase in angle of attack was expected, but with corresponding increase in Torque on the impeller since the power of the system remains constant.

$$P = \frac{2\pi NT}{60} \quad [43]$$

P=Power transmitted in watt
N=Rotational speed of impeller in rev/min
T=Torque on impeller in N.m

From:

$$\eta = \frac{\left(P_{outlet} - P_{inlet}\right).Q}{\Omega.T}$$

η = efficiency

Q = Flow rate (constant)

P_{outlet} = Pressure at outlet

P_{inlet} = Pressure at inlet (constant)

Ω =Angular Velocity in rads/sec (constant)

From Pressure = Force/Area, it means that, if the passage of the outlet is increase (as seen in figure above at outlet angle of between 42 and 45 degrees) then there will be a lower pressure at the outlet, but with the constant inlet passage it will bring our equation above to:

$$T = \frac{P_{outlet} - P_{inlet}}{\eta}$$

With P_{inlet} constant, the efficiency increase overrides the P_{outlet} at its minimum thereby resulting in the drop in torque.

CHAPTER EIGHT

CONCLUSION

8.1 Conclusion

This study successfully conceptualised a Shape Memory Smart Centrifugal Impeller that will increase fluid flow rate through a given system if the fluid temperature increases above a given transition temperature (see section 5.2 of Chapter 5). The proposed smart pumping system, makes it possible to pump more fluid through a given system with the same power and with a decrease in impeller shaft torque (see Chapter 7). Results also show that it is possible to do more work (pump more fluid) with less power using a smart pumping system (see Chapter 7).

A demonstration centrifugal pumping system, i.e. FM21, in the Department of Mechanical Engineering of the Cape Peninsula University of Technology was used to create an understanding of such systems and analytical solutions for the system was described (see Chapters 3 and 5). The optimum conditions for a pumping system based on FM21 was determined by using specific inputs and varying impeller outlet angles from 30^0 to 55^0. The study successfully identified

- Optimum impeller blade inlet angle with corresponding outlet angle and efficiency

- Optimum impeller blade inlet angle with corresponding outlet angle and impeller outlet velocity
- Optimum impeller blade inlet angle with corresponding outlet angle and fluid flow rate through the impeller
- Optimum impeller blade inlet angle with corresponding outlet angle and impeller shaft torque
- Optimum impeller blade inlet angle with corresponding outlet angle with least eddy formation in the impeller system.

The conceptualization of the Shape Memory Smart Impeller using NiTi Shape Memory Alloys was achieved using Curved Beam Theory with the specific case of a curved beam with end conditions for the particular problem to be one end (at inlet) fixed and the other end (at outlet) is restrained against rotation (see Section 5.4). Based on the energy balance law, the constitutive relation for SMA's according to the Brinson model was used to determine forward transformation, i.e. Martensite to Austenite, and the reverse transformation, i.e. Austenite to Martensite. These transformations describe the mechanism of operation of the Shape Memory Smart Impeller. Analytical solutions show the feasibility of using the approach to solve for the displacements, i.e. total, vertical and horizontal, at all instances of temperature and martensite phase fraction. The displacements, although small, changes the outlet angle of the blade from 30^0 to 55^0, thus theoretically increasing the velocity at the outlet and increasing the head of the centrifugal impeller.

Engineering Fluid Dynamics (EFD.Lab), a full-featured general purpose CAD-embedded finite volume fluid flow and heat transfer simulation tool was used to perform computational fluid dynamics analyses. The results confirmed the optimum conditions of the specific system used to conceptualize the Shape Memory Smart Impeller. It also showed the formation of eddies, that would not typically be identified with the analytical solution.

A long-term outcome will be the functioning of this smart impeller in industries and better still, the complete eradication/elimination of standard impellers. The benefits to for example the automotive industry, would be the development of more efficient cooling systems. The operating benefits of such a pumping system include an increase in the cooling effect and higher efficiency thus providing:

- Less overheating;
- Less impeller variation;
- Adaptability in adverse conditions;
- Ability to adjust itself to system changes without manual intervention.

8.2 Recommendation

This study was conducted in partial fulfillment of a MTech: Mech Eng in the Department of Mechanical Engineering of the Cape Peninsula University of Technology. It focused on the conceptualization of a Shape Memory Smart Impeller. Although successful, the need to manufacture and test the system exists. Based on the solutions provided, it is possible to produce such a system, but attention should be given to the shape and geometry of the NiTi SMA inserts. Further analytical and numerical solutions for the actuation of the inseters should also be considered, i.e. Thin Plate or Shell Theory combined with Finite Element Techniques.

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APPENDIX A1: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 30^0

System Info

Product	EFD.Lab 8 1.0. Build: 413
Computer name	FEA2
User name	Administrator
Processors	Dual Core AMD Opteron(tm) Processor 280 (4 processors)
Memory	16382 MB / 8388607 MB
Operating system	Microsoft Windows XP Professional x64 Edition Service Pack 2 (Build 3790)
CAD version	SolidWorks 2007 SP0
CPU speed	2411 MHz

General Info

Model	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\fuhnwig_master\simulate2_inlet30_outlet30\assembly2_inlet30_outlet30.SLDASM
Project name	inlet30_outlet30
Project path	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\fuhnwig_master\simulate2_inlet30_outlet30\1\1.fwp
Units system	Custom Units
Analysis type	Internal
Exclude cavities without flow conditions	On
Coordinate system	Global coordinate system
Reference axis	X

INPUT DATA

Initial Mesh Settings

Automatic initial mesh: On
Result resolution level: 5
Advanced narrow channel refinement: Off
Refinement in solid region: Off

Geometry Resolution

Evaluation of minimum gap size: Manual
Minimum gap size: 0.04 m
Evaluation of minimum wall thickness: Manual

Minimum wall thickness: 0.01 m

Computational Domain

Size

X min	-0.0499922792 m
X max	0.0461997208 m
Y min	-0.050544753 m
Y max	0.045647247 m
Z min	0.00264763727 m
Z max	0.0192808874 m

Boundary Conditions

2D plane flow	None
At X min	Default
At X max	Default
At Y min	Default
At Y max	Default
At Z min	Default
At Z max	Default

Physical Features

Heat conduction in solids: Off
Time dependent: Off
Gravitational effects: Off
Flow type: Laminar only
Cavitation: Off
High Mach number flow: Off
Default roughness: 0 micrometer

Rotating Reference Frame

Axis of coordinate system	Z
Velocity	209.43951 m/s

Default wall conditions: Adiabatic wall

Initial Conditions

Thermodynamic parameters	Static Pressure: 101325 Pa Temperature: 293.2 K
Velocity parameters	Velocity vector Velocity in X direction: 0 m/s Velocity in Y direction: 0 m/s Velocity in Z direction: 0 m/s Relative to rotating frame: Off

Material Settings

Fluids

Water

Boundary Conditions

Inlet Volume Flow 1

Type	Inlet Volume Flow
Faces	Face <1 >
Coordinate system	Face Coordinate System
Reference axis	X
Flow parameters	Flow vectors direction: Normal to face Volume flow rate normal to face: 0.3 m^3/s Relative to rotating frame: No Fully developed flow: No Inlet profile: 0
Thermodynamic parameters	Temperature: 293.2 K

stator

Type	Real wall
Faces	Face <1 > Face <1 > Face <1 >
Coordinate system	Global coordinate system
Reference axis	X

Environment Pressure 1

Type	Environment Pressure
Faces	Face <1 >
Coordinate system	Global coordinate system
Reference axis	X
Thermodynamic parameters	Environment pressure: 101325 Pa Temperature: 293.2 K

Goals

Global Goals

GG Z - Component of Torque

Type	Global Goal
Goal type	Z - Component of Torque
Coordinate system	Global coordinate system
Use in convergence	On

Surface Goals

SG Av Static Pressure _inlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@cover3-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Z - Component of Torque at stator

Type	Surface Goal
Goal type	Z - Component of Torque
Faces	Face<1>@cover3-1 Face<2>@cover3-1 Face<3>@cover3-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate_inlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<1>@cover3-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Bulk Av Static Pressure_impeller's outlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<1>@measure3-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate _outlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<1>@cover3-1
Coordinate system	Global coordinate system
Use in convergence	On

Equation Goals

Pressure drop

Type	Equation Goal
Formula	SG Av Static Pressure _inlet-SG Bulk Av Static Pressure_impeller's outlet
Dimensionality	Pressure & stress
Use in convergence	On

Torque on impeller

Type	Equation Goal
Formula	GG Z - Component of Torque -SG Z - Component of Torque at stator
Dimensionality	Torque
Use in convergence	On

Efficiency

Type	Equation Goal
Formula	Pressure drop*{Inlet Volume Flow 1:Volume flow rate normal to face:3.000e-001}/209.44/Torque on impeller
Dimensionality	No units
Use in convergence	On

Component Control Info

Disabled components: Extrude1@measure3-1@assembly2_inlet30_outlet30

Calculation Control Options

Finish Conditions

Finish conditions	If one is satisfied
Maximum travels	4
Goals convergence	Analysis interval: 0.5

Solver Refinement

Refinement: Disabled

Results Saving

Save before refinement	On

Advanced Control Options

Flow Freezing

Flow freezing strategy	Disabled

RESULTS

General Info

Iterations: 145
CPU time: 668 s

Log

Mesh generation started	20:25:40 , Feb 21
Mesh generation normally finished	20:25:47 , Feb 21
Preparing data for calculation	20:25:52 , Feb 21
Calculation started 0	20:25:57 , Feb 21
Calculation has converged since the following criteria are satisfied: 144	20:37:09 , Feb 21
Goals are converged 144	
Calculation finished 145	20:37:33 , Feb 21

Warnings: Negative pressure Minimum pressure=-1.01749e+008 Pa; dV/V=0.508021

A vortex crosses the pressure opening 1 ; Inlet flow/outlet flow=0.0867162	Boundary Condition : Environment Pressure

Calculation Mesh

Basic Mesh Dimensions

Number of cells in X	40
Number of cells in Y	40
Number of cells in Z	6

Number Of Cells

Total cells	49780
Fluid cells	22372
Solid cells	11362
Partial cells	16046
Irregular cells	0
Trimmed cells	36

Maximum refinement level: 1

Goals

Name	Unit	Value	Progress	Use in convergen	Delta	Criteria

				ce		
GG Z - Component of Torque	N*m	3342.78	100	On	6.86916074	25.5869052
SG Av Static Pressure _inlet	Pa	1.18315e+008	100	On	576070.454	1803445.05
SG Z - Component of Torque at stator	N*m	-1.33553	100	On	0.362038955	0.511200715
SG Mass Flow Rate_inlet	kg/s	299.269	100	On	0	0.299268522
SG Bulk Av Static Pressure_impeller's outlet	Pa	-4.66062e+006	100	On	301286.077	331428.882
SG Mass Flow Rate _outlet	kg/s	-299.269	100	On	0.000799035766	0.299268678
Torque on impeller	N*m	3344.12	100	On	6.84878365	25.5755294
Pressure drop	Pa	1.22975e+008	100	On	459815.918	1679642.71
Efficiency		52.6742	100	On	0.166195167	0.362899357

Min/Max Table

Name	Minimum	Maximum
Pressure [Pa]	-1.01749e+008	1.76163e+008
Temperature [K]	242.488	300.712
Density [kg/m^3]	995.613	1001.3
Velocity [m/s]	0	831.275
X-velocity [m/s]	-540.844	557.483
Y-velocity [m/s]	-550.656	542.135
Z-velocity [m/s]	-726.416	478.358
Heat Transfer Coefficient [W/m^2/K]	0	0
Shear Stress [Pa]	1.13392e-005	4.42873e+006

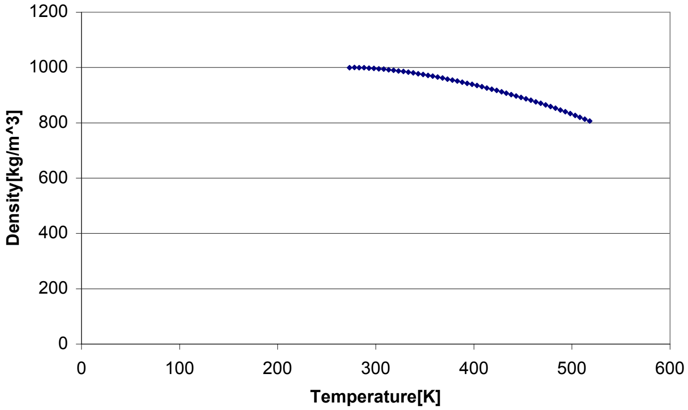
Surface Heat Flux [W/m^2]	0	0
Water Mass Fraction [ ]	1	1
Water Volume Fraction [ ]	1	1
Fluid Temperature [K]	242.488	300.712
Velocity RRF [m/s]	0	831.543
X-velocity RRF [m/s]	-547.275	560.37
Y-velocity RRF [m/s]	-552.651	546.687
Z-velocity RRF [m/s]	-726.416	478.358

Engineering Database

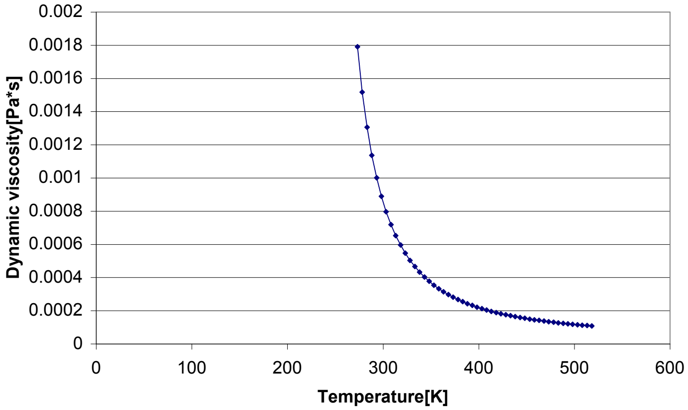
Liquids

Water

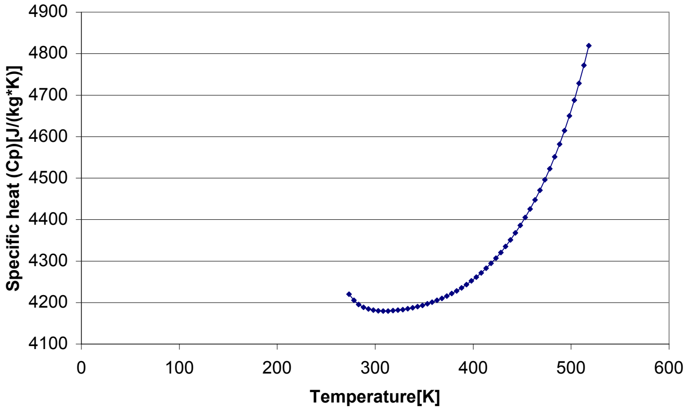
Path: Liquid FW Defined
Density



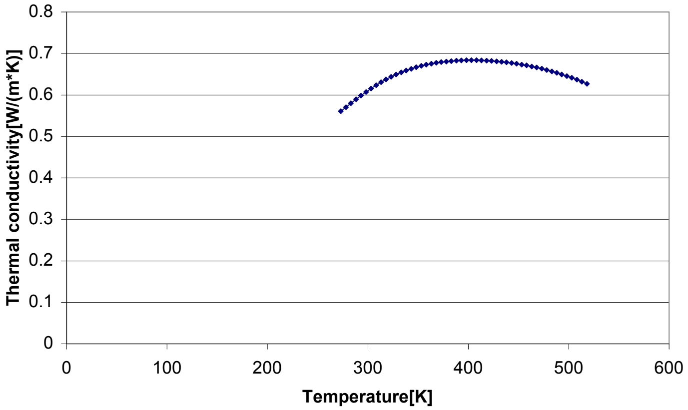
Dynamic viscosity



Specific heat (Cp)



Thermal conductivity



APPENDIX A2: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 35^0

System Info

Product	EFD.Lab 8 1.0. Build: 413
Computer name	FEA2
User name	Administrator
Processors	Dual Core AMD Opteron(tm) Processor 280 (4 processors)
Memory	16382 MB / 8388607 MB
Operating system	Microsoft Windows XP Professional x64 Edition Service Pack 2 (Build 3790)
CAD version	SolidWorks 2007 SP0
CPU speed	2411 MHz

General Info

Model	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate2_inlet30_outlet35\Assem3-1_inlet30_outlet35.SLDASM
Project name	inlet30_outlet35
Project path	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate2_inlet30_outlet35\1\1.fwp
Units system	SI (m-kg-s)
Analysis type	Internal
Exclude cavities without flow conditions	On
Coordinate system	Global coordinate system
Reference axis	X

INPUT DATA

Initial Mesh Settings

Automatic initial mesh: On
Result resolution level: 5
Advanced narrow channel refinement: Off
Refinement in solid region: Off

Geometry Resolution

Evaluation of minimum gap size: Manual
Minimum gap size: 0.04 m
Evaluation of minimum wall thickness: Manual
Minimum wall thickness: 0.01 m

APPENDIX A2: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 35^0

Computational Domain

Size

X min	-0.0473342462 m
X max	0.0488577538 m
Y min	-0.0430765393 m
Y max	0.0531154607 m
Z min	-0.0038287647 m
Z max	0.0128044854 m

Boundary Conditions

2D plane flow	None
At X min	Default
At X max	Default
At Y min	Default
At Y max	Default
At Z min	Default
At Z max	Default

Physical Features

Heat conduction in solids: Off
Time dependent: Off
Gravitational effects: Off
Flow type: Laminar only
Cavitation: Off
High Mach number flow: Off
Default roughness: 0 micrometer

Rotating Reference Frame

Axis of coordinate system	X
Velocity	209.43951 m/s

Default wall conditions: Adiabatic wall

Initial Conditions

Thermodynamic parameters	Static Pressure: 101325 Pa Temperature: 293.2 K
Velocity parameters	Velocity vector Velocity in X direction: 0 m/s Velocity in Y direction: 0 m/s Velocity in Z direction: 0 m/s Relative to rotating frame: Off

APPENDIX A2: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 35^0

Material Settings

Fluids

Water

Boundary Conditions

Environment Pressure 1

Type	Environment Pressure
Faces	Face <1 cover3-1-1@>
Coordinate system	Global coordinate system
Reference axis	X
Thermodynamic parameters	Environment pressure: 101325 Pa Temperature: 293.2 K

stator walls

Type	Real wall
Faces	Face <1 cover3-1-1@> Face <1 cover3-1-1@> Face <1 cover3-1-1@>
Coordinate system	Global coordinate system
Reference axis	X

Inlet Volume Flow 1

Type	Inlet Volume Flow
Faces	Face <1 cover3-1-1@>
Coordinate system	Face Coordinate System
Reference axis	X
Flow parameters	Flow vectors direction: Normal to face Volume flow rate normal to face: 0.3 m^3/s Relative to rotating frame: No Fully developed flow: No Inlet profile: 0
Thermodynamic parameters	Temperature: 293.2 K

Goals

Global Goals

GG Z - Component of Torque

Type	Global Goal
Goal type	Z - Component of Torque
Coordinate system	Global coordinate system
Use in convergence	On

APPENDIX A2: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 35^0

Surface Goals

SG Bulk Av Static Pressure at impeller outlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<1>@cover3-1-1 Face<2>@measure3-1-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate at outlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<2>@cover3-1-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Z - Component of Torque at stator

Type	Surface Goal
Goal type	Z - Component of Torque
Faces	Face<1>@cover3-1-1 Face<2>@cover3-1-1 Face<3>@cover3-1-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate at inlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<1>@cover3-1-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Av Static Pressure at inlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<1>@cover3-1-1
Coordinate system	Global coordinate system
Use in convergence	On

Equation Goals

Pressure drop

Type	Equation Goal

APPENDIX A2: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 35^0

Formula	SG Av Static Pressure at inlet-SG Bulk Av Static Pressure at impeller outlet
Dimensionality	Pressure & stress
Use in convergence	On

Torque on impeller

Type	Equation Goal
Formula	GG Z - Component of Torque -SG Z - Component of Torque at stator
Dimensionality	Torque
Use in convergence	On

Efficiency

Type	Equation Goal
Formula	Pressure drop*{Inlet Volume Flow 1:Volume flow rate normal to face:3.000e-001}/209.44/Torque on impeller
Dimensionality	No units
Use in convergence	On

Component Control Info

Disabled components: Extrude1@measure3-1-1@Assem3-1_inlet30_outlet35

Calculation Control Options

Finish Conditions

Finish conditions	If one is satisfied
Maximum travels	4
Goals convergence	Analysis interval: 0.5

Solver Refinement

Refinement: Disabled

Results Saving

Save before refinement	On

Advanced Control Options

Flow Freezing

Flow freezing strategy	Disabled

RESULTS

General Info

Iterations: 119
CPU time: 746 s

Log

Mesh generation started	21:59:20 , Feb 19
Mesh generation normally finished	21:59:27 , Feb 19
Preparing data for calculation	21:59:33 , Feb 19
Calculation started 0	21:59:39 , Feb 19
Calculation has converged since the following criteria are satisfied: 118	22:12:56 , Feb 19
Goals are converged 118	
Calculation finished 119	22:13:07 , Feb 19

Warnings: Negative pressure Minimum pressure=-1.12847e+008 Pa; dV/V=0.472028

A vortex crosses the pressure opening 1 ; Inlet flow/outlet flow=0.0709203	Boundary Condition : Environment Pressure

Calculation Mesh

Basic Mesh Dimensions

Number of cells in X	40
Number of cells in Y	40
Number of cells in Z	6

Number Of Cells

Total cells	49759
Fluid cells	22495
Solid cells	11305
Partial cells	15959
Irregular cells	0
Trimmed cells	22

Maximum refinement level: 1

Goals

Name	Unit	Value	Progress	Use in convergence	Delta	Criteria
GG Z -	N*m	3209.5	100	On	17.268121	25.263647

Component of Torque					6	6
SG Bulk Av Static Pressure at impeller outlet	Pa	5.33205e+007	100	On	1544878.92	1562423.29
SG Mass Flow Rate at outlet	kg/s	-300.559	100	On	0.000534568377	0.300559149
SG Z - Component of Torque at stator	N*m	-2.90776	100	On	0.385858208	0.738791416
SG Mass Flow Rate at inlet	kg/s	300.559	100	On	0	0.300559363
SG Av Static Pressure at inlet	Pa	9.7086e+007	100	On	1027504.65	2779738.77
Torque on impeller	N*m	3212.41	100	On	15.5063805	25.864391
Pressure drop	Pa	4.37655e+007	100	On	723859.045	1217315.48
Efficiency		19.5148	100	On	0.121804855	0.433164198

Min/Max Table

Name	Minimum	Maximum
Pressure [Pa]	-1.12847e+008	1.5497e+008
Temperature [K]	247.312	300.394
Density [kg/m^3]	995.658	1001.3
Velocity [m/s]	0	662.956
X-velocity [m/s]	-511.496	518.979
Y-velocity [m/s]	-537.106	503.477
Z-velocity [m/s]	-539.884	463.645
Heat Transfer Coefficient [W/m^2/K]	0	0
Shear Stress [Pa]	4.34456e-005	3.79524e+006
Surface Heat Flux [W/m^2]	0	0
Water Mass Fraction [ ]	1	1
Water Volume Fraction [ ]	1	1

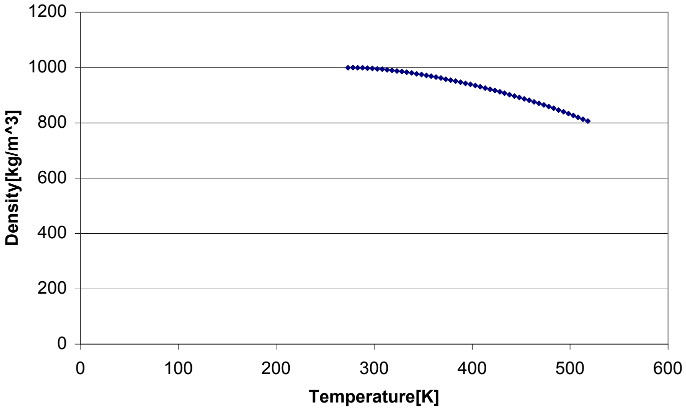
Fluid Temperature [K]	247.312	300.394
Velocity RRF [m/s]	0	660.209
X-velocity RRF [m/s]	-511.496	518.979
Y-velocity RRF [m/s]	-537.761	502.822
Z-velocity RRF [m/s]	-543.728	466.241

Engineering Database

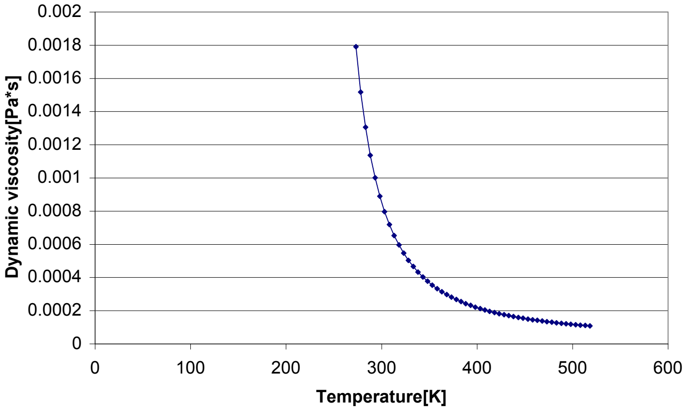
Liquids

Water

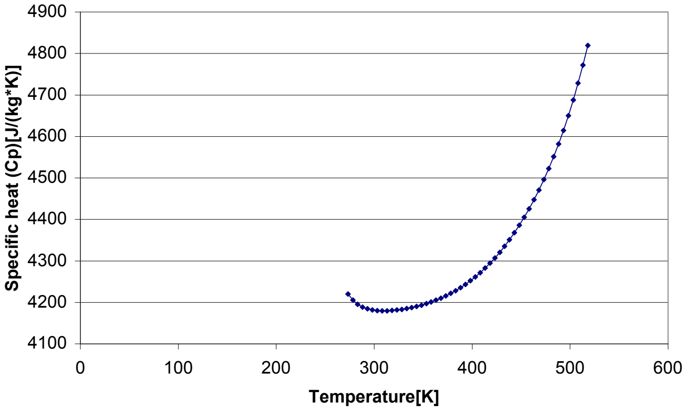
Path: Liquid FW Defined
Density



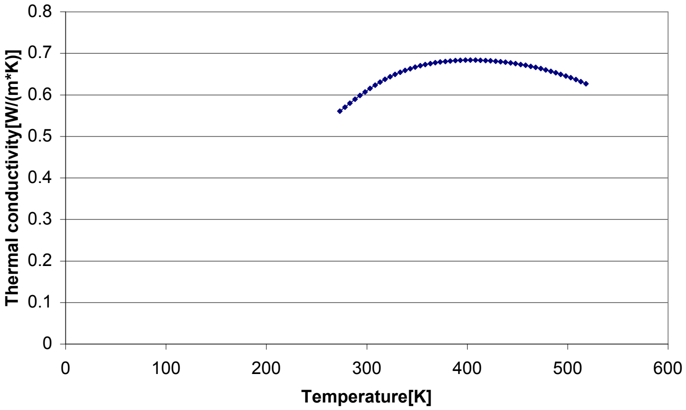
Dynamic viscosity



Specific heat (Cp)



Thermal conductivity



APPENDIX A3: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 40^0

System Info

Product	EFD.Lab 8 1.0. Build: 413
Computer name	FEA2
User name	Administrator
Processors	Dual Core AMD Opteron(tm) Processor 280 (4 processors)
Memory	16382 MB / 8388607 MB
Operating system	Microsoft Windows XP Professional x64 Edition Service Pack 2 (Build 3790)
CAD version	SolidWorks 2007 SP0
CPU speed	2411 MHz

General Info

Model	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate3_inlet30_outlet40\Assem3-2_inlet30_outlet40.SLDASM
Project name	inlet30_outlet40
Project path	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate3_inlet30_outlet40\1\1.fwp
Units system	SI (m-kg-s)
Analysis type	Internal
Exclude cavities without flow conditions	On
Coordinate system	Global coordinate system
Reference axis	X

INPUT DATA

Initial Mesh Settings

Automatic initial mesh: On
Result resolution level: 5
Advanced narrow channel refinement: Off
Refinement in solid region: Off

Geometry Resolution

Evaluation of minimum gap size: Manual
Minimum gap size: 0.04 m
Evaluation of minimum wall thickness: Manual
Minimum wall thickness: 0.01 m

APPENDIX A3: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 40^0

Computational Domain

Size

X min	-0.0570569915 m
X max	0.0391350085 m
Y min	-0.040496 m
Y max	0.055696 m
Z min	-0.00305140391 m
Z max	0.0135818462 m

Boundary Conditions

2D plane flow	None
At X min	Default
At X max	Default
At Y min	Default
At Y max	Default
At Z min	Default
At Z max	Default

Physical Features

Heat conduction in solids: Off
Time dependent: Off
Gravitational effects: Off
Flow type: Laminar only
Cavitation: Off
High Mach number flow: Off
Default roughness: 0 micrometer

Rotating Reference Frame

Axis of coordinate system	Z
Velocity	209.43951 m/s

Default wall conditions: Adiabatic wall

Initial Conditions

Thermodynamic parameters	Static Pressure: 101325 Pa Temperature: 293.2 K
Velocity parameters	Velocity vector Velocity in X direction: 0 m/s Velocity in Y direction: 0 m/s Velocity in Z direction: 0 m/s Relative to rotating frame: Off

APPENDIX A3: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 40^0

Material Settings

Fluids

Water

Boundary Conditions

Inlet Volume Flow 1

Type	Inlet Volume Flow
Faces	Face <1 cover3-2-1@>
Coordinate system	Face Coordinate System
Reference axis	X
Flow parameters	Flow vectors direction: Normal to face Volume flow rate normal to face: 0.3 m^3/s Relative to rotating frame: No Fully developed flow: No Inlet profile: 0
Thermodynamic parameters	Temperature: 293.2 K

stator walls

Type	Real wall
Faces	Face <1 cover3-2-1@> Face <1 cover3-2-1@> Face <1 cover3-2-1@>
Coordinate system	Global coordinate system
Reference axis	X

Environment Pressure 1

Type	Environment Pressure
Faces	Face <1 cover3-2-1@>
Coordinate system	Global coordinate system
Reference axis	X
Thermodynamic parameters	Environment pressure: 101325 Pa Temperature: 293.2 K

Goals

Global Goals

GG Z - Component of Torque

Type	Global Goal
Goal type	Z - Component of Torque
Coordinate system	Global coordinate system
Use in convergence	On

Surface Goals

SG Mass Flow Rate at inlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<4>@cover3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

SG BULK Av static Pressure at impeller outlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@measure3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Z - Component of Torque at stator

Type	Surface Goal
Goal type	Z - Component of Torque
Faces	Face<1>@cover3-2-1 Face<2>@cover3-2-1 Face<3>@cover3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate at outlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<2>@cover3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Av Static Pressure at inlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@cover3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

Equation Goals

Pressure Drop

Type	Equation Goal
Formula	SG Av Static Pressure at inlet-SG BULK

APPENDIX A3: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 40^0

	Av static Pressure at impeller outlet
Dimensionality	Pressure & stress
Use in convergence	On

Torque on impeller

Type	Equation Goal
Formula	GG Z - Component of Torque -SG Z - Component of Torque at stator
Dimensionality	Torque
Use in convergence	On

Efficiency

Type	Equation Goal
Formula	Pressure Drop*{Inlet Volume Flow 1:Volume flow rate normal to face:3.000e-001}/209.44/Torque on impeller
Dimensionality	No units
Use in convergence	On

Component Control Info

Disabled components: Extrude1@measure3-2-1@Assem3-2_inlet30_outlet40

Calculation Control Options

Finish Conditions

Finish conditions	If one is satisfied
Maximum travels	4
Goals convergence	Analysis interval: 0.5

Solver Refinement

Refinement: Disabled

Results Saving

Save before refinement	On

Advanced Control Options

Flow Freezing

Flow freezing strategy	Disabled

RESULTS

General Info

Iterations: 295

APPENDIX A3: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 40^0

CPU time: 2124 s

Log

Mesh generation started	09:32:05 , Feb 20
Mesh generation normally finished	09:32:12 , Feb 20
Preparing data for calculation	09:32:16 , Feb 20
Calculation started 0	09:32:21 , Feb 20
Calculation has converged since the following criteria are satisfied: 294	10:08:23 , Feb 20
Max. travel is reached 294	
Calculation finished 295	10:08:34 , Feb 20

Warnings: Negative pressure Minimum pressure=-1.20648e+008 Pa; dV/V=0.50384

A vortex crosses the pressure opening 1 ; Inlet flow/outlet flow=0.0829473	Boundary Condition : Environment Pressure

Calculation Mesh

Basic Mesh Dimensions

Number of cells in X	40
Number of cells in Y	40
Number of cells in Z	6

Number Of Cells

Total cells	49780
Fluid cells	22340
Solid cells	11404
Partial cells	16036
Irregular cells	0
Trimmed cells	15

Maximum refinement level: 1

Goals

Name	Unit	Value	Progress	Use in convergence	Delta	Criteria
GG Z - Component of Torque	N*m	3220.42	100	On	9.09904119	19.16549
SG Mass	kg/s	299.269	100	On	0	0.2992685

Flow Rate at inlet						22
SG BULK Av static Pressure at impeller outlet	Pa	-4.70621e+006	100	On	62248.2642	275354.972
SG Z - Component of Torque at stator	N*m	-14.867	57.2	On	1.05526751	0.604526347
SG Mass Flow Rate at outlet	kg/s	-299.267	100	On	0.000333429257	0.299267474
SG Av Static Pressure at inlet	Pa	1.08313e+008	100	On	179946.348	1515809.26
Torque on impeller	N*m	3235.28	100	On	8.03634147	19.2204476
Pressure Drop	Pa	1.1302e+008	100	On	182911.487	1423338.64
Efficiency		50.0384	100	On	0.104415189	0.390556572

Min/Max Table

Name	Minimum	Maximum
Pressure [Pa]	-1.20648e+008	1.65414e+008
Temperature [K]	244.738	300.899
Density [kg/m^3]	995.655	1001.3
Velocity [m/s]	0	628.068
X-velocity [m/s]	-521.685	539.826
Y-velocity [m/s]	-552.693	514.782
Z-velocity [m/s]	-549.671	471.763
Heat Transfer Coefficient [W/m^2/K]	0	0
Shear Stress [Pa]	1.07322e-005	241756
Surface Heat Flux [W/m^2]	0	0
Water Mass Fraction [ ]	1	1
Water Volume Fraction [ ]	1	1
Fluid Temperature [K]	244.738	300.899
Velocity RRF [m/s]	0	632.088
X-velocity RRF [m/s]	-521.73	544.817

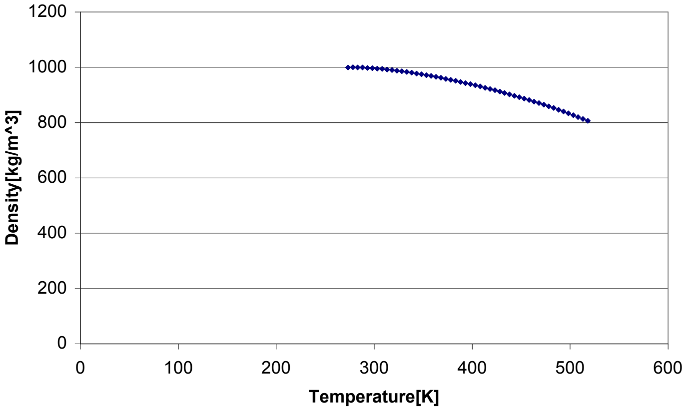
Y-velocity RRF [m/s]	-553.208	521.317
Z-velocity RRF [m/s]	-549.671	471.763

Engineering Database

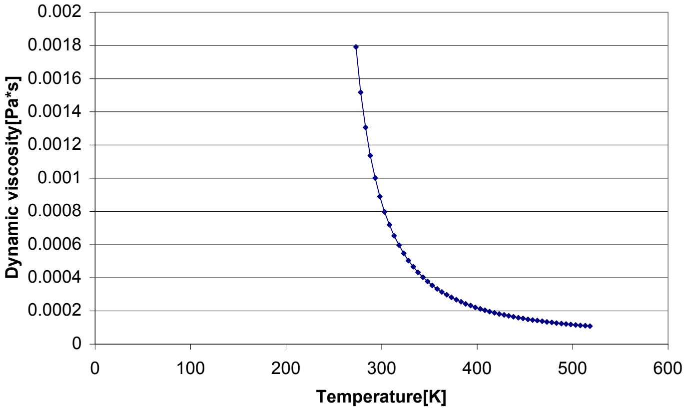
Liquids

Water

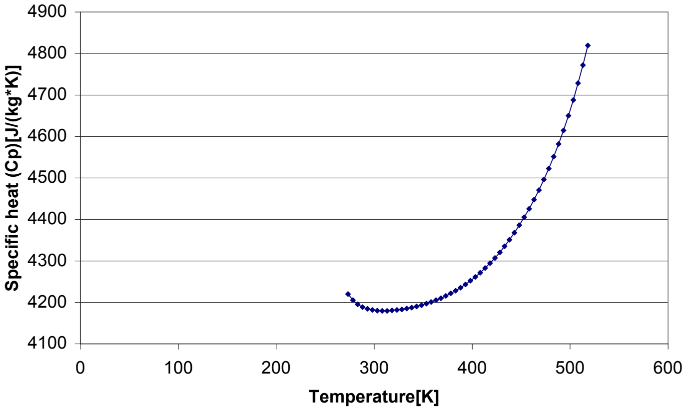
Path: Liquid FW Defined
Density



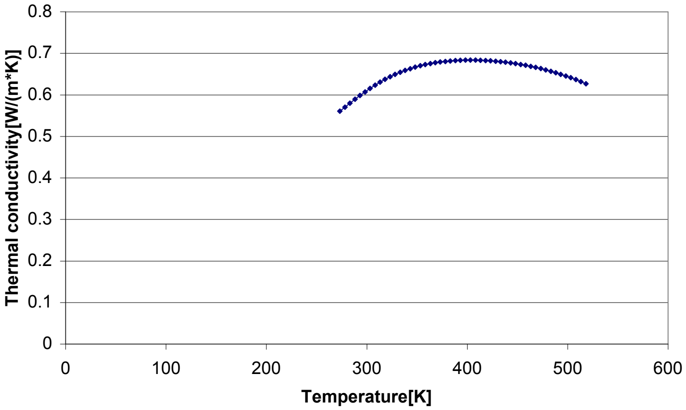
Dynamic viscosity



Specific heat (Cp)



Thermal conductivity



APPENDIX A4: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 41.5^0

System Info

Product	EFD.Lab 8 1.0. Build: 413
Computer name	FEA2
User name	Administrator
Processors	Dual Core AMD Opteron(tm) Processor 280 (4 processors)
Memory	16382 MB / 8388607 MB
Operating system	Microsoft Windows XP Professional x64 Edition Service Pack 2 (Build 3790)
CAD version	SolidWorks 2007 SP0
CPU speed	2411 MHz

General Info

Model	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate3-2_inlet30_outlet41.5\Assem3-2_inlet30_outlet41.5.SLDASM
Project name	Default (1)
Project path	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate3-2_inlet30_outlet41.5\1\1.fwp
Units system	SI (m-kg-s)
Analysis type	Internal
Exclude cavities without flow conditions	On
Coordinate system	Global coordinate system
Reference axis	X

INPUT DATA

Initial Mesh Settings

Automatic initial mesh: On
Result resolution level: 5
Advanced narrow channel refinement: Off
Refinement in solid region: Off

Geometry Resolution

Evaluation of minimum gap size: Manual
Minimum gap size: 0.04 m
Evaluation of minimum wall thickness: Manual
Minimum wall thickness: 0.01 m

APPENDIX A4: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 41.5^0

Computational Domain

Size

X min	-0.0570569915 m
X max	0.0391350085 m
Y min	-0.040496 m
Y max	0.055696 m
Z min	-0.00305140391 m
Z max	0.0135818462 m

Boundary Conditions

2D plane flow	None
At X min	Default
At X max	Default
At Y min	Default
At Y max	Default
At Z min	Default
At Z max	Default

Physical Features

Heat conduction in solids: Off
Time dependent: Off
Gravitational effects: Off
Flow type: Laminar only
Cavitation: Off
High Mach number flow: Off
Default roughness: 0 micrometer

Rotating Reference Frame

Axis of coordinate system	Z
Velocity	209.43951 m/s

Default wall conditions: Adiabatic wall

Initial Conditions

Thermodynamic parameters	Static Pressure: 101325 Pa Temperature: 293.2 K
Velocity parameters	Velocity vector Velocity in X direction: 0 m/s Velocity in Y direction: 0 m/s Velocity in Z direction: 0 m/s Relative to rotating frame: Off

APPENDIX A4: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 41.5^0

Material Settings

Fluids

Water

Boundary Conditions

stator Wall

Type	Real wall
Faces	Face <1 > Face <1 > Face <1 >
Coordinate system	Global coordinate system
Reference axis	X

Inlet Volume Flow 1

Type	Inlet Volume Flow
Faces	Face <1 >
Coordinate system	Face Coordinate System
Reference axis	X
Flow parameters	Flow vectors direction: Normal to face Volume flow rate normal to face: 0.3 m^3/s Relative to rotating frame: No Fully developed flow: No Inlet profile: 0
Thermodynamic parameters	Temperature: 293.2 K

Environment Pressure 1

Type	Environment Pressure
Faces	Face <1 >
Coordinate system	Global coordinate system
Reference axis	X
Thermodynamic parameters	Environment pressure: 101325 Pa Temperature: 293.2 K

Goals

Global Goals

GG Z - Component of Torque 1

Type	Global Goal
Goal type	Z - Component of Torque
Coordinate system	Global coordinate system
Use in convergence	On

Surface Goals

SG Z - Component of Torque at stator

Type	Surface Goal
Goal type	Z - Component of Torque
Faces	Face<1>@cover3-2-1 Face<2>@cover3-2-1 Face<3>@cover3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

Equation Goals

Torque on impeller

Type	Equation Goal
Formula	GG Z - Component of Torque 1-SG Z - Component of Torque at stator
Dimensionality	Torque
Use in convergence	On

Component Control Info

Disabled components: Extrude1@measure3-2-1@Assem3-2_inlet30_outlet41.5

Calculation Control Options

Finish Conditions

Finish conditions	If one is satisfied
Maximum travels	4
Goals convergence	Analysis interval: 0.5

Solver Refinement

Refinement: Disabled

Results Saving

Save before refinement	On

Advanced Control Options

Flow Freezing

Flow freezing strategy	Disabled

RESULTS

General Info

Iterations: 193

CPU time: 1618 s

Log

Preparing data for calculation	11:09:21 , Feb 29
Calculation started 0	11:09:26 , Feb 29
Calculation has converged since the following criteria are satisfied: 192	11:36:40 , Feb 29
Goals are converged 192	
Calculation finished 193	11:36:55 , Feb 29

Warnings: Negative pressure Minimum pressure=-1.19349e+008 Pa; dV/V=0.507242

A vortex crosses the pressure opening 1 ; Inlet flow/outlet flow=0.0876859	Boundary Condition : Environment Pressure

Calculation Mesh

Basic Mesh Dimensions

Number of cells in X	40
Number of cells in Y	40
Number of cells in Z	6

Number Of Cells

Total cells	49843
Fluid cells	22449
Solid cells	11347
Partial cells	16047
Irregular cells	0
Trimmed cells	37

Maximum refinement level: 1

Goals

Name	Unit	Value	Progress	Use in convergence	Delta	Criteria
GG Z - Component of Torque 1	N*m	3198.7	100	On	3.75146292	24.9023691
SG Z - Component of	N*m	-10.6434	100	On	0.569035336	0.727476551

Torque at stator						
Torque on impeller	N*m	3209.34	100	On	5.69231171	24.8631235

Min/Max Table

Name	Minimum	Maximum
Pressure [Pa]	-1.19349e+008	1.66599e+008
Temperature [K]	243.022	300.905
Density [kg/m^3]	995.65	1001.3
Velocity [m/s]	0	686.006
X-velocity [m/s]	-522.955	537.276
Y-velocity [m/s]	-549.808	516.965
Z-velocity [m/s]	-561.65	500.879
Heat Transfer Coefficient [W/m^2/K]	0	0
Shear Stress [Pa]	8.20053e-006	3.90581e+006
Surface Heat Flux [W/m^2]	0	0
Water Mass Fraction [ ]	1	1
Water Volume Fraction [ ]	1	1
Fluid Temperature [K]	243.022	300.905
Velocity RRF [m/s]	0	683.479
X-velocity RRF [m/s]	-527.533	542.267
Y-velocity RRF [m/s]	-550.323	523.5
Z-velocity RRF [m/s]	-561.65	500.879

Engineering Database

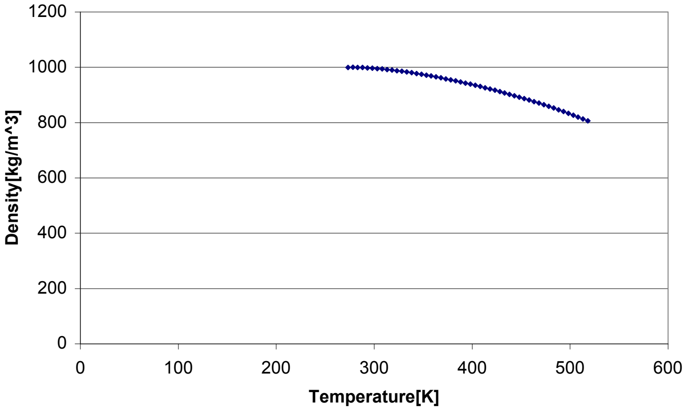
Liquids

Water

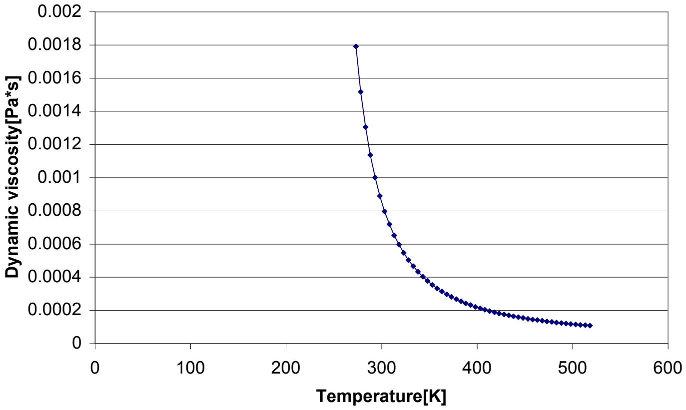
Path: Liquid FW Defined

APPENDIX A4: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 41.5^0

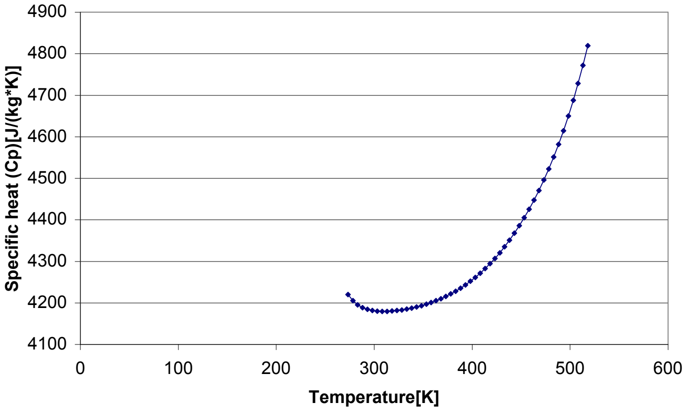
Density



Dynamic viscosity

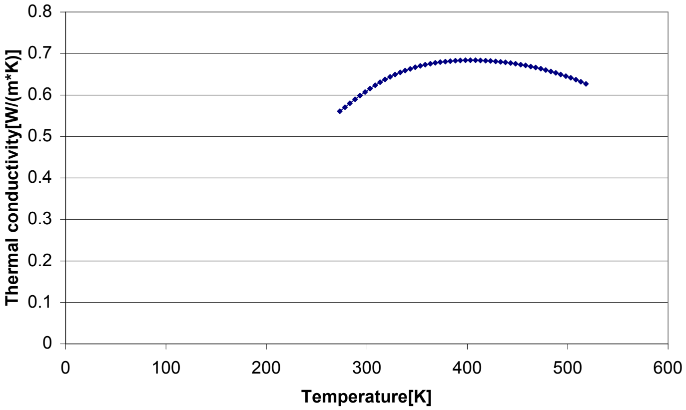


Specific heat (Cp)



APPENDIX A4: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 41.5^0

Thermal conductivity



APPENDIX A5: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 42^0

System Info

Product	EFD.Lab 8 1.0. Build: 413
Computer name	FEA2
User name	Administrator
Processors	Dual Core AMD Opteron(tm) Processor 280 (4 processors)
Memory	16382 MB / 8388607 MB
Operating system	Microsoft Windows XP Professional x64 Edition Service Pack 2 (Build 3790)
CAD version	SolidWorks 2007 SP0
CPU speed	2411 MHz

General Info

Model	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate4_inlet30_outlet42\Assem3-2_inlet30_outlet42.SLDASM
Project name	inlet30_outlet42
Project path	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate4_inlet30_outlet42\1\1.fwp
Units system	SI (m-kg-s)
Analysis type	Internal
Exclude cavities without flow conditions	On
Coordinate system	Global coordinate system
Reference axis	X

INPUT DATA

Initial Mesh Settings

Automatic initial mesh: On
Result resolution level: 5
Advanced narrow channel refinement: Off
Refinement in solid region: Off

Geometry Resolution

Evaluation of minimum gap size: Manual
Minimum gap size: 0.04 m
Evaluation of minimum wall thickness: Manual
Minimum wall thickness: 0.01 m

APPENDIX A5: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 42^0

Computational Domain

Size

X min	-0.0570569915 m
X max	0.0391350085 m
Y min	-0.040496 m
Y max	0.055696 m
Z min	-0.00305140391 m
Z max	0.0135818462 m

Boundary Conditions

2D plane flow	None
At X min	Default
At X max	Default
At Y min	Default
At Y max	Default
At Z min	Default
At Z max	Default

Physical Features

Heat conduction in solids: Off
Time dependent: Off
Gravitational effects: Off
Flow type: Laminar only
Cavitation: Off
High Mach number flow: Off
Default roughness: 0 micrometer

Rotating Reference Frame

Axis of coordinate system	Z
Velocity	209.43951 m/s

Default wall conditions: Adiabatic wall

Initial Conditions

Thermodynamic parameters	Static Pressure: 101325 Pa Temperature: 293.2 K
Velocity parameters	Velocity vector Velocity in X direction: 0 m/s Velocity in Y direction: 0 m/s Velocity in Z direction: 0 m/s Relative to rotating frame: Off

APPENDIX A5: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 42^0

Material Settings

Fluids

Water

Boundary Conditions

Environment Pressure 1

Type	Environment Pressure
Faces	Face <1 >
Coordinate system	Global coordinate system
Reference axis	X
Thermodynamic parameters	Environment pressure: 101325 Pa Temperature: 293.2 K

Inlet Volume Flow 1

Type	Inlet Volume Flow
Faces	Face <1 >
Coordinate system	Face Coordinate System
Reference axis	X
Flow parameters	Flow vectors direction: Normal to face Volume flow rate normal to face: 0.3 m^3/s Relative to rotating frame: No Fully developed flow: No Inlet profile: 0
Thermodynamic parameters	Temperature: 293.2 K

stator walls

Type	Real wall
Faces	Face <1 > Face <1 > Face <1 >
Coordinate system	Global coordinate system
Reference axis	X

Goals

Global Goals

GG Z - Component of Torque

Type	Global Goal
Goal type	Z - Component of Torque
Coordinate system	Global coordinate system
Use in convergence	On

Surface Goals

SG Mass Flow Rate at outlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<2>@cover3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate at inlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<5>@cover3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Z - Component of Torque at stator

Type	Surface Goal
Goal type	Z - Component of Torque
Faces	Face<1>@cover3-2-1 Face<2>@cover3-2-1 Face<3>@cover3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Bulk Av Static Pressure at impeller outlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@measure3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Av Static Pressure at inlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@cover3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

Equation Goals

Presuure Drop

Type	Equation Goal
Formula	SG Av Static Pressure at inlet-SG Bulk Av

APPENDIX A5: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 42^0

	Static Pressure at impeller outlet
Dimensionality	Pressure & stress
Use in convergence	On

Torque on impeller

Type	Equation Goal
Formula	GG Z - Component of Torque -SG Z - Component of Torque at stator
Dimensionality	Torque
Use in convergence	On

Efficiency

Type	Equation Goal
Formula	Presuure Drop*{Inlet Volume Flow 1:Volume flow rate normal to face:3.000e-001}/209.44/Torque on impeller
Dimensionality	No units
Use in convergence	On

Component Control Info

Disabled components: Extrude1@measure3-2-1@Assem3-2_inlet30_outlet42

Calculation Control Options

Finish Conditions

Finish conditions	If one is satisfied
Maximum travels	4
Goals convergence	Analysis interval: 0.5

Solver Refinement

Refinement: Disabled

Results Saving

Save before refinement	On

Advanced Control Options

Flow Freezing

Flow freezing strategy	Disabled

RESULTS

General Info

Iterations: 217

CPU time: 1526 s

Log

Mesh generation started	13:05:22 , Feb 20
Mesh generation normally finished	13:05:28 , Feb 20
Preparing data for calculation	13:05:33 , Feb 20
Calculation started 0	13:05:38 , Feb 20
Calculation has converged since the following criteria are satisfied: 216	13:31:38 , Feb 20
Goals are converged 216	
Calculation finished 217	13:31:51 , Feb 20

Warnings: Negative pressure Minimum pressure=-1.20248e+008 Pa; dV/V=0.510055

A vortex crosses the pressure opening 1 ; Inlet flow/outlet flow=0.0829953	Boundary Condition : Environment Pressure

Calculation Mesh

Basic Mesh Dimensions

Number of cells in X	40
Number of cells in Y	40
Number of cells in Z	6

Number Of Cells

Total cells	49801
Fluid cells	22449
Solid cells	11299
Partial cells	16053
Irregular cells	0
Trimmed cells	37

Maximum refinement level: 1

Goals

Name	Unit	Value	Progress	Use in convergence	Delta	Criteria
GG Z - Component of Torque	N*m	3178.35	100	On	9.73635562	23.8372547
SG Mass	kg/s	-299.269	100	On	0.0003968	0.2992691

Flow Rate at outlet					95326	97
SG Mass Flow Rate at inlet	kg/s	299.269	100	On	0	0.299268522
SG Z - Component of Torque at stator	N*m	-10.9272	100	On	0.490469729	0.54746314
SG Bulk Av Static Pressure at impeller outlet	Pa	-4.73273e+006	100	On	235438.506	350277.687
SG Av Static Pressure at inlet	Pa	1.09877e+008	100	On	407176.933	1696571.57
Torque on impeller	N*m	3189.28	100	On	9.70251608	23.8848807
Presuure Drop	Pa	1.1461e+008	100	On	189752.255	1540822.49
Efficiency		51.4744	100	On	0.105964994	0.350306186

Min/Max Table

Name	Minimum	Maximum
Pressure [Pa]	-1.20248e+008	1.67034e+008
Temperature [K]	242.649	300.893
Density [kg/m^3]	995.656	1001.3
Velocity [m/s]	0	690.148
X-velocity [m/s]	-535.269	539.441
Y-velocity [m/s]	-548.611	519.522
Z-velocity [m/s]	-563.685	472.289
Heat Transfer Coefficient [W/m^2/K]	0	0
Shear Stress [Pa]	7.39392e-006	3.91156e+006
Surface Heat Flux [W/m^2]	0	0
Water Mass Fraction [ ]	1	1
Water Volume Fraction [ ]	1	1
Fluid Temperature [K]	242.649	300.893
Velocity RRF [m/s]	0	687.682
X-velocity RRF [m/s]	-542.256	544.432

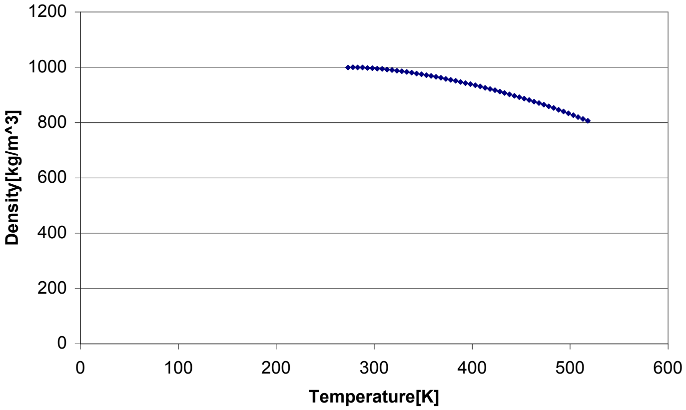
Y-velocity RRF [m/s]	-549.127	526.058
Z-velocity RRF [m/s]	-563.685	472.289

Engineering Database

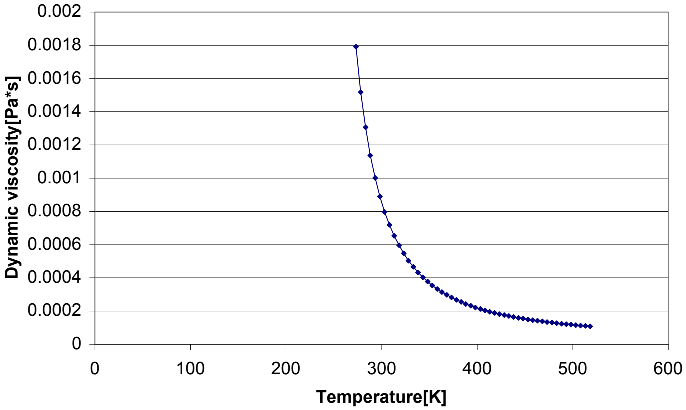
Liquids

Water

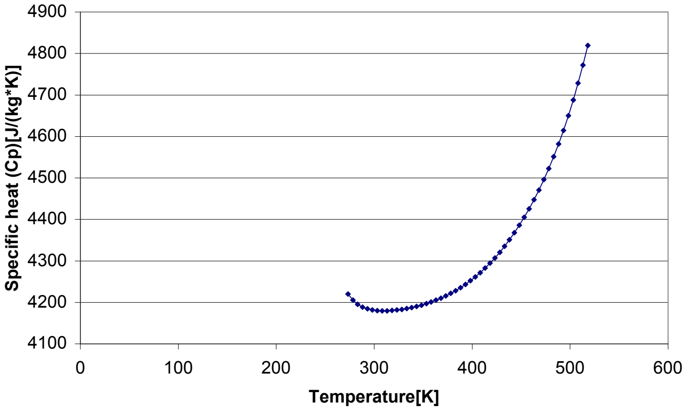
Path: Liquid FW Defined
Density



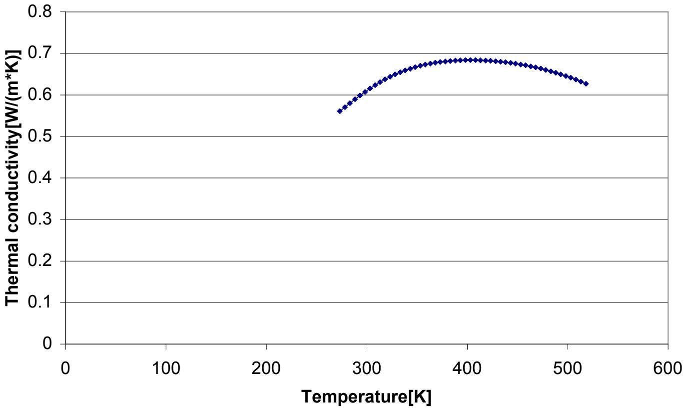
Dynamic viscosity



Specific heat (Cp)



Thermal conductivity



APPENDIX A6: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 42.5^0

System Info

Product	EFD.Lab 8 1.0. Build: 413
Computer name	FEA2
User name	Administrator
Processors	Dual Core AMD Opteron(tm) Processor 280 (4 processors)
Memory	16382 MB / 8388607 MB
Operating system	Microsoft Windows XP Professional x64 Edition Service Pack 2 (Build 3790)
CAD version	SolidWorks 2007 SP0
CPU speed	2411 MHz

General Info

Model	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate3-2_inlet30_outlet42.5\Assem3-2_inlet30_outlet42.5.SLDASM
Project name	Default (1)
Project path	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate3-2_inlet30_outlet42.5\1\1.fwp
Units system	SI (m-kg-s)
Analysis type	Internal
Exclude cavities without flow conditions	On
Coordinate system	Global coordinate system
Reference axis	X

INPUT DATA

Initial Mesh Settings

Automatic initial mesh: On
Result resolution level: 5
Advanced narrow channel refinement: Off
Refinement in solid region: Off

Geometry Resolution

Evaluation of minimum gap size: Manual
Minimum gap size: 0.04 m
Evaluation of minimum wall thickness: Manual
Minimum wall thickness: 0.01 m

APPENDIX A6: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 42.5^0

Computational Domain

Size

X min	-0.0570569915 m
X max	0.0391350085 m
Y min	-0.040496 m
Y max	0.055696 m
Z min	-0.00305140391 m
Z max	0.0135818462 m

Boundary Conditions

2D plane flow	None
At X min	Default
At X max	Default
At Y min	Default
At Y max	Default
At Z min	Default
At Z max	Default

Physical Features

Heat conduction in solids: Off
Time dependent: Off
Gravitational effects: Off
Flow type: Laminar only
Cavitation: Off
High Mach number flow: Off
Default roughness: 0 micrometer

Rotating Reference Frame

Axis of coordinate system	Z
Velocity	209.43951 m/s

Default wall conditions: Adiabatic wall

Initial Conditions

Thermodynamic parameters	Static Pressure: 101325 Pa Temperature: 293.2 K
Velocity parameters	Velocity vector Velocity in X direction: 0 m/s Velocity in Y direction: 0 m/s Velocity in Z direction: 0 m/s Relative to rotating frame: Off

APPENDIX A6: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 42.5^0

Material Settings

Fluids

Water

Boundary Conditions

Environment Pressure 1

Type	Environment Pressure
Faces	Face <1 >
Coordinate system	Global coordinate system
Reference axis	X
Thermodynamic parameters	Environment pressure: 101325 Pa Temperature: 293.2 K

Inlet Volume Flow 1

Type	Inlet Volume Flow
Faces	Face <1 >
Coordinate system	Face Coordinate System
Reference axis	X
Flow parameters	Flow vectors direction: Normal to face Volume flow rate normal to face: 0.3 m^3/s Relative to rotating frame: No Fully developed flow: No Inlet profile: 0
Thermodynamic parameters	Temperature: 293.2 K

stator Wall

Type	Real wall
Faces	Face <1 > Face <1 > Face <1 >
Coordinate system	Global coordinate system
Reference axis	X

Goals

Global Goals

GG Z - Component of Torque 1

Type	Global Goal
Goal type	Z - Component of Torque
Coordinate system	Global coordinate system
Use in convergence	On

Surface Goals

SG Z - Component of Torque at stator

Type	Surface Goal
Goal type	Z - Component of Torque
Faces	Face<1>@cover3-2-1 Face<2>@cover3-2-1 Face<3>@cover3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

Equation Goals

Torque on impeller

Type	Equation Goal
Formula	GG Z - Component of Torque 1-SG Z - Component of Torque at stator
Dimensionality	Torque
Use in convergence	On

Component Control Info

Disabled components: Extrude1@measure3-2-1@Assem3-2_inlet30_outlet42.5

Calculation Control Options

Finish Conditions

Finish conditions	If one is satisfied
Maximum travels	4
Goals convergence	Analysis interval: 0.5

Solver Refinement

Refinement: Disabled

Results Saving

Save before refinement	On

Advanced Control Options

Flow Freezing

Flow freezing strategy	Disabled

RESULTS

General Info

Iterations: 276
CPU time: 1157 s

Log

Preparing data for calculation	12:21:21 , Feb 29
Calculation started 0	12:21:27 , Feb 29
Calculation has converged since the following criteria are satisfied: 275	12:40:47 , Feb 29
Goals are converged 275	
Calculation finished 276	12:40:52 , Feb 29

Warnings: Negative pressure Minimum pressure=-1.21734e+008 Pa; dV/V=0.504098

A vortex crosses the pressure opening 1 ; Inlet flow/outlet flow=0.0849548 Boundary Condition : Environment Pressure

Calculation Mesh

Basic Mesh Dimensions

Number of cells in X	40
Number of cells in Y	40
Number of cells in Z	6

Number Of Cells

Total cells	49780
Fluid cells	22439
Solid cells	11284
Partial cells	16057
Irregular cells	0
Trimmed cells	38

Maximum refinement level: 1

Goals

Name	Unit	Value	Progress	Use in convergence	Delta	Criteria
GG Z -	N*m	3187.23	100	On	1.5603166	20.288925

Component of Torque 1					5	
SG Z - Component of Torque at stator	N*m	-10.9974	100	On	0.26114139	0.366912071
Torque on impeller	N*m	3198.23	100	On	1.82467607	20.6328398

Min/Max Table

Name	Minimum	Maximum
Pressure [Pa]	-1.21734e+008	1.68384e+008
Temperature [K]	242.239	300.861
Density [kg/m^3]	995.638	1001.3
Velocity [m/s]	0	694.135
X-velocity [m/s]	-548.479	541.447
Y-velocity [m/s]	-548.039	521.587
Z-velocity [m/s]	-565.744	494.278
Heat Transfer Coefficient [W/m^2/K]	0	0
Shear Stress [Pa]	1.31261e-005	3.90199e+006
Surface Heat Flux [W/m^2]	0	0
Water Mass Fraction [ ]	1	1
Water Volume Fraction [ ]	1	1
Fluid Temperature [K]	242.239	300.861
Velocity RRF [m/s]	0	691.722
X-velocity RRF [m/s]	-555.461	546.438
Y-velocity RRF [m/s]	-548.555	528.122
Z-velocity RRF [m/s]	-565.744	494.278

Engineering Database

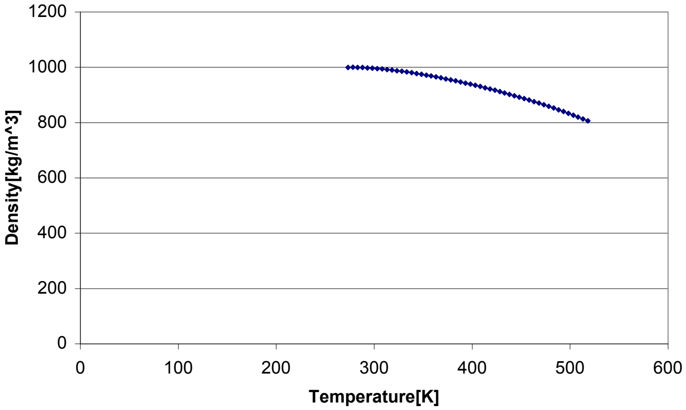
Liquids

Water

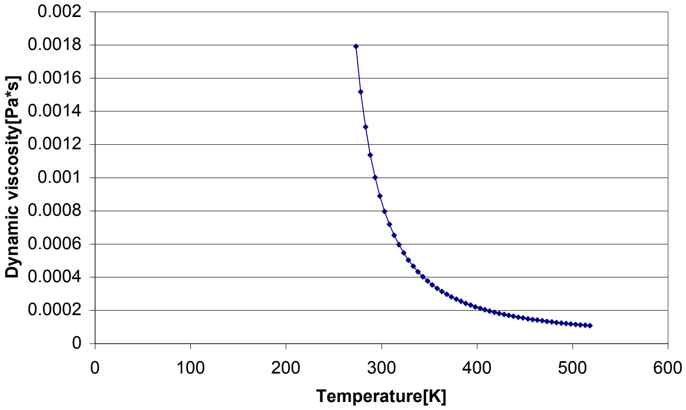
Path: Liquid FW Defined

APPENDIX A6: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 42.5^0

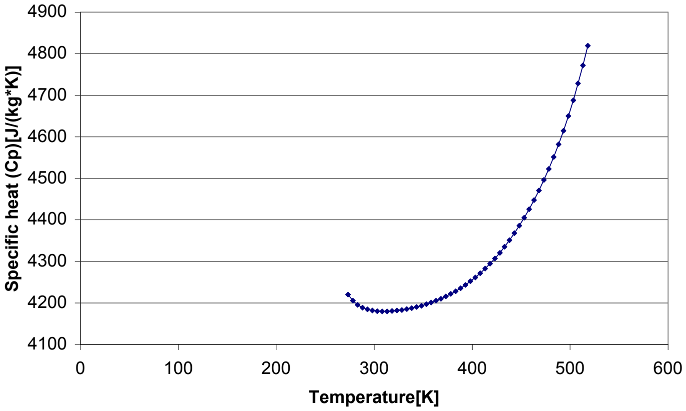
Density



Dynamic viscosity

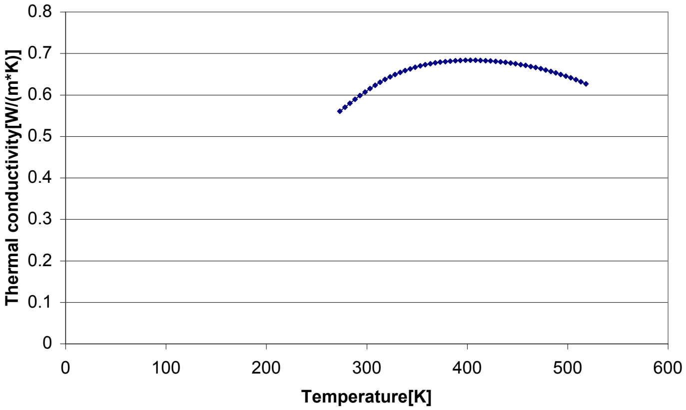


Specific heat (Cp)



APPENDIX A6: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 42.5^0

Thermal conductivity



APPENDIX A7: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 44^0

System Info

Product	EFD.Lab 8 1.0. Build: 413
Computer name	FEA2
User name	Administrator
Processors	Dual Core AMD Opteron(tm) Processor 280 (4 processors)
Memory	16382 MB / 8388607 MB
Operating system	Microsoft Windows XP Professional x64 Edition Service Pack 2 (Build 3790)
CAD version	SolidWorks 2007 SP0
CPU speed	2411 MHz

General Info

Model	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate5_inlet30_outlet44\Assembly3_inlet30_outlet44.SLDASM
Project name	inlet30_outlet44
Project path	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate5_inlet30_outlet44\1\1.fwp
Units system	SI (m-kg-s)
Analysis type	Internal
Exclude cavities without flow conditions	On
Coordinate system	Global coordinate system
Reference axis	X

INPUT DATA

Initial Mesh Settings

Automatic initial mesh: On
Result resolution level: 5
Advanced narrow channel refinement: Off
Refinement in solid region: Off

Geometry Resolution

Evaluation of minimum gap size: Manual
Minimum gap size: 0.04 m
Evaluation of minimum wall thickness: Manual
Minimum wall thickness: 0.01 m

APPENDIX A7: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 44^0

Computational Domain

Size

X min	-0.0561376687 m
X max	0.0400543313 m
Y min	-0.0416994091 m
Y max	0.0544925909 m
Z min	-0.00871892053 m
Z max	0.00791432957 m

Boundary Conditions

2D plane flow	None
At X min	Default
At X max	Default
At Y min	Default
At Y max	Default
At Z min	Default
At Z max	Default

Physical Features

Heat conduction in solids: Off
Time dependent: Off
Gravitational effects: Off
Flow type: Laminar only
Cavitation: Off
High Mach number flow: Off
Default roughness: 0 micrometer

Rotating Reference Frame

Axis of coordinate system	Z
Velocity	209.43951 m/s

Default wall conditions: Adiabatic wall

Initial Conditions

Thermodynamic parameters	Static Pressure: 101325 Pa Temperature: 293.2 K
Velocity parameters	Velocity vector Velocity in X direction: 0 m/s Velocity in Y direction: 0 m/s Velocity in Z direction: 0 m/s Relative to rotating frame: Off

APPENDIX A7: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 44^0

Material Settings

Fluids

Water

Boundary Conditions

Inlet Volume Flow 1

Type	Inlet Volume Flow
Faces	Face <1 cover3-1@>
Coordinate system	Face Coordinate System
Reference axis	X
Flow parameters	Flow vectors direction: Normal to face Volume flow rate normal to face: 0.3 m^3/s Relative to rotating frame: No Fully developed flow: No Inlet profile: 0
Thermodynamic parameters	Temperature: 293.2 K

Environment Pressure 1

Type	Environment Pressure
Faces	Face <1 cover3-1@>
Coordinate system	Global coordinate system
Reference axis	X
Thermodynamic parameters	Environment pressure: 101325 Pa Temperature: 293.2 K

stator walls

Type	Real wall
Faces	Face <1 cover3-1@> Face <1 cover3-1@> Face <1 cover3-1@>
Coordinate system	Global coordinate system
Reference axis	X

Goals

Global Goals

GG Z - Component of Torque

Type	Global Goal
Goal type	Z - Component of Torque
Coordinate system	Global coordinate system
Use in convergence	On

Surface Goals

SG Mass Flow Rate at inlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<5>@cover3-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Av Static Pressure at inlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@cover3-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Z - Compont of Torque at stator

Type	Surface Goal
Goal type	Z - Component of Torque
Faces	Face<1>@cover3-1 Face<2>@cover3-1 Face<3>@cover3-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate at outlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<2>@cover3-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Bulk Av Static Pressure at impeller outlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@measure3-1
Coordinate system	Global coordinate system
Use in convergence	On

Equation Goals

Pressure drop

Type	Equation Goal
Formula	SG Av Static Pressure at inlet-SG Bulk Av

	Static Pressure at impeller outlet
Dimensionality	Pressure & stress
Use in convergence	On

Torque on impeller

Type	Equation Goal
Formula	GG Z - Component of Torque -SG Z - Compont of Torque at stator
Dimensionality	Torque
Use in convergence	On

Efficiency

Type	Equation Goal
Formula	Pressure drop*{Inlet Volume Flow 1:Volume flow rate normal to face:3.000e-001}/209.44/Torque on impeller
Dimensionality	No units
Use in convergence	On

Component Control Info

Disabled components: Extrude1@measure3-1@Assembly3_inlet30_outlet44

Calculation Control Options

Finish Conditions

Finish conditions	If one is satisfied
Maximum travels	4
Goals convergence	Analysis interval: 0.5

Solver Refinement

Refinement: Disabled

Results Saving

Save before refinement	On

Advanced Control Options

Flow Freezing

Flow freezing strategy	Disabled

RESULTS

General Info

Iterations: 211
CPU time: 1379 s

Log

Mesh generation started	13:58:24 , Feb 20
Mesh generation normally finished	13:58:30 , Feb 20
Preparing data for calculation	13:58:34 , Feb 20
Calculation started 0	13:58:39 , Feb 20
Calculation has converged since the following criteria are satisfied: 210	14:21:54 , Feb 20
Goals are converged 210	
Calculation finished 211	14:22:06 , Feb 20

Warnings: Negative pressure Minimum pressure=-1.00924e+008 Pa; dV/V=0.49872

A vortex crosses the pressure opening Boundary Condition : Environment Pressure 1 ; Inlet flow/outlet flow=0.0903678

Calculation Mesh

Basic Mesh Dimensions

Number of cells in X	40
Number of cells in Y	40
Number of cells in Z	6

Number Of Cells

Total cells	49717
Fluid cells	22390
Solid cells	11299
Partial cells	16028
Irregular cells	0
Trimmed cells	44

Maximum refinement level: 1

Goals

Name	Unit	Value	Progress	Use in convergence	Delta	Criteria
GG Z -	N*m	3291.77	100	On	6.9252477	24.623115

Component of Torque					7	6
SG Mass Flow Rate at inlet	kg/s	299.269	100	On	0	0.299268522
SG Av Static Pressure at inlet	Pa	1.18163e+008	100	On	499702.365	1735677.07
SG Z - Compont of Torque at stator	N*m	-6.51369	100	On	0.580797985	0.584173641
SG Mass Flow Rate at outlet	kg/s	-299.267	100	On	0.000388537852	0.299266781
SG Bulk Av Static Pressure at impeller outlet	Pa	-4.47208e+006	100	On	156018.175	338005.294
Torque on impeller	N*m	3298.28	100	On	6.86668378	24.4781019
Pressure drop	Pa	1.22635e+008	100	On	423071.402	1601275.17
Efficiency		53.2583	100	On	0.0988910288	0.35330511

Min/Max Table

Name	Minimum	Maximum
Pressure [Pa]	-1.00924e+008	1.75694e+008
Temperature [K]	244.982	300.832
Density [kg/m^3]	995.657	1001.3
Velocity [m/s]	0	824.89
X-velocity [m/s]	-554.972	541.74
Y-velocity [m/s]	-552.333	534.191
Z-velocity [m/s]	-719.921	478.582
Heat Transfer Coefficient [W/m^2/K]	0	0
Shear Stress [Pa]	6.09552e-006	4.50219e+006
Surface Heat Flux [W/m^2]	0	0
Water Mass Fraction [ ]	1	1
Water Volume Fraction [ ]	1	1
Fluid Temperature [K]	244.982	300.832

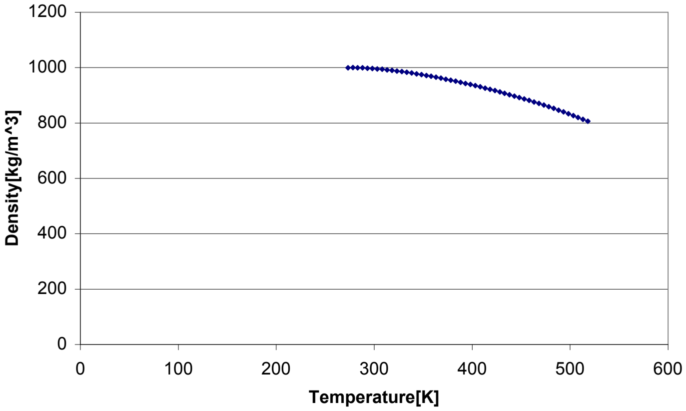
Velocity RRF [m/s]	0	825.247
X-velocity RRF [m/s]	-556.025	547.3
Y-velocity RRF [m/s]	-554.049	541.793
Z-velocity RRF [m/s]	-719.921	478.582

Engineering Database

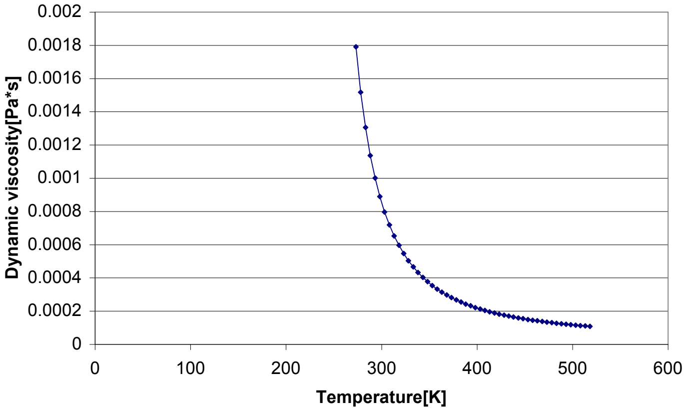
Liquids

Water

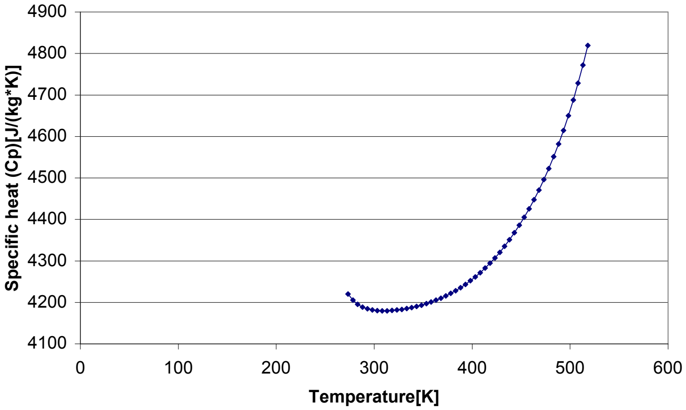
Path: Liquid FW Defined
Density



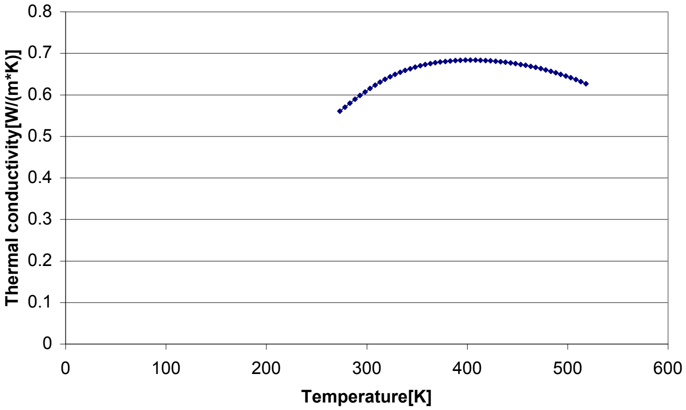
Dynamic viscosity



Specific heat (Cp)



Thermal conductivity



APPENDIX A8: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 45^0

System Info

Product	EFD.Lab 8 1.0. Build: 413
Computer name	FEA2
User name	Administrator
Processors	Dual Core AMD Opteron(tm) Processor 280 (4 processors)
Memory	16382 MB / 8388607 MB
Operating system	Microsoft Windows XP Professional x64 Edition Service Pack 2 (Build 3790)
CAD version	SolidWorks 2007 SP0
CPU speed	2411 MHz

General Info

Model	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate6_inlet30_outlet45\Assembly3_inlet30_outlet45.SLDASM
Project name	inlet30_out45
Project path	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate6_inlet30_outlet45\1\1.fwp
Units system	SI (m-kg-s)
Analysis type	Internal
Exclude cavities without flow conditions	On
Coordinate system	Global coordinate system
Reference axis	X

INPUT DATA

Initial Mesh Settings

Automatic initial mesh: On
Result resolution level: 5
Advanced narrow channel refinement: Off
Refinement in solid region: Off

Geometry Resolution

Evaluation of minimum gap size: Manual
Minimum gap size: 0.04 m
Evaluation of minimum wall thickness: Manual
Minimum wall thickness: 0.01 m

APPENDIX A8: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 45^0

Computational Domain

Size

X min	-0.0561376687 m
X max	0.0400543313 m
Y min	-0.0416994091 m
Y max	0.0544925909 m
Z min	-0.00871892053 m
Z max	0.00791432957 m

Boundary Conditions

2D plane flow	None
At X min	Default
At X max	Default
At Y min	Default
At Y max	Default
At Z min	Default
At Z max	Default

Physical Features

Heat conduction in solids: Off
Time dependent: Off
Gravitational effects: Off
Flow type: Laminar only
Cavitation: Off
High Mach number flow: Off
Default roughness: 0 micrometer

Rotating Reference Frame

Axis of coordinate system	Z
Velocity	209.43951 m/s

Default wall conditions: Adiabatic wall

Initial Conditions

Thermodynamic parameters	Static Pressure: 101325 Pa Temperature: 293.2 K
Velocity parameters	Velocity vector Velocity in X direction: 0 m/s Velocity in Y direction: 0 m/s Velocity in Z direction: 0 m/s Relative to rotating frame: Off

APPENDIX A8: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 45^0

Material Settings

Fluids

Water

Boundary Conditions

Environment Pressure 1

Type	Environment Pressure
Faces	Face <1 cover3-1@>
Coordinate system	Global coordinate system
Reference axis	X
Thermodynamic parameters	Environment pressure: 101325 Pa Temperature: 293.2 K

Inlet Volume Flow 1

Type	Inlet Volume Flow
Faces	Face <1 cover3-1@>
Coordinate system	Face Coordinate System
Reference axis	X
Flow parameters	Flow vectors direction: Normal to face Volume flow rate normal to face: 0.3 m^3/s Relative to rotating frame: No Fully developed flow: No Inlet profile: 0
Thermodynamic parameters	Temperature: 293.2 K

stator wall

Type	Real wall
Faces	Face <1 cover3-1@> Face <1 cover3-1@> Face <1 cover3-1@>
Coordinate system	Global coordinate system
Reference axis	X

Goals

Global Goals

GG Z - Component of Torque

Type	Global Goal
Goal type	Z - Component of Torque
Coordinate system	Global coordinate system
Use in convergence	On

APPENDIX A8: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 45^0

Surface Goals

SG Mass Flow Rate at outlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<2>@cover3-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate at inlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<1>@cover3-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Bulk Av Static Pressure at impeller outlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@measure3-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Av Static Pressure at inlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@cover3-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Z - Component of Torque at stator

Type	Surface Goal
Goal type	Z - Component of Torque
Faces	Face<1>@cover3-1 Face<2>@cover3-1 Face<3>@cover3-1
Coordinate system	Global coordinate system
Use in convergence	On

Equation Goals

Pressure Drop

Type	Equation Goal
Formula	SG Av Static Pressure at inlet-SG Bulk Av

	Static Pressure at impeller outlet
Dimensionality	Pressure & stress
Use in convergence	On

Torque on impeller

Type	Equation Goal
Formula	GG Z - Component of Torque -SG Z - Component of Torque at stator
Dimensionality	Torque
Use in convergence	On

Equation Goal 1

Type	Equation Goal
Formula	Pressure Drop*{Inlet Volume Flow 1:Volume flow rate normal to face:3.000e-001}/209.44/Torque on impeller
Dimensionality	No units
Use in convergence	On

Component Control Info

Disabled components: Extrude1@measure3-1@Assembly3_inlet30_outlet45

Calculation Control Options

Finish Conditions

Finish conditions	If one is satisfied
Maximum travels	4
Goals convergence	Analysis interval: 0.5

Solver Refinement

Refinement: Disabled

Results Saving

Save before refinement	On

Advanced Control Options

Flow Freezing

Flow freezing strategy	Disabled

RESULTS

General Info

Iterations: 168

CPU time: 746 s

Log

Mesh generation started	15:01:13 , Feb 20
Mesh generation normally finished	15:01:20 , Feb 20
Preparing data for calculation	15:01:24 , Feb 20
Calculation started 0	15:01:28 , Feb 20
Calculation has converged since the following criteria are satisfied: 167	15:14:01 , Feb 20
Goals are converged 167	
Calculation finished 168	15:14:12 , Feb 20

Warnings: Negative pressure Minimum pressure=-1.01975e+008 Pa; dV/V=0.500823

A vortex crosses the pressure opening 1 ; Inlet flow/outlet flow=0.0884177	Boundary Condition : Environment Pressure

Calculation Mesh

Basic Mesh Dimensions

Number of cells in X	40
Number of cells in Y	40
Number of cells in Z	6

Number Of Cells

Total cells	49801
Fluid cells	22314
Solid cells	11419
Partial cells	16068
Irregular cells	0
Trimmed cells	35

Maximum refinement level: 1

Goals

Name	Unit	Value	Progress	Use in convergence	Delta	Criteria
GG Z - Component of Torque	N*m	3308.62	100	On	11.5432768	28.0025068
SG Mass	kg/s	-299.269	100	On	0.0007813	0.2992687

Flow Rate at outlet					25122	01
SG Mass Flow Rate at inlet	kg/s	299.269	100	On	0	0.299268522
SG Bulk Av Static Pressure at impeller outlet	Pa	-4.44126e+006	100	On	169242.835	350593.796
SG Av Static Pressure at inlet	Pa	1.19047e+008	100	On	496570.855	1894350.07
SG Z - Component of Torque at stator	N*m	-4.38065	100	On	0.444504628	0.456384513
Torque on impeller	N*m	3313	100	On	11.7995962	27.9005724
Pressure Drop	Pa	1.23488e+008	100	On	520012.709	1751805.78
Efficiency		53.3907	100	On	0.137089653	0.353518209

Min/Max Table

Name	Minimum	Maximum
Pressure [Pa]	-1.01975e+008	1.767e+008
Temperature [K]	243.247	300.858
Density [kg/m^3]	995.626	1001.3
Velocity [m/s]	0	838.928
X-velocity [m/s]	-550.088	545.129
Y-velocity [m/s]	-557.937	539.49
Z-velocity [m/s]	-733.777	472.716
Heat Transfer Coefficient [W/m^2/K]	0	0
Shear Stress [Pa]	9.01013e-006	393215
Surface Heat Flux [W/m^2]	0	0
Water Mass Fraction [ ]	1	1
Water Volume Fraction [ ]	1	1
Fluid Temperature [K]	243.247	300.858
Velocity RRF [m/s]	0	839.283
X-velocity RRF [m/s]	-551.141	550.624

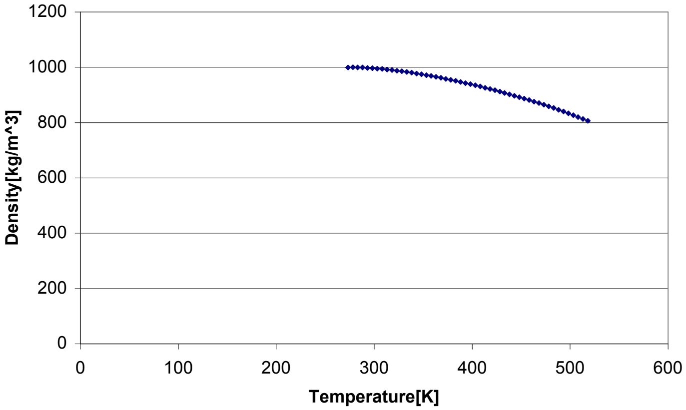
Y-velocity RRF [m/s]	-561.699	547.093
Z-velocity RRF [m/s]	-733.777	472.716

Engineering Database

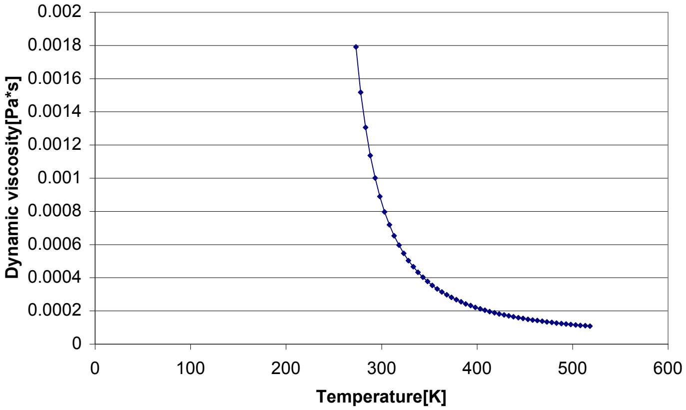
Liquids

Water

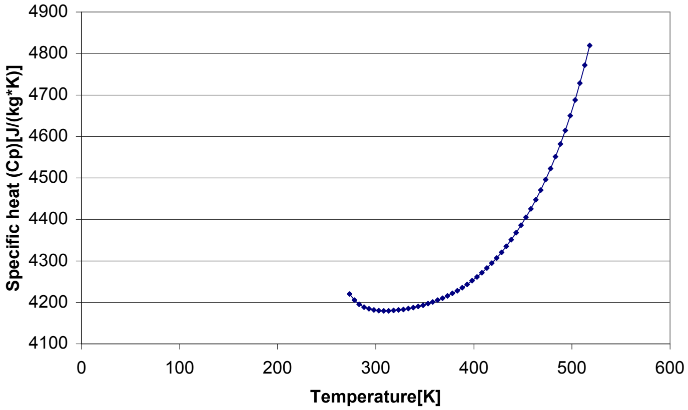
Path: Liquid FW Defined
Density



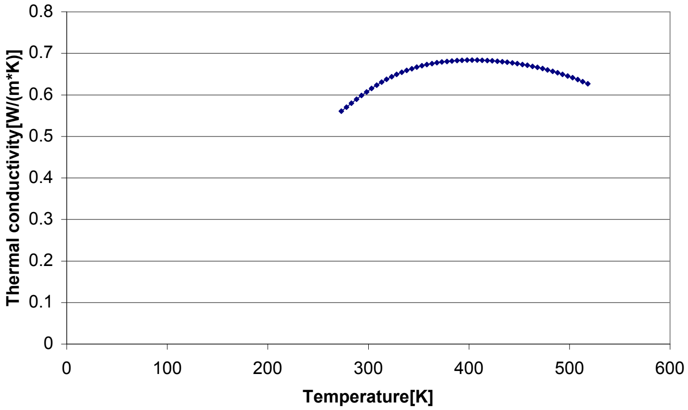
Dynamic viscosity



Specific heat (Cp)



Thermal conductivity



APPENDIX A9: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 46^0

System Info

Product	EFD.Lab 8 1.0. Build: 413
Computer name	FEA2
User name	Administrator
Processors	Dual Core AMD Opteron(tm) Processor 280 (4 processors)
Memory	16382 MB / 8388607 MB
Operating system	Microsoft Windows XP Professional x64 Edition Service Pack 2 (Build 3790)
CAD version	SolidWorks 2007 SP0
CPU speed	2411 MHz

General Info

Model	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate7_inlet30_outlet46\Assem4_inlet30_outlet46.SLDASM
Project name	inlet30_outlet46
Project path	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate7_inlet30_outlet46\1\1.fwp
Units system	SI (m-kg-s)
Analysis type	Internal
Exclude cavities without flow conditions	On
Coordinate system	Global coordinate system
Reference axis	X

INPUT DATA

Initial Mesh Settings

Automatic initial mesh: On
Result resolution level: 5
Advanced narrow channel refinement: Off
Refinement in solid region: Off

Geometry Resolution

Evaluation of minimum gap size: Manual
Minimum gap size: 0.04 m
Evaluation of minimum wall thickness: Manual
Minimum wall thickness: 0.01 m

APPENDIX A9: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 46^0

Computational Domain

Size

X min	-0.0459669402 m
X max	0.0502250598 m
Y min	-0.0401346033 m
Y max	0.0560573967 m
Z min	-0.00654898132 m
Z max	0.0100842688 m

Boundary Conditions

2D plane flow	None
At X min	Default
At X max	Default
At Y min	Default
At Y max	Default
At Z min	Default
At Z max	Default

Physical Features

Heat conduction in solids: Off
Time dependent: Off
Gravitational effects: Off
Flow type: Laminar only
Cavitation: Off
High Mach number flow: Off
Default roughness: 0 micrometer

Rotating Reference Frame

Axis of coordinate system	Z
Velocity	209.43951 m/s

Default wall conditions: Adiabatic wall

Initial Conditions

Thermodynamic parameters	Static Pressure: 101325 Pa Temperature: 293.2 K
Velocity parameters	Velocity vector Velocity in X direction: 0 m/s Velocity in Y direction: 0 m/s Velocity in Z direction: 0 m/s Relative to rotating frame: Off

APPENDIX A9: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 46^0

Material Settings

Fluids

Water

Boundary Conditions

Inlet Volume Flow 1

Type	Inlet Volume Flow
Faces	Face <1 cover4-1@>
Coordinate system	Face Coordinate System
Reference axis	X
Flow parameters	Flow vectors direction: Normal to face Volume flow rate normal to face: 0.3 m^3/s Relative to rotating frame: No Fully developed flow: No Inlet profile: 0
Thermodynamic parameters	Temperature: 293.2 K

stator walls

Type	Real wall
Faces	Face <1 cover4-1@> Face <1 cover4-1@> Face <1 cover4-1@>
Coordinate system	Global coordinate system
Reference axis	X

Environment Pressure 1

Type	Environment Pressure
Faces	Face <1 cover4-1@>
Coordinate system	Global coordinate system
Reference axis	X
Thermodynamic parameters	Environment pressure: 101325 Pa Temperature: 293.2 K

Goals

Global Goals

GG Z - Component of Torque

Type	Global Goal
Goal type	Z - Component of Torque
Coordinate system	Global coordinate system
Use in convergence	On

Surface Goals

SG Mass Flow Rate at outlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<2>@cover4-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Bulk Av Static Pressure at impeller outlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@measure4-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate at inlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<5>@cover4-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Av Static Pressure at inlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@cover4-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Z - Component of Torque at stator

Type	Surface Goal
Goal type	Z - Component of Torque
Faces	Face<1>@cover4-1 Face<2>@cover4-1 Face<3>@cover4-1
Coordinate system	Global coordinate system
Use in convergence	On

Equation Goals

Presssure Drop

Type	Equation Goal
Formula	SG Av Static Pressure at inlet-SG Bulk Av

	Static Pressure at impeller outlet
Dimensionality	Pressure & stress
Use in convergence	On

Torque on impeller

Type	Equation Goal
Formula	GG Z - Component of Torque -SG Z - Component of Torque at stator
Dimensionality	Torque
Use in convergence	On

Efficiency

Type	Equation Goal
Formula	Presssure Drop*{Inlet Volume Flow 1:Volume flow rate normal to face:3.000e-001}/209.44/Torque on impeller
Dimensionality	No units
Use in convergence	On

Component Control Info

Disabled components: Extrude1@measure4-1@Assem4_inlet30_outlet46

Calculation Control Options

Finish Conditions

Finish conditions	If one is satisfied
Maximum travels	4
Goals convergence	Analysis interval: 0.5

Solver Refinement

Refinement: Disabled

Results Saving

Save before refinement	On

Advanced Control Options

Flow Freezing

Flow freezing strategy	Disabled

RESULTS

General Info

Iterations: 162

CPU time: 718 s

Log

Mesh generation started	15:40:10 , Feb 20
Mesh generation normally finished	15:40:16 , Feb 20
Preparing data for calculation	15:40:21 , Feb 20
Calculation started 0	15:40:25 , Feb 20
Calculation has converged since the following criteria are satisfied: 161	15:52:25 , Feb 20
Goals are converged 161	
Calculation finished 162	15:52:32 , Feb 20

Warnings: Negative pressure Minimum pressure=-1.01684e+008 Pa; dV/V=0.5131

A vortex crosses the pressure opening Boundary Condition : Environment Pressure
1 ; Inlet flow/outlet flow=0.0851425

Calculation Mesh

Basic Mesh Dimensions

Number of cells in X	40
Number of cells in Y	40
Number of cells in Z	6

Number Of Cells

Total cells	49780
Fluid cells	22275
Solid cells	11428
Partial cells	16077
Irregular cells	0
Trimmed cells	36

Maximum refinement level: 1

Goals

Name	Unit	Value	Progress	Use in convergence	Delta	Criteria
GG Z - Component of Torque	N*m	3327.77	100	On	11.0983986	28.6026344
SG Mass	kg/s	-299.268	100	On	0.0005547	0.2992682

Flow Rate at outlet					94172	25
SG Bulk Av Static Pressure at impeller outlet	Pa	-4.6558e+006	100	On	336988.293	348918.786
SG Mass Flow Rate at inlet	kg/s	299.269	100	On	0	0.299268522
SG Av Static Pressure at inlet	Pa	1.19439e+008	100	On	265061.964	1889093.74
SG Z - Component of Torque at stator	N*m	-6.21354	100	On	0.618890114	0.904380404
Torque on impeller	N*m	3333.99	100	On	11.641144	28.2454649
Presssure Drop	Pa	1.24094e+008	100	On	374645.28	1747969.81
Efficiency		53.315	100	On	0.153753912	0.343020986

Min/Max Table

Name	Minimum	Maximum
Pressure [Pa]	-1.01684e+008	1.76654e+008
Temperature [K]	241.981	300.826
Density [kg/m^3]	995.614	1001.3
Velocity [m/s]	0	830.851
X-velocity [m/s]	-545.557	561.885
Y-velocity [m/s]	-553.021	556.792
Z-velocity [m/s]	-723.228	410.195
Heat Transfer Coefficient [W/m^2/K]	0	0
Shear Stress [Pa]	3.51288e-006	4.52508e+006
Surface Heat Flux [W/m^2]	0	0
Water Mass Fraction [ ]	1	1
Water Volume Fraction [ ]	1	1
Fluid Temperature [K]	241.981	300.826
Velocity RRF [m/s]	0	830.675
X-velocity RRF [m/s]	-549.808	571.867

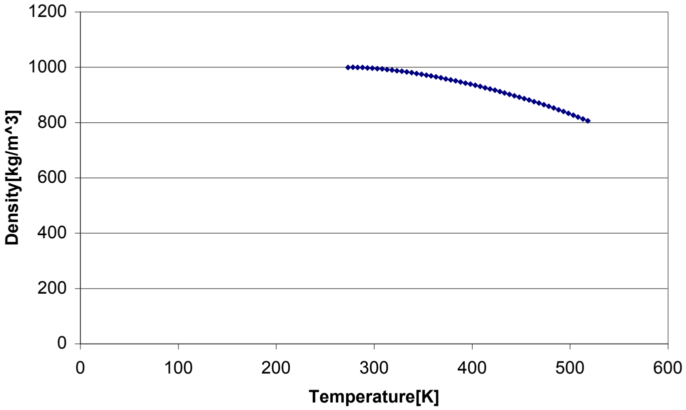
Y-velocity RRF [m/s]	-555.859	562.012
Z-velocity RRF [m/s]	-723.228	410.195

Engineering Database

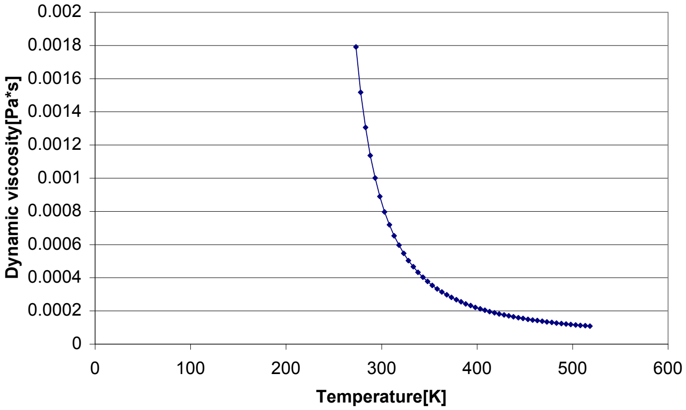
Liquids

Water

Path: Liquid FW Defined
Density

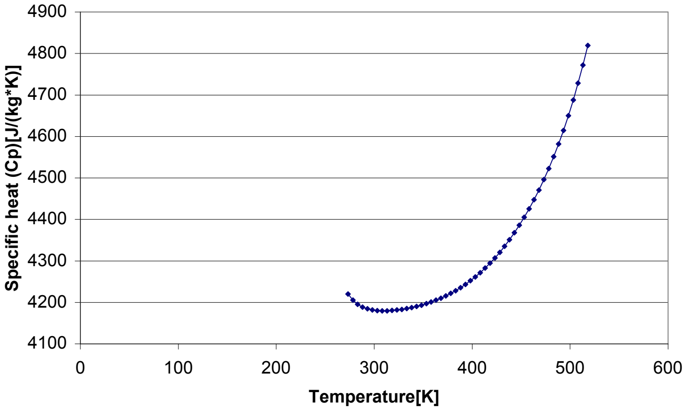


Dynamic viscosity

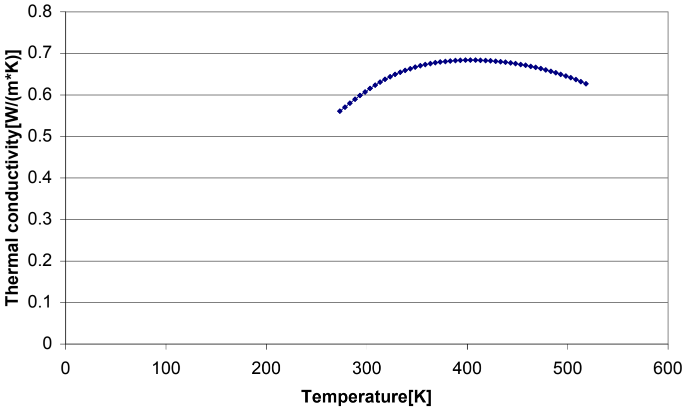


APPENDIX A9: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 46^0

Specific heat (Cp)



Thermal conductivity



APPENDIX A10: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 48^0

System Info

Product	EFD.Lab 8 1.0. Build: 413
Computer name	FEA2
User name	Administrator
Processors	Dual Core AMD Opteron(tm) Processor 280 (4 processors)
Memory	16382 MB / 8388607 MB
Operating system	Microsoft Windows XP Professional x64 Edition Service Pack 2 (Build 3790)
CAD version	SolidWorks 2007 SP0
CPU speed	2411 MHz

General Info

Model	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate8_inlet30_outlet48\Assem5_inlet30_outlet48.SLDASM
Project name	inlet30_outlet48
Project path	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate8_inlet30_outlet48\1\1.fwp
Units system	SI (m-kg-s)
Analysis type	Internal
Exclude cavities without flow conditions	On
Coordinate system	Global coordinate system
Reference axis	X

INPUT DATA

Initial Mesh Settings

Automatic initial mesh: On
Result resolution level: 5
Advanced narrow channel refinement: Off
Refinement in solid region: Off

Geometry Resolution

Evaluation of minimum gap size: Manual
Minimum gap size: 0.04 m
Evaluation of minimum wall thickness: Manual
Minimum wall thickness: 0.01 m

APPENDIX A10: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 48^0

Computational Domain

Size

X min	-0.0514326445 m
X max	0.0447593555 m
Y min	-0.0483066476 m
Y max	0.0478853524 m
Z min	0.00188716267 m
Z max	0.0185204128 m

Boundary Conditions

2D plane flow	None
At X min	Default
At X max	Default
At Y min	Default
At Y max	Default
At Z min	Default
At Z max	Default

Physical Features

Heat conduction in solids: Off
Time dependent: Off
Gravitational effects: Off
Flow type: Laminar only
Cavitation: Off
High Mach number flow: Off
Default roughness: 0 micrometer

Rotating Reference Frame

Axis of coordinate system	Z
Velocity	209.43951 m/s

Default wall conditions: Adiabatic wall

Initial Conditions

Thermodynamic parameters	Static Pressure: 101325 Pa Temperature: 293.2 K
Velocity parameters	Velocity vector Velocity in X direction: 0 m/s Velocity in Y direction: 0 m/s Velocity in Z direction: 0 m/s Relative to rotating frame: Off

APPENDIX A10: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 48^0

Material Settings

Fluids

Water

Boundary Conditions

stator walls

Type	Real wall
Faces	Face <1 cover5-1@> Face <1 cover5-1@> Face <1 cover5-1@>
Coordinate system	Global coordinate system
Reference axis	X

Inlet Volume Flow 1

Type	Inlet Volume Flow
Faces	Face <1 cover5-1@>
Coordinate system	Face Coordinate System
Reference axis	X
Flow parameters	Flow vectors direction: Normal to face Volume flow rate normal to face: 0.3 m^3/s Relative to rotating frame: No Fully developed flow: No Inlet profile: 0
Thermodynamic parameters	Temperature: 293.2 K

Environment Pressure 1

Type	Environment Pressure
Faces	Face <1 cover5-1@>
Coordinate system	Global coordinate system
Reference axis	X
Thermodynamic parameters	Environment pressure: 101325 Pa Temperature: 293.2 K

Goals

Global Goals

GG Z - Component of Torque

Type	Global Goal
Goal type	Z - Component of Torque
Coordinate system	Global coordinate system
Use in convergence	On

Surface Goals

SG Bulk Av Static Pressure at impeller outlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@measure5-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Z - Component of Torque at stator

Type	Surface Goal
Goal type	Z - Component of Torque
Faces	Face<1>@cover5-1 Face<3>@cover5-1 Face<2>@cover5-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate at inlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<5>@cover5-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate at outlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<2>@cover5-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Av Static Pressure at inlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@cover5-1
Coordinate system	Global coordinate system
Use in convergence	On

Equation Goals

Pressure Drop

Type	Equation Goal
Formula	SG Av Static Pressure at inlet-SG Bulk Av

	Static Pressure at impeller outlet
Dimensionality	Pressure & stress
Use in convergence	On

Torque on impeller

Type	Equation Goal
Formula	GG Z - Component of Torque -SG Z - Component of Torque at stator
Dimensionality	Torque
Use in convergence	On

Efficiency

Type	Equation Goal
Formula	Pressure Drop*{Inlet Volume Flow 1:Volume flow rate normal to face:3.000e-001}/209.44/Torque on impeller
Dimensionality	No units
Use in convergence	On

Component Control Info

Disabled components: Extrude1@measure5-1@Assem5_inlet30_outlet48

Calculation Control Options

Finish Conditions

Finish conditions	If one is satisfied
Maximum travels	4
Goals convergence	Analysis interval: 0.5

Solver Refinement

Refinement: Disabled

Results Saving

Save before refinement	On

Advanced Control Options

Flow Freezing

Flow freezing strategy	Disabled

RESULTS

General Info

Iterations: 154
CPU time: 790 s

Log

Mesh generation started	19:53:43 , Feb 20
Mesh generation normally finished	19:53:49 , Feb 20
Preparing data for calculation	19:53:55 , Feb 20
Calculation started 0	19:53:59 , Feb 20
Calculation has converged since the following criteria are satisfied: 153	20:07:17 , Feb 20
Goals are converged 153	
Calculation finished 154	20:07:28 , Feb 20

Warnings: Negative pressure Minimum pressure=-1.20456e+008 Pa; dV/V=0.512009

A vortex crosses the pressure opening 1 ; Inlet flow/outlet flow=0.0828767	Boundary Condition : Environment Pressure

Calculation Mesh

Basic Mesh Dimensions

Number of cells in X	40
Number of cells in Y	40
Number of cells in Z	6

Number Of Cells

Total cells	49738
Fluid cells	22328
Solid cells	11278
Partial cells	16132
Irregular cells	0
Trimmed cells	40

Maximum refinement level: 1

APPENDIX A10: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 48^0

Goals

Name	Unit	Value	Progress	Use in convergence	Delta	Criteria
GG Z - Component of Torque	N*m	3362.8	100	On	9.85940066	25.0946564
SG Bulk Av Static Pressure at impeller outlet	Pa	-4.61839e+006	100	On	287555.808	348823.543
SG Z - Component of Torque at stator	N*m	-2.65802	100	On	0.479256199	0.487791631
SG Mass Flow Rate at inlet	kg/s	299.269	100	On	0	0.299268522
SG Mass Flow Rate at outlet	kg/s	-299.268	100	On	0.000838875871	0.299268063
SG Av Static Pressure at inlet	Pa	1.21093e+008	100	On	444174.727	1851853.85
Torque on impeller	N*m	3365.46	100	On	9.93465644	25.0525999
Pressure Drop	Pa	1.25711e+008	100	On	546823.257	1717350.7
Efficiency		53.5046	100	On	0.114821205	0.377317033

Min/Max Table

Name	Minimum	Maximum
Pressure [Pa]	-1.20456e+008	1.78909e+008
Temperature [K]	239.569	300.704
Density [kg/m^3]	995.65	1001.3
Velocity [m/s]	0	835.979
X-velocity [m/s]	-541.012	555.869
Y-velocity [m/s]	-555.399	544.834
Z-velocity [m/s]	-730.57	518.269

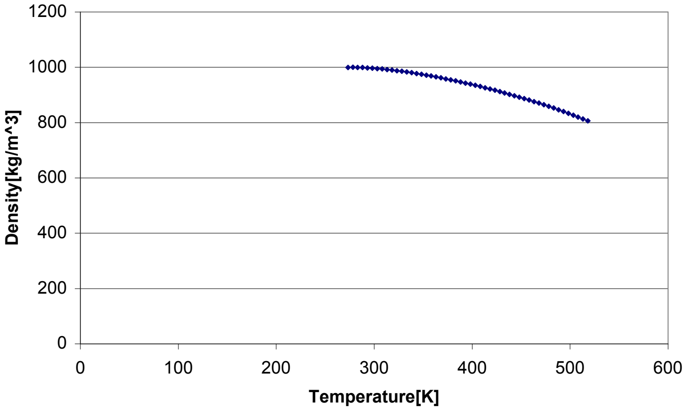
Heat Transfer Coefficient [W/m^2/K]	0	0
Shear Stress [Pa]	7.71174e-006	4.68796e+006
Surface Heat Flux [W/m^2]	0	0
Water Mass Fraction [ ]	1	1
Water Volume Fraction [ ]	1	1
Fluid Temperature [K]	239.569	300.704
Velocity RRF [m/s]	0	835.946
X-velocity RRF [m/s]	-546.722	559.028
Y-velocity RRF [m/s]	-556.841	549.688
Z-velocity RRF [m/s]	-730.57	518.269

Engineering Database

Liquids

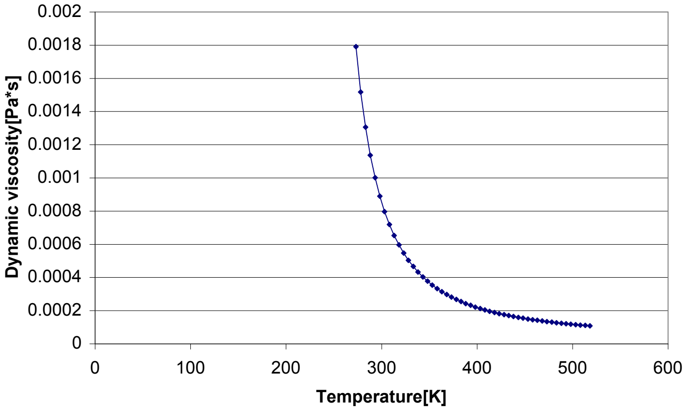
Water

Path: Liquid FW Defined
Density

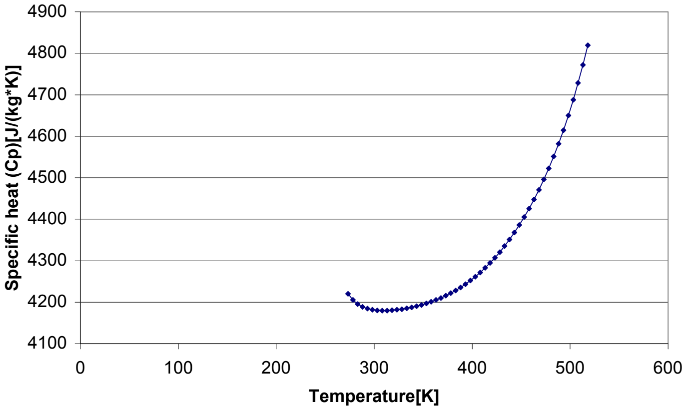


APPENDIX A10: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 48^0

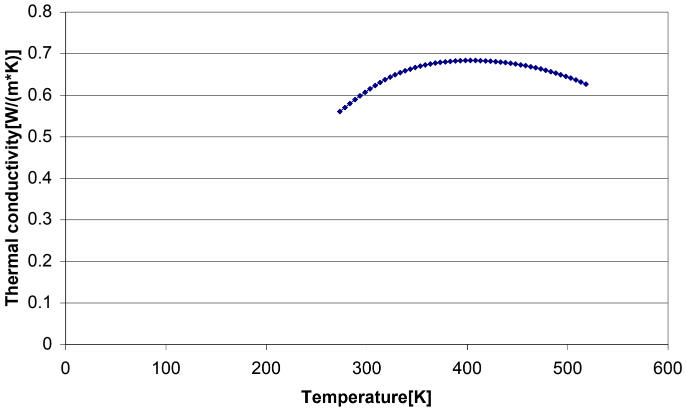
Dynamic viscosity



Specific heat (Cp)



Thermal conductivity



System Info

Product	EFD.Lab 8 1.0. Build: 413
Computer name	FEA2
User name	Administrator
Processors	Dual Core AMD Opteron(tm) Processor 280 (4 processors)
Memory	16382 MB / 8388607 MB
Operating system	Microsoft Windows XP Professional x64 Edition Service Pack 2 (Build 3790)
CAD version	SolidWorks 2007 SP0
CPU speed	2411 MHz

General Info

Model	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate9_inlet30_outlet50\Assem4_inlet30_outlet50.SLDASM
Project name	inlet30_outlet50
Project path	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate9_inlet30_outlet50\1\1.fwp
Units system	SI (m-kg-s)
Analysis type	Internal
Exclude cavities without flow conditions	On
Coordinate system	Global coordinate system
Reference axis	X

INPUT DATA

Initial Mesh Settings

Automatic initial mesh: On
Result resolution level: 5
Advanced narrow channel refinement: Off
Refinement in solid region: Off

Geometry Resolution

Evaluation of minimum gap size: Manual
Minimum gap size: 0.04 m
Evaluation of minimum wall thickness: Manual
Minimum wall thickness: 0.01 m

APPENDIX A11: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 50^0

Computational Domain

Size

X min	-0.0459669402 m
X max	0.0502250598 m
Y min	-0.0401346033 m
Y max	0.0560573967 m
Z min	-0.00654898132 m
Z max	0.0100842688 m

Boundary Conditions

2D plane flow	None
At X min	Default
At X max	Default
At Y min	Default
At Y max	Default
At Z min	Default
At Z max	Default

Physical Features

Heat conduction in solids: Off
Time dependent: Off
Gravitational effects: Off
Flow type: Laminar only
Cavitation: Off
High Mach number flow: Off
Default roughness: 0 micrometer

Rotating Reference Frame

Axis of coordinate system	Z
Velocity	209.43951 m/s

Default wall conditions: Adiabatic wall

Initial Conditions

Thermodynamic parameters	Static Pressure: 101325 Pa Temperature: 293.2 K
Velocity parameters	Velocity vector Velocity in X direction: 0 m/s Velocity in Y direction: 0 m/s Velocity in Z direction: 0 m/s Relative to rotating frame: Off

APPENDIX A11: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 50^0

Material Settings

Fluids

Water

Boundary Conditions

Inlet Volume Flow 1

Type	Inlet Volume Flow
Faces	Face <1 cover4-1@>
Coordinate system	Face Coordinate System
Reference axis	X
Flow parameters	Flow vectors direction: Normal to face Volume flow rate normal to face: 0.3 m^3/s Relative to rotating frame: No Fully developed flow: No Inlet profile: 0
Thermodynamic parameters	Temperature: 293.2 K

stator Wall

Type	Real wall
Faces	Face <1 cover4-1@> Face <1 cover4-1@> Face <1 cover4-1@>
Coordinate system	Global coordinate system
Reference axis	X

Environment Pressure 1

Type	Environment Pressure
Faces	Face <1 cover4-1@>
Coordinate system	Global coordinate system
Reference axis	X
Thermodynamic parameters	Environment pressure: 101325 Pa Temperature: 293.2 K

Goals

Global Goals

GG Z - Component of Torque

Type	Global Goal
Goal type	Z - Component of Torque
Coordinate system	Global coordinate system
Use in convergence	On

APPENDIX A11: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 50^0

Surface Goals

SG Bulk Av Static Pressure at impeller outlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@measure4-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate at inlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<5>@cover4-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Av Static Pressure at inlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@cover4-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate at outlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<2>@cover4-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Z - Component of Torque at stator

Type	Surface Goal
Goal type	Z - Component of Torque
Faces	Face<2>@cover4-1 Face<1>@cover4-1 Face<3>@cover4-1
Coordinate system	Global coordinate system
Use in convergence	On

Equation Goals

Pressure Drop

Type	Equation Goal
Formula	SG Av Static Pressure at inlet-SG Bulk Av

	Static Pressure at impeller outlet
Dimensionality	Pressure & stress
Use in convergence	On

Torque on impeller

Type	Equation Goal
Formula	GG Z - Component of Torque -SG Z - Component of Torque at stator
Dimensionality	Torque
Use in convergence	On

Efficiency

Type	Equation Goal
Formula	Pressure Drop*{Inlet Volume Flow 1:Volume flow rate normal to face:3.000e-001}/209.44/Torque on impeller
Dimensionality	No units
Use in convergence	On

Component Control Info

Disabled components: Extrude1@measure4-1@Assem4_inlet30_outlet50

Calculation Control Options

Finish Conditions

Finish conditions	If one is satisfied
Maximum travels	4
Goals convergence	Analysis interval: 0.5

Solver Refinement

Refinement: Disabled

Results Saving

Save before refinement	On

Advanced Control Options

Flow Freezing

Flow freezing strategy	Disabled

RESULTS

General Info

Iterations: 167
CPU time: 736 s

Log

Mesh generation started	20:27:14 , Feb 20
Mesh generation normally finished	20:27:21 , Feb 20
Preparing data for calculation	20:27:26 , Feb 20
Calculation started 0	20:27:30 , Feb 20
Calculation has converged since the following criteria are satisfied: 166	20:39:47 , Feb 20
Goals are converged 166	
Calculation finished 167	20:39:52 , Feb 20

Warnings: Negative pressure Minimum pressure=-1.20214e+008 Pa; dV/V=0.495874

A vortex crosses the pressure opening Boundary Condition : Environment Pressure 1 ; Inlet flow/outlet flow=0.0866046

Calculation Mesh

Basic Mesh Dimensions

Number of cells in X	40
Number of cells in Y	40
Number of cells in Z	6

Number Of Cells

Total cells	49780
Fluid cells	22160
Solid cells	11524
Partial cells	16096
Irregular cells	0
Trimmed cells	37

Maximum refinement level: 1

Goals

Name	Unit	Value	Progress	Use in convergen	Delta	Criteria

				ce		
GG Z - Component of Torque	N*m	3421.23	100	On	15.4808611	28.9305991
SG Bulk Av Static Pressure at impeller outlet	Pa	-4.33698e+006	100	On	247330.017	370764.698
SG Mass Flow Rate at inlet	kg/s	299.269	100	On	0	0.299268522
SG Av Static Pressure at inlet	Pa	1.2631e+008	100	On	198012.491	2058889.16
SG Mass Flow Rate at outlet	kg/s	-299.266	100	On	0.000689752417	0.299266433
SG Z - Component of Torque at stator	N*m	-9.35824	100	On	0.444954715	0.464934415
Torque on impeller	N*m	3430.59	100	On	15.5750148	28.881947
Pressure Drop	Pa	1.30647e+008	100	On	294534.863	1906635.49
Efficiency		54.5498	100	On	0.140409828	0.38022635

Min/Max Table

Name	Minimum	Maximum
Pressure [Pa]	-1.20214e+008	1.83694e+008
Temperature [K]	237.284	300.816
Density [kg/m^3]	995.645	1001.3
Velocity [m/s]	0	844.228
X-velocity [m/s]	-567.118	562.671
Y-velocity [m/s]	-558.323	556.048
Z-velocity [m/s]	-735.381	480.733
Heat Transfer Coefficient [W/m^2/K]	0	0
Shear Stress [Pa]	3.57214e-006	4.81012e+006
Surface Heat Flux [W/m^2]	0	0

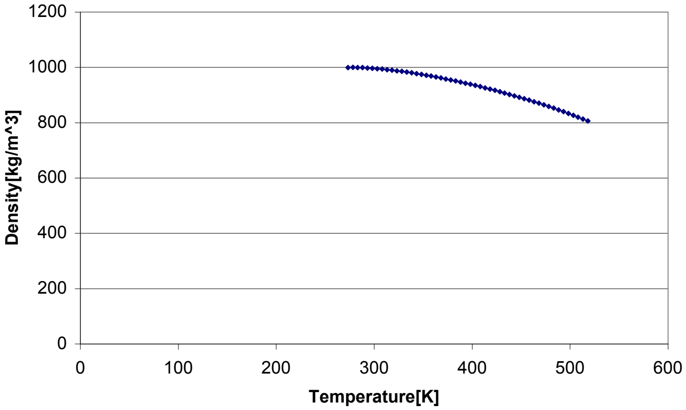
Water Mass Fraction [ ]	1	1
Water Volume Fraction [ ]	1	1
Fluid Temperature [K]	237.284	300.816
Velocity RRF [m/s]	0	843.973
X-velocity RRF [m/s]	-571.866	567.487
Y-velocity RRF [m/s]	-561.414	559.758
Z-velocity RRF [m/s]	-735.381	480.733

Engineering Database

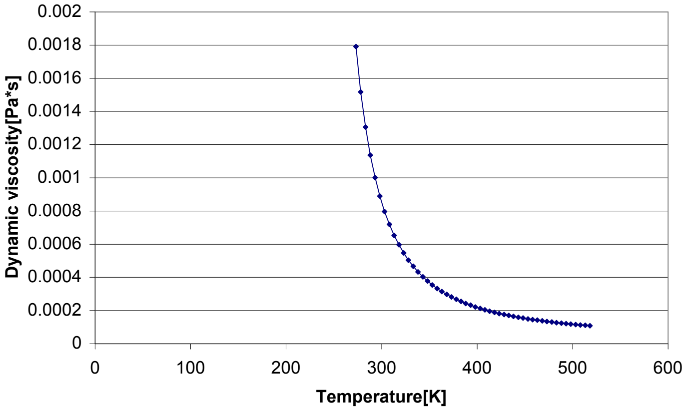
Liquids

Water

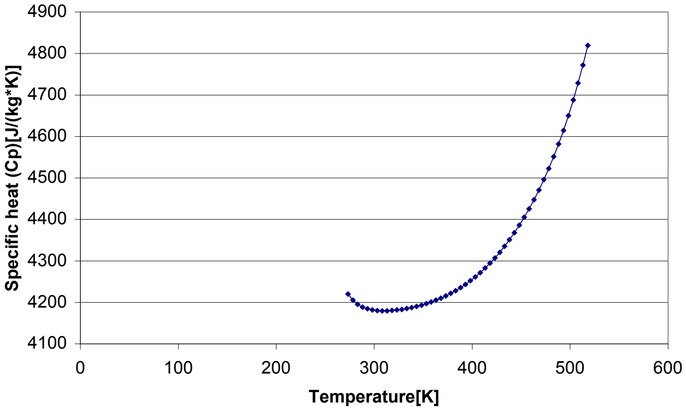
Path: Liquid FW Defined
Density



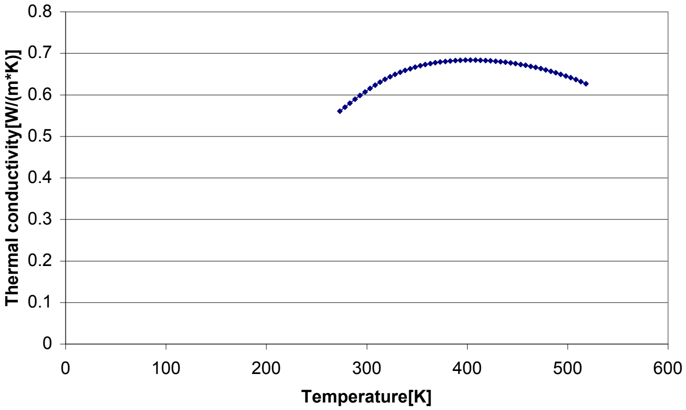
Dynamic viscosity



Specific heat (Cp)



Thermal conductivity



APPENDIX A12: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 55^0

System Info

Product	EFD.Lab 8 1.0. Build: 413
Computer name	FEA2
User name	Administrator
Processors	Dual Core AMD Opteron(tm) Processor 280 (4 processors)
Memory	16382 MB / 8388607 MB
Operating system	Microsoft Windows XP Professional x64 Edition Service Pack 2 (Build 3790)
CAD version	SolidWorks 2007 SP0
CPU speed	2411 MHz

General Info

Model	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate10_inlet30_outlet55\Assem5_inlet30_outlet55.SLDASM
Project name	inlet30_outlet55
Project path	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate10_inlet30_outlet55\1\1.fwp
Units system	SI (m-kg-s)
Analysis type	Internal
Exclude cavities without flow conditions	On
Coordinate system	Global coordinate system
Reference axis	X

INPUT DATA

Initial Mesh Settings

Automatic initial mesh: On
Result resolution level: 5
Advanced narrow channel refinement: Off
Refinement in solid region: Off

Geometry Resolution

Evaluation of minimum gap size: Manual
Minimum gap size: 0.04 m
Evaluation of minimum wall thickness: Manual
Minimum wall thickness: 0.01 m

APPENDIX A12: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 55^0

Computational Domain

Size

X min	-0.0514326445 m
X max	0.0447593555 m
Y min	-0.0483066476 m
Y max	0.0478853524 m
Z min	0.00188716267 m
Z max	0.0185204128 m

Boundary Conditions

2D plane flow	None
At X min	Default
At X max	Default
At Y min	Default
At Y max	Default
At Z min	Default
At Z max	Default

Physical Features

Heat conduction in solids: Off
Time dependent: Off
Gravitational effects: Off
Flow type: Laminar only
Cavitation: Off
High Mach number flow: Off
Default roughness: 0 micrometer

Rotating Reference Frame

Axis of coordinate system	Z
Velocity	209.43951 m/s

Default wall conditions: Adiabatic wall

Initial Conditions

Thermodynamic parameters	Static Pressure: 101325 Pa Temperature: 293.2 K
Velocity parameters	Velocity vector Velocity in X direction: 0 m/s Velocity in Y direction: 0 m/s Velocity in Z direction: 0 m/s Relative to rotating frame: Off

APPENDIX A12: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 55^0

Material Settings

Fluids

Water

Boundary Conditions

stator Wall

Type	Real wall
Faces	Face <1 cover5-1@> Face <1 cover5-1@> Face <1 cover5-1@>
Coordinate system	Global coordinate system
Reference axis	X

Inlet Volume Flow 1

Type	Inlet Volume Flow
Faces	Face <1 cover5-1@>
Coordinate system	Face Coordinate System
Reference axis	X
Flow parameters	Flow vectors direction: Normal to face Volume flow rate normal to face: 0.3 m^3/s Relative to rotating frame: No Fully developed flow: No Inlet profile: 0
Thermodynamic parameters	Temperature: 293.2 K

Environment Pressure 1

Type	Environment Pressure
Faces	Face <1 cover5-1@>
Coordinate system	Global coordinate system
Reference axis	X
Thermodynamic parameters	Environment pressure: 101325 Pa Temperature: 293.2 K

Goals

Global Goals

GG Z - Component of Torque

Type	Global Goal
Goal type	Z - Component of Torque
Coordinate system	Global coordinate system
Use in convergence	On

Surface Goals

SG Z - Component of Torque at stator

Type	Surface Goal
Goal type	Z - Component of Torque
Faces	Face<1>@cover5-1 Face<2>@cover5-1 Face<3>@cover5-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate at outlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<2>@cover5-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Av Static Pressure at inlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@cover5-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Bulk Av Static Pressure at impeller outlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@measure5-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate at inlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<5>@cover5-1
Coordinate system	Global coordinate system
Use in convergence	On

Equation Goals

Presure Drop

Type	Equation Goal
Formula	SG Av Static Pressure at inlet-SG Bulk Av

	Static Pressure at impeller outlet
Dimensionality	Pressure & stress
Use in convergence	On

Torque on impeller

Type	Equation Goal
Formula	GG Z - Component of Torque -SG Z - Component of Torque at stator
Dimensionality	Torque
Use in convergence	On

Efficiency

Type	Equation Goal
Formula	Presure Drop*{Inlet Volume Flow 1:Volume flow rate normal to face:3.000e-001}/209.44/Torque on impeller
Dimensionality	No units
Use in convergence	On

Component Control Info

Disabled components: Extrude1@measure5-1@Assem5_inlet30_outlet55

Calculation Control Options

Finish Conditions

Finish conditions	If one is satisfied
Maximum travels	4
Goals convergence	Analysis interval: 0.5

Solver Refinement

Refinement: Disabled

Results Saving

Save before refinement	On

Advanced Control Options

Flow Freezing

Flow freezing strategy	Disabled

APPENDIX A12: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 55^0

RESULTS

General Info

Iterations: 129
CPU time: 585 s

Log

Mesh generation started	20:54:45 , Feb 20
Mesh generation normally finished	20:54:52 , Feb 20
Preparing data for calculation	20:54:57 , Feb 20
Calculation started 0	20:55:01 , Feb 20
Calculation has converged since the following criteria are satisfied: 128	21:04:45 , Feb 20
Goals are converged 128	
Calculation finished 129	21:04:50 , Feb 20

Warnings: Negative pressure Minimum pressure=-1.16412e+008 Pa; dV/V=0.499466

A vortex crosses the pressure opening Boundary Condition : Environment Pressure 1 ; Inlet flow/outlet flow=0.0824577

Calculation Mesh

Basic Mesh Dimensions

Number of cells in X	40
Number of cells in Y	40
Number of cells in Z	6

Number Of Cells

Total cells	49738
Fluid cells	22217
Solid cells	11374
Partial cells	16147
Irregular cells	0
Trimmed cells	42

Maximum refinement level: 1

Goals

Name	Unit	Value	Progress	Use in convergen	Delta	Criteria

				ce		
GG Z - Component of Torque	N*m	3503.83	100	On	29.5377437	30.025117
SG Z - Component of Torque at stator	N*m	-2.16163	100	On	0.559309985	0.595085581
SG Mass Flow Rate at outlet	kg/s	-299.268	100	On	0.00189396535	0.299268412
SG Av Static Pressure at inlet	Pa	1.33764e+008	100	On	1283574.07	2072918.53
SG Bulk Av Static Pressure at impeller outlet	Pa	-3.89871e+006	100	On	206094.954	354814.865
SG Mass Flow Rate at inlet	kg/s	299.269	100	On	0	0.299268522
Torque on impeller	N*m	3505.99	100	On	28.4206756	29.8007646
Presure Drop	Pa	1.37662e+008	100	On	1323501.36	1949021.47
Efficiency		56.2427	100	On	0.0929482693	0.362407826

Min/Max Table

Name	Minimum	Maximum
Pressure [Pa]	-1.16412e+008	1.91696e+008
Temperature [K]	237.43	300.695
Density [kg/m^3]	995.593	1001.3
Velocity [m/s]	0	876.779
X-velocity [m/s]	-576.48	574.177
Y-velocity [m/s]	-569.688	573.12
Z-velocity [m/s]	-757.069	468.916
Heat Transfer Coefficient [W/m^2/K]	0	0
Shear Stress [Pa]	1.08593e-005	721757
Surface Heat Flux [W/m^2]	0	0

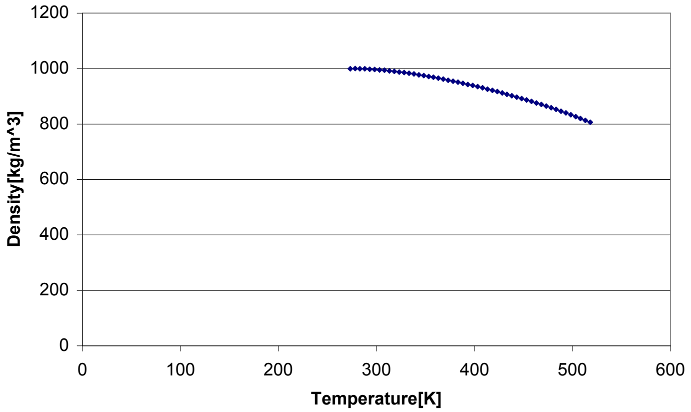
Water Mass Fraction [ ]	1	1
Water Volume Fraction [ ]	1	1
Fluid Temperature [K]	237.43	300.695
Velocity RRF [m/s]	0	877.203
X-velocity RRF [m/s]	-582.946	577.28
Y-velocity RRF [m/s]	-571.382	577.974
Z-velocity RRF [m/s]	-757.069	468.916

Engineering Database

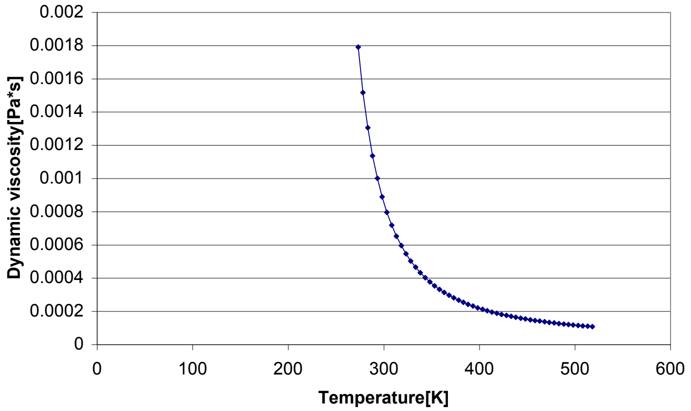
Liquids

Water

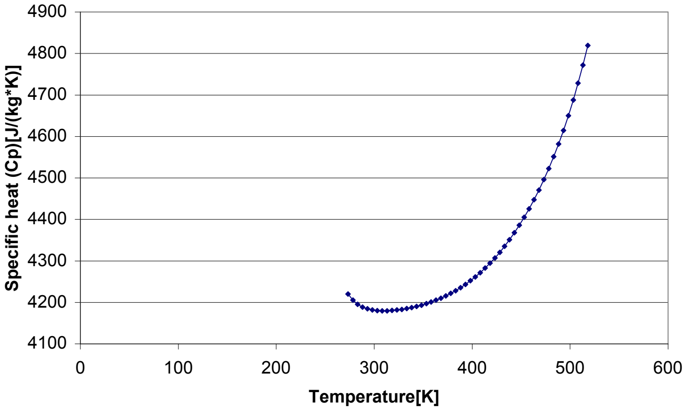
Path: Liquid FW Defined
Density



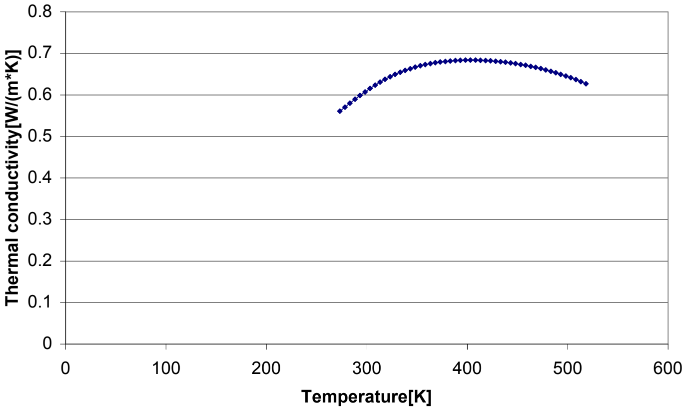
Dynamic viscosity



Specific heat (Cp)



Thermal conductivity



APPENDIX A13: FM21 LABORATORY RESULTS

Sample Number	Orifice Differential Pressure dPo [kPa]	Pump 1 Differential Pressure dPp1 [kPa]	Pump 2 Differential Pressure dPp2 [kPa]	Motor 1 Speed n1 [Hz]	Motor 2 Speed n2 [Hz]	Motor 1 Input Power Pe1 [W]	Motor 2 Input Power Pe2 [W]	Water Temperature Tw [°C]	Operating Mode
1	7.007	39.961	0.000	45	0	289.79	0.00	41.0	Single
2	6.887	39.854	0.322	44	0	284.42	0.00	41.2	Single
3	6.836	40.605	0.107	44	0	277.59	0.00	41.5	Single
4	6.870	41.895	0.000	44	0	281.49	0.00	41.8	Single
5	6.853	42.109	0.322	44	0	283.20	0.00	41.6	Single
6	6.768	42.324	0.752	44	0	283.45	0.00	41.9	Single
7	6.648	42.969	0.752	44	0	280.52	0.00	42.1	Single
8	6.750	42.646	0.537	44	0	285.89	0.00	42.3	Single
9	6.597	43.506	0.645	44	0	282.96	0.00	42.3	Single
10	6.648	43.828	0.000	44	0	278.81	0.00	42.5	Single
11	6.699	43.828	0.000	44	0	282.23	0.00	42.7	Single
12	6.648	44.150	0.000	44	0	280.76	0.00	43.0	Single
13	6.682	43.506	0.322	44	0	279.30	0.00	43.3	Single
14	6.631	44.473	0.000	44	0	284.67	0.00	43.2	Single
15	6.545	44.902	0.000	44	0	283.94	0.00	43.6	Single
16	6.511	44.473	0.000	44	0	286.87	0.00	43.6	Single
17	6.477	44.580	0.215	44	0	281.25	0.00	43.9	Single
18	6.443	44.365	0.752	44	0	284.18	0.00	43.8	Single
19	6.443	44.795	0.430	44	0	283.69	0.00	44.0	Single
20	6.426	44.473	0.645	44	0	272.46	0.00	44.2	Single
21	6.511	44.365	0.537	44	0	280.03	0.00	44.4	Single
22	6.306	44.043	0.537	44	0	277.10	0.00	44.7	Single
23	6.426	44.795	0.107	44	0	273.68	0.00	44.7	Single
24	6.460	44.580	0.215	44	0	283.20	0.00	44.8	Single
25	6.511	44.150	0.000	44	0	282.71	0.00	45.0	Single
26	6.426	44.365	0.000	44	0	275.39	0.00	45.3	Single
27	6.357	44.580	0.215	44	0	282.23	0.00	45.4	Single
28	6.357	44.473	0.107	44	0	283.45	0.00	45.4	Single
29	6.340	44.473	0.000	44	0	276.37	0.00	45.7	Single
30	6.357	44.043	0.107	44	0	277.34	0.00	45.7	Single
31	6.306	44.365	0.000	44	0	285.89	0.00	45.8	Single
32	6.238	44.365	0.215	44	0	283.45	0.00	46.1	Single
33	6.238	44.580	0.645	44	0	279.30	0.00	46.2	Single
34	6.152	44.473	0.430	44	0	281.25	0.00	46.4	Single
35	6.169	44.365	0.000	44	0	281.98	0.00	46.4	Single
36	7.485	44.795	0.107	44	0	285.16	0.00	46.6	Single
37	7.639	44.365	0.107	44	0	281.01	0.00	46.7	Single
38	7.793	44.150	0.537	44	0	278.08	0.00	46.8	Single
39	7.878	44.043	0.107	44	0	273.44	0.00	46.9	Single
40	8.101	44.580	0.430	44	0	286.13	0.00	47.2	Single
41	8.101	44.365	0.000	44	0	282.71	0.00	47.1	Single
42	8.152	44.795	0.000	44	0	282.71	0.00	47.4	Single
43	8.271	44.795	0.000	44	0	274.17	0.00	47.4	Single
44	8.306	44.258	0.430	44	0	283.94	0.00	47.6	Single
45	8.425	44.473	0.215	44	0	289.31	0.00	47.8	Single
46	8.408	44.580	0.645	44	0	274.17	0.00	47.8	Single
47	8.477	44.473	0.322	44	0	281.01	0.00	47.9	Single
48	8.528	43.828	0.107	44	0	281.25	0.00	47.9	Single
49	8.613	44.473	0.107	44	0	276.61	0.00	48.2	Single
50	6.563	45.654	1.182	44	0	292.24	0.00	47.9	Single

APPENDIX A13: FM21 LABORATORY RESULTS

Sample Number	**Orifice Differential Pressure dPo [kPa]**	**Pump 1 Differential Pressure dPp1 [kPa]**	**Pump 2 Differential Pressure dPp2 [kPa]**	**Motor 1 Speed n1 [Hz]**	**Motor 2 Speed n2 [Hz]**	**Motor 1 Input Power Pe1 [W]**	**Motor 2 Input Power Pe2 [W]**	**Water Temperature Tw [°C]**	**Operating Mode**
51	6.460	45.332	3.545	44	0	281.01	0.00	47.8	Single
52	6.323	45.332	3.330	44	0	281.98	0.00	48.0	Single
53	6.289	45.332	3.438	44	0	283.20	0.00	48.1	Single
54	6.204	45.117	3.223	44	0	278.32	0.00	48.2	Single
55	6.375	45.225	3.223	44	0	279.30	0.00	48.2	Single
56	6.306	45.010	3.330	44	0	279.54	0.00	48.3	Single
57	6.221	45.439	2.900	44	0	280.52	0.00	48.4	Single
58	6.238	45.225	2.900	44	0	280.76	0.00	48.5	Single
59	6.204	45.225	2.900	44	0	285.64	0.00	48.7	Single
60	6.221	44.902	3.545	44	0	276.12	0.00	48.7	Single
61	6.272	45.332	3.008	44	0	276.86	0.00	48.9	Single
62	6.255	45.225	3.545	44	0	281.01	0.00	48.7	Single
63	6.169	45.439	2.578	44	0	281.98	0.00	49.0	Single
64	6.289	45.010	3.438	44	0	280.76	0.00	49.0	Single
65	6.187	44.795	3.223	44	0	279.54	0.00	49.0	Single
66	6.187	44.902	2.793	44	0	286.38	0.00	49.2	Single
67	6.221	44.795	3.330	44	0	282.96	0.00	49.2	Single
68	6.204	44.795	3.330	44	0	284.91	0.00	49.3	Single
69	6.255	44.795	3.438	44	0	282.71	0.00	49.4	Single
70	6.255	44.795	3.330	44	0	280.27	0.00	49.4	Single
71	6.135	45.439	2.686	44	0	282.23	0.00	49.7	Single
72	6.152	44.902	2.578	44	0	287.11	0.00	49.7	Single
73	6.204	45.225	3.008	44	0	280.03	0.00	49.9	Single
74	6.084	45.117	2.793	44	0	283.45	0.00	49.8	Single
75	6.118	45.117	3.545	44	0	285.40	0.00	50.1	Single
76	6.084	45.117	3.008	44	0	282.71	0.00	50.0	Single
77	6.135	44.902	3.115	44	0	276.61	0.00	50.0	Single
78	6.169	45.010	3.545	44	0	280.52	0.00	50.2	Single
79	6.135	44.580	3.115	44	0	281.74	0.00	50.1	Single
80	6.204	44.580	3.438	44	0	278.81	0.00	50.2	Single
81	6.118	44.688	2.686	44	0	279.54	0.00	50.3	Single
82	6.084	45.225	2.900	44	0	273.68	0.00	50.4	Single
83	6.016	44.902	3.115	44	0	282.47	0.00	50.5	Single
84	6.016	44.795	3.652	44	0	276.37	0.00	50.6	Single
85	6.050	44.688	2.793	44	0	278.81	0.00	50.7	Single
86	6.016	44.580	2.900	44	0	278.56	0.00	50.8	Single
87	5.981	44.580	3.223	44	0	283.94	0.00	50.7	Single
88	6.101	44.580	3.330	44	0	278.56	0.00	50.8	Single
89	5.999	44.902	3.545	44	0	273.68	0.00	51.0	Single
90	5.999	44.795	2.900	44	0	273.68	0.00	51.1	Single
91	6.016	44.365	3.438	44	0	277.83	0.00	50.9	Single
92	6.101	44.580	3.438	44	0	277.83	0.00	51.0	Single
93	5.964	44.258	3.223	44	0	278.08	0.00	51.1	Single
94	6.033	44.688	3.223	44	0	278.81	0.00	51.2	Single
95	5.981	44.580	2.900	44	0	272.46	0.00	51.3	Single
96	5.981	44.258	3.115	44	0	284.67	0.00	51.2	Single
97	6.033	44.580	3.223	44	0	278.56	0.00	51.3	Single
98	6.033	45.010	3.223	44	0	278.32	0.00	51.3	Single
99	5.947	44.688	3.223	44	0	281.25	0.00	51.5	Single
100	5.930	44.902	3.330	44	0	282.71	0.00	51.6	Single

APPENDIX A14: FM21 LABORATORY RESULTS

Sample Number	Density of water rho [kg/m³]	Orifice Discharge Coefficient Cd	Volume Flowrate Qv [dm³/s]	Pump 1 Inlet Velocity V1 [m/s]	Pump 1 Outlet Velocity V2 [m/s]	Pump 2 Inlet Velocity V3 [m/s]	Pump 2 Outlet Velocity V4 [m/s]	Pump 1 Total Head H1 [m]	Pump 2 Total Head H2 [m]	Combined Total Head Ht [m]	Pump 1 Power Output P1 [W]	Pump 2 Power Output P2 [W]	Combined Power Output Pt [W]	Pump 1 Efficiency E1 [%]	Pump 2 Efficiency E2 [%]	Overall Efficiency Egr [%]
1	991.9	0.610	1.037	3.64	3.64	3.64	3.64	4.15	0.05	4.15	41.9	0.5	41.9	14.5	0.0	14.5
2	991.8	0.610	1.028	3.61	3.61	3.61	3.61	4.14	0.08	4.14	41.5	0.8	41.5	14.6	0.0	14.6
3	991.7	0.610	1.025	3.60	3.60	3.60	3.60	4.22	0.06	4.22	42.1	0.6	42.1	15.2	0.0	15.2
4	991.6	0.610	1.027	3.60	3.60	3.60	3.60	4.35	0.05	4.35	43.5	0.5	43.5	15.5	0.0	15.5
5	991.7	0.610	1.026	3.60	3.60	3.60	3.60	4.38	0.08	4.38	43.7	0.8	43.7	15.4	0.0	15.4
6	991.6	0.610	1.020	3.58	3.58	3.58	3.58	4.40	0.13	4.40	43.6	1.2	43.6	15.4	0.0	15.4
7	991.5	0.610	1.011	3.55	3.55	3.55	3.55	4.47	0.13	4.47	43.9	1.2	43.9	15.6	0.0	15.6
8	991.4	0.610	1.018	3.57	3.57	3.57	3.57	4.43	0.10	4.43	43.9	1.0	43.9	15.4	0.0	15.4
9	991.4	0.610	1.007	3.53	3.53	3.53	3.53	4.52	0.11	4.52	44.3	1.1	44.3	15.6	0.0	15.6
10	991.3	0.610	1.011	3.55	3.55	3.55	3.55	4.55	0.05	4.55	44.8	0.5	44.8	16.1	0.0	16.1
11	991.3	0.610	1.015	3.56	3.56	3.56	3.56	4.56	0.05	4.56	44.9	0.5	44.9	15.9	0.0	15.9
12	991.1	0.610	1.011	3.55	3.55	3.55	3.55	4.59	0.05	4.59	45.1	0.5	45.1	16.1	0.0	16.1
13	991.0	0.610	1.013	3.56	3.56	3.56	3.56	4.52	0.08	4.52	44.6	0.8	44.6	16.0	0.0	16.0
14	991.1	0.610	1.009	3.54	3.54	3.54	3.54	4.62	0.05	4.62	45.4	0.5	45.4	15.9	0.0	15.9
15	990.9	0.610	1.003	3.52	3.52	3.52	3.52	4.67	0.05	4.67	45.5	0.5	45.5	16.0	0.0	16.0
16	990.9	0.610	1.000	3.51	3.51	3.51	3.51	4.62	0.05	4.62	45.0	0.5	45.0	15.7	0.0	15.7
17	990.8	0.610	0.998	3.50	3.50	3.50	3.50	4.63	0.07	4.63	44.9	0.7	44.9	16.0	0.0	16.0
18	990.8	0.610	0.995	3.49	3.49	3.49	3.49	4.61	0.13	4.61	44.6	1.2	44.6	15.7	0.0	15.7
19	990.7	0.610	0.995	3.49	3.49	3.49	3.49	4.66	0.09	4.66	45.0	0.9	45.0	15.9	0.0	15.9
20	990.7	0.610	0.994	3.49	3.49	3.49	3.49	4.62	0.11	4.62	44.7	1.1	44.7	16.4	0.0	16.4
21	990.6	0.610	1.001	3.51	3.51	3.51	3.51	4.61	0.10	4.61	44.9	1.0	44.9	16.0	0.0	16.0
22	990.5	0.610	0.985	3.46	3.46	3.46	3.46	4.58	0.10	4.58	43.8	1.0	43.8	15.8	0.0	15.8
23	990.4	0.610	0.994	3.49	3.49	3.49	3.49	4.66	0.06	4.66	45.0	0.6	45.0	16.4	0.0	16.4
24	990.4	0.610	0.997	3.50	3.50	3.50	3.50	4.64	0.07	4.64	44.9	0.7	44.9	15.9	0.0	15.9
25	990.3	0.610	1.001	3.51	3.51	3.51	3.51	4.59	0.05	4.59	44.6	0.5	44.6	15.8	0.0	15.8
26	990.2	0.610	0.994	3.49	3.49	3.49	3.49	4.62	0.05	4.62	44.6	0.5	44.6	16.2	0.0	16.2
27	990.2	0.610	0.989	3.47	3.47	3.47	3.47	4.64	0.07	4.64	44.5	0.7	44.5	15.8	0.0	15.8
28	990.1	0.610	0.989	3.47	3.47	3.47	3.47	4.63	0.06	4.63	44.4	0.6	44.4	15.7	0.0	15.7
29	990.0	0.610	0.988	3.47	3.47	3.47	3.47	4.63	0.05	4.63	44.4	0.5	44.4	16.1	0.0	16.1
30	990.0	0.610	0.989	3.47	3.47	3.47	3.47	4.58	0.06	4.58	44.0	0.6	44.0	15.9	0.0	15.9
31	990.0	0.610	0.985	3.46	3.46	3.46	3.46	4.62	0.05	4.62	44.2	0.5	44.2	15.4	0.0	15.4
32	989.9	0.610	0.980	3.44	3.44	3.44	3.44	4.62	0.07	4.62	43.9	0.7	43.9	15.5	0.0	15.5
33	989.8	0.610	0.980	3.44	3.44	3.44	3.44	4.64	0.11	4.64	44.1	1.1	44.1	15.8	0.0	15.8
34	989.7	0.610	0.973	3.41	3.41	3.41	3.41	4.63	0.09	4.63	43.7	0.9	43.7	15.5	0.0	15.5
35	989.7	0.610	0.974	3.42	3.42	3.42	3.42	4.62	0.05	4.62	43.7	0.5	43.7	15.5	0.0	15.5
36	989.7	0.610	1.073	3.77	3.77	3.77	3.77	4.66	0.06	4.66	48.6	0.6	48.6	17.0	0.0	17.0
37	989.6	0.610	1.084	3.80	3.80	3.80	3.80	4.62	0.06	4.62	48.6	0.6	48.6	17.3	0.0	17.3
38	989.6	0.610	1.095	3.84	3.84	3.84	3.84	4.60	0.10	4.60	48.9	1.1	48.9	17.6	0.0	17.6
39	989.5	0.610	1.101	3.86	3.86	3.86	3.86	4.59	0.06	4.59	49.0	0.6	49.0	17.9	0.0	17.9
40	989.4	0.610	1.117	3.92	3.92	3.92	3.92	4.64	0.09	4.64	50.3	1.0	50.3	17.6	0.0	17.6
41	989.4	0.610	1.117	3.92	3.92	3.92	3.92	4.62	0.05	4.62	50.1	0.5	50.1	17.7	0.0	17.7
42	989.3	0.610	1.120	3.93	3.93	3.93	3.93	4.66	0.05	4.66	50.7	0.5	50.7	17.9	0.0	17.9
43	989.3	0.610	1.128	3.96	3.96	3.96	3.96	4.66	0.05	4.66	51.1	0.5	51.1	18.6	0.0	18.6
44	989.2	0.610	1.131	3.97	3.97	3.97	3.97	4.61	0.09	4.61	50.6	1.0	50.6	17.8	0.0	17.8
45	989.1	0.610	1.139	4.00	4.00	4.00	4.00	4.63	0.07	4.63	51.2	0.8	51.2	17.7	0.0	17.7
46	989.1	0.610	1.138	3.99	3.99	3.99	3.99	4.64	0.11	4.64	51.3	1.3	51.3	18.7	0.0	18.7
47	989.1	0.610	1.142	4.01	4.01	4.01	4.01	4.63	0.08	4.63	51.3	0.9	51.3	18.3	0.0	18.3
48	989.1	0.610	1.146	4.02	4.02	4.02	4.02	4.57	0.06	4.57	50.8	0.7	50.8	18.0	0.0	18.0
49	988.9	0.610	1.152	4.04	4.04	4.04	4.04	4.63	0.06	4.63	51.8	0.7	51.8	18.7	0.0	18.7
50	989.1	0.610	1.005	3.53	3.53	3.53	3.53	4.75	0.17	4.75	46.4	1.7	46.4	15.9	0.0	15.9

APPENDIX A14: FM21 LABORATORY RESULTS

Sample Number	Density of water rho [kg/m^3]	Orifice Discharge Coefficient Cd	Volume Flowrate Qv [dm^3/s]	Pump 1 Inlet Velocity V1 [m/s]	Pump 1 Outlet Velocity V2 [m/s]	Pump 2 Inlet Velocity V3 [m/s]	Pump 2 Outlet Velocity V4 [m/s]	Pump 1 Total Head H1 [m]	Pump 2 Total Head H2 [m]	Combined Total Head Ht [m]	Pump 1 Power Output P1 [W]	Pump 2 Power Output P2 [W]	Combined Power Output Pt [W]	Pump 1 Efficiency E1 [%]	Pump 2 Efficiency E2 [%]	Overall Efficiency Egr [%]
51	989.1	0.610	0.997	3.50	3.50	3.50	3.50	4.72	0.41	4.72	45.7	4.0	45.7	16.3	0.0	16.3
52	989.0	0.610	0.987	3.46	3.46	3.46	3.46	4.72	0.39	4.72	45.2	3.7	45.2	16.0	0.0	16.0
53	989.0	0.610	0.984	3.45	3.45	3.45	3.45	4.72	0.40	4.72	45.1	3.8	45.1	15.9	0.0	15.9
54	989.0	0.610	0.977	3.43	3.43	3.43	3.43	4.70	0.38	4.70	44.6	3.6	44.6	16.0	0.0	16.0
55	989.0	0.610	0.991	3.48	3.48	3.48	3.48	4.71	0.38	4.71	45.3	3.7	45.3	16.2	0.0	16.2
56	988.9	0.610	0.986	3.46	3.46	3.46	3.46	4.69	0.39	4.69	44.8	3.7	44.8	16.0	0.0	16.0
57	988.9	0.610	0.979	3.43	3.43	3.43	3.43	4.73	0.35	4.73	44.9	3.3	44.9	16.0	0.0	16.0
58	988.8	0.610	0.980	3.44	3.44	3.44	3.44	4.71	0.35	4.71	44.8	3.3	44.8	16.0	0.0	16.0
59	988.8	0.610	0.978	3.43	3.43	3.43	3.43	4.71	0.35	4.71	44.7	3.3	44.7	15.6	0.0	15.6
60	988.7	0.610	0.979	3.43	3.43	3.43	3.43	4.68	0.41	4.68	44.4	3.9	44.4	16.1	0.0	16.1
61	988.6	0.610	0.983	3.45	3.45	3.45	3.45	4.72	0.36	4.72	45.0	3.4	45.0	16.3	0.0	16.3
62	988.7	0.610	0.982	3.44	3.44	3.44	3.44	4.71	0.41	4.71	44.8	3.9	44.8	16.0	0.0	16.0
63	988.6	0.610	0.975	3.42	3.42	3.42	3.42	4.73	0.31	4.73	44.8	3.0	44.8	15.9	0.0	15.9
64	988.6	0.610	0.984	3.45	3.45	3.45	3.45	4.69	0.40	4.69	44.8	3.8	44.8	15.9	0.0	15.9
65	988.6	0.610	0.976	3.43	3.43	3.43	3.43	4.67	0.38	4.67	44.2	3.6	44.2	15.8	0.0	15.8
66	988.5	0.610	0.976	3.43	3.43	3.43	3.43	4.68	0.34	4.68	44.3	3.2	44.3	15.5	0.0	15.5
67	988.5	0.610	0.979	3.44	3.44	3.44	3.44	4.67	0.39	4.67	44.3	3.7	44.3	15.7	0.0	15.7
68	988.5	0.610	0.978	3.43	3.43	3.43	3.43	4.67	0.39	4.67	44.3	3.7	44.3	15.5	0.0	15.5
69	988.4	0.610	0.982	3.44	3.44	3.44	3.44	4.67	0.40	4.67	44.4	3.8	44.4	15.7	0.0	15.7
70	988.4	0.610	0.982	3.44	3.44	3.44	3.44	4.67	0.39	4.67	44.4	3.7	44.4	15.9	0.0	15.9
71	988.3	0.610	0.972	3.41	3.41	3.41	3.41	4.73	0.33	4.73	44.6	3.1	44.6	15.8	0.0	15.8
72	988.3	0.610	0.974	3.42	3.42	3.42	3.42	4.68	0.31	4.68	44.2	3.0	44.2	15.4	0.0	15.4
73	988.2	0.610	0.978	3.43	3.43	3.43	3.43	4.71	0.36	4.71	44.7	3.4	44.7	16.0	0.0	16.0
74	988.2	0.610	0.968	3.40	3.40	3.40	3.40	4.70	0.34	4.70	44.1	3.2	44.1	15.6	0.0	15.6
75	988.1	0.610	0.971	3.41	3.41	3.41	3.41	4.70	0.41	4.70	44.3	3.9	44.3	15.5	0.0	15.5
76	988.2	0.610	0.968	3.40	3.40	3.40	3.40	4.70	0.36	4.70	44.1	3.4	44.1	15.6	0.0	15.6
77	988.1	0.610	0.972	3.41	3.41	3.41	3.41	4.68	0.37	4.68	44.1	3.5	44.1	15.9	0.0	15.9
78	988.0	0.610	0.975	3.42	3.42	3.42	3.42	4.69	0.41	4.69	44.3	3.9	44.3	15.8	0.0	15.8
79	988.1	0.610	0.972	3.41	3.41	3.41	3.41	4.65	0.37	4.65	43.8	3.5	43.8	15.5	0.0	15.5
80	988.1	0.610	0.978	3.43	3.43	3.43	3.43	4.65	0.40	4.65	44.0	3.8	44.0	15.8	0.0	15.8
81	988.0	0.610	0.971	3.41	3.41	3.41	3.41	4.66	0.33	4.66	43.9	3.1	43.9	15.7	0.0	15.7
82	988.0	0.610	0.968	3.40	3.40	3.40	3.40	4.71	0.35	4.71	44.2	3.3	44.2	16.2	0.0	16.2
83	987.9	0.610	0.963	3.38	3.38	3.38	3.38	4.68	0.37	4.68	43.7	3.4	43.7	15.5	0.0	15.5
84	987.9	0.610	0.963	3.38	3.38	3.38	3.38	4.67	0.42	4.67	43.6	4.0	43.6	15.8	0.0	15.8
85	987.8	0.610	0.966	3.39	3.39	3.39	3.39	4.66	0.34	4.66	43.6	3.1	43.6	15.6	0.0	15.6
86	987.8	0.610	0.963	3.38	3.38	3.38	3.38	4.65	0.35	4.65	43.4	3.2	43.4	15.6	0.0	15.6
87	987.8	0.610	0.960	3.37	3.37	3.37	3.37	4.65	0.38	4.65	43.3	3.5	43.3	15.2	0.0	15.2
88	987.8	0.610	0.970	3.40	3.40	3.40	3.40	4.65	0.39	4.65	43.7	3.7	43.7	15.7	0.0	15.7
89	987.7	0.610	0.962	3.37	3.37	3.37	3.37	4.68	0.41	4.68	43.6	3.9	43.6	15.9	0.0	15.9
90	987.7	0.610	0.962	3.37	3.37	3.37	3.37	4.67	0.35	4.67	43.5	3.2	43.5	15.9	0.0	15.9
91	987.7	0.610	0.963	3.38	3.38	3.38	3.38	4.63	0.40	4.63	43.2	3.8	43.2	15.5	0.0	15.5
92	987.7	0.610	0.970	3.40	3.40	3.40	3.40	4.65	0.40	4.65	43.7	3.8	43.7	15.7	0.0	15.7
93	987.7	0.610	0.959	3.37	3.37	3.37	3.37	4.62	0.38	4.62	42.9	3.5	42.9	15.4	0.0	15.4
94	987.6	0.610	0.965	3.38	3.38	3.38	3.38	4.66	0.38	4.66	43.6	3.6	43.6	15.6	0.0	15.6
95	987.5	0.610	0.960	3.37	3.37	3.37	3.37	4.65	0.35	4.65	43.3	3.2	43.3	15.9	0.0	15.9
96	987.6	0.610	0.960	3.37	3.37	3.37	3.37	4.62	0.37	4.62	43.0	3.4	43.0	15.1	0.0	15.1
97	987.6	0.610	0.965	3.38	3.38	3.38	3.38	4.65	0.38	4.65	43.4	3.6	43.4	15.6	0.0	15.6
98	987.5	0.610	0.965	3.38	3.38	3.38	3.38	4.69	0.38	4.69	43.9	3.6	43.9	15.8	0.0	15.8
99	987.5	0.610	0.958	3.36	3.36	3.36	3.36	4.66	0.38	4.66	43.2	3.5	43.2	15.4	0.0	15.4
100	987.4	0.610	0.956	3.36	3.36	3.36	3.36	4.68	0.39	4.68	43.4	3.6	43.4	15.3	0.0	15.3

APPENDIX A15: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 30^0

System Info

Product	EFD.Lab 8 1.0. Build: 413
Computer name	FEA2
User name	Administrator
Processors	Dual Core AMD Opteron(tm) Processor 280 (4 processors)
Memory	16382 MB / 8388607 MB
Operating system	Microsoft Windows XP Professional x64 Edition Service Pack 2 (Build 3790)
CAD version	SolidWorks 2007 SP0
CPU speed	2411 MHz

General Info

Model	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate3-1_inlet30_outlet30\Assem3-1_inlet30_outlet3o.SLDASM
Project name	Default (1)
Project path	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate3-1_inlet30_outlet30\1\1.fwp
Units system	SI (m-kg-s)
Analysis type	Internal
Exclude cavities without flow conditions	On
Coordinate system	Global coordinate system
Reference axis	X

INPUT DATA

Initial Mesh Settings

Automatic initial mesh: On
Result resolution level: 5
Advanced narrow channel refinement: Off
Refinement in solid region: Off

Geometry Resolution

Evaluation of minimum gap size: Manual
Minimum gap size: 0.04 m
Evaluation of minimum wall thickness: Manual
Minimum wall thickness: 0.01 m

APPENDIX A15: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 30^0

Computational Domain

Size

X min	-0.0473342462 m
X max	0.0488577538 m
Y min	-0.0430765393 m
Y max	0.0531154607 m
Z min	-0.0038287647 m
Z max	0.0128044854 m

Boundary Conditions

2D plane flow	None
At X min	Default
At X max	Default
At Y min	Default
At Y max	Default
At Z min	Default
At Z max	Default

Physical Features

Heat conduction in solids: Off
Time dependent: Off
Gravitational effects: Off
Flow type: Turbulent only
Cavitation: Off
High Mach number flow: Off
Default roughness: 0 micrometer

Rotating Reference Frame

Axis of coordinate system	Z
Velocity	282.74 m/s

Default wall conditions: Adiabatic wall

Initial Conditions

Thermodynamic parameters	Static Pressure: 101325 Pa Temperature: 293.2 K
Velocity parameters	Velocity vector Velocity in X direction: 0 m/s Velocity in Y direction: 0 m/s Velocity in Z direction: 0 m/s Relative to rotating frame: Off

Material Settings

Fluids

Water

Boundary Conditions

Inlet Volume Flow 1

Type	Inlet Volume Flow
Faces	Face <1 cover3-2-1@>
Coordinate system	Face Coordinate System
Reference axis	X
Flow parameters	Flow vectors direction: Normal to face Volume flow rate normal to face: 0.00101 m^3/s Relative to rotating frame: No Fully developed flow: No Inlet profile: 0
Thermodynamic parameters	Temperature: 293.2 K

Environment Pressure 1

Type	Environment Pressure
Faces	Face <1 cover3-2-1@>
Coordinate system	Global coordinate system
Reference axis	X
Thermodynamic parameters	Environment pressure: 101325 Pa Temperature: 293.2 K

stator Wall 1

Type	Real wall
Faces	Face <1 cover3-2-1@> Face <1 cover3-2-1@> Face <1 cover3-2-1@>
Coordinate system	Global coordinate system
Reference axis	X

Goals

Global Goals

GG Z - Component of Torque 1

Type	Global Goal
Goal type	Z - Component of Torque
Coordinate system	Global coordinate system
Use in convergence	On

Surface Goals

SG Av Static Pressure _inlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@cover3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate_inlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<1>@cover3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Bulk Av Static Pressure _impeller outlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@measure3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Z - Component of Torque at stator

Type	Surface Goal
Goal type	Z - Component of Torque
Faces	Face<1>@cover3-2-1 Face<2>@cover3-2-1 Face<3>@cover3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate _outlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<2>@cover3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

Equation Goals

Pressure drop

Type	Equation Goal
Formula	SG Av Static Pressure _inlet-SG Bulk Av

	Static Pressure _impeller outlet
Dimensionality	Pressure & stress
Use in convergence	On

Torque on impeller

Type	Equation Goal
Formula	GG Z - Component of Torque 1-SG Z - Component of Torque at stator
Dimensionality	Torque
Use in convergence	On

Efficiency

Type	Equation Goal
Formula	Pressure drop*{Inlet Volume Flow 1:Volume flow rate normal to face:1.010e-003}/282.74/Torque on impeller
Dimensionality	No units
Use in convergence	On

Component Control Info

Disabled components: Extrude1@measure3-2-1@Assem3-1_inlet30_outlet3o

Calculation Control Options

Finish Conditions

Finish conditions	If one is satisfied
Maximum travels	4
Goals convergence	Analysis interval: 0.5

Solver Refinement

Refinement: Disabled

Results Saving

Save before refinement	On

Advanced Control Options

Flow Freezing

Flow freezing strategy	Disabled

RESULTS

General Info

Iterations: 295
CPU time: 1570 s

Log

Mesh generation started	11:13:11 , Jul 21
Mesh generation normally finished	11:13:17 , Jul 21
Preparing data for calculation	11:13:22 , Jul 21
Calculation started 0	11:13:26 , Jul 21
Calculation has converged since the following criteria are satisfied: 294	11:39:42 , Jul 21
Max. travel is reached 294	
Calculation finished 295	11:39:51 , Jul 21

Warnings: A vortex crosses the pressure opening Boundary Condition : Environment Pressure 1 ; Inlet flow/outlet flow=0.605375

Calculation Mesh

Basic Mesh Dimensions

Number of cells in X	40
Number of cells in Y	40
Number of cells in Z	6

Number Of Cells

Total cells	49801
Fluid cells	23112
Solid cells	11113
Partial cells	15576
Irregular cells	0
Trimmed cells	26

Maximum refinement level: 1

Goals

Name	Unit	Value	Progress	Use in convergence	Delta	Criteria
GG Z - Component of	N*m	-0.623886	100	On	0.0334975099	0.0986754648

Torque 1						
SG Av Static Pressure _inlet	Pa	49512.4	100	On	651.88992	739.150748
SG Mass Flow Rate_inlet	kg/s	1.00754	100	On	0	0.00100753736
SG Bulk Av Static Pressure _impeller outlet	Pa	96843.8	100	On	177.339752	219.744227
SG Z - Component of Torque at stator	N*m	0.0186791	100	On	0.00178236351	0.00224133559
SG Mass Flow Rate _outlet	kg/s	-1.00792	100	On	0.000222912072	0.00100792126
Torque on impeller	N*m	-0.642565	100	On	0.0350691759	0.0966930243
Pressure drop	Pa	-47331.4	100	On	370.632373	686.774081
Efficiency		0.263128	43.5	On	0.0157636393	0.00686383192

Min/Max Table

Name	Minimum	Maximum
Pressure [Pa]	-11046.2	167971
Temperature [K]	293.141	293.223
Density [kg/m^3]	997.561	997.577
Velocity [m/s]	0	23.3842
X-velocity [m/s]	-13.3343	10.3095
Y-velocity [m/s]	-22.911	11.9444
Z-velocity [m/s]	-7.11698	10.5381
Heat Transfer Coefficient [W/m^2/K]	0	0
Shear Stress [Pa]	1.30718e-007	11549.6
Surface Heat Flux [W/m^2]	0	0
Water Mass Fraction [ ]	1	1
Water Volume Fraction [ ]	1	1
Fluid Temperature [K]	293.141	293.223

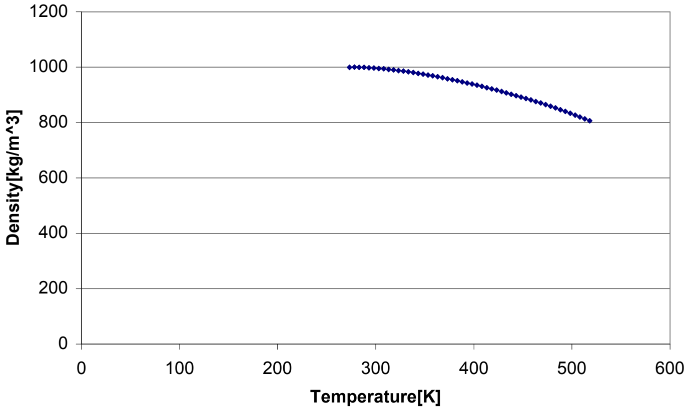
Velocity RRF [m/s]	0	15.457
X-velocity RRF [m/s]	-11.6694	15.4561
Y-velocity RRF [m/s]	-13.6327	13.7425
Z-velocity RRF [m/s]	-7.11698	10.5381

Engineering Database

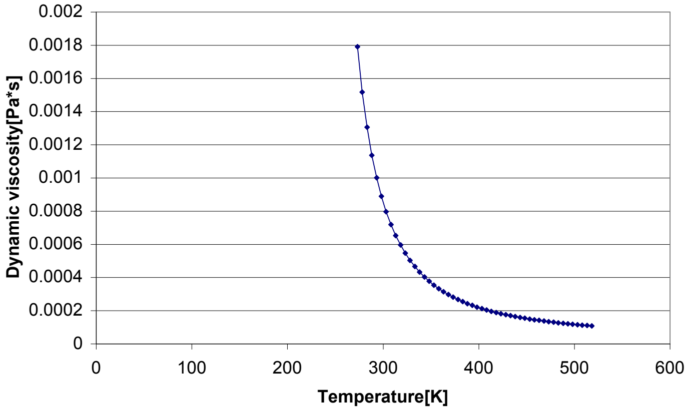
Liquids

Water

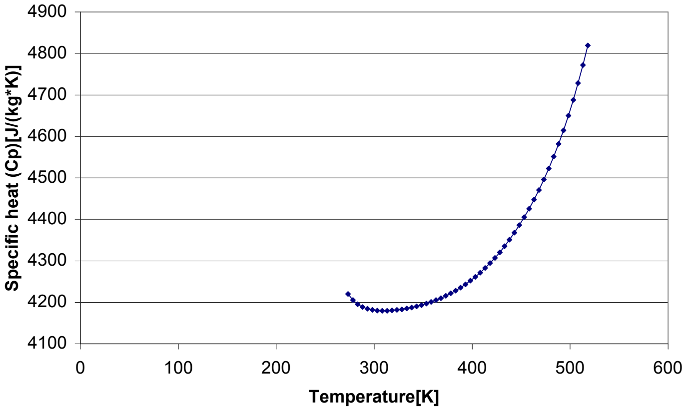
Path: Liquid FW Defined
Density



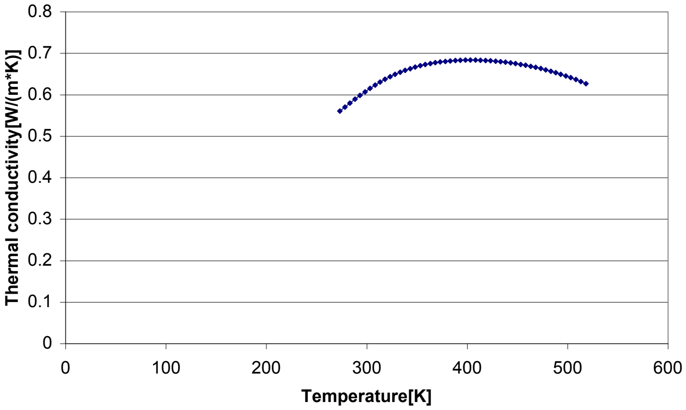
Dynamic viscosity



Specific heat (Cp)



Thermal conductivity



APPENDIX A16: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 35^0

System Info

Product	EFD.Lab 8 1.0. Build: 413
Computer name	FEA2
User name	Administrator
Processors	Dual Core AMD Opteron(tm) Processor 280 (4 processors)
Memory	16382 MB / 8388607 MB
Operating system	Microsoft Windows XP Professional x64 Edition Service Pack 2 (Build 3790)
CAD version	SolidWorks 2007 SP0
CPU speed	2411 MHz

General Info

Model	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate2_inlet30_outlet35\Assem3-1_inlet30_outlet35.SLDASM
Project name	inlet30_outlet35
Project path	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate2_inlet30_outlet35\1\1.fwp
Units system	SI (m-kg-s)
Analysis type	Internal
Exclude cavities without flow conditions	On
Coordinate system	Global coordinate system
Reference axis	X

INPUT DATA

Initial Mesh Settings

Automatic initial mesh: On
Result resolution level: 5
Advanced narrow channel refinement: Off
Refinement in solid region: Off

Geometry Resolution

Evaluation of minimum gap size: Manual
Minimum gap size: 0.04 m
Evaluation of minimum wall thickness: Manual
Minimum wall thickness: 0.01 m

APPENDIX A16: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 35^0

Computational Domain

Size

X min	-0.0473342462 m
X max	0.0488577538 m
Y min	-0.0430765393 m
Y max	0.0531154607 m
Z min	-0.0038287647 m
Z max	0.0128044854 m

Boundary Conditions

2D plane flow	None
At X min	Default
At X max	Default
At Y min	Default
At Y max	Default
At Z min	Default
At Z max	Default

Physical Features

Heat conduction in solids: Off
Time dependent: Off
Gravitational effects: Off
Flow type: Laminar only
Cavitation: Off
High Mach number flow: Off
Default roughness: 0 micrometer

Rotating Reference Frame

Axis of coordinate system	Z
Velocity	282.74 m/s

Default wall conditions: Adiabatic wall

Initial Conditions

Thermodynamic parameters	Static Pressure: 101325 Pa Temperature: 293.2 K
Velocity parameters	Velocity vector Velocity in X direction: 0 m/s Velocity in Y direction: 0 m/s Velocity in Z direction: 0 m/s Relative to rotating frame: Off

APPENDIX A16: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 35^0

Material Settings

Fluids

Water

Boundary Conditions

Environment Pressure 1

Type	Environment Pressure
Faces	Face <1 >
Coordinate system	Global coordinate system
Reference axis	X
Thermodynamic parameters	Environment pressure: 101325 Pa Temperature: 293.2 K

stator walls

Type	Real wall
Faces	Face <1 > Face <1 > Face <1 >
Coordinate system	Global coordinate system
Reference axis	X

Inlet Volume Flow 1

Type	Inlet Volume Flow
Faces	Face <1 >
Coordinate system	Face Coordinate System
Reference axis	X
Flow parameters	Flow vectors direction: Normal to face Volume flow rate normal to face: 0.00101 m^3/s Relative to rotating frame: No Fully developed flow: No Inlet profile: 0
Thermodynamic parameters	Temperature: 293.2 K

Goals

Global Goals

GG Z - Component of Torque

Type	Global Goal
Goal type	Z - Component of Torque
Coordinate system	Global coordinate system
Use in convergence	On

Surface Goals

SG Bulk Av Static Pressure at impeller outlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<1>@cover3-1-1 Face<2>@measure3-1-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate at outlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<2>@cover3-1-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Z - Component of Torque at stator

Type	Surface Goal
Goal type	Z - Component of Torque
Faces	Face<1>@cover3-1-1 Face<2>@cover3-1-1 Face<3>@cover3-1-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate at inlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<1>@cover3-1-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Av Static Pressure at inlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<1>@cover3-1-1
Coordinate system	Global coordinate system
Use in convergence	On

Equation Goals

Pressure drop

Type	Equation Goal

Formula	SG Av Static Pressure at inlet-SG Bulk Av Static Pressure at impeller outlet
Dimensionality	Pressure & stress
Use in convergence	On

Torque on impeller

Type	Equation Goal
Formula	GG Z - Component of Torque -SG Z - Component of Torque at stator
Dimensionality	Torque
Use in convergence	On

Efficiency

Type	Equation Goal
Formula	Pressure drop*{Inlet Volume Flow 1:Volume flow rate normal to face:1.010e-003}/282.74/Torque on impeller
Dimensionality	No units
Use in convergence	On

Component Control Info

Disabled components: Extrude1@measure3-1-1@Assem3-1_inlet30_outlet35

Calculation Control Options

Finish Conditions

Finish conditions	If one is satisfied
Maximum travels	4
Goals convergence	Analysis interval: 0.5

Solver Refinement

Refinement: Disabled

Results Saving

Save before refinement	On

Advanced Control Options

Flow Freezing

Flow freezing strategy	Disabled

RESULTS

General Info

Iterations: 295
CPU time: 1292 s

Log

Mesh generation started	12:08:09 , Jun 24
Mesh generation normally finished	12:08:14 , Jun 24
Preparing data for calculation	12:18:11 , Jul 21
Calculation started 0	12:18:16 , Jul 21
Calculation has converged since the following criteria are satisfied: 294	12:39:53 , Jul 21
Max. travel is reached 294	
Calculation finished 295	12:39:57 , Jul 21

Warnings: A vortex crosses the pressure opening Boundary Condition : Environment Pressure 1 ; Inlet flow/outlet flow=0.586491

Calculation Mesh

Basic Mesh Dimensions

Number of cells in X	40
Number of cells in Y	40
Number of cells in Z	6

Number Of Cells

Total cells	49759
Fluid cells	22495
Solid cells	11305
Partial cells	15959
Irregular cells	0
Trimmed cells	22

Maximum refinement level: 1

Goals

Name	Unit	Value	Progress	Use in convergence	Delta	Criteria
GG Z - Component of	N*m	-0.491413	100	On	0.0137018842	0.0758072374

Torque						
SG Bulk Av Static Pressure at impeller outlet	Pa	83255	96.8	On	224.443985	217.394915
SG Mass Flow Rate at outlet	kg/s	-1.00723	100	On	0.000302458874	0.00100722726
SG Z - Component of Torque at stator	N*m	0.0050612	46.2	On	0.00228108684	0.00105580806
SG Mass Flow Rate at inlet	kg/s	1.00754	100	On	0	0.00100753736
SG Av Static Pressure at inlet	Pa	51313.6	100	On	630.765881	934.740874
Torque on impeller	N*m	-0.496474	100	On	0.0120839682	0.0748128099
Pressure drop	Pa	-31941.4	79	On	1117.64459	883.272064
Efficiency		0.229822	100	On	0.00338679931	0.00559271416

Min/Max Table

Name	Minimum	Maximum
Pressure [Pa]	-14170.9	146138
Temperature [K]	293.171	293.223
Density [kg/m^3]	997.562	997.569
Velocity [m/s]	0	15.565
X-velocity [m/s]	-13.325	10.7572
Y-velocity [m/s]	-15.1172	11.9444
Z-velocity [m/s]	-8.03284	10.6781
Heat Transfer Coefficient [W/m^2/K]	0	0
Shear Stress [Pa]	4.09914e-008	4770.98
Surface Heat Flux [W/m^2]	0	0
Water Mass Fraction [ ]	1	1
Water Volume Fraction [ ]	1	1
Fluid Temperature [K]	293.171	293.223

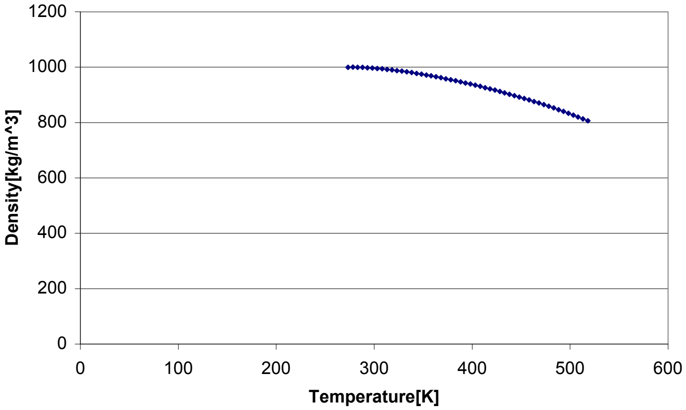
Velocity RRF [m/s]	0	15.4014
X-velocity RRF [m/s]	-11.6694	15.3994
Y-velocity RRF [m/s]	-13.3043	13.1989
Z-velocity RRF [m/s]	-8.03284	10.6781

Engineering Database

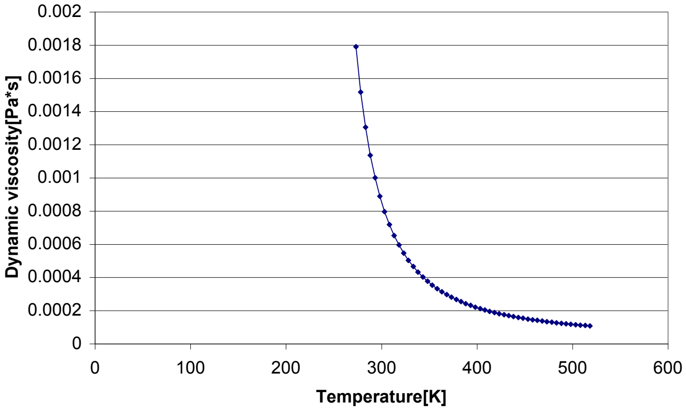
Liquids

Water

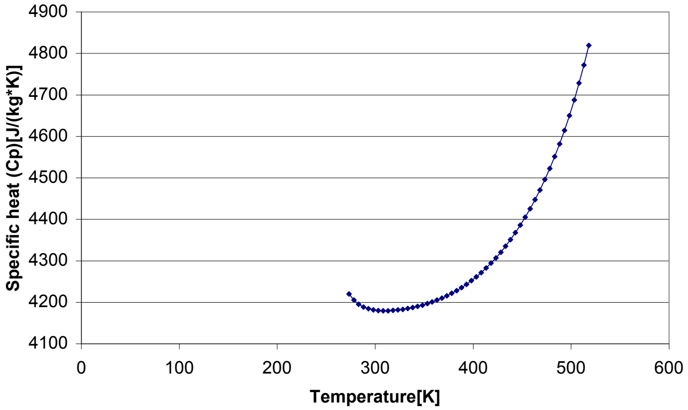
Path: Liquid FW Defined
Density



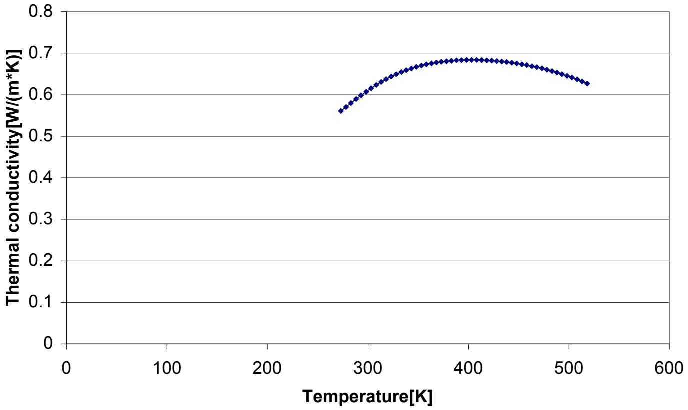
Dynamic viscosity



Specific heat (Cp)



Thermal conductivity



APPENDIX A17: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 40^0

System Info

Product	EFD.Lab 8 1.0. Build: 413
Computer name	FEA2
User name	Administrator
Processors	Dual Core AMD Opteron(tm) Processor 280 (4 processors)
Memory	16382 MB / 8388607 MB
Operating system	Microsoft Windows XP Professional x64 Edition Service Pack 2 (Build 3790)
CAD version	SolidWorks 2007 SP0
CPU speed	2411 MHz

General Info

Model	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate3_inlet30_outlet40\Assem 3-2_inlet30_outlet40.SLDASM
Project name	inlet30_outlet40
Project path	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate3_inlet30_outlet40\1\1.fwp
Units system	SI (m-kg-s)
Analysis type	Internal
Exclude cavities without flow conditions	On
Coordinate system	Global coordinate system
Reference axis	X

INPUT DATA

Initial Mesh Settings

Automatic initial mesh: On
Result resolution level: 5
Advanced narrow channel refinement: Off
Refinement in solid region: Off

Geometry Resolution

Evaluation of minimum gap size: Manual
Minimum gap size: 0.04 m
Evaluation of minimum wall thickness: Manual
Minimum wall thickness: 0.01 m

APPENDIX A17: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 40^0

Computational Domain

Size

X min	-0.0570569915 m
X max	0.0391350085 m
Y min	-0.040496 m
Y max	0.055696 m
Z min	-0.00305140391 m
Z max	0.0135818462 m

Boundary Conditions

2D plane flow	None
At X min	Default
At X max	Default
At Y min	Default
At Y max	Default
At Z min	Default
At Z max	Default

Physical Features

Heat conduction in solids: Off
Time dependent: Off
Gravitational effects: Off
Flow type: Laminar only
Cavitation: Off
High Mach number flow: Off
Default roughness: 0 micrometer

Rotating Reference Frame

Axis of coordinate system	Z
Velocity	282.74 m/s

Default wall conditions: Adiabatic wall

Initial Conditions

Thermodynamic parameters	Static Pressure: 101325 Pa Temperature: 293.2 K
Velocity parameters	Velocity vector Velocity in X direction: 0 m/s Velocity in Y direction: 0 m/s Velocity in Z direction: 0 m/s Relative to rotating frame: Off

APPENDIX A17: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 40^0

Material Settings

Fluids

Water

Boundary Conditions

Inlet Volume Flow 1

Type	Inlet Volume Flow
Faces	Face <1 >
Coordinate system	Face Coordinate System
Reference axis	X
Flow parameters	Flow vectors direction: Normal to face Volume flow rate normal to face: 0.00101 m^3/s Relative to rotating frame: No Fully developed flow: No Inlet profile: 0
Thermodynamic parameters	Temperature: 293.2 K

stator walls

Type	Real wall
Faces	Face <1 > Face <1 > Face <1 >
Coordinate system	Global coordinate system
Reference axis	X

Environment Pressure 1

Type	Environment Pressure
Faces	Face <1 >
Coordinate system	Global coordinate system
Reference axis	X
Thermodynamic parameters	Environment pressure: 101325 Pa Temperature: 293.2 K

Goals

Global Goals

GG Z - Component of Torque

Type	Global Goal
Goal type	Z - Component of Torque
Coordinate system	Global coordinate system
Use in convergence	On

Surface Goals

SG Mass Flow Rate at inlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<4>@cover3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

SG BULK Av static Pressure at impeller outlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@measure3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Z - Component of Torque at stator

Type	Surface Goal
Goal type	Z - Component of Torque
Faces	Face<1>@cover3-2-1 Face<2>@cover3-2-1 Face<3>@cover3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate at outlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<2>@cover3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Av Static Pressure at inlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@cover3-2-1
Coordinate system	Global coordinate system
Use in convergence	On

Equation Goals

Pressure Drop

Type	Equation Goal
Formula	SG Av Static Pressure at inlet-SG BULK

	Av static Pressure at impeller outlet
Dimensionality	Pressure & stress
Use in convergence	On

Torque on impeller

Type	Equation Goal
Formula	GG Z - Component of Torque -SG Z - Component of Torque at stator
Dimensionality	Torque
Use in convergence	On

Efficiency

Type	Equation Goal
Formula	Pressure Drop*{Inlet Volume Flow 1:Volume flow rate normal to face:1.010e-003}/282.74/Torque on impeller
Dimensionality	No units
Use in convergence	On

Component Control Info

Disabled components: Extrude1@measure3-2-1@Assem3-2_inlet30_outlet40

Calculation Control Options

Finish Conditions

Finish conditions	If one is satisfied
Maximum travels	4
Goals convergence	Analysis interval: 0.5

Solver Refinement

Refinement: Disabled

Results Saving

Save before refinement	On

Advanced Control Options

Flow Freezing

Flow freezing strategy	Disabled

RESULTS

General Info

Iterations: 227
CPU time: 977 s

Log

Mesh generation started	09:32:05 , Feb 20
Mesh generation normally finished	09:32:12 , Feb 20
Preparing data for calculation	12:54:02 , Jul 21
Calculation started 0	12:54:07 , Jul 21
Calculation has converged since the following criteria are satisfied: 226	13:10:31 , Jul 21
Goals are converged 226	
Calculation finished 227	13:10:35 , Jul 21

Warnings: A vortex crosses the pressure opening Boundary Condition : Environment Pressure 1 ; Inlet flow/outlet flow=0.684654

Calculation Mesh

Basic Mesh Dimensions

Number of cells in X	40
Number of cells in Y	40
Number of cells in Z	6

Number Of Cells

Total cells	49780
Fluid cells	22340
Solid cells	11404
Partial cells	16036
Irregular cells	0
Trimmed cells	15

Maximum refinement level: 1

Goals

Name	Unit	Value	Progress	Use in convergence	Delta	Criteria
GG Z - Component of	N*m	-0.763468	100	On	0.0173733891	0.0935733619

Torque						
SG Mass Flow Rate at inlet	kg/s	1.00754	100	On	0	0.00100753736
SG BULK Av static Pressure at impeller outlet	Pa	97787.5	100	On	101.421735	126.845577
SG Z - Component of Torque at stator	N*m	-0.0531057	100	On	0.00217130717	0.00222651471
SG Mass Flow Rate at outlet	kg/s	-1.0074	100	On	0.000350520763	0.00100740144
SG Av Static Pressure at inlet	Pa	46366	100	On	669.134629	1167.84516
Torque on impeller	N*m	-0.710362	100	On	0.0180386328	0.0913682248
Pressure Drop	Pa	-51421.5	100	On	584.877569	1154.82182
Efficiency		0.258582	100	On	0.0041159955	0.00636091423

Min/Max Table

Name	Minimum	Maximum
Pressure [Pa]	-43381.8	146367
Temperature [K]	293.162	293.231
Density [kg/m^3]	997.561	997.571
Velocity [m/s]	0	18.1416
X-velocity [m/s]	-14.0055	17.1396
Y-velocity [m/s]	-16.4995	12.036
Z-velocity [m/s]	-7.2231	11.7866
Heat Transfer Coefficient [W/m^2/K]	0	0
Shear Stress [Pa]	7.12656e-007	15728.9
Surface Heat Flux [W/m^2]	0	0
Water Mass Fraction [ ]	1	1
Water Volume Fraction [ ]	1	1
Fluid Temperature [K]	293.162	293.231

Velocity RRF [m/s]	0	17.3702
X-velocity RRF [m/s]	-13.9084	15.7182
Y-velocity RRF [m/s]	-10.5552	17.097
Z-velocity RRF [m/s]	-7.2231	11.7866

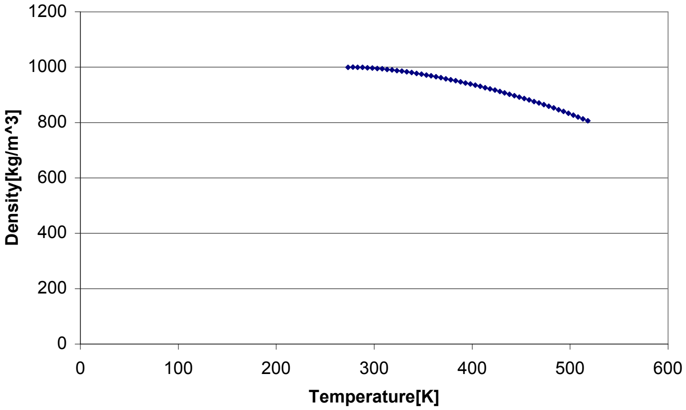
Engineering Database

Liquids

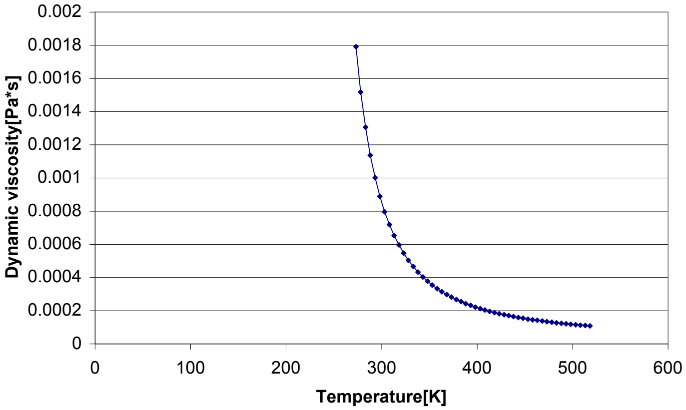
Water

Path: Liquid FW Defined

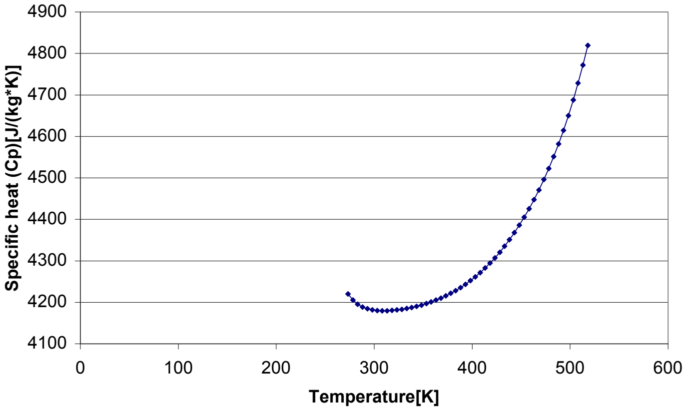
Density



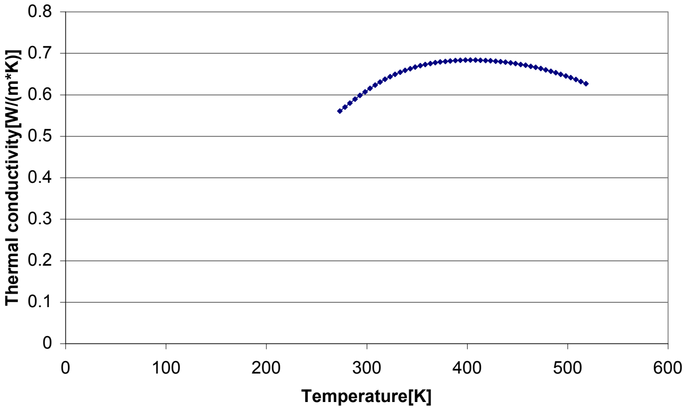
Dynamic viscosity



Specific heat (Cp)



Thermal conductivity



APPENDIX A18: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 45^0

System Info

Product	EFD.Lab 8 1.0. Build: 413
Computer name	FEA2
User name	Administrator
Processors	Dual Core AMD Opteron(tm) Processor 280 (4 processors)
Memory	16382 MB / 8388607 MB
Operating system	Microsoft Windows XP Professional x64 Edition Service Pack 2 (Build 3790)
CAD version	SolidWorks 2007 SP0
CPU speed	2411 MHz

General Info

Model	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate6_inlet30_outlet45\Assembly3_inlet30_outlet45.SLDASM
Project name	inlet30_out45
Project path	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate6_inlet30_outlet45\1\1.fwp
Units system	SI (m-kg-s)
Analysis type	Internal
Exclude cavities without flow conditions	On
Coordinate system	Global coordinate system
Reference axis	X

INPUT DATA

Initial Mesh Settings

Automatic initial mesh: On
Result resolution level: 5
Advanced narrow channel refinement: Off
Refinement in solid region: Off

Geometry Resolution

Evaluation of minimum gap size: Manual
Minimum gap size: 0.04 m
Evaluation of minimum wall thickness: Manual
Minimum wall thickness: 0.01 m

APPENDIX A18: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 45^0

Computational Domain

Size

X min	-0.0561376687 m
X max	0.0400543313 m
Y min	-0.0416994091 m
Y max	0.0544925909 m
Z min	-0.00871892053 m
Z max	0.00791432957 m

Boundary Conditions

2D plane flow	None
At X min	Default
At X max	Default
At Y min	Default
At Y max	Default
At Z min	Default
At Z max	Default

Physical Features

Heat conduction in solids: Off
Time dependent: Off
Gravitational effects: Off
Flow type: Laminar only
Cavitation: Off
High Mach number flow: Off
Default roughness: 0 micrometer

Rotating Reference Frame

Axis of coordinate system	Z
Velocity	282.74 m/s

Default wall conditions: Adiabatic wall

Initial Conditions

Thermodynamic parameters	Static Pressure: 101325 Pa Temperature: 293.2 K
Velocity parameters	Velocity vector Velocity in X direction: 0 m/s Velocity in Y direction: 0 m/s Velocity in Z direction: 0 m/s Relative to rotating frame: Off

APPENDIX A18: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 45^0

Material Settings

Fluids

Water

Boundary Conditions

Environment Pressure 1

Type	Environment Pressure
Faces	Face <1 >
Coordinate system	Global coordinate system
Reference axis	X
Thermodynamic parameters	Environment pressure: 101325 Pa Temperature: 293.2 K

Inlet Volume Flow 1

Type	Inlet Volume Flow
Faces	Face <1 >
Coordinate system	Face Coordinate System
Reference axis	X
Flow parameters	Flow vectors direction: Normal to face Volume flow rate normal to face: 0.00101 m^3/s Relative to rotating frame: No Fully developed flow: No Inlet profile: 0
Thermodynamic parameters	Temperature: 293.2 K

stator wall

Type	Real wall
Faces	Face <1 > Face <1 > Face <1 >
Coordinate system	Global coordinate system
Reference axis	X

Goals

Global Goals

GG Z - Component of Torque

Type	Global Goal
Goal type	Z - Component of Torque
Coordinate system	Global coordinate system
Use in convergence	On

Surface Goals

SG Mass Flow Rate at outlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<2>@cover3-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Bulk Av Static Pressure at impeller outlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@measure3-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate at inlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<1>@cover3-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Av Static Pressure at inlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@cover3-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Z - Component of Torque at stator

Type	Surface Goal
Goal type	Z - Component of Torque
Faces	Face<1>@cover3-1 Face<2>@cover3-1 Face<3>@cover3-1
Coordinate system	Global coordinate system
Use in convergence	On

Equation Goals

Pressure Drop

Type	Equation Goal
Formula	SG Av Static Pressure at inlet-SG Bulk Av

	Static Pressure at impeller outlet
Dimensionality	Pressure & stress
Use in convergence	On

Torque on impeller

Type	Equation Goal
Formula	GG Z - Component of Torque -SG Z - Component of Torque at stator
Dimensionality	Torque
Use in convergence	On

Efficiency

Type	Equation Goal
Formula	Pressure Drop*{Inlet Volume Flow 1:Volume flow rate normal to face:1.010e-003}/282.74/Torque on impeller
Dimensionality	No units
Use in convergence	On

Component Control Info

Disabled components: Extrude1@measure3-1@Assembly3_inlet30_outlet45

Calculation Control Options

Finish Conditions

Finish conditions	If one is satisfied
Maximum travels	4
Goals convergence	Analysis interval: 0.5

Solver Refinement

Refinement: Disabled

Results Saving

Save before refinement	On

Advanced Control Options

Flow Freezing

Flow freezing strategy	Disabled

APPENDIX A18: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 45^0

RESULTS

General Info

Iterations: 196
CPU time: 842 s

Log

Mesh generation started	15:01:13 , Feb 20
Mesh generation normally finished	15:01:20 , Feb 20
Preparing data for calculation	13:22:30 , Jul 21
Calculation started 0	13:22:34 , Jul 21
Calculation has converged since the following criteria are satisfied: 195	13:37:00 , Jul 21
Goals are converged 195	
Calculation finished 196	13:37:04 , Jul 21

Warnings: A vortex crosses the pressure opening Boundary Condition : Environment Pressure 1 ; Inlet flow/outlet flow=0.654743

Calculation Mesh

Basic Mesh Dimensions

Number of cells in X	40
Number of cells in Y	40
Number of cells in Z	6

Number Of Cells

Total cells	49801
Fluid cells	22314
Solid cells	11419
Partial cells	16068
Irregular cells	0
Trimmed cells	35

Maximum refinement level: 1

Goals

Name	Unit	Value	Progress	Use in convergence	Delta	Criteria
GG Z - Component of	N*m	-0.661783	100	On	0.00307707714	0.0954172366

Torque						
SG Mass Flow Rate at outlet	kg/s	-1.00784	100	On	0.00044280674	0.00100784075
SG Bulk Av Static Pressure at impeller outlet	Pa	97864.5	100	On	90.0547681	91.4530727
SG Mass Flow Rate at inlet	kg/s	1.00754	100	On	0	0.00100753736
SG Av Static Pressure at inlet	Pa	50005.8	100	On	1010.15622	1215.20297
SG Z - Component of Torque at stator	N*m	-0.0427399	100	On	0.00194122427	0.00196554622
Torque on impeller	N*m	-0.619043	100	On	0.00497709626	0.0934605635
Pressure Drop	Pa	-47858.8	100	On	1058.99338	1133.16828
Efficiency		0.276169	100	On	0.00578683543	0.00706834657

Min/Max Table

Name	Minimum	Maximum
Pressure [Pa]	-37831.8	137165
Temperature [K]	293.148	293.223
Density [kg/m^3]	997.561	997.575
Velocity [m/s]	0	17.7307
X-velocity [m/s]	-13.7236	13.4026
Y-velocity [m/s]	-15.1734	9.49496
Z-velocity [m/s]	-15.3079	10.1141
Heat Transfer Coefficient [W/m^2/K]	0	0
Shear Stress [Pa]	2.42096e-007	6521.84
Surface Heat Flux [W/m^2]	0	0
Water Mass Fraction [ ]	1	1
Water Volume Fraction [ ]	1	1
Fluid Temperature [K]	293.148	293.223

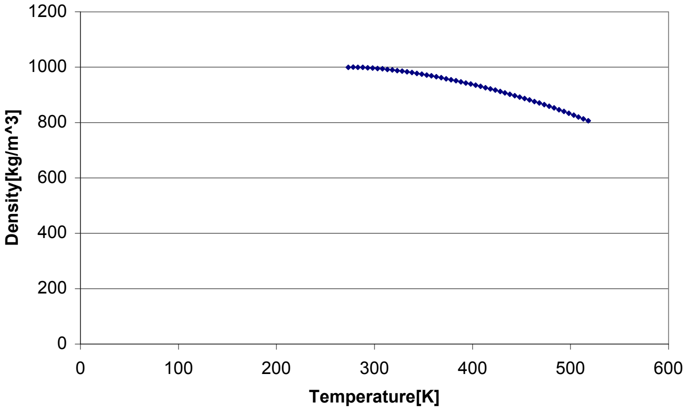
Velocity RRF [m/s]	0	16.7583
X-velocity RRF [m/s]	-13.0324	15.5256
Y-velocity RRF [m/s]	-10.8152	16.4646
Z-velocity RRF [m/s]	-15.3079	10.1141

Engineering Database

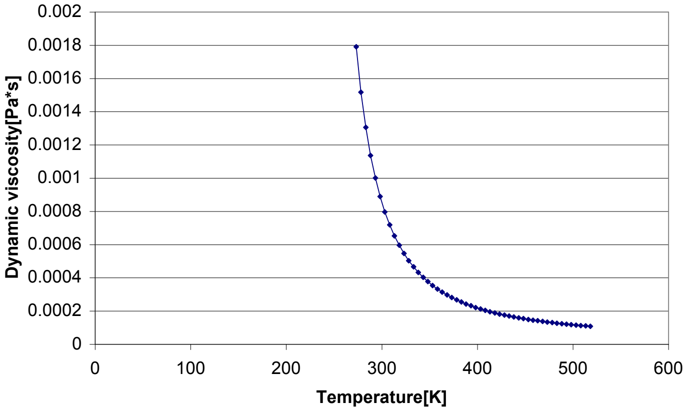
Liquids

Water

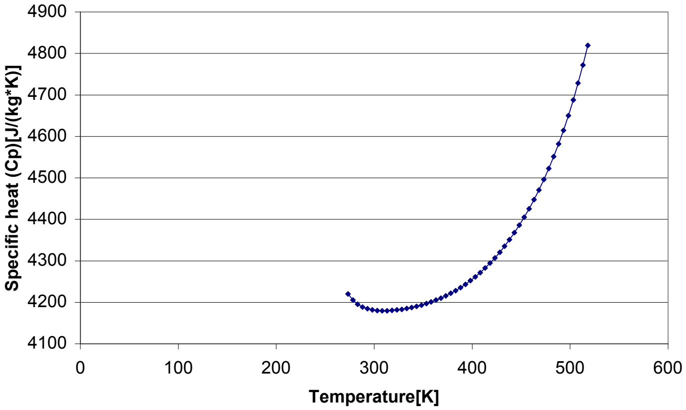
Path: Liquid FW Defined
Density



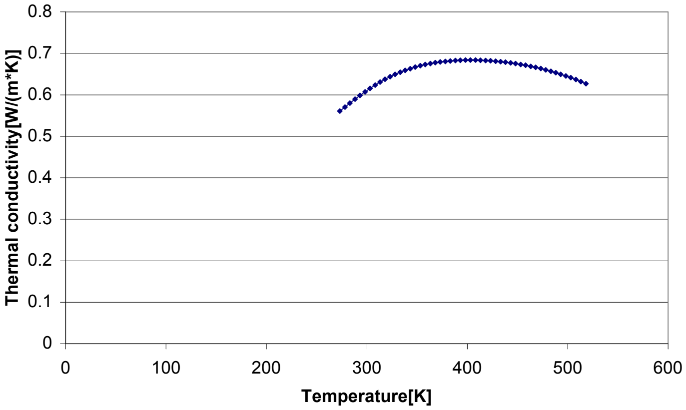
Dynamic viscosity



Specific heat (Cp)



Thermal conductivity



APPENDIX A19: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 50^0

System Info

Product	EFD.Lab 8 1.0. Build: 413
Computer name	FEA2
User name	Administrator
Processors	Dual Core AMD Opteron(tm) Processor 280 (4 processors)
Memory	16382 MB / 8388607 MB
Operating system	Microsoft Windows XP Professional x64 Edition Service Pack 2 (Build 3790)
CAD version	SolidWorks 2007 SP0
CPU speed	2411 MHz

General Info

Model	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate9_inlet30_outlet50\Assem4_inlet30_outlet50.SLDASM
Project name	inlet30_outlet50
Project path	C:\Documents and Settings\Administrator\Desktop\Fuhnwi\EFD_final\simulate9_inlet30_outlet50\1\1.fwp
Units system	SI (m-kg-s)
Analysis type	Internal
Exclude cavities without flow conditions	On
Coordinate system	Global coordinate system
Reference axis	X

INPUT DATA

Initial Mesh Settings

Automatic initial mesh: On
Result resolution level: 5
Advanced narrow channel refinement: Off
Refinement in solid region: Off

Geometry Resolution

Evaluation of minimum gap size: Manual
Minimum gap size: 0.04 m
Evaluation of minimum wall thickness: Manual
Minimum wall thickness: 0.01 m

APPENDIX A19: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 50^0

Computational Domain

Size

X min	-0.0459669402 m
X max	0.0502250598 m
Y min	-0.0401346033 m
Y max	0.0560573967 m
Z min	-0.00654898132 m
Z max	0.0100842688 m

Boundary Conditions

2D plane flow	None
At X min	Default
At X max	Default
At Y min	Default
At Y max	Default
At Z min	Default
At Z max	Default

Physical Features

Heat conduction in solids: Off
Time dependent: Off
Gravitational effects: Off
Flow type: Laminar only
Cavitation: Off
High Mach number flow: Off
Default roughness: 0 micrometer

Rotating Reference Frame

Axis of coordinate system	Z
Velocity	282.74 m/s

Default wall conditions: Adiabatic wall

Initial Conditions

Thermodynamic parameters	Static Pressure: 101325 Pa Temperature: 293.2 K
Velocity parameters	Velocity vector Velocity in X direction: 0 m/s Velocity in Y direction: 0 m/s Velocity in Z direction: 0 m/s Relative to rotating frame: Off

APPENDIX A19: FULL REPORT ON INLET ANGLE 30^0 OUTLET ANGLE 50^0

Material Settings

Fluids

Water

Boundary Conditions

Inlet Volume Flow 1

Type	Inlet Volume Flow
Faces	Face <1 >
Coordinate system	Face Coordinate System
Reference axis	X
Flow parameters	Flow vectors direction: Normal to face Volume flow rate normal to face: 0.00101 m^3/s Relative to rotating frame: No Fully developed flow: No Inlet profile: 0
Thermodynamic parameters	Temperature: 293.2 K

stator Wall

Type	Real wall
Faces	Face <1 > Face <1 > Face <1 >
Coordinate system	Global coordinate system
Reference axis	X

Environment Pressure 1

Type	Environment Pressure
Faces	Face <1 >
Coordinate system	Global coordinate system
Reference axis	X
Thermodynamic parameters	Environment pressure: 101325 Pa Temperature: 293.2 K

Goals

Global Goals

GG Z - Component of Torque

Type	Global Goal
Goal type	Z - Component of Torque
Coordinate system	Global coordinate system
Use in convergence	On

Surface Goals

SG Bulk Av Static Pressure at impeller outlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@measure4-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate at inlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<5>@cover4-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Av Static Pressure at inlet

Type	Surface Goal
Goal type	Static Pressure
Calculate	Average value
Faces	Face<2>@cover4-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Mass Flow Rate at outlet

Type	Surface Goal
Goal type	Mass Flow Rate
Faces	Face<2>@cover4-1
Coordinate system	Global coordinate system
Use in convergence	On

SG Z - Component of Torque at stator

Type	Surface Goal
Goal type	Z - Component of Torque
Faces	Face<2>@cover4-1 Face<1>@cover4-1 Face<3>@cover4-1
Coordinate system	Global coordinate system
Use in convergence	On

Equation Goals

Pressure Drop

Type	Equation Goal
Formula	SG Av Static Pressure at inlet-SG Bulk Av

	Static Pressure at impeller outlet
Dimensionality	Pressure & stress
Use in convergence	On

Torque on impeller

Type	Equation Goal
Formula	GG Z - Component of Torque -SG Z - Component of Torque at stator
Dimensionality	Torque
Use in convergence	On

Efficiency

Type	Equation Goal
Formula	Pressure Drop*{Inlet Volume Flow 1:Volume flow rate normal to face:1.010e-003}/282.74/Torque on impeller
Dimensionality	No units
Use in convergence	On

Component Control Info

Disabled components: Extrude1@measure4-1@Assem4_inlet30_outlet50

Calculation Control Options

Finish Conditions

Finish conditions	If one is satisfied
Maximum travels	4
Goals convergence	Analysis interval: 0.5

Solver Refinement

Refinement: Disabled

Results Saving

Save before refinement	On

Advanced Control Options

Flow Freezing

Flow freezing strategy	Disabled

RESULTS

General Info

Iterations: 295
CPU time: 3099 s

Log

Mesh generation started	20:27:14 , Feb 20
Mesh generation normally finished	20:27:21 , Feb 20
Preparing data for calculation	18:35:33 , Jul 21
Calculation started 0	18:35:45 , Jul 21
Calculation has converged since the following criteria are satisfied: 294	19:28:06 , Jul 21
Max. travel is reached 294	
Calculation finished 295	19:28:11 , Jul 21

Warnings: A vortex crosses the pressure opening Boundary Condition : Environment Pressure 1 ; Inlet flow/outlet flow=0.638591

Calculation Mesh

Basic Mesh Dimensions

Number of cells in X	40
Number of cells in Y	40
Number of cells in Z	6

Number Of Cells

Total cells	49780
Fluid cells	22160
Solid cells	11524
Partial cells	16096
Irregular cells	0
Trimmed cells	37

Maximum refinement level: 1

Goals

Name	Unit	Value	Progress	Use in convergence	Delta	Criteria
GG Z - Component of	N*m	-0.564819	100	On	0.0148669575	0.0851981452

Torque						
SG Bulk Av Static Pressure at impeller outlet	Pa	98191.1	8.1	On	1136.09135	92.2586084
SG Mass Flow Rate at inlet	kg/s	1.00754	100	On	0	0.00100753736
SG Av Static Pressure at inlet	Pa	52491.7	86.8	On	1308.30385	1136.63645
SG Mass Flow Rate at outlet	kg/s	-1.00885	100	On	0.000134708076	0.00100884674
SG Z - Component of Torque at stator	N*m	-0.0195632	100	On	0.00161460765	0.00163570832
Torque on impeller	N*m	-0.545256	100	On	0.0157663626	0.0836902501
Pressure Drop	Pa	-45699.5	43.2	On	2441.2305	1055.1798
Efficiency		0.299395	35.8	On	0.0168095305	0.00601802565

Min/Max Table

Name	Minimum	Maximum
Pressure [Pa]	-29979	136683
Temperature [K]	293.103	293.223
Density [kg/m^3]	997.561	997.586
Velocity [m/s]	0	14.9925
X-velocity [m/s]	-13.98	9.60818
Y-velocity [m/s]	-11.564	12.331
Z-velocity [m/s]	-8.31073	6.72397
Heat Transfer Coefficient [W/m^2/K]	0	0
Shear Stress [Pa]	7.30753e-007	7945.8
Surface Heat Flux [W/m^2]	0	0
Water Mass Fraction [ ]	1	1
Water Volume Fraction [ ]	1	1
Fluid Temperature [K]	293.103	293.223

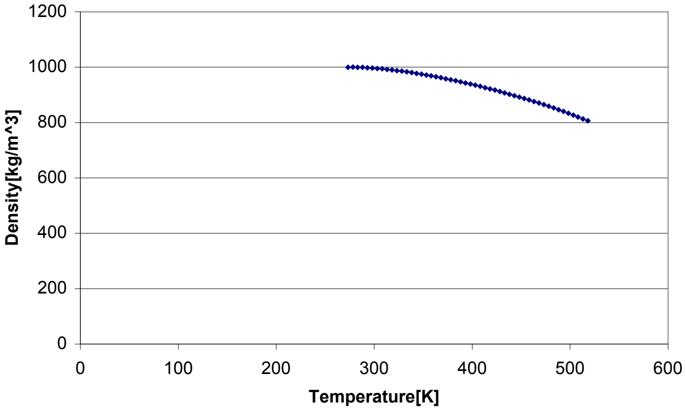
Velocity RRF [m/s]	0	16.3495
X-velocity RRF [m/s]	-10.8376	16.2268
Y-velocity RRF [m/s]	-13.6908	13.0448
Z-velocity RRF [m/s]	-8.31073	6.72397

Engineering Database

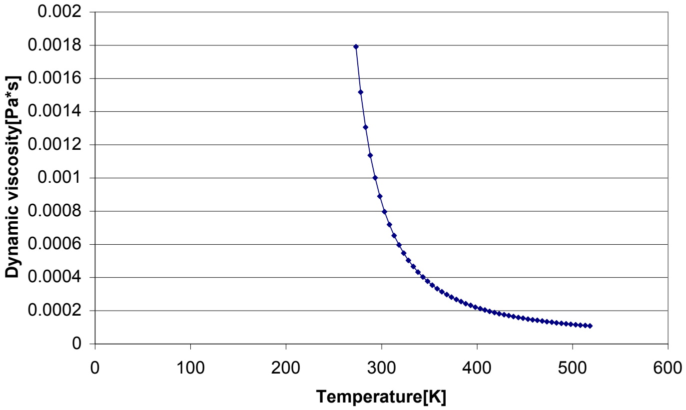
Liquids

Water

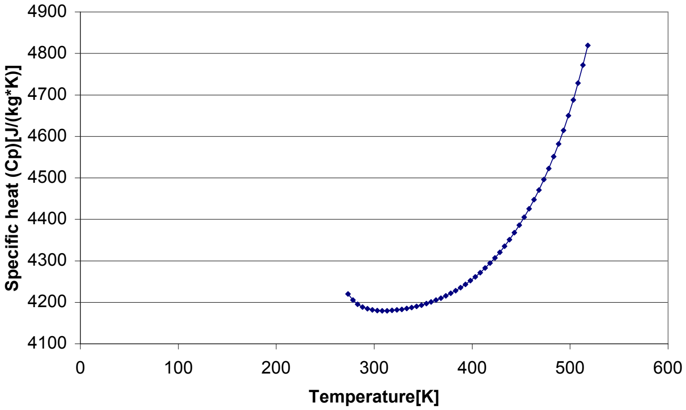
Path: Liquid FW Defined
Density



Dynamic viscosity



Specific heat (Cp)



Thermal conductivity