EVALUATION OF CENTRIFUGAL PUMP PERFORMANCE DERATING PROCEDURES FOR NON-NEWTONIAN SLURRIES

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Co-supervisor: Prof. P. T. Slatter

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ABSTRACT

The performance of a centrifugal pump is altered for slurry or viscous materials (Stepanoff, 1969) and this needs to be accounted for. Usually, the suitable selection and evaluation of centrifugal pumps is based only on water pump performance curves supplied by the pump manufacturer (Wilson, Addie, Sellgren & Clift, 1997). In 1984 Walker and Goulas conducted a number of pump performance tests with kaolin clay slurries and coal slurries on a Warman 4/3 AH horizontal slurry pump and a Hazleton 3-inch B CTL horizontal pump (Walker and Goulas, 1984).

Walker and Goulas have analysed the test data and correlated the performance derating both at the best efficiency flow rate (BEP) and at 10% of the best efficiency flow rate (0.1 BEP) to the modified pump Reynolds number (NRep). They have noticed that the head and the efficiency reduction ratio decreased for the pump Reynolds number less then10^6.

Furthermore, Walker and Goulas obtained a reasonably good agreement (± 5%) between pump test data for non-Newtonian materials and pump performance prediction using the Hydraulics Institute chart. Sery and Slatter (2002) have investigated pump deration for non-Newtonian yield pseudoplastic materials. The NRep was calculated using the Bingham plastic viscosity (μ_p). Results have shown good agreement with regard to head and efficiency reduction ratios in comparison with previous work. However, Sery and Slatter's pump performance correlation using the HI chart did not reach the same conclusion. Error margin of ± 20% and ± 10% were found for head and efficiency respectively.

This study is an attempt to reconcile the differences between Walker and Goulas (1984) and Sery and Slatter (2002) and extend the evaluation of these derating methods to pseudoplastic materials. The test work was conducted in the Flow Process Research Centre laboratory of the Cape Peninsula University of Technology using two centrifugal pumps; a Warman 6/4 and a GIW 4/3. The materials used were water, CMC solution bentonite and kaolin suspension at different concentrations (7% and 9% by weight for bentonite; 5%, 6% and 7% by weight for CMC; 17%, 19% and 21% by volume for kaolin).

The apparatus were calibrated and the magnitude of a possible error on the measured and the computed variables were determined. Pressure gradient tests were performed in the 60mm,

80mm and 150mm pipes in order to generate data for the rheological characterisation. The 6/4 Warman centrifugal pump was tested at 1100, 1200, 1300 and 1400 rpm, while the 4/3 GIW at 1300, 1600, 1900 and 2100 rpm. Pump data were corrected using the ISO 9909 for rotodynamic pump and compiled per speed of rotation (flow rate, head, efficiency and power) before being analysed with the deration procedures found in the literature.

It is concluded that the results obtained in this work corroborate those found in the literature for the correlation of head and efficiency to the pump Reynolds number. The head reduction ratio (HR) and the efficiency reduction ratio (ER) decreased for NRe_p less than 10^6.
Furthermore, the reduction of the pump performance (HR and ER) experienced by higher specific speed pumps (NS=0.53 and 0.74) are less than those found in low specific speed pumps (NS=0.27 and 0.43) (Walker and Goulas, 1984).

Error margins found when using the HI deration chart, primarily meant for Newtonian viscous fluids, are not conclusive as in Walker and Goulas studies (1984). The test work with the Warman 6/4 pump indicated a margin of ± 10% for the head and ± 20% for the efficiency. On the other hand, an error of ± 15% for both the head and the efficiency for the GIW 4/3 pump.
Thus, the use of the HI deration procedure in the prediction of centrifugal pump deration for non-Newtonian fluids must be carefully considered. This needs to be investigated further.

DECLARATION

I, Batthe Matanda Kabamba hereby declare that this thesis represent the outgrowth of my own hard work and has not been submitted for a degree at another university. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of technology.

Batthe Matanda Kabamba

Cape Town, September 2006

DEDICATION

To my wife Patricia,

sons Ulrich and Randy Kabamba

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NOMENCLATURE

Symbol	Description	Unit
a	acceleration	m/s^2
A	cross sectional area	m^2
BEP	best efficiency point	-
ID	internal pipe diameter	m
E	sum of mean error squared	-
ER	efficiency ratio	-
f	fanning friction factor	-
g	gravitational acceleration	m/s^2
H	head	m
HR	head ratio	-
K	fluid consistency index	$Pa.s^n$
k	hydraulic roughness	m
L	pipe length	m
M	mass	kg
N	number of data points	-
N	speed of rotation	rpm
NS	pump specific speed	rpm
NRep	pump Reynolds number	-
n	flow behaviour index	-
n'	slope of logarithmic plot	-
p	pressure or static pressure	Pa
P	power	W
Q	volumetric flow rate	m^3/s
R	radius	m
Re	Reynolds Number	-
r	radius from the centre line	m
t	time	s
T	shaft torque	N.m
u	point velocity	m/s
V	average velocity	m/s
W	work	J

z	elevation from datum	m

Greek symbols

γ	shear rate	s^{-1}
Δ	increment	-
μ	dynamic viscosity	Pa.s
μ_p	plastic viscosity	Pa.s
ν	kinematic viscosity	mm^2/s
ρ	fluid or slurry density	kgm^{-3}
τ	shear stress	Pa
τ_y	yield stress	Pa
σ	standard deviation	-
η	coefficient of rigidity	-
η_{pump}	pump efficiency	%
μ_{app}	apparent viscosity	Pa.s
ω	angular velocity	radians/s

Subscripts

abs	absolute
atmo	atmospheric
calc	calculated
e	efficiency
h	head
gauge	gauge
i	impeller
in (1)	to the suction side
m	slurry
o	at the wall
out (2)	to the discharge side
q	flow
w	water

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Non-Newtonian laminar pipe flow is now facing much broader application, particularly in the mining and mineral industry where vast tonnages of material need to be hydraulically transported each year (Wilson *et al.*, 1997).

Abulnaga (2002) observed that centrifugal slurry pumps are available in a number of specialised designs. They are capable of moving thousands of tons of material per hour with drive capacities up to one megawatt (Wilson *et al.*, 1997). With such versatility and robustness, they have become the most commonly used pumps in slurry transport systems.

However, their choice and selection for fine particle slurry service is problematic. Usually, slurry pumps are designed differently; their design is governed by different hydraulic relationships than conventional water pumps although they are universally tested on water as a reference fluid (Abulnaga, 2002). When a centrifugal pump handles slurry or viscous materials rather than water, the performance of the pump is altered. The head and efficiency of the pump are reduced (Stepanoff, 1969).

In 1984 Walker and Goulas conducted a number of pump performance tests with kaolin clay slurries and coal slurries on a Warman 4/3 AH horizontal slurry pump and a Hazleton 3-inch B CTL horizontal pump. They have analysed the test data and were able to correlate the observed performance derating at the best efficiency flow rate (BEP) and at 10% of the best efficiency flow rate (0.1BEP) to the modified pump Reynolds number (NRep). The head and efficiency reduction ratio decreased for the pump Reynolds number less then10^6.
Furthermore, Walker and Goulas noted a reasonably good agreement (± 5%) between pump test data for non-Newtonian materials and pump performance prediction using the HI chart.

Sery and Slatter (2002) have investigated pump deration for non-Newtonian yield pseudoplastic materials. Deration started for pump Reynolds numbers less then 10^6. The pump Reynolds number was calculated using the plastic viscosity. In comparison with previous work (Walker and Goulas, 1984), this has shown good agreement with regard to head and efficiency reduction ratios. However, Sery and Slatter's pump performance correlation using the Hydraulics Institute Chart did not reach the same conclusion. Prediction margin of 20% and 10% for head and efficiency respectively was found. The fluids used in the aforementioned investigations were all described by the yield pseudoplastic rheological model.

The slurries were tested on a pipeline loop with four test sections of diameters 60, 80, 150 and 200 mm. The test work was conducted in the Flow Process Research Centre Laboratory of the Cape Peninsula University of Technology.

This study is an extension of the work conducted by Walker and Goulas (1984) and Sery and Slatter (2002). However, in the present work, materials for the experimental investigation have been chosen to represent various rheological models. These models are:

- pseudoplastic;
- Bingham plastic; and
- yield pseudoplastic.

The test work was conducted with two centrifugal pumps: a Warman 6/4 and a GIW 4/3

1.2 STATEMENT OF RESEARCH PROBLEM

There is no reliable procedure that is unanimously accepted for the prediction of centrifugal pump deration for non-Newtonian slurries. Walker and Goulas (1984) introduced a procedure to correlate the pump performance for Bingham plastic fluids. The good agreement noted by Walker and Goulas between pump test data and pump performance calculation using the HI chart could not be corroborated by workers such as Sery and Slatter. The only reliable approaches open to designers of pumping systems for non-Newtonian fluids are either pilot tests or full scale pump tests. Design procedures are therefore costly.

1.3 OBJECTIVES OF THE STUDY

The objectives of this project are:

- to perform clear water pump tests for calibration purposes;
- to perform slurry pump tests using non-Newtonian fluids;
- to perform rheological characterisation of the fluids tested; and
- to evaluate and correlate the experimental data using existing pump derating procedures.

1.4 RESEARCH DESIGN AND METHODOLOGY

To reach the objectives assigned, this work is subdivided into several steps:

1. Literature review (Chapter 2): Basic concepts of fluids mechanics are reviewed; and the rheological models for time independent slurries and the effects of viscous non-Newtonian slurry on the performance of centrifugal pumps are presented. Previous work done by Walker and Goulas (1984), Sery and Slatter (2002) were found to be relevant.

2. Experimental work (Chapter 3): Laboratory experiments were performed at The Cape Peninsula University of Technology Flow Process Research Centre as mentioned above. Water, bentonite, carboxyl methyl cellulose (CMC) and kaolin were selected respectively.

3. Analysis of data (Chapter 4): data collected during tests were analysed with Walker and Goulas and the Hydraulics Institute Chart procedures presented in the literature and the results of analysis are discussed.

1.5 DELINEATION OF THE STUDY

This research project is limited to time independent non-Newtonian fluids and to the following specific pump types: – 6/4 Warman

–4/3 GIW

1.6 BENEFITS AND CONTRIBUTION

Besides presenting new experimental evidence of non-Newtonian viscous effects on pump performance, the work seeks to confirm any of the findings by either Walker and Goulas (1984) or Sery and Slatter (2002) with regard to the correlation of HR and ER with pump Reynolds number, and the use of the HI chart to predict the performance of a centrifugal pump for non-Newtonian fluids.

CHAPTER 2

THEORY AND LITERATURE REVIEW

2.1 INTRODUCTION

This chapter deals with the theory and the literature relevant to the understanding of centrifugal pump deration procedures. Since this work encompasses the flow of fluids, the present chapter will review the basic concepts of fluid mechanics. As non-Newtonian fluids are our main concern, emphasis will be put on non-Newtonian fluids' fundamental theory. Rheological models applicable to non-Newtonian slurries with time independent effects are described. Literature relevant to the centrifugal slurry pump is presented. The effect of non-Newtonian viscous materials on the performance of centrifugal slurry pumps is examined. Relationships that are used to estimate this effect on the pump head and overall efficiency are reviewed. This chapter will conclude with the research aspects identified through the literature reviewed.

2.2 FUNDAMENTAL CONCEPTS OF FLUIDS MECHANICS

The liquid with which engineers are mainly concerned is water. It is used as a solvent in many solid/liquid mixtures. Some mixtures are said to be Newtonian while others, however, are non-Newtonian (Fox, 1977). This work, will deal with the latter type of fluids. It is relevant to describe some of the physical properties of these fluids.

2.2.1 Fluids properties

In this work, the focus will be on the average conditions of variables such as pressure, temperature, density, speed, torque and flow. The complete behaviour of a fluid that is accounting for the action of each individual molecule will not be analysed. Each of the fluids under investigation will be considered as a *continuum*, which has a continuous distribution of matter with no empty space (Streeter and Wylie, 1985).

Some of the terms describing the properties of fluids are reviewed below.

2.2.1.1 Fluid Pressure

Pressure is a result of innumerable molecular collisions within a fluid (Massey, 1975).
Any part of the fluid must experience forces exerted on it by the surrounding fluid or by the solid boundaries of its container (Streeter and Wylie, 1985).
Pressure intensity cannot be measured directly, all instruments that are used to measure it, in fact, indicate a difference of pressure. A gauge pressure displays readings that are the difference between the absolute pressure and atmospheric pressure ($p_{abs} = p_{gauge} + p_{atm}$). A pressure is a scalar quantity expressed in the international unit [N/m^2], which is now termed pascal [Pa]. Other units such as atmosphere and bar may be used to express pressures of greater magnitude [1] (Massey, 1975).

2.2.1.2 Fluid density

Density is the ratio of the mass of a given amount of substance to the volume occupied by that substance (Streeter and Wylie, 1985). The density is a function of temperature. Regarded as the reference liquid, water has a density of 1000.00 kg/m^3 at 4°C, while at 20°C its density is about 998.2 kg/m^3. The relative density of a given material is the ratio of its density to that of water at the same temperature.

2.2.1.3 Fluid viscosity

Within any fluid, the resistance to the movement of one layer of fluid over an adjacent one is ascribed to its viscosity (Massey, 1975). Newton postulated that, for the straight and parallel motion of a given fluid, the tangential stress between two adjacent layers is proportional to

[1] I.e. at sea level pressure =0 bar, gauge pressure=1 bar absolute = 101 kPa = 10.3 m water = 1 atm.

the velocity gradient in a direction perpendicular to the layers (in Barr, 1931). Mathematically, Newton's hypothesis is formulated as shown in Equation 2.1.

$$\tau = \frac{F}{A} \infty \frac{\partial u}{\partial y}, \tag{2.1}$$

or

$$\tau = \mu \frac{\partial u}{\partial y} \tag{2.2}$$

where μ (Greek "mu") is a constant for a particular fluid at a particular temperature. This coefficient of proportionality μ is known as the coefficient of viscosity or, merely, the viscosity of the fluid. Viscosity μ is then a property of the fluid and a scalar quantity. The basic SI unit of viscosity is Pa.s (Pascal second) or (kg/ms). The viscosity of water at 5°C and 20°C is about 1.519 10^{-3} and 1.005 10^{-3} Pa.s respectively. The poise[2] is another current unity of viscosity (Streeter & Wylie, 1985). Further considerations on non-Newtonian fluid viscosity are mentioned in paragraph 2.4.

The ratio of viscosity to density is known as the kinematic viscosity and is denoted by the Greek symbol ν "nu". The kinematic viscosity is expressed in m2/s as basic unit. This latter unit is too large for most purposes and so the mm2/s (Stokes) is in wide use.

2.2.2 Fundamental equations

When considering a control volume (Fox, 1977) of liquid moving from ABCD to A'B'C'D' in a short interval of time dt as depicted on Figure 2.1, one can apply three basic principles:

1. During the time interval dt there is no change in the mass of the control volume.
2. Any change in energy (kinetic and potential) of the control volume is equal to the work done on the volume in time dt.
3. The change in momentum of the control volume is equal to the sum of the impulses of the external forces on the control volume in time dt.

Three fundamental equations are derived from these basic principles.

[2] 1 Pa.s = 10 P (poise), 1 x 10^{-3} Pa.s = 1 cP (centipoise)

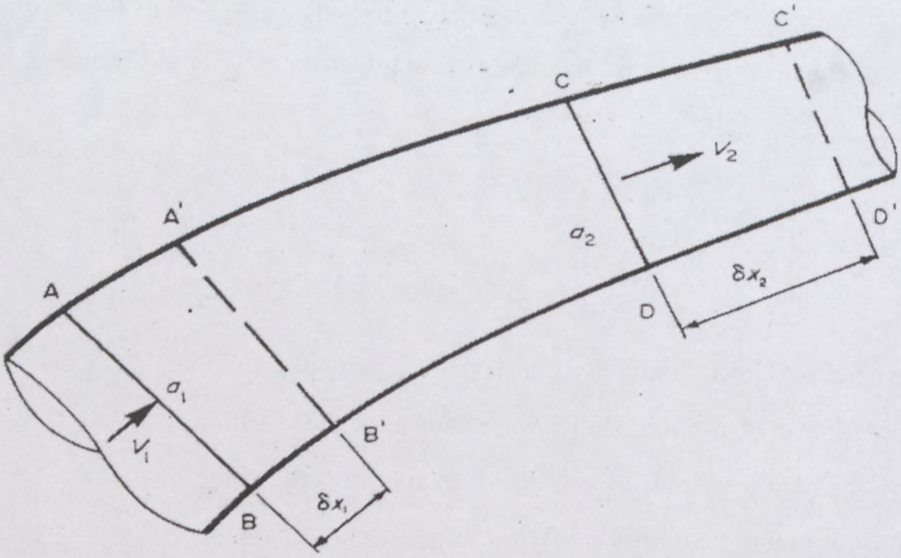

Figure 2.1: A control volume (Fox, 1977)

2.2.2.1 Continuity equation

Consider that in the volume control no fluid enters or escapes during a short time interval dt. Then no change in the mass of the controlled volume occurs, and the mass flow rate is constant. This is mathematically expressed by Equation 2.3.

$$\rho_1 A_1 V_1 dt = \rho_2 A_2 V_2 dt \tag{2.3}$$

If the fluid is assumed to be incompressible, then its density is constant ($\rho_1 = \rho_2$). Equation 2.3 becomes:

$$A_1 V_1 = A_2 V_2 = Q, \tag{2.4}$$

where: A is the cross sectional area

V is the mean velocity

Q is the volumetric flow rate or discharge (m^3/s)

Equation 2.4 is known as the continuity equation. It is of great use in hydraulics and fluid flow related sciences (Fox, 1977).

2.2.2.2 Energy equation

Streeter and Wylie (1985) stated that the change in total energy of the control volume is proportional to the work done on that system by pressure forces. The mathematical expression for an incompressible fluid is given by:

$$\frac{1}{2}\rho dt\left[A_2V_2^2 - A_1V_1^2\right] + \rho g dt\left[A_2V_2 - A_1V_1\right] = p_1A_1V_1dt - p_2A_2V_2dt + W - E \qquad (2.5)$$

where: g is the acceleration owing to gravity (g = 9.81 m/s^2),

W is the work done and

E is the heat energy output

The simplification of the above equation leads to the well known Bernoulli equation (Streeter and Wylie, 1985):

$$\alpha_1\frac{V_1^2}{2g} + Z_1 + \frac{P_1}{\rho g} + \Delta H_p = \alpha_2\frac{V_2^2}{2g} + Z_2 + \frac{P_2}{\rho g} + \Delta h_f \qquad (2.6)$$

where ΔH_p is the pump head input (work done per unit weight)

Δh_f is the friction head loss (energy loss per unit mass)

α_1 and α_2 are the kinetic energy correction factors at the upstream and downstream respectively.

Each term is referred to as head, and is expressed in joules per Newton. Pressure and head are related by the following equation:

$$P = \rho g \Delta H_p \qquad (2.7)$$

2.3 FLOW OF NON-NEWTONIAN FLUIDS IN STRAIGHT PIPES

2.3.1 Introduction

A good understanding of flow through straight pipes is important before considering the flow through centrifugal pumps. Both laminar and turbulent flow will be considered.

2.3.2 The shear stress distribution in a circular pipe

The shear stress distribution in a pipe can be physically demonstrated (Massey, 1975). Consider a small concentric cylinder of radius r in a pipe of radius R and length L over which a difference of pressure ΔP exists as shown on Figure 2.2. The shear stress τ_{rz}, acts uniformly on the curved surface of the cylinder as a reacting force opposite to the flow motion. Applying forces balance, the shear stress within the pipe at a given radius r can be expressed by Equation 2.8 below (Massey, 1975).

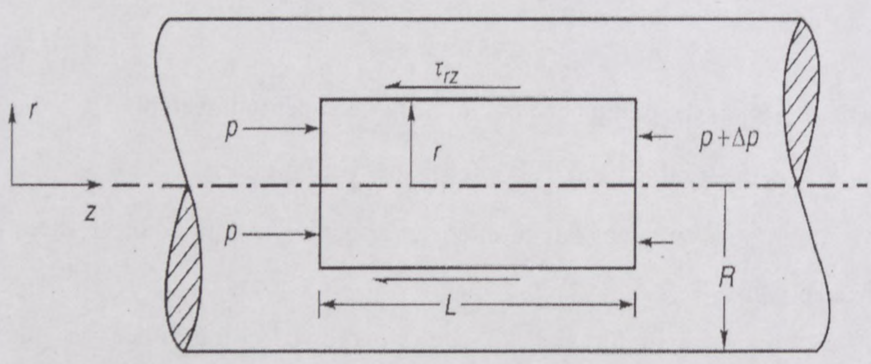

Figure 2.2: Shear stress distribution in a pipe (Chhabra and Richardson, 1999)

$$\tau = \frac{r}{2}\frac{\Delta P}{L} \tag{2.8}$$

The shear stress is zero at the pipe centre and reaches its maximum τ_0 at the pipe wall. Equation 2.9 below expresses the wall shear stress that can be easily calculated, from the pressure drop across a known length of straight pipe.

$$\tau_0 = \frac{D}{4}\frac{\Delta P}{L} \tag{2.9}$$

2.3.3 Friction factor

The friction factor is derived from the momentum equation, applied to a constant diameter straight pipe as follows:

$$A\Delta P = \rho g A(\Delta h + \Delta L) = F_f + F_g \tag{2.10}$$

where F_f = friction force

F_g = gravity force

Again, a force balance across the pipe sections gives the wall shear stress as expressed in Equation 2.9.Then the Fanning friction factor shown by Equation 2.11 is defined as the ratio of the wall shear stress to the dynamic pressure of the flow (Abulnaga, 2002).

$$f = \frac{2\tau_0}{\rho V^2} \tag{2.11}$$

The friction factor is a function of two parameters, the Reynolds number and the relative pipe wall roughness (k/d) Massey (1975). In laminar flow, the pipe roughness has no influence on the friction factor (Vennard & Street, 1976). The friction factor Equation 2.11 is reduced to Equation 2.12 for laminar flow.

$$f = \frac{16}{R_e} \tag{2.12}$$

However for Reynolds numbers greater than 2100, the flow depends on the roughness of the pipe (Abulnaga, 2002). In this case, the Colebrook and White relation can be used to estimate the friction factor (Colebrook, 1939).

$$\frac{1}{\sqrt{f}} = -4\log\left[\frac{k}{3.7D} + \frac{1.26}{R_e\sqrt{f}}\right] \tag{2.13}$$

The Moody diagram shown in Figure 2.3 is actually the most frequently used chart for predicting values of f for both laminar and turbulent flow (Massey, 1975). Intermediate regimes such as critical and transition zones are represented as well. Massey (1975) has presented the use of the Moody diagram as suitable for ordinary commercial pipes.

2.3.4 Head loss owing to friction in pipe

Many authors such as Massey (1975), Fox (1977) and Streeter and Wylie (1985) have referred to the energy dissipation caused by friction during the flow of a fluid through a pipe. This energy loss manifests itself as a head loss, which is easily detected by an appropriately connected manometer (Slatter, 1994). The French engineer Darcy investigated the dissipation of energy by fluid friction in a long straight pipe of constant diameter. He established the following head loss relation (Equation 2.14) named after him (Massey, 1975).

$$\Delta h = \frac{4fL}{D}\left(\frac{V^2}{2g}\right) \tag{2.14}$$

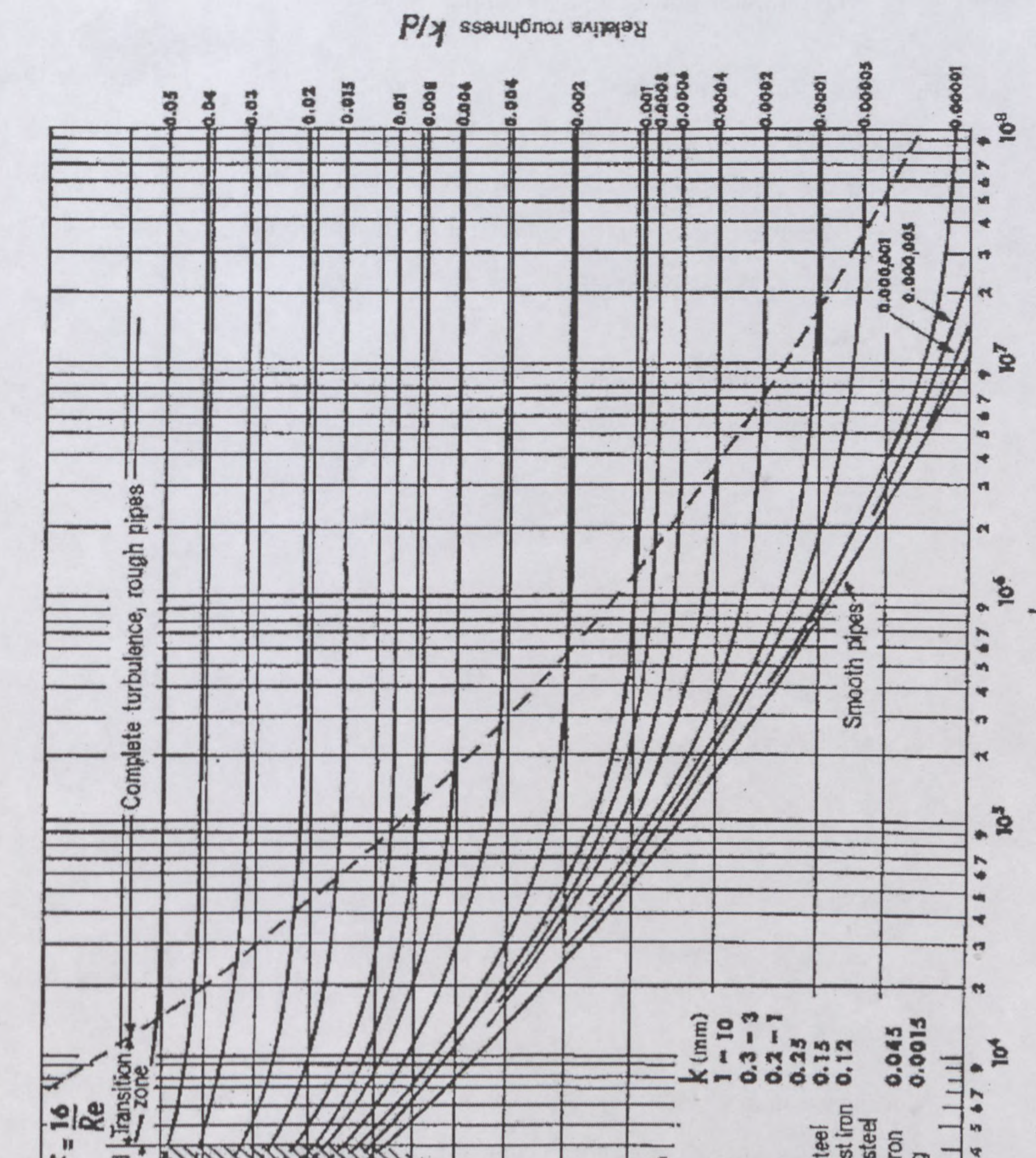

Figure 2.3: Moody diagram (Massey, 1975)

2.3.5 The Laminar flow of non-Newtonian fluids

The laminar flow of non-Newtonian fluids is characterised by the fact that the shear stress arising from the friction between layers follows a certain function of the velocity gradient. It is not directly proportional to the velocity gradient as for Newtonian fluids. The relationship between the shear stress and the shear rate is complex, the yield pseudoplastic will be considered here as a general case.

Non-Newtonian fluids are often best modelled as yield pseudoplastics (Govier and Aziz, 1972; Hanks, 1979). Govier and Aziz (1972) described the general equation of laminar pipe flow as

$$-\frac{du}{dr} = F(\tau) \tag{2.15}$$

The force balance applied to a cylindrical element as shown on the shear stress distribution (Figure 2.2) yields

$$\pi r^2 dp = 2\pi r \tau dL \tag{2.16}$$

or

$$dr = \frac{R\, d\tau}{\tau_0} \tag{2.17}$$

After integration of Equation 2.17, one can find the expression of τ_0 as shown by Equation 2.9 above. The flow rate can be obtained by integrating the velocity profile over the cross section.

$$Q = 2\pi \int_0^R urdr \tag{2.18}$$

where boundary conditions for the pipe are:
For r = R, u = 0, (no slip at the pipe wall)
For r = 0 du/dr = 0, the slope of the velocity distribution is zero at the pipe centreline (Janna, 1983). Equation 2.18 becomes:

$$Q = \pi\left[ur - \int r^2 \frac{du}{dr}dr\right]_0^R = -\pi\int_0^R r^2 \frac{du}{dr}dr \tag{2.19}$$

Two cases are encountered:

a) in the plug region: $0 \le r \le r_{plug}$

$0 \le \tau \le \tau_y$

and $F(\tau) = 0$

This means that the fluid does not shear; adjacent laminae are stationary relative to one another.

b) in the sheared region: $r_{plug} \le r \le R$

$\tau \le \tau \le \tau_0$

and $F(\tau) = \left(\frac{1}{K}\right)^{\frac{1}{n}}(\tau - \tau_y)^{\frac{1}{n}}$

The fluid moves as a plug at a uniform plug velocity u plug. Then the discharge is the sum of the flow through the sheared region ($r_{plug} \le r \le R$) and the plug ($0 \le r \le r_{plug}$). For a fluid with a yield stress, Equation 2.19 becomes

$$\frac{8V}{D} = \frac{4}{\tau_0^3}\left(\frac{1}{K}\right)^{\frac{1}{n}}\int_{\tau_y}^{\tau_0}\tau^2(\tau - \tau_y)^{\frac{1}{n}}d\tau \tag{2.20}$$

After integration, one obtains:

$$\frac{8V}{D} = \frac{4n}{\tau_0^3}\left(\frac{1}{K}\right)^{\frac{1}{n}}(\tau_0 - \tau_y)^{\frac{n+1}{n}}\left[\frac{(\tau_0 - \tau_y)^2}{3n+1} + 2\tau_y\frac{(\tau_0 - \tau_y)}{2n+1} + \frac{\tau_y^2}{n+1}\right] \tag{2.21}$$

Equation 2.21 is of fundamental importance in capillary viscometers (Slatter, 1994) for the following reasons:

- The pseudo-shear rate (8V/D) is a unique function of the rheogram f (τ) and the wall shear stress τ_0, provided that there is no time dependency or slip at the wall and provided that the flow is laminar

- The relationship between (8V/D) and τ_0 can be obtained by direct numerical integration using data directly from a rheometer without using a conventional rheological model.
- Since (8V/D) is a unique function of the rheogram f (τ) and the wall shear stress τ_0, it is independent of pipe diameter and can be used for scale-up and design in laminar flow.

2.4 RHEOLOGY

2.4.1 Definition

Translated from Greek "rheos" (flow) and "logos" (knowledge), rheology is the science of flow phenomena. Chhabra and Richardson (1999) have regarded rheology as the viscous characteristics of homogeneous solid/liquid mixtures. This work will share the same view for practical purposes.

2.4.2 Rheological model

There are a number of rheological models (model equations) that relate shear stress and shear rate (Chhabra and Richardson, 1999). A few common models act as the basis for engineering design calculations. These models are presented in the following section including the Newtonian model (constant viscosity) mentioned in paragraph 2.2.1.3.

2.4.2.1 Newtonian model

Sir Isaac Newton postulated the relationship between the shear stress and the shear rate in a fluid as follows (in Barr, 1931):

"The resistance which arises from the lack of slipperiness originating in a fluid other things being equal is proportional to the velocity by which the parts of the fluid are being separated from each other."

Newton's hypothesis can be expressed mathematically as Equation 2.2

Presented in terms of the axially symmetric flow of a fluid in a pipe, Newton's relation becomes:

$$\tau = \mu\left[-\frac{du}{dr}\right] \tag{2.22}$$

This linear relationship is graphically presented in Figure 2.4 below. The viscous flow behaviour can be completely characterised by one parameter (μ). Water, oils and glycerine are examples of fluids that obey this linear relationship; they are said to be Newtonian fluids. The next paragraph will discuss characteristics of non-Newtonian fluids.

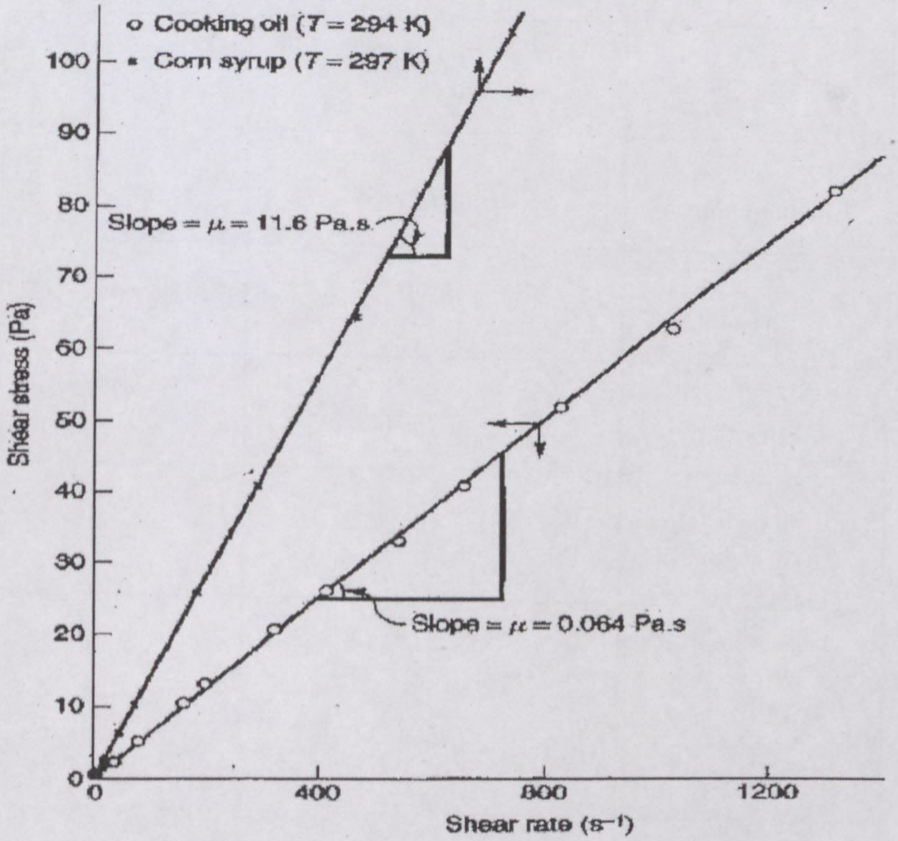

Figure 2.4: Newtonian rheogram (Chhabra and Richardson, 1999)

2.4.2.2 Non-Newtonian model

Non-Newtonian models describe fluids whose flow curves (shear stress versus shear rate) are non-linear and/or do not pass through the origin. Chhabra and Richardson (1999) have observed that the apparent viscosity (shear stress divided by shear rate) for this category of fluids is not constant. Many fluid models have been proposed to describe a non-Newtonian behaviour. Some of the most popular are shown in the Table 2.1 below.

Table 2. 1: Rheological models (Chhabra and Richardson, 1985)

Fluid model	Constitutive equation	Number of parameters	Parameters
Newtonian	$\tau = \mu\left(-\frac{du}{dr}\right)$	1	μ
Bingham plastic	$\tau = \tau_y + K\left(-\frac{du}{dr}\right)$	2	τ_y and K
Casson	$\sqrt{\tau} = \sqrt{\tau_y} + \sqrt{\mu_c(-\frac{du}{dr})}$	2	τ_y and μ_c
e- function	$\mu = \mu_o.\exp\left[m.(-\frac{du}{dr})\right]$	2	μ_o and m
Ostwald de waele or power-law (pseudoplastic)	$\tau = K\left(-\frac{du}{dr}\right)^n$	2	K and n
Ellis	$\mu = \frac{\mu_0}{1+\left(\frac{\tau}{\tau_{\frac{1}{2}}}\right)^{\alpha-1}}$	3	μ_0, α and $\tau_{1/2}$
Herschel-Bulkley or yield pseudoplastic	$\tau = \tau_y + K\left(-\frac{du}{dr}\right)^n$	3	τ_y, n and K

For practical purposes, it is important to select a suitable rheological model amongst those presented. The next section will deal with the choice of models.

2.4.3 Choice of rheological model

Several rheological models are available (Table 2.1). However, opinions are divided in the literature as to which rheological model should be used to model the laminar flow of non-Newtonian slurries (Chhabra and Richardson, 1985).

The choice of model becomes extremely important, not only for rheological characterisation in laminar flow, but, even more important, in turbulent flow predictions (Hanks and Ricks, 1975). Data can be measured in laminar flow even in tubes of smaller diameter (Shook and Roco, 1991) and extrapolated to much higher shear stresses for turbulent flow predictions (Thomas and Wilson, 1987).

The pseudoplastic model is favoured by researchers such as Kemblowski and Kolodziejski (1973), Chhabra and Richardson (1985) and Heywood *et al.* (1993). Xu *et al.* (2002) and Duckworth *et al.* (1986) chose as more desirable the Bingham plastic model.

These rheological relationships can be accommodated in the yield pseudoplastic model (Thomas and Wilson, 1987).

2.4.4 The yield pseudoplastic or Herschel-Bulkley rheological model

The constitutive rheological equation of the yield pseudoplastic model is:

$$\tau = \tau_y + K\left(-\frac{du}{dr}\right)^n, \qquad (2\ 23)$$

where τ_y is the yield stress (Pa)

K is the fluid consistency index ($Pa.s^n$)

n is the flow behaviour index,

$\left(-\frac{du}{dr}\right) = \dot{\gamma}$ is the shear rate (s^{-1})

These three parameters are very important in the determination of the flow behaviour of solid/liquid mixtures. Here are some particular characteristics of each parameter.

1. The yield stress (τ_y)

Chhabra and Richardson (1999) have mentioned that, strictly speaking, it is not possible to ascertain the existence of true yield stress in any real material. However, the concept has proved to be convenient in practice. The yield stress of slurry is generally regarded as the minimum shear stress that is required to initiate a sustainable flow.

2. The fluid consistency index (*K*)

The consistency index (*K*) can be viewed as the value of the apparent viscosity of the fluid at a shear rate of unity (Chhabra and Richardson, 1999).

3. The flow behaviour index (*n*)

The flow behaviour index, n, indicates the degree of curvature of the rheogram together with the fluid consistency index *K* (Chhabra and Richardson, 1999).

Both K and n are empirical curve-fitting parameters. They are specific to a given set of slurry conditions and cannot be separated from each other (Chhabra and Richardson, 1999). Figure 2.5 depicts various non-Newtonian slurries and the shape of the rheogram for each slurry type on linear axes.

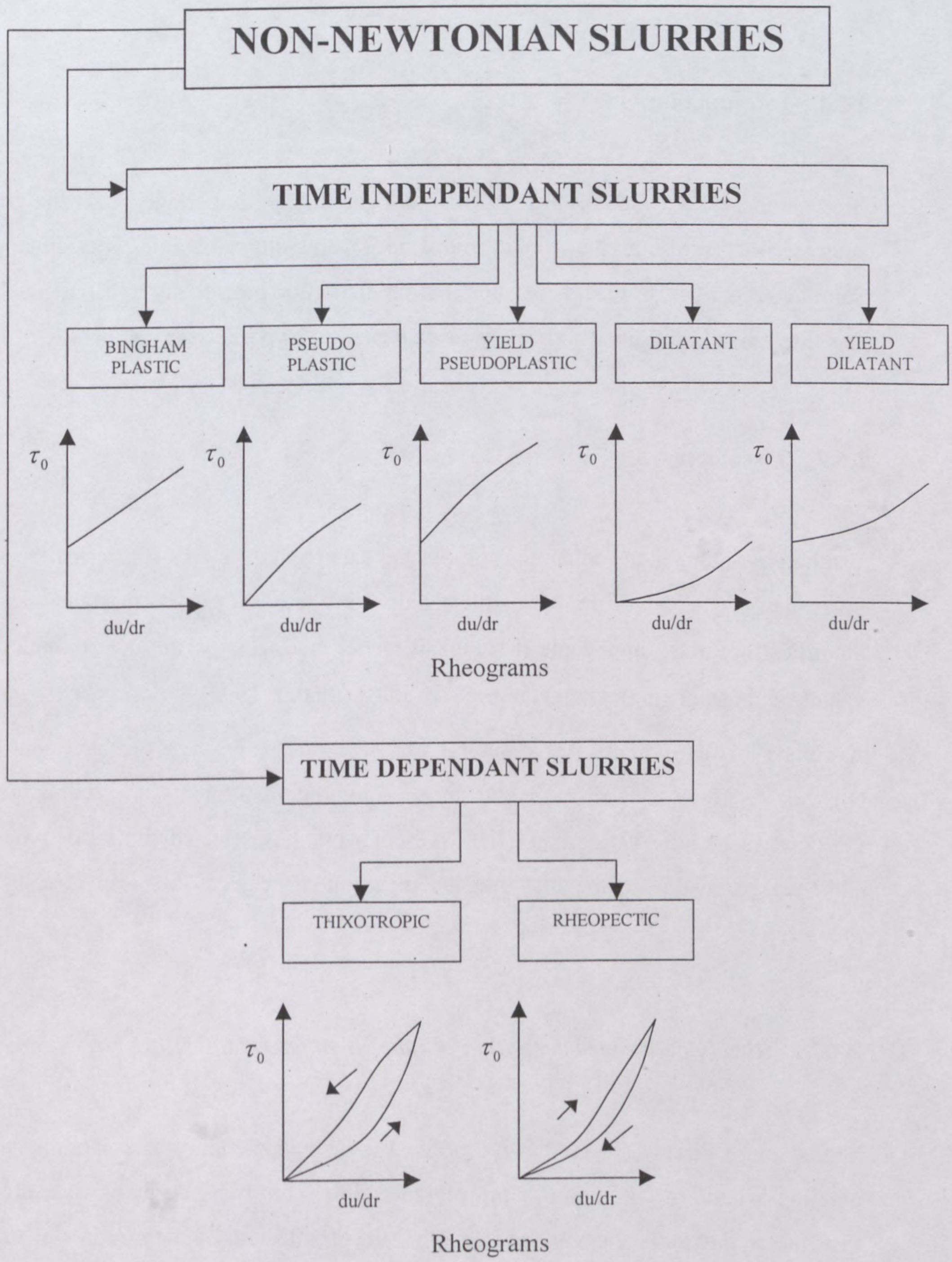

Figure 2.5: Non-Newtonian slurries rheogram (Brown and Heywood, 1991).

2.5 RHEOLOGICAL CHARACTERISATION

2.5.1 Introduction

Brown and Heywood (1991) have highlighted the importance of the rheological characterisation of non-Newtonian fluids in several slurry-handling design applications. Some aspects of this are, for instance, the prediction of pipe-sizing and frictional-pressure-loss through straight pipe and fittings, as well as the pump selection and sizing.

2.5.2 Viscometry

Viscometry includes the collection of physical data from tests on a sample of the fluid under investigation; the establishment of the relationship between shear stress and shear rate; the identification of the applicable rheological model; and, finally, the determination of actual values of constants in the model e.g. τ_y, K and n (Slatter, 1994).

A variety of instruments (viscometers) can be used to measure these viscous properties (Brown & Heywood, 1991). The most common instruments are either rotary type viscometers or tube viscometers. The present work has selected the latter type for slurry characterisation due to the fact that the pipes on the rig can be used directly as a tube rheometer.

2.5.2.1 Rheological characterisation of tube viscometer data

Slatter and Lazarus, (1988) have described a tube viscometer as essentially a miniature pipeline where the flow rate and pressure drop can be accurately measured. A tube viscometer measures the volumetric flow rate of a tested fluid through the tube and the pressure drop over a known length of the tube. The parameters required to obtain a rheogram from a tube viscometer are:

– the slurry volumetric flow rate; Q

– the inside diameter of the viscometer tube; D

– the length of the viscometer tube, L; and

– the pressure drop due to laminar friction, ΔP.

The average fluid velocity in the tube viscometer is found from Equation 2.24

$$V = \frac{4Q}{\pi D^2} \tag{2.24}$$

and the wall shear stress, τ_0 , is calculated from the measured pressure loss using Equation 2.9.

2.5.3 The Rabinowitsch-Mooney relation

Data from a tube viscometer are plotted as τ_0 versus (8V/D) and are called a pseudo-shear diagram. The pseudo-shear diagram for different pipe diameters in a laminar flow region should be coincident, whereas the turbulent pipe data will vary for different pipe diameters (Slatter, 1994). Therefore, Govier and Aziz (1972) have shown how to determine the rheological constants, See Section 2.4.4, for the data in the laminar region. The rate of shear at the pipe tube wall (true shear rate) may be determined from the general equation of Rabinowitsch (1929) and Mooney (1931) expressed by:

$$\left(-\frac{du}{dr}\right)_0 = \left(\frac{3n' + 1}{4n'}\right)\frac{8V}{D} \tag{2.25}$$

where

$$n' = \frac{d(\ln \tau_o)}{d\left(\ln \frac{8V}{D}\right)} \tag{2.26}$$

n' is the slope of the logarithmic plot of the wall shear stress, τ_0, versus the pseudo shear rate, $\frac{8V}{D}$. For a Newtonian fluid the value of n' is equal to 1, and Equation 2.25 is reduced to Equation 2.27 below.

$$\left(-\frac{du}{dr}\right)_o = \frac{8V}{D} \tag{2.27}$$

If the fluid is of such a nature that the plot is not a straight line the value of n' will be a function of $\frac{8V}{D}$. The value of n' will have to be established for each value of wall shear stress τ_0.

2.6 CLASSIFICATION OF PUMPS

2.6.1 Introduction

Brown and Heywood (1991) have noted the availability of a wide range of pumps. They have pointed out that pumps are not uniformly classified because of the large number of criteria that are used to describe them. This section will provide general information on pumps.

2.6.2 Classification

Brown and Heywood (1991) and Wilson *et al.* (1997) have broadly classified pumps into two main categories:

1. Centrifugal pumps or dynamic pumps: energy is generated by the centrifugal motion of a vortex. The fluid velocities within the pumps are greater than at exit.

2. Positive displacement pumps: energy is imparted progressively to a discrete volume of fluids. This is isolated between the moving and stationary parts in cavities in rotor, screw, cylinder or diaphragm, with seal or fine clearance between the moving component and the casing. A direct mechanical action moves these cavities from the suction to the discharge side. As a result, the flow path in displacement pumps is not continuous, and the discharged fluid flow is pulsating.

The present work will not discuss the second category of pump.

2.7 CENTRIFUGAL PUMPS

2.7.1 Introduction

Abulnaga (2002) describes a centrifugal slurry pump as the workhorse of slurry flows. In practice, centrifugal slurry pumps are a development of conventional centrifugal pumps used for single-phase liquids (Delaroute, 1991). They are characterised by some additional details when compared with clean liquids pumps: robust design, wear resistant materials and large passageways to allow solid particles to pass through (Wilson *et al.*, 1997).

2.7.2 Theoretical aspect of slurry pumps

Sayers (1964) has reported that the head developed by a centrifugal pump can be expressed by the theoretical Euler's equation below:

$$H_p = \frac{T\omega}{\rho_m g Q} = S_m\left(\frac{u_2V_2 - u_1V_1}{g}\right) \quad \textbf{(2.28)}$$

where T= torque at pump shaft

ω = shaft speed (radians/s)

$u_{1,2}$ = velocity vector at vane entrance and exit of the impeller

$V_{1,2}$ = normal velocity vector at vane entrance and exit of the impeller.

At constant impeller speed, it is shown that the losses occurring in the pump result in the deviation of the theoretical Euler head from the delivered pump head (Wilson *et al.*, 1997). Furthermore, Wilson *et al.* (1997) have underlined that the pump characteristic head-discharge curves are established from the combination of different pump losses as illustrated in Figure 2.6.

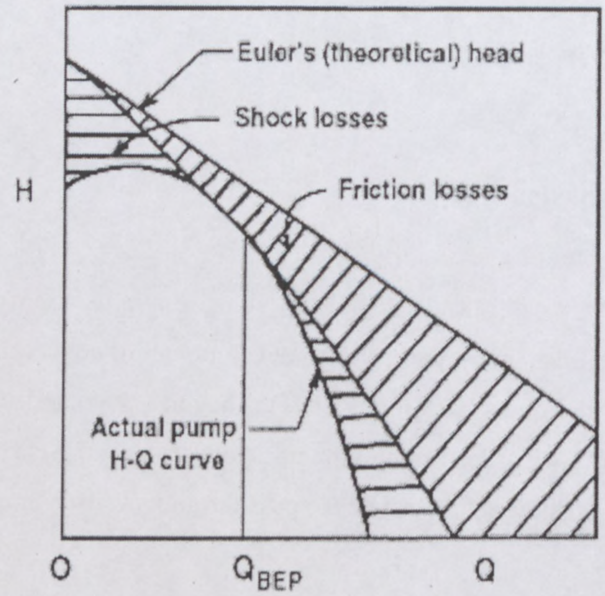

Figure 2.6: Losses in a centrifugal pump (Wilson *et al.*, 1997)

2.7.3 Pump performance calculation

The head, efficiency and power of a centrifugal pump are determined for a given fluid flowing through the pump at constant speed (Wilson *et al.*, 1997).

2.7.3.1 Pump head

The head generated by a pump is defined as the energy transferred to the unit of weight of a pumped liquid. The pump head ΔH_p is expressed using Bernoulli's equation as shown by Equation 2.6.

2.7.3.2 Pump power

Equation 2.29 expresses the power developed by a centrifugal pump.

$$P_{out} = \rho_m g Q \Delta H_p \quad \textbf{(2.29)}$$

The input power to the pump from the drive assembly is determined from the torque on the shaft as shown by Equation 2.30:

$$P_{in} = \frac{2\pi NT}{60} \qquad \textbf{(2.30)}$$

where:

T = torque of the pump shaft (N.m)

N = shaft speed (RPM)

The value of the torque needs to be corrected. The correction requires that the torque at zero load must be subtracted from the torque value recorded. Usually, the torque at zero load is obtained when running the motor and speed-torque unit disconnected from the centrifugal pump shaft.

2.7.3.3 Pump efficiency

The efficiency of the pump is the ratio of the output power to the input power. It is expressed by:

$$\eta_{pump} = \frac{P_{out}}{P_{in}} \qquad \textbf{(2. 31)}$$

2.7.4 Pump characteristics curves

2.7.4.1 Typical characteristics curves

These curves are mostly produced from experimental tests carried out on clear water (Wilson *et al.*, 1997). An example of pump characteristic curves is presented in Figure 2.7.
The point of maximum efficiency is called the Best Efficiency Point (BEP) and varies with the pump speed. In pump selection practice it is advised to select a pump that will run at an appropriate speed as close to the BEP as possible (Wilson *et al.*, 1997).

2.7.4.2 Pump specific speed (NS)

The pump specific speed, conditionally assumed as a dimensionless number, is obtained by manipulating the ratios which form the dimensionless axis of the dimensionless pump characteristic plot in order to eliminate the impeller diameter (Wilson *et al.*, 1997). Each pump design has a particular specific speed. Equation 2.32 gives the pump specific speed relation.

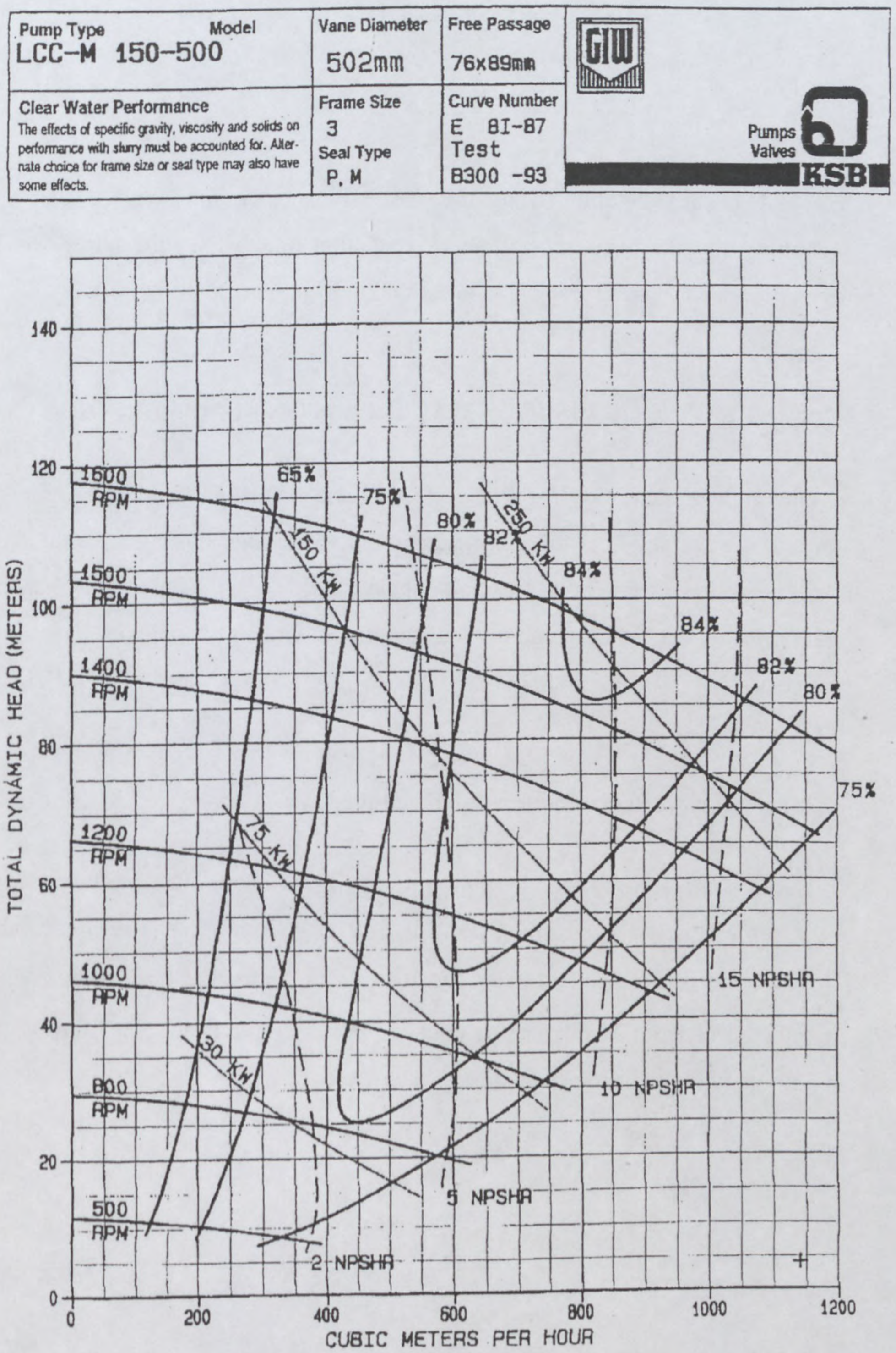

Figure 2.7: A typical pump characteristic curve for a slurry pump (GIW, 1993)

$$NS = \frac{N(Q)^{1/2}}{gH^{(3/4)}} \tag{2. 32}$$

where:

N = Pump speed of rotation [rev/min]

H = Pump head at BEP[m]

Q = Pump flow rate at BEP [m^3/s]

H and Q are determined at the best-efficiency point. Walker and Goulas plotted meaningfully the head and efficiency reduction ratio versus the NRep for different pump specific speeds. These graphs are presented in Figure 5.1 and Figure 5.2.

2.8 EFFECT OF VISCOUS MATERIALS ON PUMP PERFORMANCE

Many authors such as Wilson *et al.* (1997) and Abulnaga (2002) have reported that slurry produces adverse effects on pump performance. Viscous slurry causes the pump to generate less head and to be less efficient (Wilson *et al.*, 1997). Therefore, when pumping slurry rather than clear water, pump curves have to be derated to compensate for the effects of the viscosity.

2.8.1 Slurry effect on pump performance

Viscous slurries are formed by a mixture of fine solid particles and water in which the solid will settle slowly (Angle and Crisswell, 1997). Wilson *et al.* (1997) have shown that for a given homogeneous mixture of density ρ_m the effective head generated by the pump, expressed in units of mixture, is equal to the effective head generated by the pump when pumping water expressed in units of water.
Figure 2.8 shows how viscous slurry affects the performance of a centrifugal pump.

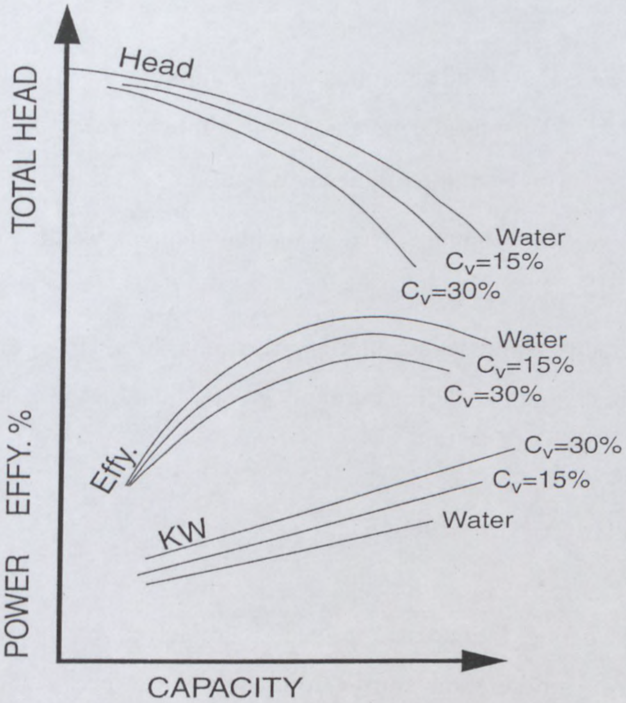

Figure 2.8: Effect of viscous slurry on centrifugal pump characteristics (Angle and Crisswell, 1997).

The pressure produced when pumping water is less than the pressure produced when pumping slurry and the power consumption is then calculated from:

$$P_w = \rho_w g Q_w H_e \quad (2.33)$$

$$P_m = \rho_w g Q_m H_e \rho_m \quad (2.34)$$

$$P_m = \rho_m P_w \quad (2.35)$$

For a given pump speed and flow rate, the reduction in head developed and pump efficiency is defined by the following ratios (Stepanoff, 1969):

$$\text{Head ratio} = HR = \frac{H_m}{H_w} \quad (2.36)$$

$$\text{Efficiency ratio} = ER = \frac{\eta_m}{\eta_w} \tag{2.37}$$

where H_m = head generated when pumping slurry (m slurry)

H_w = head generated when pumping water (m water)

η_m = pump efficiency when pumping slurry

η_w = pump efficiency when pumping water.

For volumetric solids concentrations less than 20%, HR is taken as being equal to ER. For higher concentrations, HR is normally greater than ER (Wilson *et al.,* 1992).

2.9 PREVIOUS WORKS

Work predating the present project is reviewed in this section. It was observed that procedures for derating slurry from their water performance characteristics are at best empirical (Wonnacott, 1993).

Two models available for centrifugal pump deration are the correlation of head and efficiency reduction to the pump Reynolds number (Walker and Goulas, 1984) and the Hydraulics Institute deration chart (Hydraulics Institute, 1983).

a) Correlation of head and efficiency reduction to pump Reynolds number

Walker and Goulas (1984) have correlated the head and efficiency reduction to the pump Reynolds number as depicted in Figure 2.9. Experimental data were obtained from mixtures of coal and water and kaolin and water.

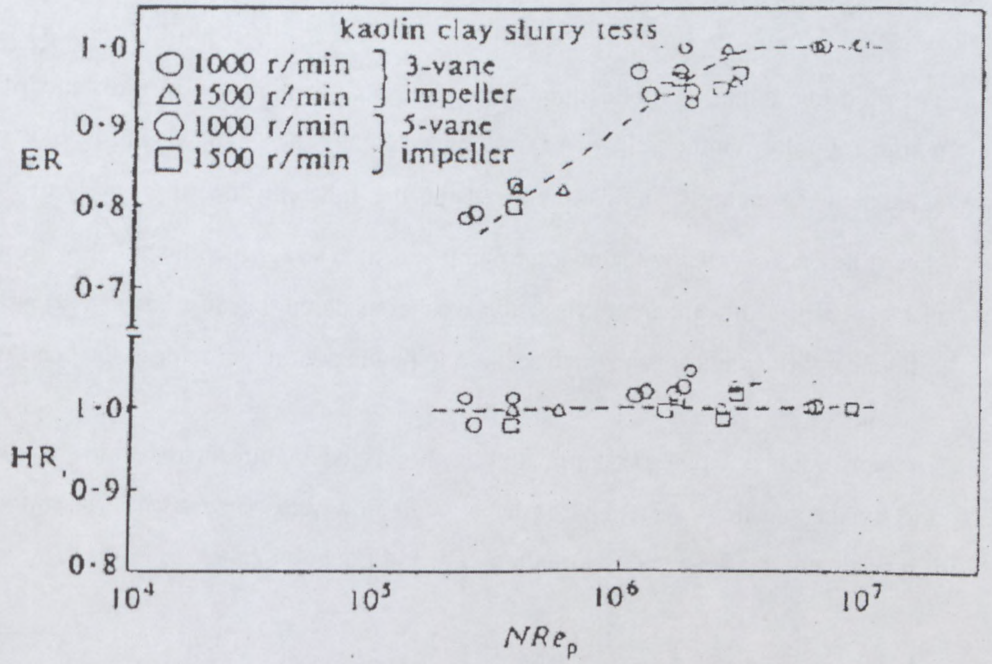

Figure 2.9: Correlation of head and efficiency reduction ratio (HR; ER) to pump Reynolds number (Walker and Goulas, 1984)

- Standard pump Reynolds number

A Reynolds number is defined as a ratio of inertial forces to viscous forces. The standard Newtonian pump Reynolds number is described by Equation 2.38 (Massey, 1970).

$$NR_{ep} = \frac{\omega D_i^2 \rho}{\mu} \tag{2.38}$$

where:

ω = pump rotational speed [rad/s]

D_i = impeller diameter [m]

ρ = density of the material [kg/m^3]

μ = viscosity [Pa.s]

- Modified pump Reynolds number

The modified pump Reynolds number has the same formulation as the standard Newtonian pump Reynolds number. However, in their original paper, Walker and Goulas (1984) have calculated the pump Reynolds number using the apparent viscosity (μ_{app}) of the fluid at a shear rate of 2ω (ω being the angular pump speed). They argued that for low flow conditions (10% QBEP); the apparent viscosity was considered because of its sensitivity to the influence of the yield stress which seemed to be the dominant factor in the head reduction.

The performance would be dominated by the viscous nature of the fluids at low flow rates and by the plastic or secant viscosity at high flow rates (near BEP). The modified pump Reynolds number is given by Equation 2.39 and Equation 2.40.

$$NR_{ep} = \frac{\omega D_i^2 \rho_m}{\mu_{app}} \tag{2.39}$$

where:

μ_{app} = apparent viscosity at shear rate of 2ω in Pa.s.

Slatter and Wasp (2004) show that at high shear rates the apparent viscosity approaches the plastic viscosity. Therefore, one can use the alternative equation (Equation 2.40) for high shear rates where the apparent viscosity is replaced by the plastic viscosity.

$$NR_{ep} = \frac{\omega D_i^2 \rho_m}{\mu_p} \tag{2.40}$$

where:

μ_p = Plastic viscosity [Pa.s] or η = coefficient of rigidity for Bingham fluid or K.

The procedure recommends that from the efficiency performance curve with water, the best efficiency point (BEP) be established for each speed of rotation tested. The flow at BEP is calculated by optimisation of an equation best fitted on the efficiency test curve. From the flow rate at BEP, one can calculate the operating point at 0.1BEP and find the corresponding head and efficiency.

2.10 PLASTIC VISCOSITY AND APPARENT VISCOSITY CALCULATION

Consider the behaviour of red mud slurry calculated from the rotary viscometer depicted on Figure 2.10. Important parameters for a Bingham plastic fluid are the yield stress (τ_0) and the coefficient of rigidity (η), also commonly referred to as the plastic viscosity (μ_p) or equivalent to the fluid consistency index K for a Bingham slurry (Bootle, 2006).

The plastic viscosity is defined as the slope of the shear stress versus shear rate line at high shear rates. The yield stress for this material is the point where the straight line intercepts the Y axis. For the red mud, the yield stress is estimated to 23 Pascal and the plastic viscosity is calculated using Equation 2.41 (Bootle, 2006).

$$\mu_p = \frac{(38Pa - 23Pa)}{(500\sec^{-1} - 0\sec^{-1})} = 0.03Pa.\sec \quad \textbf{(2.41)}$$

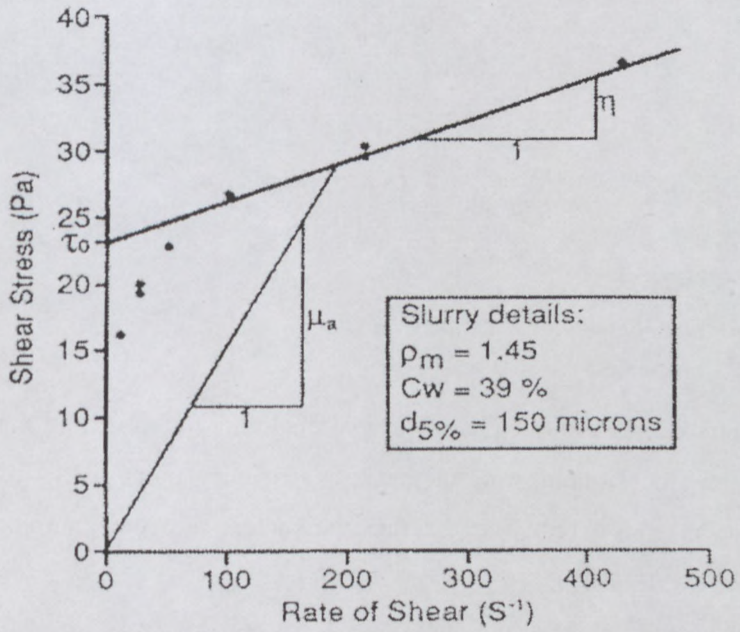

Figure 2.10: Behaviour of red mud slurry calculated from rotary viscometer measurements (Warman, 1991)

To calculate the apparent viscosity, Duckham has proposed values for shear rate between 100 and 1000 s^{-1} and has suggested the use of 100 s^{-1} for pseudoplastic and Bingham plastic material. Walker and Goulas thought the estimation to be vague as it is probable that shear rate depends on both rotational speed of the impeller and the flow rate for any particular pump (Walker and Goulas, 1984).

The apparent viscosity of a non-Newtonian fluid can be expressed like the viscosity of a Newtonian fluid described in section 2.4.2.1. Its rheological plot is a straight line starting from the origin with slope equal to the viscosity (Warman, 1991).

A similar straight line can be drawn from the origin to any point on the rheological plot of a non-Newtonian fluid; Figure 2.10 presents the case of a Bingham plastic fluid (the red mud mentioned above). This line yields a line with apparent viscosity slope for the particular shear rate and shear stress chosen. One can observe that the apparent viscosity is dependent upon the chosen point. At other shear rates and shear stresses, the apparent viscosity will differ. Bootle (2006) has referred to two examples of apparent viscosity calculations as presented in Equation 2.42 and 2.43.

$$\mu_a @ 200\sec^{-1} = \frac{(29Pa - 0Pa)}{(200\sec^{-1} - 0\sec^{-1})} = 0.145Pa.\sec \qquad \textbf{(2.42)}$$

$$\mu_a @ 500\sec^{-1} = \frac{(38Pa - 0Pa)}{(500\sec^{-1} - 0\sec^{-1})} = 0.076Pa.\sec \qquad \textbf{(2.43)}$$

b) The Hydraulics Institute Chart

The Hydraulics Institute chart uses two diagrams for correcting liquid viscosity. In the first diagram, the pumping rate at the best efficiency point (BEP) of the water performance curves is considered. The diagram parameters are: the pumping head at BEP and the kinematic viscosity ν.

Values found when combining the above parameters enable us to obtain a rate correlation parameter from the diagram. This parameter serves as the independent variable in the second diagram from which C_h, C_q and C_η are determined. C_h, C_q and C_η are the correction factors for the head, capacity and efficiency curves respectively.

The second diagram gives four different C_h values that are necessary in order to establish the pumping head vs. pump capacity curve, using several points. The four factors are for the following different capacities: 0.6 QBEP, 0.8 QBEP, Q BEP, 1.2 QBEP (Hydraulics Institute Chart, 1983)

The plastic viscosity considered as well as the consistency index (section 2.4.4), will be used in the nomogram for the HI prediction calculations (section 5.8).

Thus, one can easily plot the corrected performance curves, valid for the viscous liquid, from the calculated heads and efficiencies versus the corrected pump capacities. Figure 2.11 shows the Hydraulics Institute chart.

It should be noted that the Hydraulics Institute deration chart should be used to correct the viscosity of Newtonian homogenous liquids only. However, Walker and Goulas (1984) noted a reasonably good agreement (± 5 %) between pump test data for non-Newtonian materials and pump performance calculations using the HI chart.

The work by Sery and Slatter (2002) followed the Walker and Goulas approach. They have examined the existing derating procedures for non-Newtonian slurries using data obtained from tests with a Warman 4/3 centrifugal pump.

Kaolin slurry was used and comparison with previous work has shown good agreement. A drop in HR and ER was noticed for pump Reynolds number less than 8.10^5. Furthermore Sery and Slatter predicted the pump performance based on the Hydraulics Institute deration chart. Glycerine was tested and prediction margins of 20% and 10% were found for head and efficiency respectively.

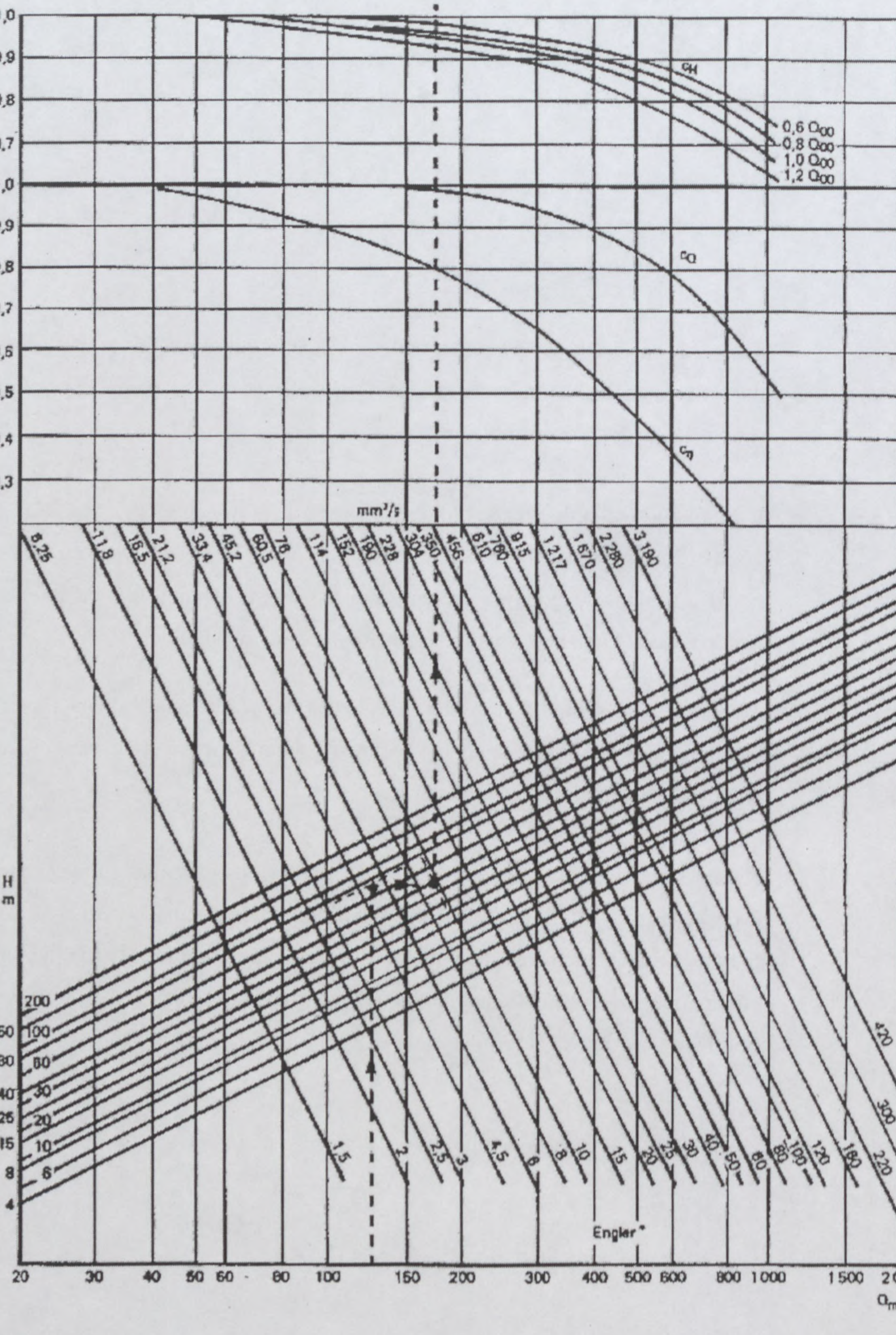

Figure 2.11: The Hydraulics Institute deration chart (Hydraulics Institute chart, 1983).

2.11 CONCLUSION

In this chapter, some basic concepts relative to fluid mechanics have been presented as valuable foundation of this work. Rheological models applicable to non-Newtonian slurries as well as the rheological characterisation have been reviewed. The theory relevant to centrifugal slurry pumps has been presented. The effect of viscous materials on the performance of a slurry pump has been explored. Existing deration procedures for centrifugal slurry pumps have been examined. A summary of previous work on the deration procedures has been presented and the following research aspects have been identified.

2.12 RESEARCH ASPECTS IDENTIFIED

In their work, Walker and Goulas (1984) have correlated the head and efficiency reduction to the pump Reynolds number to predict the performance of centrifugal pumps for non-Newtonian materials, especially those described by the yield pseudo plastic model. The standard pump Reynolds number has been modified: using the apparent viscosity (calculated at 2ω) for low flow rates and the plastic viscosity for high flow rates.

Sery and Slatter (2002) have analysed centrifugal pump data with the existing deration procedures. They considered the investigated fluid (yield pseudoplastic) in terms of the Bingham plastic model. Similar results to the previous work were found. However, the following questions arise.

2.12.1 Deration procedures

The calculation of an apparent viscosity in the pump volute still remains a matter of conjecture (Sery and Slatter, 2004). The use of the plastic viscosity has no solid background, given that the plastic viscosity is merely a fitting parameter suitable to Bingham plastic fluids. Therefore, the choice of an appropriate viscosity for both the pump Reynolds number method and the Hydraulics Institute deration chart is critically important.

Walker and Goulas (1984) have established that friction losses experienced by higher specific speed pumps are less than those produced in low specific speed pumps. They have plotted data (HR and ER versus NRep) from different pumps whose specific speed values were 0.27, 0.43, 0.53 and 0.74 respectively. Two different specific speed pumps (0.43 and 0.52) will be used in the test work. Results will be compared in the light of the above statement.

Hydraulic Institute prediction results differ from those by Walker and Goulas (1984).

2.12.2 Material tested

No mention has been made regarding the evaluation of both deration procedures for centrifugal pumps handling pseudoplastic fluids. The present work will attempt to fill the gap.

In their work, Walker and Goulas (1984) added an aqueous solution of sodium silicate to alter the viscosity of the kaolin clay. This practice will not be followed during slurry mixing for this project.

The present study is an extension of the Walker and Goulas (1984) work including the use of pseudoplastic and Bingham plastic materials. All the materials to be tested are characterised as time independent non-Newtonian fluids.

CHAPTER 3

EXPERIMENTAL INVESTIGATION

3.1 INTRODUCTION

The experimental apparatus and the test procedures are described in this chapter. In addition, the theory of error calculation, the pipe pressure gradient test results and the centrifugal pump test results are presented and the materials tested are described.

The experimental work was performed after the apparatus had been calibrated for the following objectives:

- to measure the rheology accurately;
- to perform a pump performance test at different speeds of rotation with a 6/4 Warman pump and a 4/3 GIW pump respectively; and
- to provide a database for evaluating existing deration procedures.

3.2 DESCRIPTION OF THE EXPERIMENTAL RIG

The rig included a 3.11 m^3 cylindro-conical steel mixing-tank, two centrifugal slurry pumps driven by electric motors, and two speed-torque units connected between each motor and the pump shaft. An electrical board held both the main power switch and a 90 kW Klöckner Moeller variable-speed drive. Pipes of diameter 65 mm, 80 mm, 150 mm and 200 mm constitute the loops through which the slurry was recirculated.

A magnetic flux flow meter was placed on each vertical return line. Two pressure transducers were connected to the pump inlet and outlet tappings on one side and two differential pressure transducers were installed on the PVC clear return lines on the other side. Two auxiliary electric motors were used to run the mixer and the cooling system.
A steel weigh tank (capacity 1.2 m^3) of a cylindro-conical shape and mounted on a scale platform was utilised during the flow meter calibration or to measure the weight of a certain volume of pumped material.

Test data were captured from the rig through sensors (i.e. differential pressure transducer, flow meter) as analogue electrical signals. The data acquisition unit converted the magnitude of the analogue electrical signals into digital electrical signals capable of being processed by the computer. Stored digital numbers were converted into the magnitude equivalent to the desired analogue electrical signal (pressure or flow) by calculation in the computer using calibration constants.

Depending on the type of test required, two test sections were defined:

1) For the centrifugal pump test, the flow meter and the pump bay represented the test section. The pump bay in this case regrouped the inlet and the discharge pipe from the flanges up to the pressure tappings, including the pump itself and the torque speed unit.
2) The pressure gradient test section was limited by two pressure tappings that had a length interval ranging from 3 m to 5.36 m on the horizontal return straight PVC pipe. The discharge vertical pipe holding the flow meter was placed several meters following the last tapping on the test section before the mixing tank. A schematic diagram of the rig is presented in Appendix A.

3.3 EXPERIMENTAL APPARATUS

The present section deals with the instruments used for both pump and pipe test. Pictures of the experimental instruments are given in Appendix A.

3.3.1 Centrifugal slurry pump

Two centrifugal slurry pumps were available at the FPRC pipe rig: a Warman 6/4 and a Georgia Iron Works (GIW) 4/3 that had, respectively, specific speeds of 0.52 and 0.43. Both pumps were metal, single-stage end-suction. A 90 kW squirrel cage induction motor and a 45 kW squirrel cage motor drove the 6/4 and 4/3 centrifugal pumps respectively. The pump characteristics are shown in Table 3.1 and Table 3.2.

Table 3. 1: 6/4 Warman pump characteristics (Warman Africa Limited, 1988)

6/4 WARMAN							
PUMP		**IMPELLER**				**LINER**	**Pump performance curve**
SIZE	TYPE	VANES	TYPES	MAT'L	VANE Ø	MAT'L	*WPA 64 A01* *MARCH 1988*
6/4	*AH*	*5*	*CLOSED*	*METAL*	*365*	*METAL*	
		GLAND SEALED PUMP					
FRAME		**NORM MAX RPM**			**NORM MAX KW**		**MAX PARTICLE SIZE (mm)**
D/E		*1830*			60/120		*51 Sphere*

Table 3. 2: 4/3 GIW pump characteristics (GIW, 1996)

4/3 GIW							
PUMP		**IMPELLER**				**LINER**	**Pump performance curve**
SIZE	TYPE	VANES	TYPES	MAT'L	VANE Ø	MAT'L	*E 101-87* *Test* *B188A-93*
4/3	*LCC-MC 80-300*	*3*	*OPEN*	*METAL*	*310*	*METAL*	
		MECHANICAL SEALED PUMP					
FRAME		**NORM MAX RPM**			**NORM MAX KW**		**MAX PARTICLE SIZE (mm)**
1		*2760*					*27x51*

3.3.2 Pressure tappings and pods

The commissioning of the rig or a pipe pressure gradient test (for rheology) required that the pressure along a known length of the pipe be measured. For a centrifugal pump test, the pressures at the inlet and at the outlet of the pump needed to be measured as well.

In the case of the pipe pressure gradient test, two pressure tappings were connected over determined lengths of 3 m, 3.65 m and 5.65 m for the 65 mm, 80 mm and 150 mm pipes respectively. Each tapping had a valve that allowed connection of the tested pipe to a solid pod. Nylon tubes of 3 mm internal diameter were used to transmit the pressure from the solid pods to the differential pressure transducers. Each pod had a top valve for flushing the line and evacuating air bubbles, and a bottom valve to flush away collected solids with clear water.

To perform a centrifugal pump test, a reading was taken of the pressure from the suction and the discharge pipes through the tappings and the solid pods. The pressure tappings were located at twice the distance of the suction or the discharge internal diameter (2D) from pump flanges for both the suction and discharge sides. Again, the slurry pressures from the suction and the discharge lines were transmitted to the appropriate pressure transducers through the water-filled solid pods and nylon tubes; a compound pressure transducer (vacuum plus positive pressure) was used for the suction side, while a positive pressure transducer was mounted at the discharge.

3.3.3 Pressure transducers

The pressure in the suction and discharge pipes of a centrifugal pump and across a known length of a straight pipe was measured using two types of pressure transducers:

- For a centrifugal pump, two Fuji electric point pressure transducers were placed at the inlet and the outlet pipe of the pump. The maximum pressure of the PPT was 3000 kPa with an accuracy of 0.25 %. The hand held communicator (HHC) was used to set up the PPT to an experimental range of –100 to 200 kPa for the suction PPT and 0 to 1500 kPa for the discharge PPT.
- Two differential pressure transducers (DP cell) were utilised to measure the differential pressure between two points on the pipe test section. The DP cell had the same characteristics as the PPT: a maximum power supply of 28V DC, a DC current output of 4 to 20 mA. While the maximum pressure range of the two transducers was from 6 kPa (low DP Cell) to 130 kPa (high DP Cell), the actual experimental range for the high DP Cell was limited to 80 kPa.

3.3.4 Hand held communicator (HHC)

A multifunction Fuji electric hand-held communicator type FXW 10 AY1-A3 helped to calibrate the PPT and the DP cell. It was mainly used to double-check pressure readings and to change the range of the instrument (PPT or DP Cell) to be calibrated. After calibration, the HHC allowed the comparison of data displayed with the logged values on the test program.

3.3.5 Digital Manometer (DM)

Replacing the old and cumbersome U-tube manometer, the digital manometer was made of an air piston pump and two digital pressure readers for the low- and the high-pressure values A love controls DM was used for low-pressure readings within the range of 0 to 6.9 kPa. High-pressure readings were obtained by means of a Dwyer DM, which had a maximum range of 1 MPa. Connections were made between the DM, the air pump and the pressure transducer. The pump pressurised the line while the manometers displayed the pressure generated.

3.3.6 Flow meter

Two Krohne magnetic flux flow meters were fitted on the vertical return line of the 65 mm and 80 mm test pipes. A Safmag magnetic flux flow meter was placed on the vertical return line of the 150 mm pipe. The only method to ensure accurate flow readings was to calibrate the flow meters using the weight tank and a stopwatch. The 65 mm and 80 mm flow meters were calibrated prior to the study.

3.3.7 Mixer

A shaft and an electrical motor constituting a mixer were placed vertically on top of the mixing tank. The shaft fitted with two axial vanes stirrers was 2.70 m long and had a diameter of 0.25 m. The driver was a squirrel cage electrical motor of 18.5 kW. The mixer was run during the slurry preparation and before each test to ensure the homogeneity of the mixture.

3.3.8 Speed -torque unit

Two Kyowa speed-torque units placed between the electrical motors and the centrifugal pumps replaced the old load-cell devices. A speed-torque unit of 1 kN.m was fixed between the 4/3 pump shaft and the 45 kW motor. The characteristics of the device were the following:

- type TP-100K MAB; and
- serial number 3X0580001.

On the other side, a speed-torque unit of 2 kN.m connected the 6/4 Warman pump shaft and the driver. The characteristics of the device were the following:

- type TP-200K MAB; and
- serial number 3Z0360001.

The shaft of the speed-torque unit rotated at the same speed as the pump and displayed the speed of rotation and the current shaft torque via a digital meter.

3.3.9 Data acquisition unit (DAU) and computer

The outputs of the instruments used to capture measured variables were monitored by means of an Agalent 34970A data acquisition and switch unit. The data acquisition unit was equipped with several input channels which converted the analogue signals from various devices (i.e. flow meter, DP cells, etc.) into digital signals. An Intel Celeron 2.40 GHZ, 260 RAM PC was used to save the captured data for further analysis. Microsoft Excel spreadsheets were set up to process the data. The test programs were written in Visual Basic 6.

3.3.10 Cooling tower and cooling System

A cooling system consisting of 10 m-long jacket pipes surrounding the 80 mm and 150 mm test pipes. Water from the cooling tower was pumped through the jacket pipes in the opposite direction to the tested slurry and recirculated. The heat could be exchanged between the slurry (high temperature) and water (ambient temperature) owing to the position of the two pipes.

3.4 EXPERIMENTAL PROCEDURES

The experimental procedures consisted of various operations. The most important of these were the calibration of the instruments, the determination of viscous properties of fluids and the determination of the pump performance curves.

3.4.1 Calibration

The calibration of the instruments used in the experiment was a pivotal task to ensure the reliability of the results for the present study. It should be borne in mind that any experimental work is subject to error, the magnitude of which should be evaluated.

3.4.1.1 Flow meter

Each magnetic flow meter had a limited capacity which was a function of its size. The flow meter accuracy was ± 0.5% for velocity ≥ 0.5 m/s and ± 0.025% of full scale for velocity ≤ 0.5 m/s according to the manufacturer's catalogue.

3.4.1.2 Differential pressure transducer

Two differential pressure transducers manufactured to operate in the ranges of 0 to 6 kPa and 0 to 130 kPa were calibrated using a digital manometer and the hand-held communicator. The calibration procedure is described below.

1) The low- and the high-pressure digital manometers were both connected to the air pump by means of a four-way junction. The fourth plug was connected to the high side of the DP cell.
2) The HHC (set in the pressure display mode) was connected to the electrical part of the DP Cell.
3) The air pump allowed the increase or the adjustment of the pressure within the system. The displayed pressure read either from the digital manometer or from the HHC – and these had to be the same – was recorded along with the transducer output voltage monitored by the DAU.

The calibration equation was obtained by performing a linear regression on the co-ordinates pressure versus transducer DC voltage output. The coefficient of correlation R^2 had to be at least 0.999. A typical graph of the above calibration is shown in Figure 3.1.

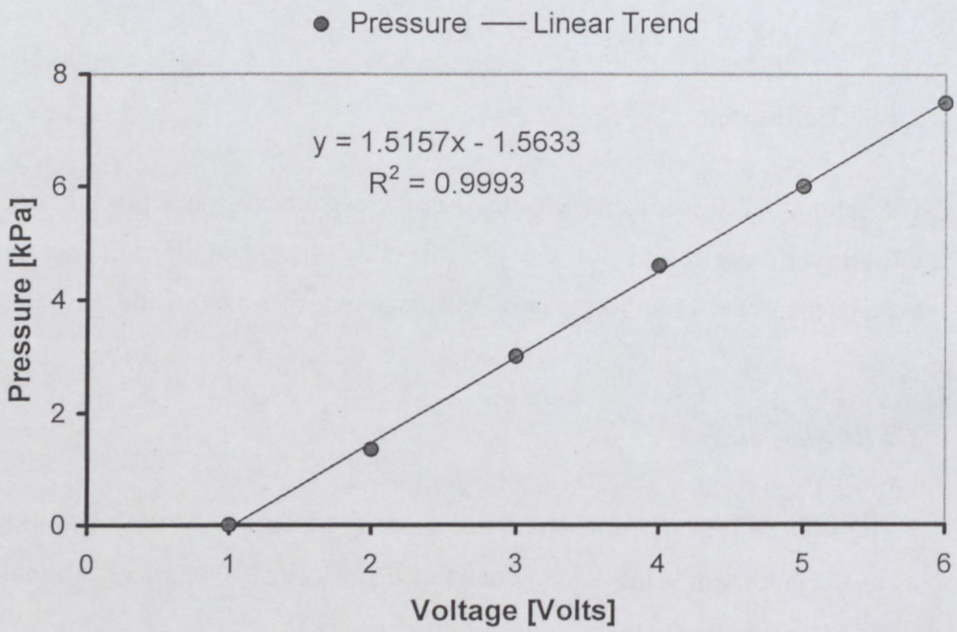

Figure 3.1: Typical calibration graph for DP cell

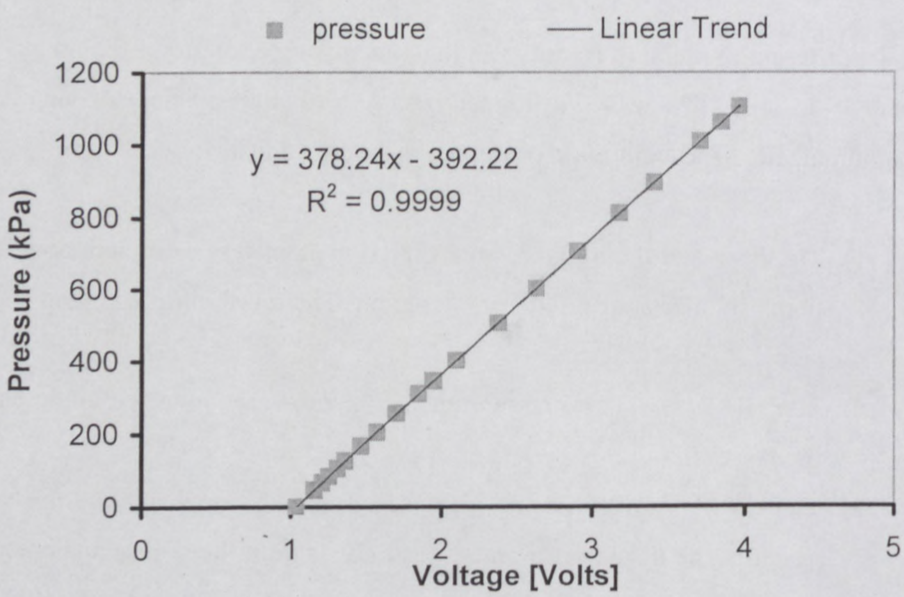

Figure 3.2: Typical calibration graph for absolute pressure transducer

3.4.1.3 The point pressure transducer

The point pressure transducer that had to be connected to the pump discharge was calibrated using the HHC and the air-compressor. The PPT required a pressure supply higher than 1000 kPa in order to be calibrated. The calibration procedure followed the same steps as for the DP cell. At the last stage, a plot of the PPT output voltage versus the HHC pressure readings gave the calibration constants as shown in Figure 3.2.

The above procedure was repeated for the PTT to be connected to the suction side for the positive values. The maximum pressure set up was 200 kPa. A vacuum pump was used to apply negative pressure up to -75 kPa. Pressure readings versus DC output voltage were plotted, and the calibration equation obtained is shown in Figure 3.3.

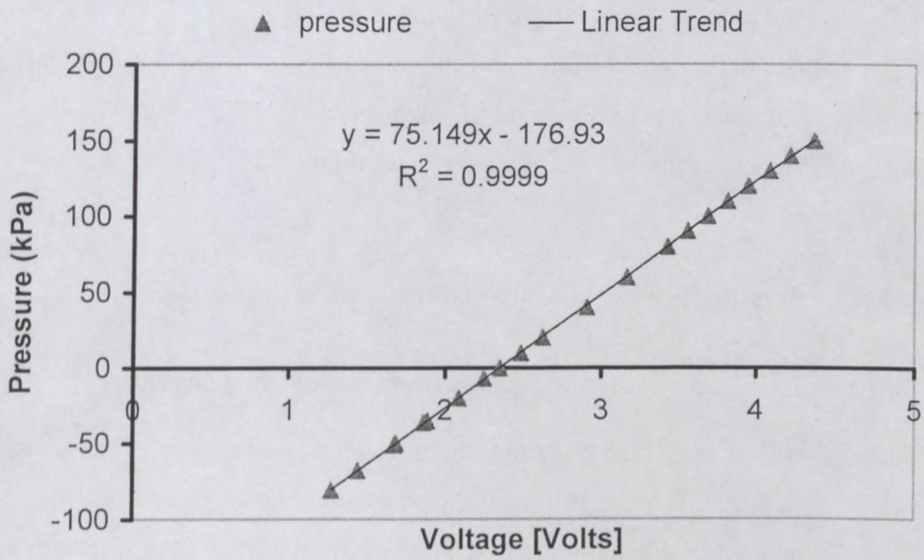

Figure 3.3: Typical calibration graph for compound pressure transducer

3.4.1.4 The speed-torque unit

The speed-torque unit was placed between the motor and the centrifugal pump shaft. It rotated at the same as the pump speed. Calibration consisted of correlating the data logger voltages to the torque displayed. The constants of calibration obtained from a linear regression were stored in the computer and used during the tests. The speed was not calibrated; however, the displayed values were double-checked using a tachometer.

3.4.2 The pump test procedure

A centrifugal pump test seeks to establish the performance of the pump when pumping different fluids. This is expressed as a plot of head, efficiency and power versus flow rate. The test procedure followed in the study, is described in the section below.

- Warming up of instrumentation (torque transducer, centrifugal pump and electrical motor) for at least thirty minutes while the fluid (water or slurry) circulated through the rig to ensure a homogeneous mixture.
- A representative sample was taken through a sampling tap along the test loop to measure the relative density (see Appendix G).
- The reading of the measured variable started after the selection of the desired pump speed. At a particular constant speed, the valve was manipulated to increase or decrease the flow.
- The pump was run for four different speeds
- The data were collected and processed to obtain the final plot of head, efficiency and power versus flow rate for each speed.
- The procedure was repeated for other fluids.

3.4.3 Pressure gradient test procedure

The objectives to be achieved when performing straight pipe test are:

- with water as the test fluid, the test seeks to determine the roughness of the pipe. It is possible to determine the pipe roughness by comparing the Colebrook-White equation with the measured pressure drop across a known length of pipe (King, 2002). Results of water tests are presented in Figures 3.7 to 3.9 and in Appendix B; and
- with slurries, laminar pipe test data are used to determine the rheological parameters.

Results are presented in a plot of shear stress versus pseudo-shear rate. Figures 3.4 to 3.6 show the pseudo-shear diagram for CMC 5%, kaolin 17% and bentonite 7% in 63 mm, 80 mm and 150 mm diameter pipes respectively.

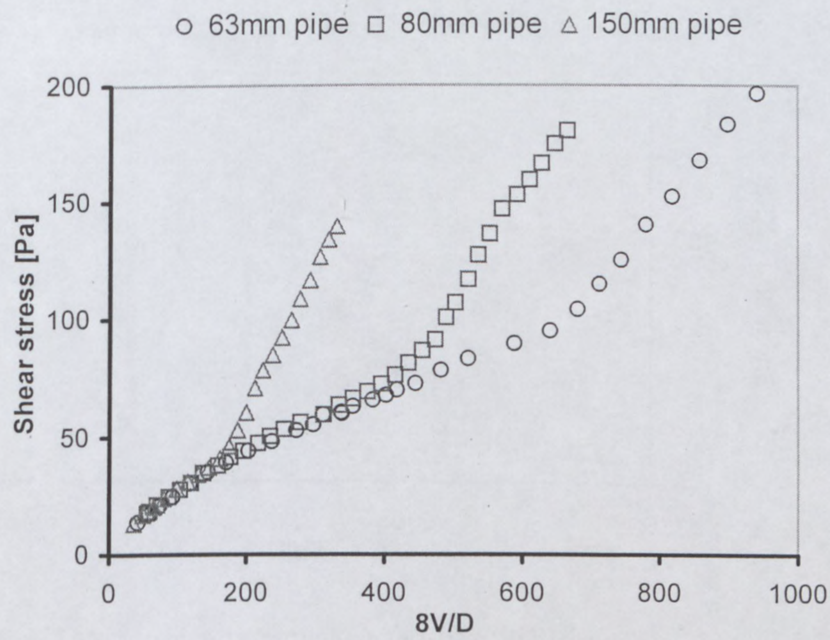

Figure 3.4: Pressure gradient test for CMC 5%

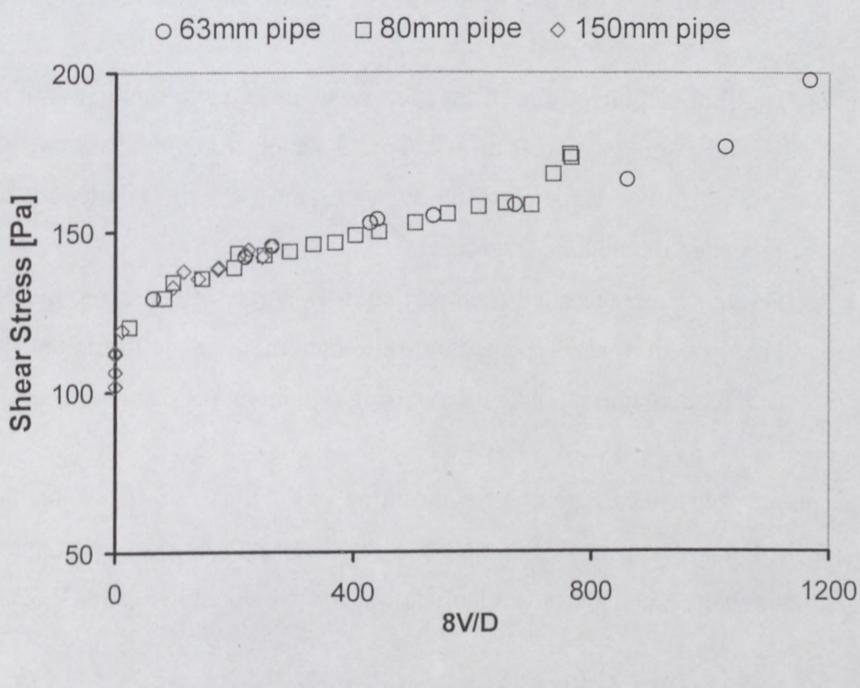

Figure 3.5: Pressure gradient test for kaolin 17%

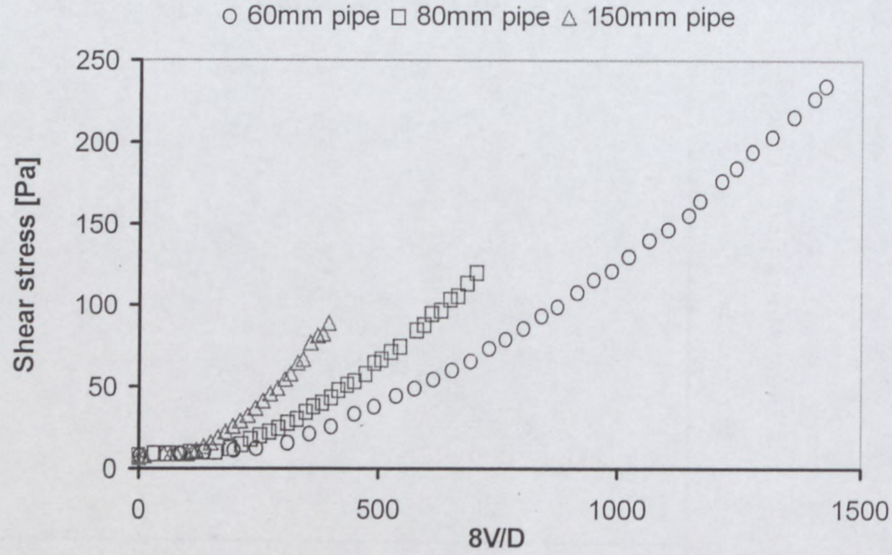

Figure 3.6: Pressure gradient test for bentonite 7%

The steps followed during the pipe test are presented in the following section.

1. The pump was warmed up for thirty minutes, and the slurry was mixed at the same time.
2. The first tapping on the test section was connected to the high-pressure DP cell. The second tapping, placed at a known distance from the first one (3 m, 3.65 m or 5.65 m), was connected to the low-pressure DP cell. The length between tappings depended on the pipe test loop.
3. The computer recorded each particular flow rate selected and the pressure readings. The procedure was repeated until the maximum or the minimum flow was reached. One reading corresponded to one single point on the pseudo-shear diagram.

The above steps were repeated for the three pipe loops. The data obtained for each pipe tested had to overlap in the laminar region when plotted on one graph. The rheological parameters were calculated from laminar data as explained in section 2.5.3 and 2.4.4.

3.5 EXPERIMENTAL ERRORS

Routine measurements, even with high-quality instruments, are not perfectly accurate, and a small margin of error is accepted (Brinkworth, 1968). A brief introduction to error theory is given below, and the analysis of the experimental errors encountered in the determination of centrifugal pump performance is presented.

3.5.1 Error theory

Whenever measurements are made, errors occur, except when the measurement is a discrete count. Therefore, steps have to be taken to evaluate the accuracy and precision of the measurements (Barry, 1991). Two different types of error exist: systematic errors and random errors.

3.5.1.1 Systematic errors

Systematic errors are those due to known conditions and which vary with these conditions. The conditions might be:

- natural (temperature, atmospheric pressure, humidity);
- instrumental (graduation, range, calibration); and
- personal-physical limitations (a tendency to observe to the right or the left in estimating length; poor ability in noting times at the beginning and end, and of intervals, when using a stopwatch).

In this study, precautionary procedures were used to prevent the occurrence of systematic errors, for example repeating measurements at least three times. During calibration, care was taken regarding the correlation coefficients that are required to be at least $R^2 = 0.9999$.

3.5.1.2 Random errors

Random errors are due to improbable variation. They have a tendency to be mutually compensating and are random in occurrence and size. Only by studying the discrepancies that occur among repeated measurements of the same quantity can one evaluate this type of error (Barry, 1991). Thus, if in a large number of readings the values are distributed in a characteristic symmetrical way around the mean value, known as the normal or Gaussian distribution, experimental data can be analysed by statistical methods (Brinkworth, 1968). In this study, statistical method was used to determine the magnitude of error.

3.5.2 Evaluation of errors

3.5.2.1 Single errors

The uncertainty or error associated with a measurement (or, alternatively, the accuracy) of a variable X can be expressed as:

$$X = A \pm \Delta a \tag{3.1}$$

This means that the true value of X lies between $X = A - \Delta a$ and $X = A + \Delta a$, where Δa is called the maximum error or absolute error. It is expressed in the same unit as the variable. Δa is here the smallest division of the instrument, that is, the smallest value detected by the instrument (Barry, 1991). Δa is calculated from the standard deviation of a set repeated measurement as well. The absolute error for A at 99.9% confidence interval is given in Equation 3.2

$$\Delta a = 3.29\sigma \tag{3.2}$$

If A at 95% confidence level is considered, then the absolute error may be approximated by

$$\Delta a = 2\sigma \tag{3.3}$$

In relative terms, the error can be expressed as:

$$X = A \pm \frac{\Delta a}{A} \tag{3.4}$$

where $\pm \frac{\Delta a}{A}$ is the relative error and is generally given in the form of a percentage.

3.5.2.2 Combined errors

When a variable is a result of a calculation of other variables with their subsequent errors, the resulting error is the combination of the independent variables' errors (mean quadratic value of the independent errors). If a variable X is a function of n other variables, i.e. X=F (a, b, c…n), the expected highest error can be calculated from Equation 3.5 (Brinkworth, 1968).

$$\left(\frac{\Delta X}{X}\right)^2 = \sum\left(\frac{\partial X}{\partial n}\right)^2\left(\frac{n}{X}\right)^2\left(\frac{\Delta n}{n}\right)^2 \tag{3.5}$$

where:

	X	=	the computed result;
	ΔX	=	the computed absolute error;
	n	=	the independent variable involved; and
	Δn	=	the independent variable absolute error.

3.6 ERRORS IN MEASURED VARIABLES

a) Pressure

The pressure transducers used had an accuracy of ± 0.25%. Care was taken during the calibration procedure that a correlation coefficient attained at least the value of 0.9999.

b) Flow rate

The flow meter manufacturer gave a relative error of about ± 0.5% for each flow meter.

c) Relative density

A chemical balance used for the relative density test presented a very small percentage of error (0.1%). However, the RD test was performed at least tree times for each tested material and the largest difference in these measurements was taken as a representative of the true error. The highest error was then found to be 0.35%

3.7 COMBINED ERRORS

In this section, errors of principal pump, derived variables are presented. True values of accuracy will depend on current measured values. In general, the accuracy becomes greater as the number of measured values increases.

3.7.1 Pipe area

The cross-section areas of inlet and outlet pipes were calculated using:

$$A = \pi \frac{D^2}{4} \tag{3.6}$$

Applying Equation 3.5 to the above equation, the following was obtained:

$$\left(\frac{\Delta A}{A}\right)^2 = \left(\pi \frac{D}{2}\right)^2 \left(\frac{\Delta D}{A}\right)^2 \tag{3.7}$$

Following that, the expected highest error for the area calculation is:

$$\frac{\Delta A}{A} = \pm \sqrt{\left(\pi \frac{D}{2}\right)^2 \left(\frac{\Delta D}{A}\right)^2} \tag{3.8}$$

Introducing Equation 3.6 into Equation 3.8 gives:

$$\frac{\Delta A}{A} = \pm \sqrt{\left(2 \frac{\Delta D}{D}\right)^2} \tag{3.9}$$

3.7.2 Velocity V

The velocity is derived from Equation 3.10

$$Q = V * A \tag{3.10}$$

then

$$V = \frac{Q}{A} = \frac{Q}{\left(\pi \frac{D^2}{4}\right)} \tag{3.11}$$

The application of Equation 3.5 to the above equation gives:

$$\left(\frac{\Delta V}{V}\right)^2 = \left(\frac{\Delta Q}{Q}\right)^2 + 4\left(\frac{\Delta D}{D}\right)^2 \quad (3.12)$$

The velocity expected highest error is then given by:

$$\frac{\Delta V}{V} = \pm\sqrt{\left(\frac{\Delta Q}{Q}\right)^2 + 4\left(\frac{\Delta D}{D}\right)^2} \quad (3.13)$$

3.7.3 Pressure at inlet and outlet pipe (P_1 and P_2)

The pressure at the inlet of the pipe (P_1) and at the outlet of the pipe (P_2) was derived from Equation 3.14 and Equation 3.15 respectively.

$$P_1 = \rho_1 g H_{1m} + \rho_1 g H_{1w} \quad (3.14)$$

$$P_2 = \rho_2 g H_{2m} + \rho_2 g H_{2w} \quad (3.15)$$

where: H_{1m} is the inlet tapping height above inlet centre line

H_{2m} is the outlet tapping height above outlet centre line

H_{1w} is the inlet water column height above inlet tapping

H_{2w} is the outlet water column height above outlet tapping

The application of Equation 3.5 to the above equations gives:

$$\left(\frac{\Delta P_1}{P_1}\right)^2 = (\rho_1 g)^2\left(\frac{H_{1m}}{P_1}\right)^2\left(\frac{\Delta H_{1m}}{H_{1m}}\right)^2 + (\rho_1 g)^2\left(\frac{H_{1w}}{P_1}\right)^2\left(\frac{\Delta H_{1w}}{H_{1w}}\right)^2 \quad (3.16)$$

The pressure at the inlet pipe expected highest error is given by:

$$\left(\frac{\Delta P_1}{P_1}\right) = \pm\sqrt{(\rho_1 g)^2\left(\frac{H_{m1}}{P_1}\right)^2\left(\frac{\Delta H_{1m}}{H_{1m}}\right)^2 + (\rho_1 g)^2\left(\frac{H_{1w}}{P_1}\right)^2\left(\frac{\Delta H_{1w}}{H_{1w}}\right)^2} \quad (3.17)$$

After introducing Equation 3.14 into Equation 3.17, the final expression for the suction side becomes:

$$\left(\frac{\Delta P_1}{P_1}\right) = \pm\sqrt{\left(\frac{H_{1m}}{H_{1m}+H_{1w}}\right)^2\left(\frac{\Delta H_{1m}}{H_{1m}}\right)^2 + \left(\frac{H_{1w}}{H_{1m}+H_{1w}}\right)^2\left(\frac{\Delta H_{1w}}{H_{1w}}\right)^2} \quad (3.18)$$

Similarly, the expected highest error expression for the discharge pressure is:

$$\left(\frac{\Delta P_2}{P_2}\right) = \pm\sqrt{\left(\frac{H_{2m}}{H_{2m}+H_{2w}}\right)^2\left(\frac{\Delta H_{2m}}{H_{2m}}\right)^2 + \left(\frac{H_{2w}}{H_{2m}+H_{2w}}\right)^2\left(\frac{\Delta H_{2w}}{H_{2w}}\right)^2} \quad (3.19)$$

3.7.4 Total pump suction and discharge Head.

The total suction head H_1 is derived from Equation 3.20:

$$H_1 = \frac{P_1}{\rho_1 g} + Z_1 + \frac{V_1^2}{2g} \quad (3.20)$$

the total discharge head H_2 is given by Equation 3.21 as:

$$H_2 = \frac{P_2}{\rho_2 g} + Z_2 + \frac{V_2^2}{2g} \quad (3.21)$$

Replacing the velocity V_1 in Equation 3.20 using Equation 3.11, the total head at the suction side H_1 becomes:

$$H_1 = \frac{P_1}{\rho_1 g} + Z_1 + \frac{\left(\frac{Q}{\left(\pi \frac{D^2}{4}\right)}\right)^2}{2g} \qquad (3.22)$$

then

$$H_1 = \frac{P_1}{\rho_1 g} + Z_1 + \frac{8Q^2}{\pi^2 D^4 g} \qquad (3.23)$$

The application of the Equation 3.5 to Equation 3.23, where z is assumed errorless and P, Q and D are variables, gives:

$$\left(\frac{\Delta H_1}{H_1}\right)^2 = \left(\frac{1}{\rho_1 g}\right)^2 \left(\frac{p_1}{H_1}\right)^2 \left(\frac{\Delta P_1}{P_1}\right)^2 + \left(\frac{16Q}{\pi^2 D^4 g}\right)^2 \left(\frac{Q}{H_1}\right)^2 \left(\frac{\Delta Q}{Q}\right)^2 - \left(\frac{32Q^2}{\pi^2 D^5 g}\right)^2 \left(\frac{D}{H_1}\right)^2 \left(\frac{\Delta D}{D}\right)^2 \qquad (3.24)$$

Replacing Equation 3.23 within Equation 3.24 gives Equation 3.25:

$$\left(\frac{\Delta H_1}{H_1}\right)^2 = \left(\frac{1}{\rho_1 g}\right)^2 \left(\frac{P_1}{\frac{P_1}{\rho_1 g} + \frac{8Q^2}{\pi^2 D^4 g}}\right)^2 \left(\frac{\Delta P_1}{P_1}\right)^2 + \left(\frac{16Q}{\pi^2 D^4 g}\right)^2 \left(\frac{Q}{\frac{P_1}{\rho_1 g} + \frac{8Q^2}{\pi^2 D^4 g}}\right)^2 \left(\frac{\Delta Q}{Q}\right)^2 - \left(\frac{32Q^2}{\pi^2 D^5 g}\right)^2 \left(\frac{D}{\frac{P_1}{\rho_1 g} + \frac{8Q^2}{\pi^2 D^4 g}}\right)^2 \left(\frac{\Delta D}{D}\right)^2 \qquad (3.25)$$

Equation 3.25 can be written as:

$$\left(\frac{\Delta H_1}{H_1}\right)^2 = K_1^2 \left(\frac{\Delta P_1}{P_1}\right)^2 + K_2^2 \left(\frac{\Delta Q}{Q}\right)^2 + K_3^2 \left(\frac{\Delta D}{D}\right)^2 \qquad (3.26)$$

where K_1, K_2 and K_3 are constant:

$$K_1 = \left(\frac{P_1}{P_1 + \frac{8Q^2 \rho_1 g}{\pi^2 D^4 g}}\right) \qquad (3.27)$$

$$K_2 = \left(\frac{16Q^2}{\frac{\pi^2 D^4 g P_1}{\rho_1 g} + 8Q^2} \right) \quad 3.28)$$

$$K_3 = -\left(\frac{32Q^2 D}{\frac{\pi^2 D^5 g P_1}{\rho_1 g} + 8Q^2 D} \right) \quad (3.29)$$

The expected highest error for the suction head is then given by:

$$\left(\frac{\Delta H_1}{H_1}\right) = \pm\sqrt{K_1^2\left(\frac{\Delta P_1}{P_1}\right)^2 + K_2^2\left(\frac{\Delta Q}{Q}\right)^2 + K_3^2\left(\frac{\Delta D}{D}\right)^2} \quad (3.30)$$

Following the same procedure, the expected highest error for the discharge is given by

$$\left(\frac{\Delta H_2}{H_2}\right) = \pm\sqrt{K_1^2\left(\frac{\Delta P_2}{P_2}\right)^2 + K_2^2\left(\frac{\Delta Q}{Q}\right)^2 + K_3^2\left(\frac{\Delta D}{D}\right)^2} \quad (3.31)$$

3.7.5 Pump power (P_{out})

The pump shaft brake power P_{out} is derived from

$$P_{out} = \rho_s g Q H \quad (3.32)$$

The application of Equation 3.5 to the above equation gives:

$$\left(\frac{\Delta P_{out}}{P_{out}}\right)^2 = (\rho_s g H)^2\left(\frac{Q}{P_{out}}\right)^2\left(\frac{\Delta Q}{Q}\right)^2 + (\rho_s g Q)^2\left(\frac{H}{P_{out}}\right)^2\left(\frac{\Delta H}{H}\right)^2 \quad (3.33)$$

The introduction of Equation 3.32 into Equation 3.33 gives Equation 3.35:

$$\left(\frac{\Delta P_{out}}{P_{out}}\right)^2 = (\rho_s gH)^2\left(\frac{Q}{\rho_s gHQ}\right)^2\left(\frac{\Delta Q}{Q}\right)^2 + (\rho_s gQ)^2\left(\frac{H}{\rho_s gHQ}\right)^2\left(\frac{\Delta H}{H}\right)^2 \tag{3.34}$$

The pump-shaft brake power expected highest error is then given by:

$$\left(\frac{\Delta P_{out}}{P_{out}}\right) = \pm\sqrt{\left(\frac{\Delta Q}{Q}\right)^2 + \left(\frac{\Delta H}{H}\right)^2} \tag{3.35}$$

3.7.6 Pump input power (P_{in})

The pump input power P_{in} is derived from

$$P_{in} = 2\pi nT \tag{3.36}$$

The application of Equation 3.5 to the above equation gives:

$$\left(\frac{\Delta P_{in}}{P_{in}}\right)^2 = (2\pi n)^2\left(\frac{T}{P_{in}}\right)^2\left(\frac{\Delta T}{T}\right)^2 + (2\pi T)^2\left(\frac{n}{P_{in}}\right)^2\left(\frac{\Delta n}{n}\right)^2 \tag{3.37}$$

Introducing Equation 36 into Equation 37 gives:

$$\left(\frac{\Delta P_{in}}{P_{in}}\right)^2 = (2\pi n)^2\left(\frac{T}{2\pi nT}\right)^2\left(\frac{\Delta T}{T}\right)^2 + (2\pi T)^2\left(\frac{n}{2\pi nT}\right)^2\left(\frac{\Delta n}{n}\right)^2 \tag{3. 38}$$

The pump input power expected highest error is then given by:

$$\left(\frac{\Delta P_{in}}{P_{in}}\right) = \pm\sqrt{\left(\frac{\Delta T}{T}\right)^2 + \left(\frac{\Delta n}{n}\right)^2} \tag{3.39}$$

3.7.7 Pump efficiency

The pump efficiency η_{pump} is derived from

$$\eta_{pump} = \frac{P_{out}}{P_{in}} \tag{3.40}$$

The pump efficiency expected highest error is then given by Equation 3.41

$$\left(\frac{\Delta P_{out}}{P_{in}}\right) = \pm \frac{P_{out}}{P_{in}} \sqrt{\left(\frac{\Delta P_{out}}{P_{out}}\right)^2 + \left(\frac{\Delta P_{in}}{P_{in}}\right)^2} \tag{3.41}$$

The highest expected errors on the computed variables are shown in Table 3.10, Table 3.11, Table 3.12 and Table 3.13. True values expressing the magnitude of the error depend on current measured values. The next section will look at an example of numerical calculation.

3.7.8 Numerical application for the pipe diameter and pipe cross-section area error

The errors on the pipe diameter and the cross-section area were calculated using the instrument's accuracy on one hand and the standard deviation of the current measurements on the other hand. The results were compared.

3.7.8.1 Calculation of error using the instrument accuracy

The vernier used for the diameter measurement had an accuracy of 1/50 mm. This means that the absolute error made when measuring the pipe diameter was Δa = 0.020 mm. The average diameter from thirty random readings is given in the Table 3.3 below.

Table 3.3: Internal pipe diameter

6/4 Warman		4/3 GIW	
Internal diameter Inlet (mm)	**Internal diameter Outlet (mm)**	**Internal diameter Inlet (mm)**	**Internal diameter Outlet (mm)**
156.465	106.399	106.399	77.727

The relative error on the diameter and the cross-section area for the suction and discharge pipes of both pumps are given in Table 3.4 and Table 3.5 below. The absolute error was obtained from the instrument accuracy as stated in Section 3.5.2.1.

Table 3.4: 6/4 Warman suction and discharge pipe cross-section relative error

6/4 Warman				
	Pipe internal diameter [mm]	**Absolute error [mm]**	**Internal diameter relative error [±%]**	**Expected highest error for the cross-section [±%]**
Inlet	156.465	0.02	0.013	0.026
Outlet	106.399	0.02	0.019	0.038

Table 3.5: 4/3 GIW suction and discharge pipe cross-section relative error

4/3 GIW				
Pump pipe side	**Pipe internal diameter [mm]**	**Absolute error [mm]**	**Internal diameter relative error [±%]**	**Expected highest error for the cross-section [±%]**
Inlet	106.399	0.02	0.0188	0.038
Outlet	77.727	0.02	0.0257	0.051

3.7.8.2 Error made using the standard deviation for pipe diameter measurement

Table 3.6: 6/4 Warman suction and discharge pipe standard deviation on 45 measurement readings

6/4 Warman		
	Internal diameter Inlet [mm]	**Internal diameter Outlet [mm]**
Standard deviation (σ)	0.340	0.336
Average	156.465	106.399

Considering the above measurements at 95% confidence level, then Equation 3.3 may approximate the absolute error.

Table 3.7: 6/4 Warman suction and discharge pipe cross section relative error using the standard deviation.

6/4 Warman				
Pump pipe side	**Pipe internal diameter [mm]**	**Absolute error at 95% confidence [mm]**	**Internal diameter relative error [±%]**	**Expected highest error for the cross-section [±%]**
Inlet	156.465	0.681	0.4349	0.087
Outlet	106.399	0.672	0.6315	1.263

Table 3.8: 4/3 GIW suction and discharge pipe standard deviation on 45 measurement readings

4/3 GIW		
	Internal diameter Inlet [mm]	**Internal diameter Outlet [mm]**
Standard deviation (σ)	0.336	0.359
Average	106.399	77.727

Table 3.9: 4/3 GIW suction and discharge pipe cross section relative error using the standard deviation.

4/3 GIW				
	Pipe internal diameter [mm]	Absolute error at 95% confidence [mm]]	Internal diameter relative error [±%]	Expected highest error for the cross-section [±%]
Inlet	106.399	0.672	0.631	1.263
Outlet	77.727	0.718	0.923	1.847

Errors calculated using the standard deviation of current measurements are greater than those calculated using instrument accuracy. However, for the standard deviation method errors are less than 2% and can be considered as being within acceptable limits.

3.7.8.3 Error of principal computed variables

Five measurable variables were recorded more than one hundred times while the pump speed was kept constant. The mean of each variable and its standard deviation were calculated, hence the relative error at 95% of confidence level was determined using Equation 3.3. The highest expected errors for the velocity, the head, the power and the efficiency were then calculated using Equation 3.10 to Equation 3.41.

Results for 1000 rpm, 1100 rpm, 1400 rpm and 1600 rpm are presented in Tables 3.10 to 3.13. Appendix E presents the expected errors on the computed variables for other pump speeds.

Table 3.9: 4/3 GIW suction and discharge pipe cross section relative error using the standard deviation.

4/3 GIW				
	Pipe internal diameter [mm]	**Absolute error at 95% confidence [mm]]**	**Internal diameter relative error [±%]**	**Expected highest error for the cross-section [±%]**
Inlet	106.399	0.672	0.631	1.263
Outlet	77.727	0.718	0.923	1.847

Errors calculated using the standard deviation of current measurements are greater than those calculated using instrument accuracy. However, for the standard deviation method errors are less than 2% and can be considered as being within acceptable limits.

3.7.8.3 Error of principal computed variables

Five measurable variables were recorded more than one hundred times while the pump speed was kept constant. The mean of each variable and its standard deviation were calculated, hence the relative error at 95% of confidence level was determined using Equation 3.3. The highest expected errors for the velocity, the head, the power and the efficiency were then calculated using Equation 3.10 to Equation 3.41.

Results for 1000 rpm, 1100 rpm, 1400 rpm and 1600 rpm are presented in Tables 3.10 to 3.13. Appendix E presents the expected errors on the computed variables for other pump speeds.

Table 3.10: Errors of computed variables for the 6/4 Warman at 1000rpm

6/4 Warman at 1000 rpm									
Variables	Measure ments average	Standard deviation	Absolute error at 95% conf.	Relative error [±%]	EXPECTED HIGHEST ERROR [± %]				
					Velocity	Head	Pump power out	Pump power in	Efficiency
Pump flow rate [l/s]	90.782	0.198	0.396	0.436					
Pump speed [rpm]	1002.919	0.0696	0.139	0.0139					
Pressure suction [kPa]	-16.276	0.130	0.261	-1.603	0.973	1.946		1.924	
Pressure discharge [kPa]	95.037	1.078	2.156	2.268	1.336	2.526	1.995		
Pump shaft.torque [N.m]	206.736	1.989	3.978	1.924					1.802

Table 3.11: Errors of computed variables for the 6/4 Warman at 1400rpm

6/4 Warman at 1400 rpm									
Variables	Measure ments average	Standard deviation	Absolute error at 95% conf.	Relative error [±%]	EXPECTED HIGHEST ERROR [± %]				
					Velocity	Head	Pump power out	Pump power in	Efficiency
Pump flow rate [l/s]	124.470	2.237	4.474	3.595					
Pump speed [rpm]	1404.333	0.267	0.534	0.0380					
Pressure suction [kPa]	-31.501	8.254	16.507	-52.403	3.698	14.349		5.436	
Pressure discharge [kPa]	151.183	24.294	48.588	32.139	3.810	2.874	4.602		
Pump shaft torque [N.m]	390.701	10.620	21.240	5.436					4.630

Table 3.12: Errors of computed variables for the 4/3 GIW at 1600rpm

4/3 GIW at 1600 rpm									
Variables	Measure ments average	Standard deviation	Absolute error at 95% conf.	Relative error [±%]	EXPECTED HIGHEST ERROR [± %]				
					Velocity	Head	Pump power out	Pump power in	Efficiency
Pump flow rate [l/s]	29.663	0.0422	0.084	0.285					
Pump speed [rpm]	1601.215	0.491	0.982	0.061					
Pressure suction [kPa]	-15.193	0.190	0.380	-2.498	1.295	2.589		8.351	
Pressure discharge [kPa]	303.161	1.458	2.917	0.962	1.869	3.736	2.605		
Pump shaft torque [N.m]	81.333	3.396	6.792	8.350					6.080

Table 3.13: Errors of computed variables for the 4/3 GIW at 1100rpm

4/3 GIW at 1100 rpm									
Variables	Measure ments average	Standard deviation	Absolute error at 95% conf.	Relative error [±%]	EXPECTED HIGHEST ERROR [± %]				
					Velocity	Head	Pump power out	Pump power in	Efficiency
Pump flow rate [l/s]	20.015	0.021	0.042	0.211					
Pump speed [rpm]	1100.075	0.006	0.011	0.001					
Pressure suction [kPa]	-6.696	0.046	0.092	-1.377	1.280	2.561		9.393	
Pressure discharge [kPa]	147.407	0.762	1.524	1.034	1.859	3.717	2.569		
Pump shaft torque [N.m]	38.226	1.795	3.591	9.393					6.330

3.8 WATER TEST RESULTS IN STRAIGHT PIPES

The values of roughness obtained for three straight pipes are presented in Table 3.14.

Table 3.14: Roughness values for straight pipes

NOMINAL DIAMETER [mm]	INTERNAL DIAMETER [mm]	PIPE ROUGHNESS (k) [µm]
60	57.68	8
80	81.20	8
150	150.60	8

Figure 3.7 to Figure 3.9 present the comparison of water test data to the Colebrook–white equation.

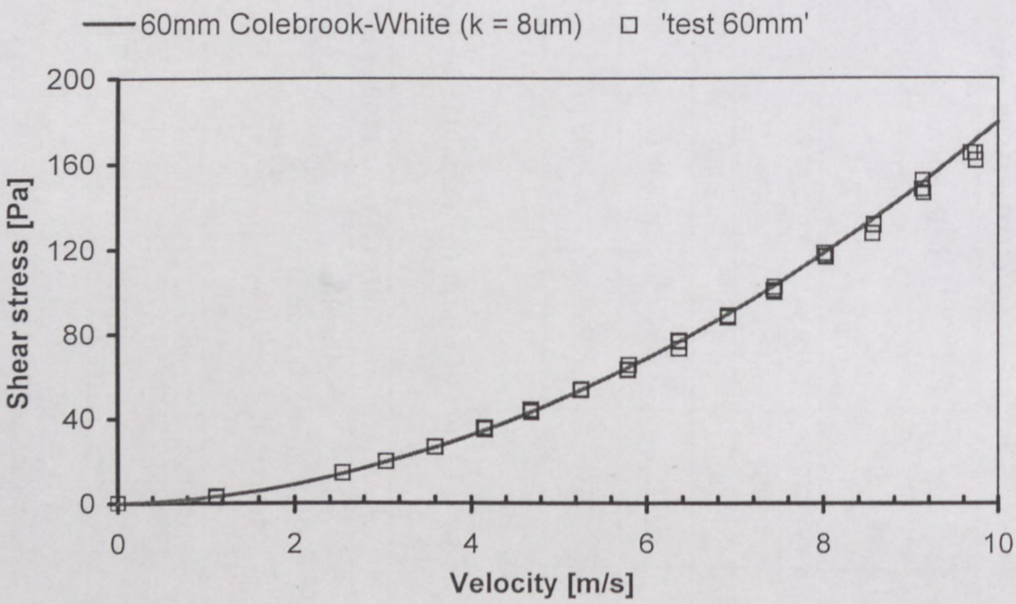

Figure 3.7: Water test in 57.68 mm straight pipe

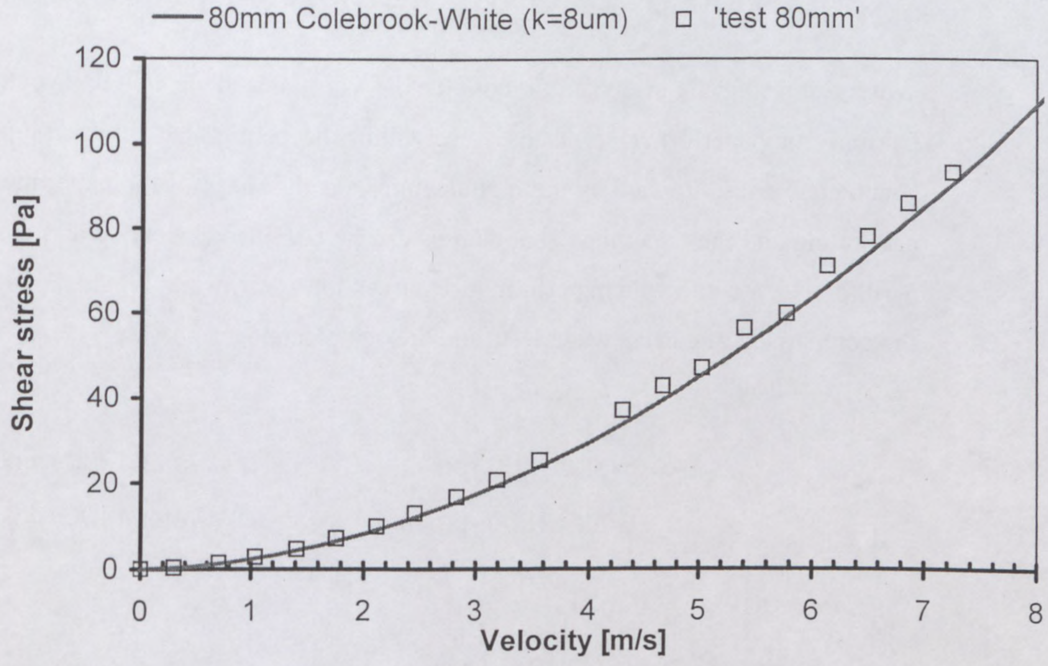

Figure 3.8: Water test in 81.20 mm straight pipe

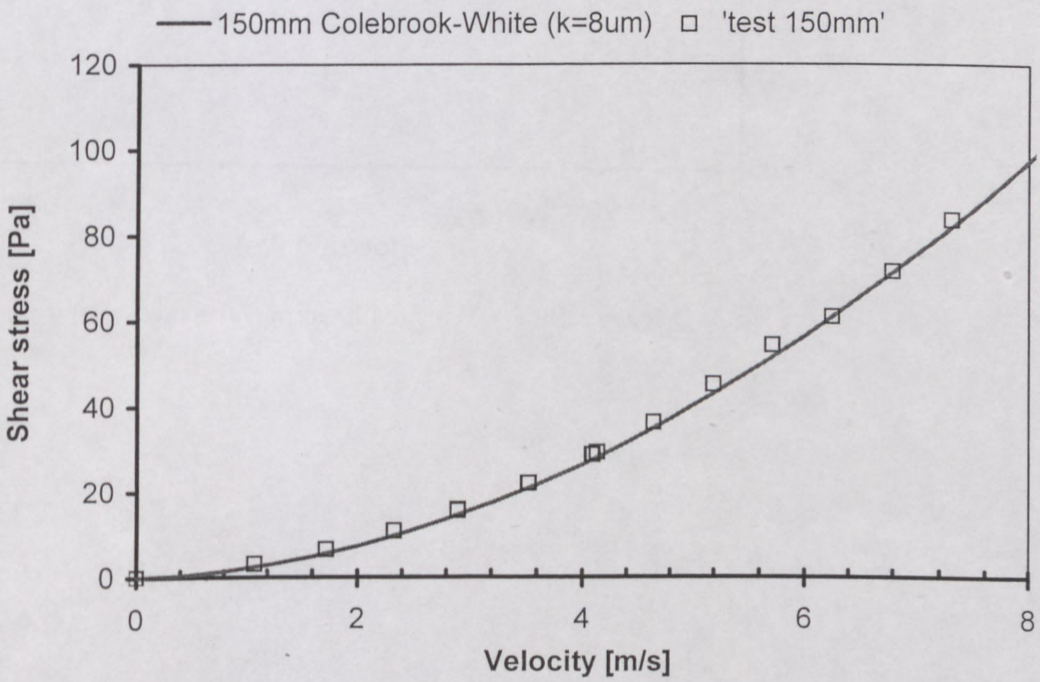

Figure 3.9: Water test in 150.60 mm straight pipe

3.9 WATER TEST RESULTS FOR CENTRIFUGAL PUMPS

Water test results are presented for both the 6/4 Warman and the 4/3 GIW centrifugal pumps. Current pump performance results were within the permissible limits compared with the catalogue curves supplied by the manufacturer. At this stage of the experimental work, the calibration and the experimental apparatus can be considered accurate and credible. Figures 3.10 to 3.15 show the pump performance curves for water, while Figures 3.16 to 3.19 depict the comparison of current water tests and the pump catalogue curves.

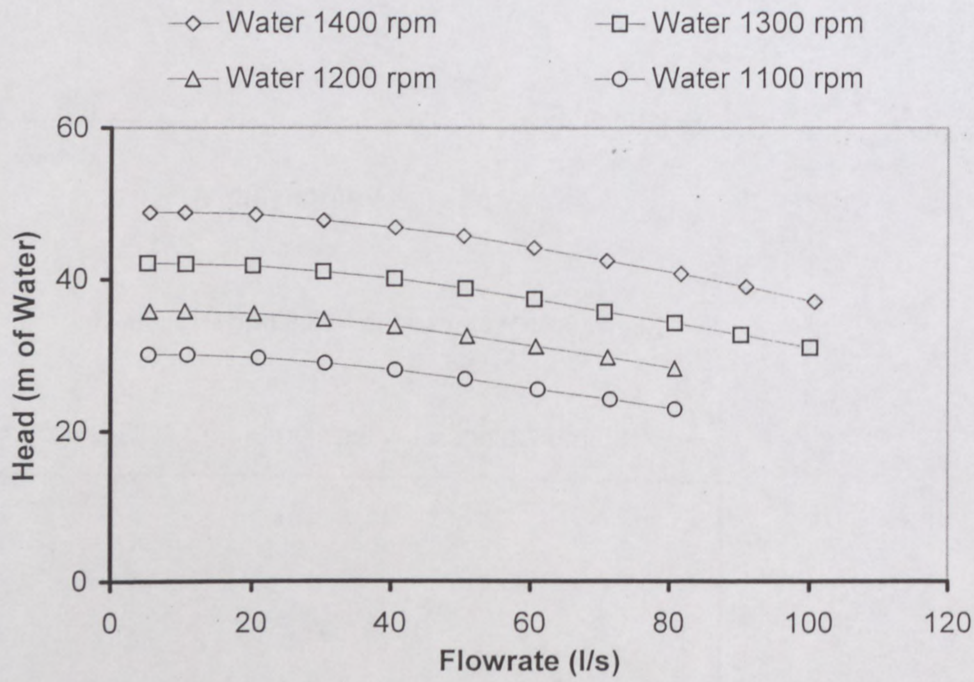

Figure 3.10: 6/4 Warman head performance curves

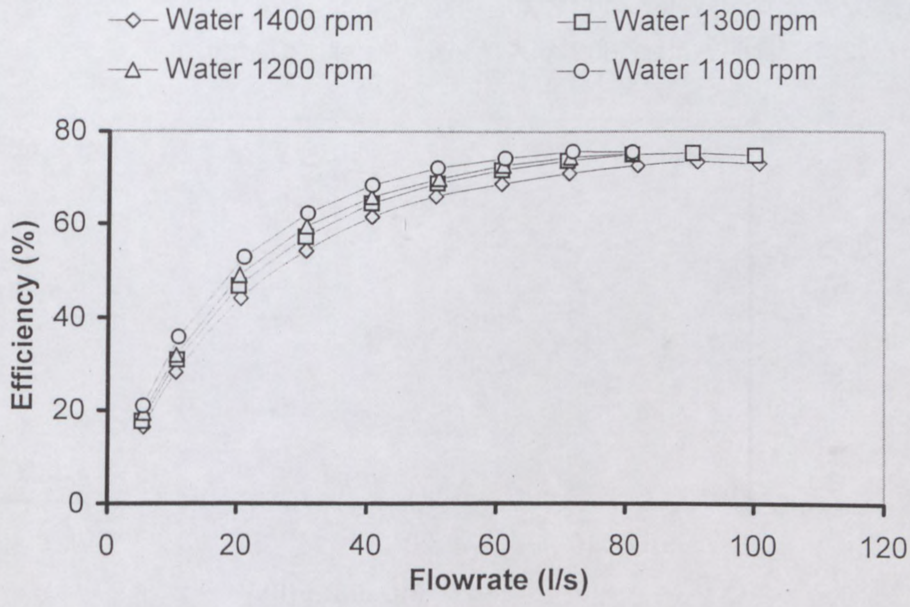

Figure 3.11: 6/4 Warman efficiency performance curves

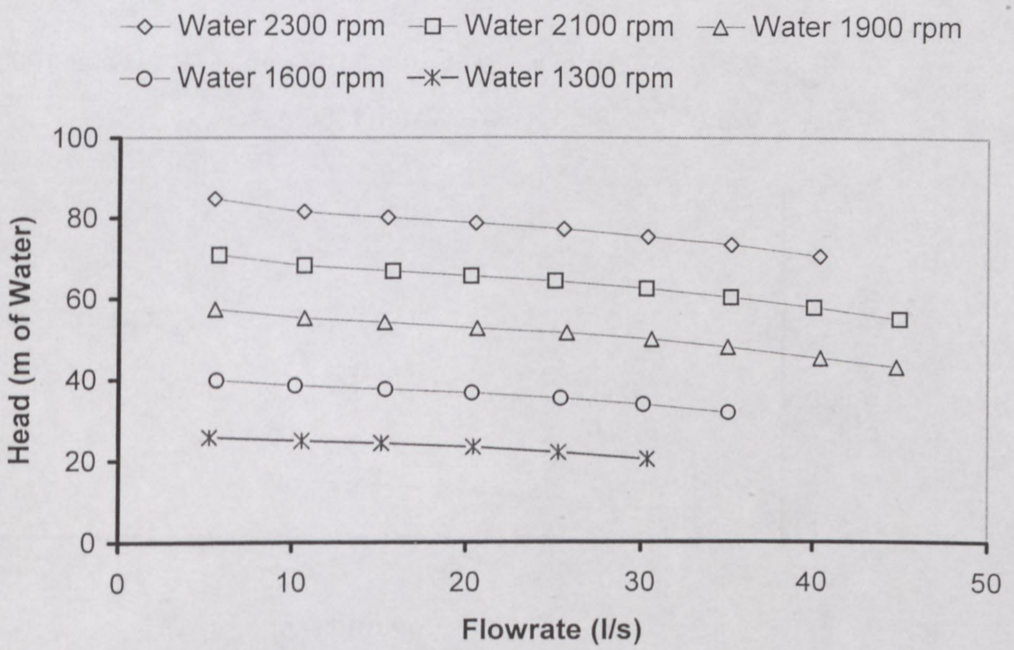

Figure 3.12: 4/3 GIW head performance curves

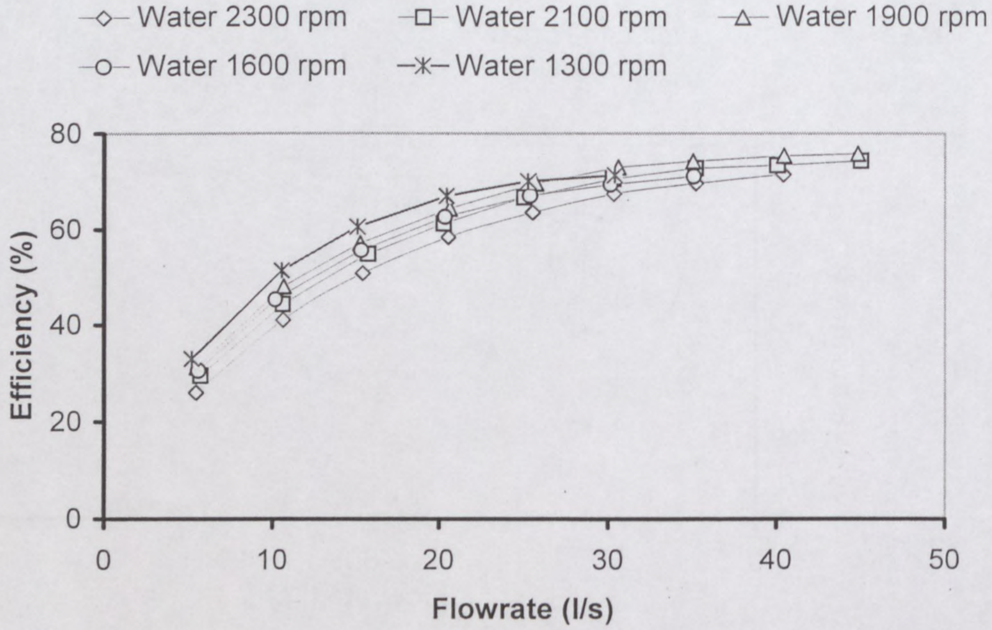

Figure 3.13: 4/3 GIW efficiency performance curves

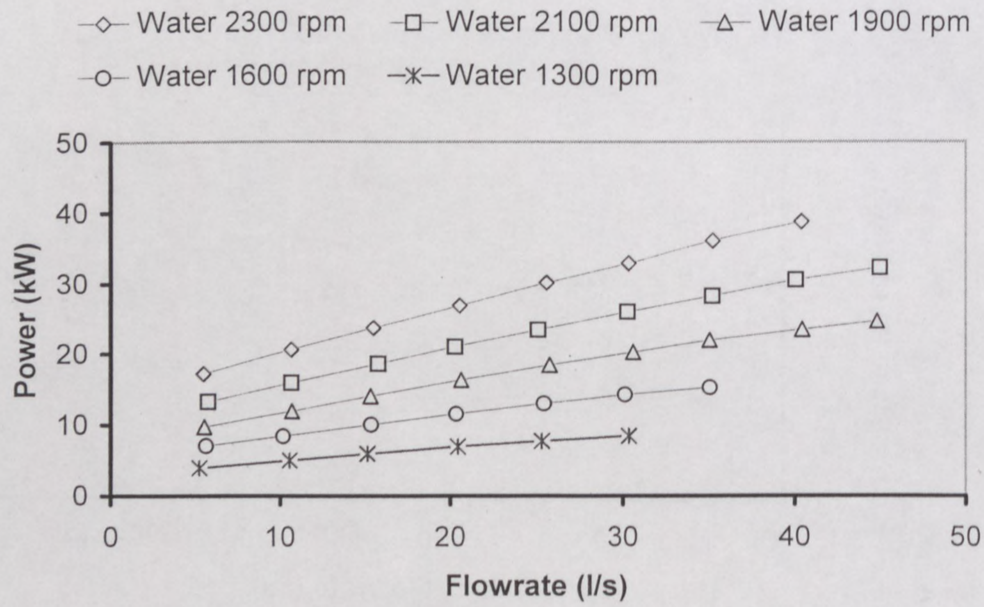

Figure 3.14: 4/3 GIW Power performance curves

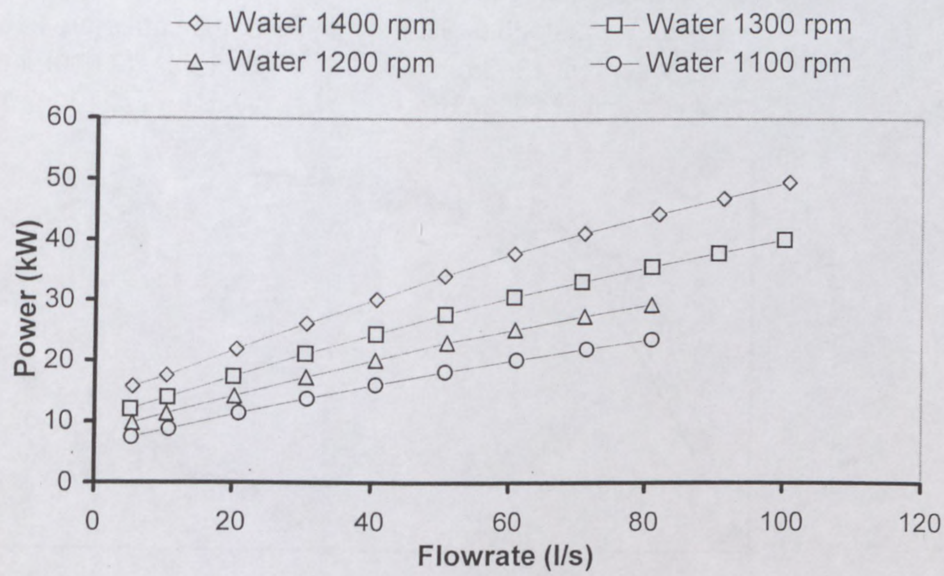

Figure 3.15: 6/4 Warman power performance curves

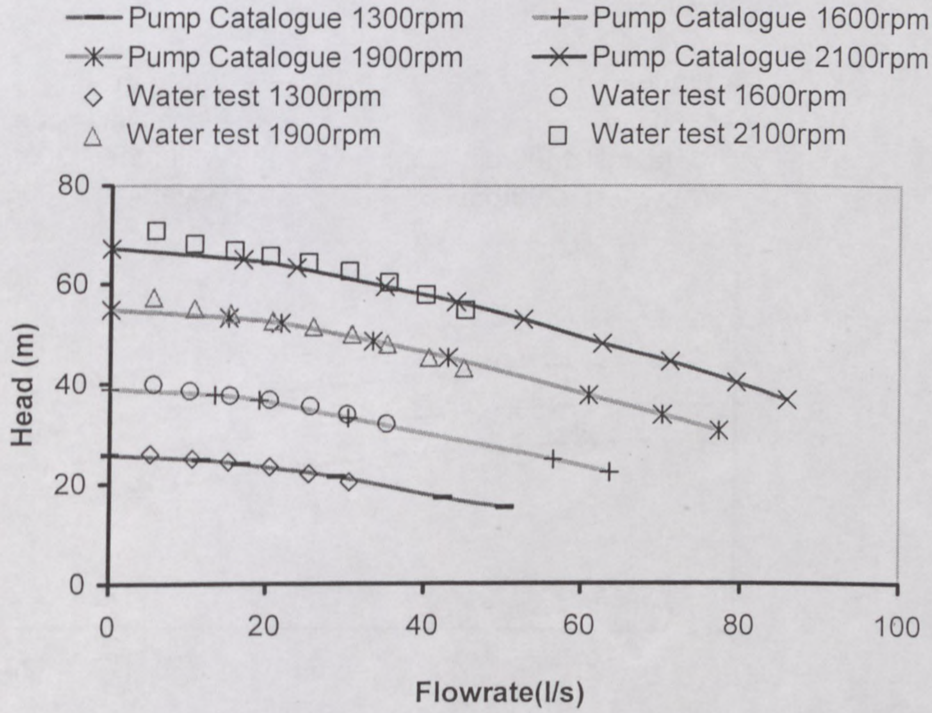

Figure 3.16: 4/3 GIW comparison of water test and catalogue curves (head)

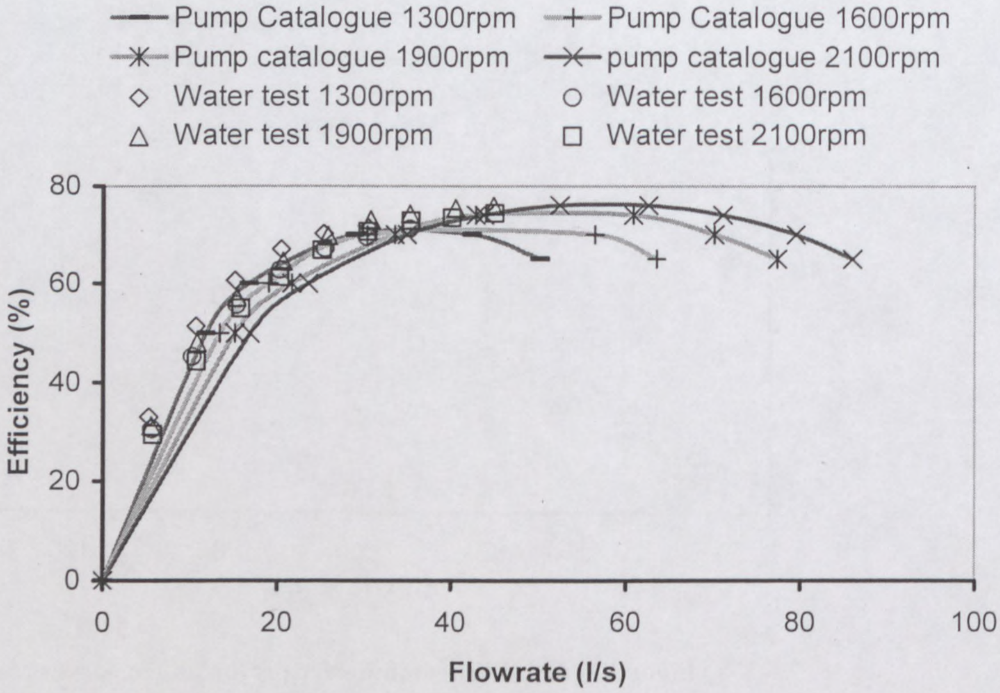

Figure 3.17: 4/3 GIW comparisons of water test and catalogue curves (efficiency)

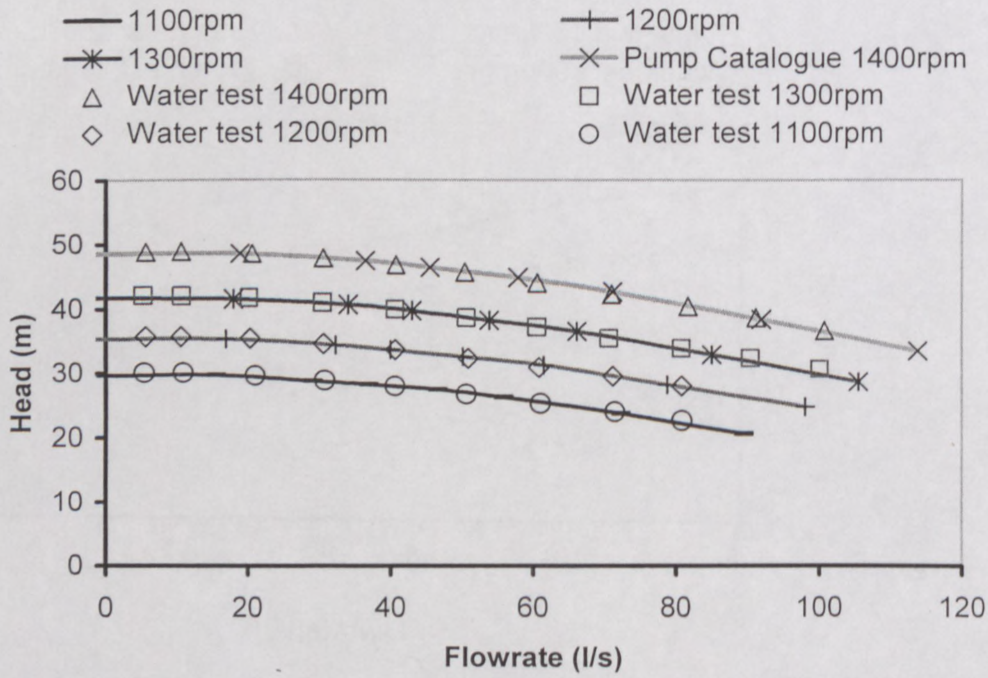

Figure 3.18: 6/4 Warman comparison of water test and catalogue curves for the head

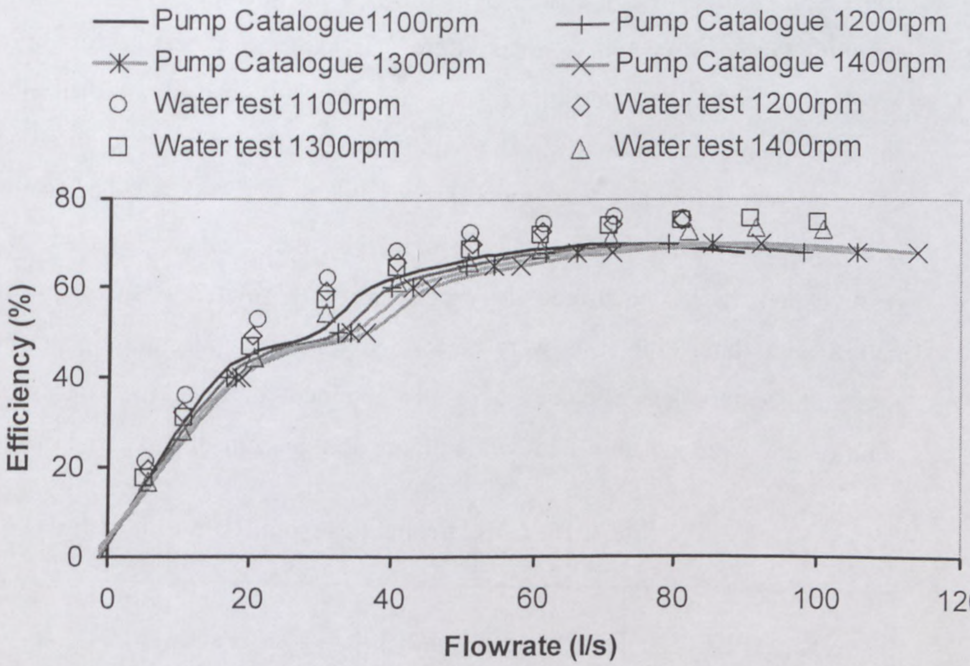

Figure 3.19: 6/4 Warman, comparisons of water test and catalogue curves for the efficiency

3.10 MATERIALS TESTED

A number of fluids presenting non-Newtonian behaviour were tested to complete this study. The fluids selected were carboxyl methyl cellulose (CMC) (pseudoplastic behaviour), kaolin (yield pseudoplastic behaviour) and bentonite (Bingham plastic behaviour). A detailed description of these fluids and they respective pipe test results and rheological parameters are given in the next section.

3.10.1 Carboxyl methyl cellulose (CMC)

Protea Industrial Chemicals haD supplied the yellowish granular powder used to make the CMC solutions. Norilose (the powder's commercial name) is a water-soluble anionic colloid, This product is widely used in industry for multiple applications, for example: in resin emulsion, paints, paper glue and as a chemical reagent.

The CMC solution was prepared by adding the powder progressively to tap water while agitating the solution with a mixer. Care was taken to avoid the formation of lumps. A weight-by-weight concentration of 9% CMC was firstly mixed and then diluted to 7%, 6% and 5%. Each concentration was thoroughly mixed over 48 hours to allow better absorption of the powder before any test. It was not possible to test 9% CMC because of the excessive heat generated in PVC pipes caused mainly by the resistance to flow of the fluid. The relative density was measured daily because of the material's predisposition to alter its nature with time. Pipe tests were performed for each concentration preceding the pump performance test. The rheological results obtained for the three concentrations of CMC solution are given in Table 3.15, while Figure 3.20 presents the material rheogram.

Table 3. 15: CMC properties from RD and pipe tests

SAMPLE	DENSITY [kg/m^3]	K [Pa.s^n]	n
CMC 5 %	1028.3	1.3745	0.6875
CMC 6 %	1032.3	1.9702	0.6551
CMC 7 %	1036.8	3.6886	0.5978

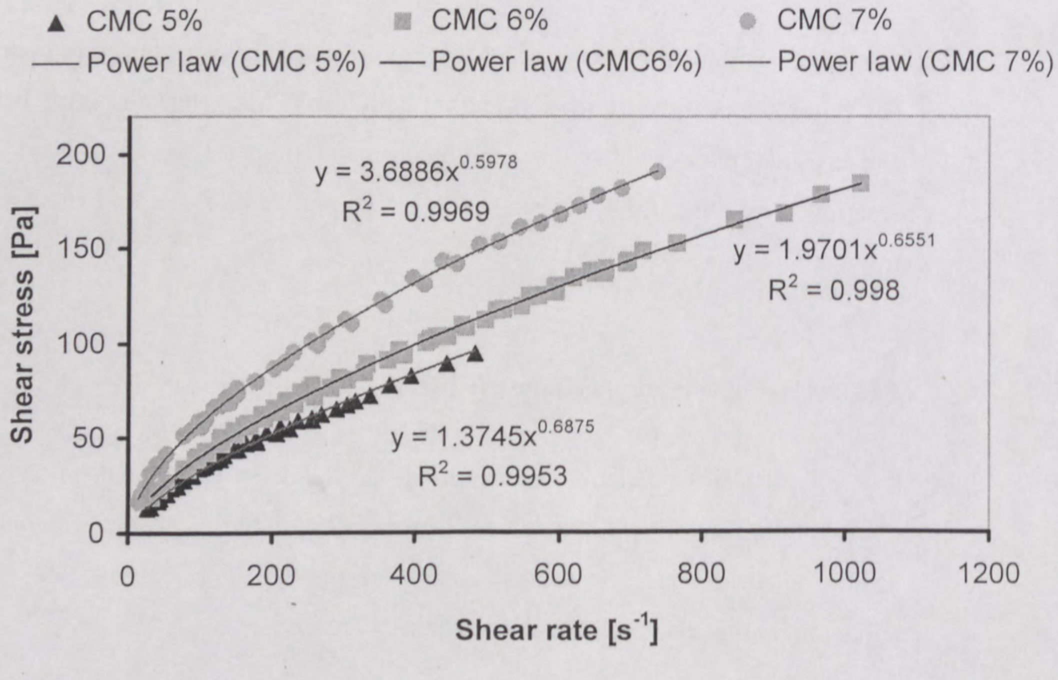

Figure 3.20: Rheogram for CMC tested in 60, 80 and 150 mm diameter pipes

3.10.2 Kaolin

Serina Kaolin (Pty) Ltd supplied the kaolin used for this study. The dry white powder was mixed with tap water to obtain kaolin paste at the desired concentrations. Before any application, kaolin was thoroughly mixed to homogenise the suspension, as its particles settle slowly. A 17% volumetric concentration was prepared and tested. Following this, the concentration was increased to 19% and 21%. The pipe test always precedes the pump performance test.

The values of the rheological parameters are given in Table.3.16 and the rheogram in Figure 3.21.

Table 3.16: Kaolin properties from RD and pipe rheology tests

SAMPLE	DENSITY [kg/m^3]	τ_y [Pa]	K [Pa.s^n]	n
Kaolin 17 %	1284.0	104.850	2.126	0.430
Kaolin 19 %	1315.9	152.779	0.791	0.623
Kaolin 21 %	1351.1	218.04	1.479	0.534

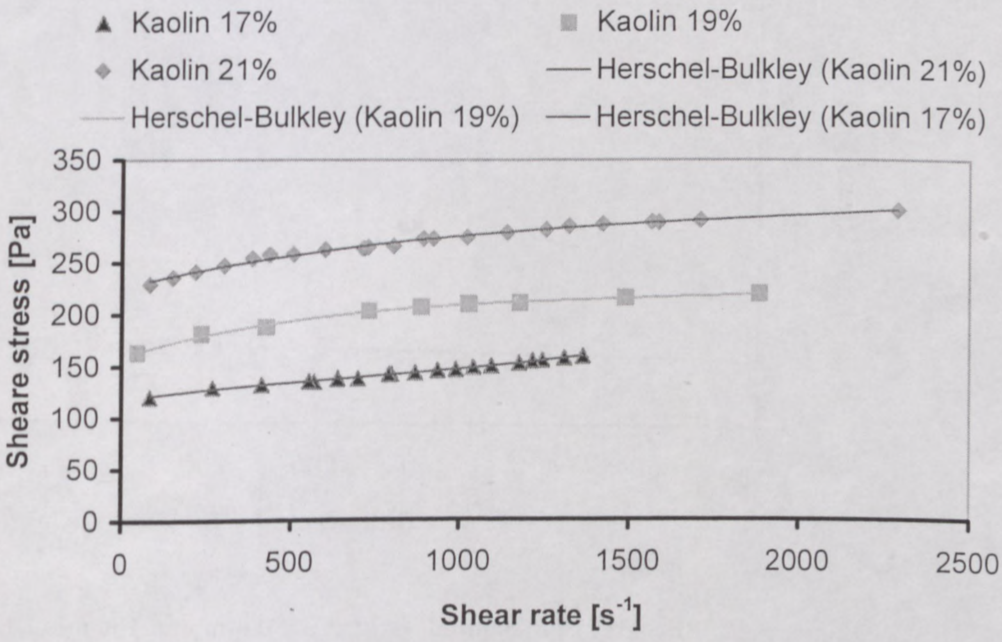

Figure 3.21: Rheogram for kaolin tested in 60, 80 and 150 mm diameter pipes

3.10.3 Bentonite

The drilling mud was obtained in dry powder from Protea Industrial Chemicals. Bentonite slurry was prepared by mixing the powder with tap water. Knowing that bentonite mud has some thickening properties, the weight-by-weight mixture concentrations of 7% and 9% were left to stand for five days to hydrate fully before the test. Pump tests were run after the pipe tests for each concentration. The values of the rheological parameters are presented in Table 3.17 and the rheogram is shown in Figure 3.22.

Table 3. 17: Bentonite properties from RD and pipe rheology tests

SAMPLE	DENSITY [kg/m^3]	τ_y [Pa]	K [Pa.s^n]	n
Bentonite 7 %	1046.4	7.685	0.006	1
Bentonite 9 %	1064.7	35.180	0.020	1

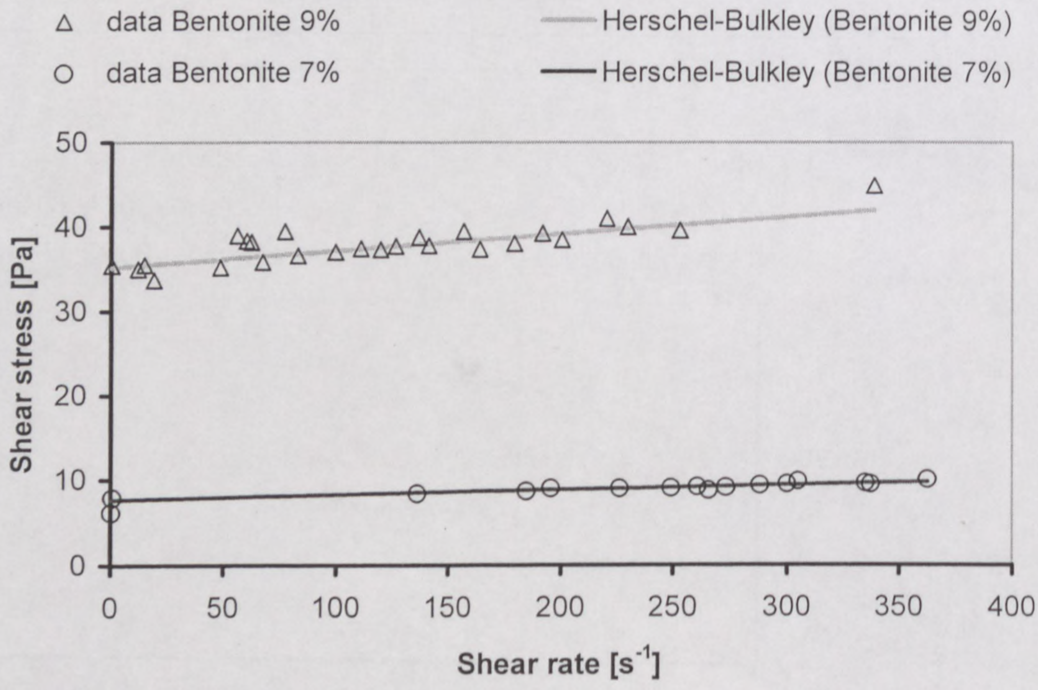

Figure 3.22: Rheogram for Bentonite tested in 80 mm and 150 mm Diameter pipes

3.11 CONCLUSIONS

The pipe rig was commissioned using clear water, and the experimental apparatus and the test procedures have been fully described.

Calibration of experimental apparatus was conducted in order to ascertain the validity and the accuracy of pipe and pump data to be collected.

The experimental errors have been analysed and their magnitudes were within acceptable margins.

Materials presenting three rheological behaviours when mixed with water were selected: CMC, kaolin and bentonite for pseudoplastic, yield pseudoplastic and Bingham plastic behaviours respectively.

Prepared slurries were tested in three pipes of internal diameters of 60, 80 and 150 mm respectively. Centrifugal pump tests were performed on a 6/4 Warman and a 4/3 GIW pump; a database for performance with non-Newtonian materials was compiled. Water test results are presented for both pipe and pump in this chapter, while slurry test results are presented in Appendix D.

The database as set was used to evaluate existing deration procedures for the prediction of centrifugal pump performance. Chapter 4 contains all the details related to that evaluation.

CHAPTER 4

ANALYSIS OF EXPERIMENTAL RESULTS

4.1 INTRODUCTION

In this chapter, experimental pump test results are analysed using the theoretical models referred to in Chapter 2. Calculations related to Walker and Goulas and the Hydraulics Institute Chart deration procedures are presented. Since the fluid rheology is paramount in this analysis, a rheological characterisation procedure is presented. The Walker and Goulas derating procedure is analysed with the rheological models that have been presented in Section 3.10 of Chapter 3 for low shear rate. At high shear rate, both the Walker and Goulas and the Hydraulics Institute Chart deration procedures are analysed with the rheological parameters obtained from the Bingham model forced to fit the laminar data of the material tested.

4.2 RHEOLOGICAL CHARACTERISATION

The steps followed for the rheological characterisation of yield pseudoplastic, Bingham plastic and pseudoplastic fluids are presented progressively:

Data points from the pressure gradient test in different pipe diameters (60 mm, 80 mm and 150 mm) have been plotted on a pseudo-shear diagram (τ_0 VS 8V/D). For each material tested, the laminar data are co-linear (Slatter, 1994). Figures 4.1 to 4.8 present the data for CMC, kaolin and bentonite. The true shear rate of laminar data is determined using Rabinowitsch-Mooney relation (Equation 2.25 and 2.26).

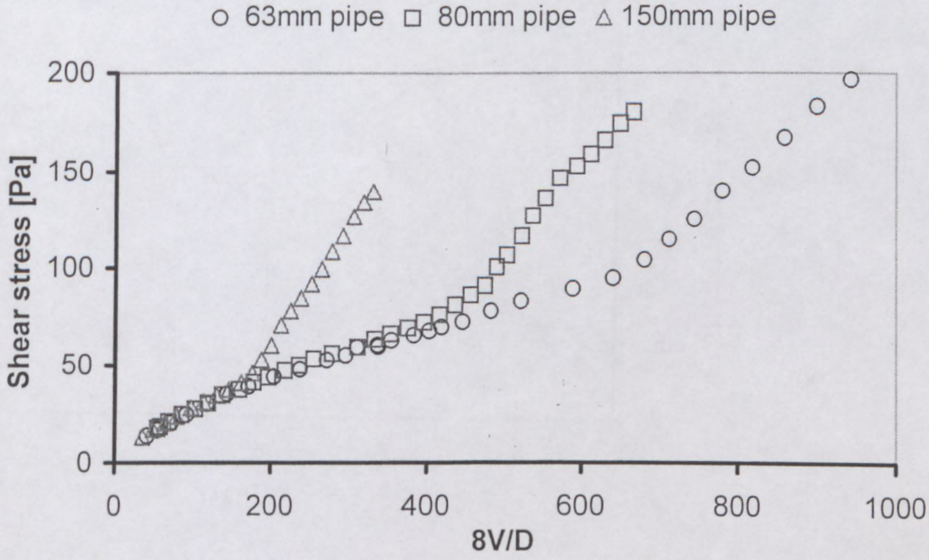

Figure 4.1: Pseudo-shear diagram for CMC 5%

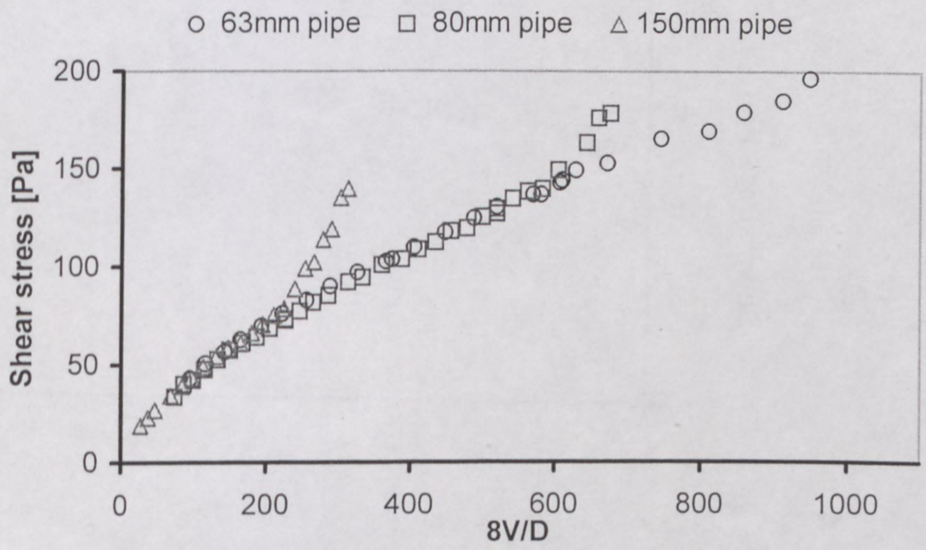

Figure 4.2: Pseudo-shear diagram for CMC 6%

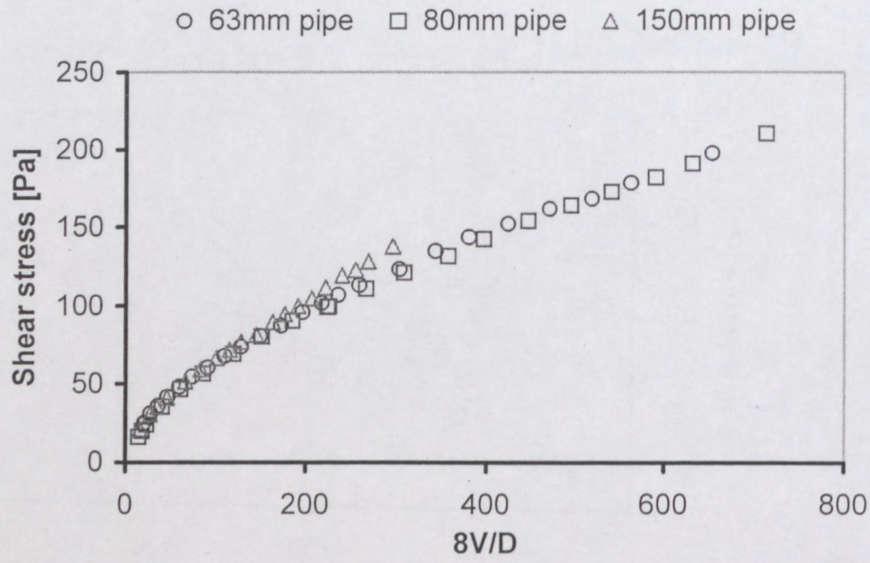

Figure 4.3: Pseudo-shear diagram for CMC 7%

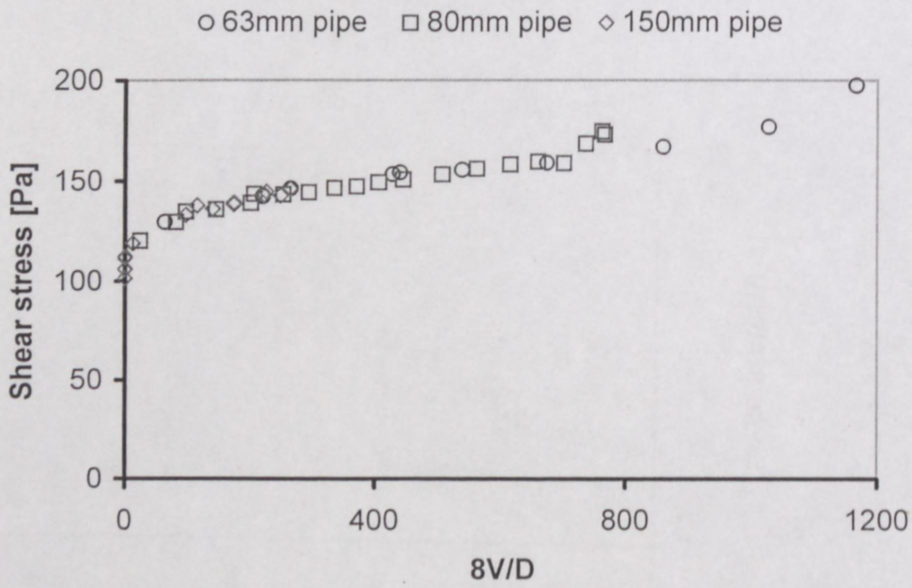

Figure 4.4: Pseudo-shear diagram for kaolin 17%

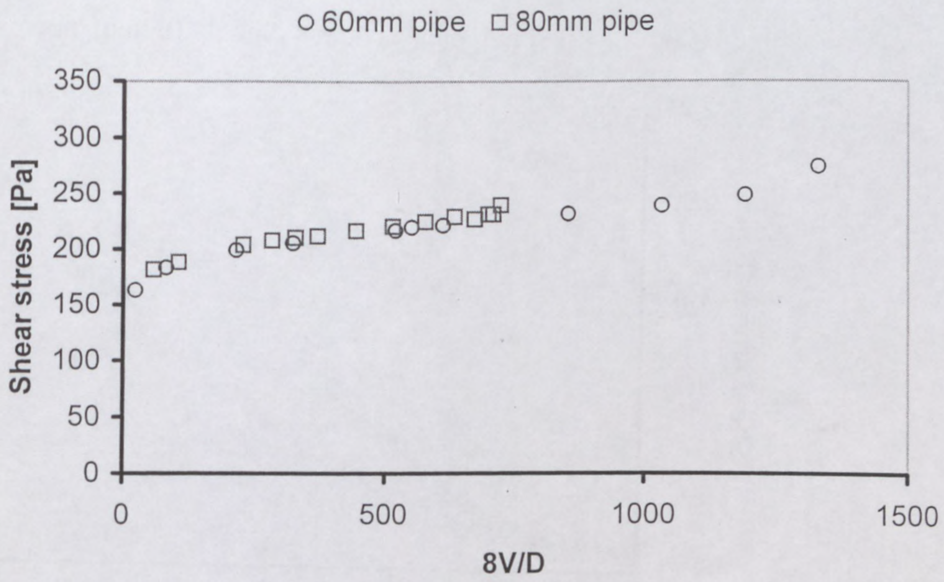

Figure 4.5: Pseudo-shear diagram for kaolin 19%

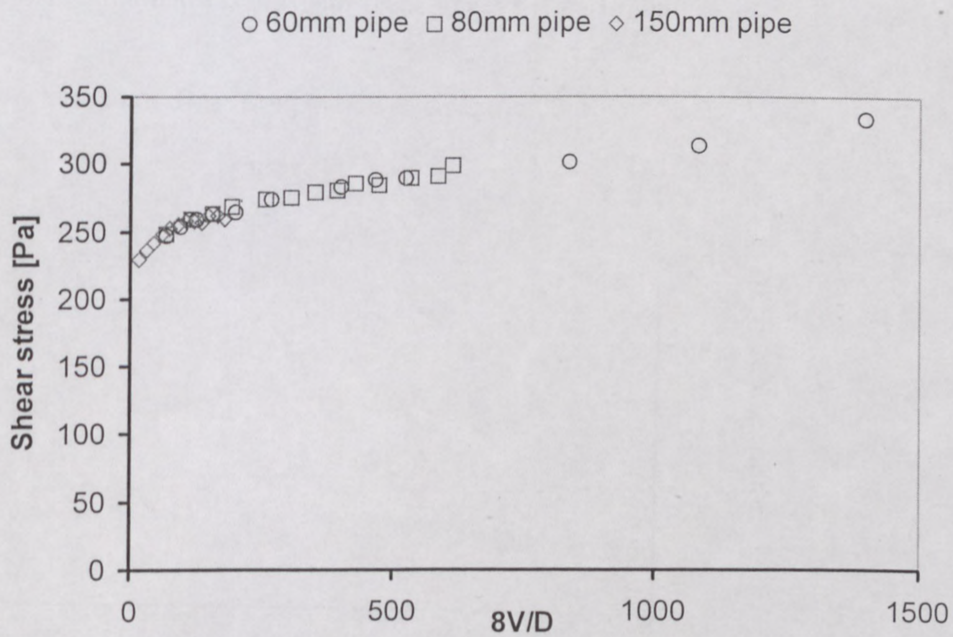

Figure 4.6: Pseudo-shear diagram for kaolin 21%

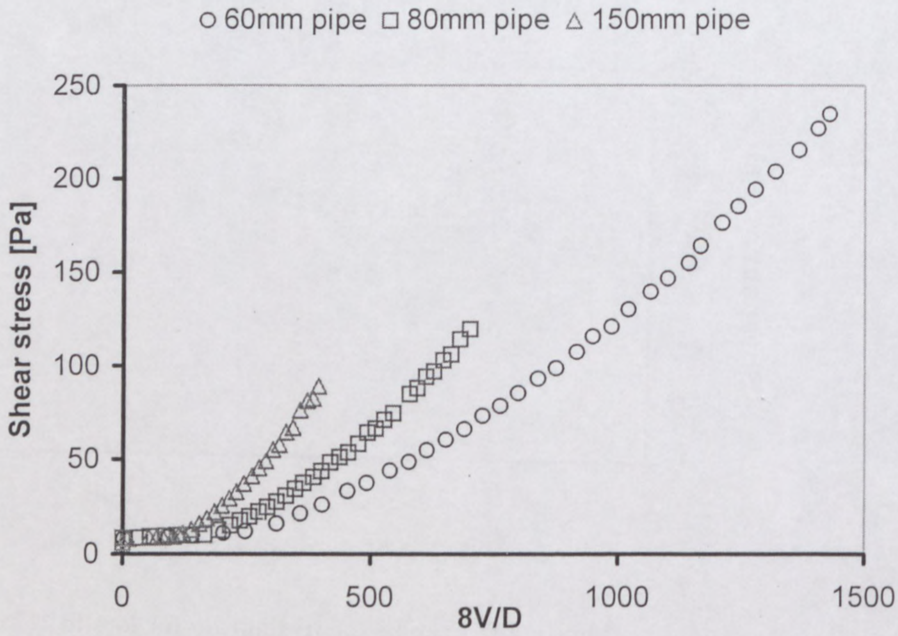

Figure 4.7: Pseudo-shear diagram for bentonite 7%

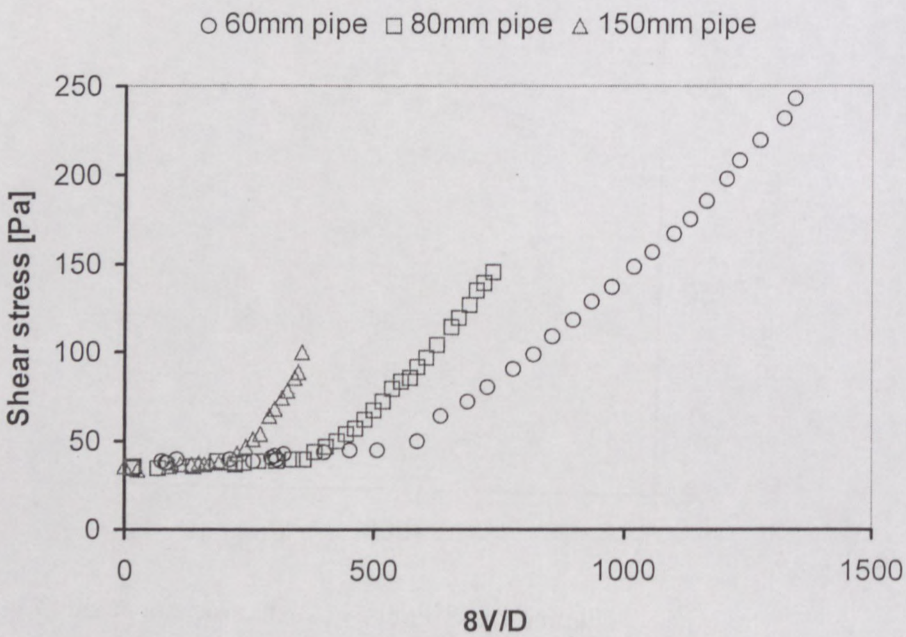

Figure 4.8: Pseudo-shear diagram for bentonite 9%

The rheological parameters (τ_y, K and n) were extracted from the data using the least square error curve fitting of Equation 2.23. Tables 4.1 and 4.2 present the rheological parameters for kaolin and bentonite and their respective values of the least square error.

Table 4.1: Kaolin rheological parameters

SAMPLE	Solver optimisation			
	τ_y	K	n	Least error^2 [%]
Kaolin 17 %	104.85	2.126	0.430	0.34
Kaolin 19 %	152.779	0.791	0.623	0.36
Kaolin 21 %	218.04	1.479	0.534	0.89

Table 4.2: Bentonite rheological parameters

SAMPLE	Solver optimisation			
	τ_y	K	n	Least error^2 [%]
Bentonite 7 %	7.685	0.0058	1	0.49
Bentonite 9 %	35.179	0.020	1	0.86

For pseudoplastic materials, a simple fit with an Excel power law model on the rheogram gives the rheological constants K and n, (Slatter, 1994). Table 3.15 has presented the rheological parameters for CMC and Figure 3.20 depicted the corresponding rheogram.

4.3 CENTRIFUGAL PUMP PERFORMANCE TEST RESULTS

Centrifugal pump performance tests have been performed for three different slurries and for water. The results were corrected and compiled; some are shown in Figures 4.9 to 4.14. Appendices C and D contain results for water and slurry tests respectively. Pump data were corrected according to the international standard ISO 9906 for rotodynamic pumps.

Two major types of correction were brought to the pump data:

- the torque values recorded during tests were corrected as mentioned in Section 2.7.3.2 of Chapter 2; and
- whenever applicable, the total head was corrected for each material tested. The correction consisted of accounting for the total pump head calculated, plus the head losses due to friction that occurred between the pressure tapping points and the pump flanges.

The international standard ISO 9906 for rotodynamic pumps suggests the following criteria for the correction:

$$Hj_1 + Hj_2 \geq 0.005\ H \tag{4.1}$$

where Hj_1 and Hj_2 represent the head losses due to friction between the pressure tappings and the flanges for the suction and the discharge of the pump.

For a set of data where Equation 4.1 is satisfied, the correction is applied.

If it is considered that the pipe between the measuring points and the flanges is unobstructed, straight, of constant circular cross-section and of length L (that is actually the case), the Standard ISO 9906 suggests again that the friction losses may be calculated using the Colebrook-White relation, Equation 2.13 and the Darcy formula, Equation 2.14

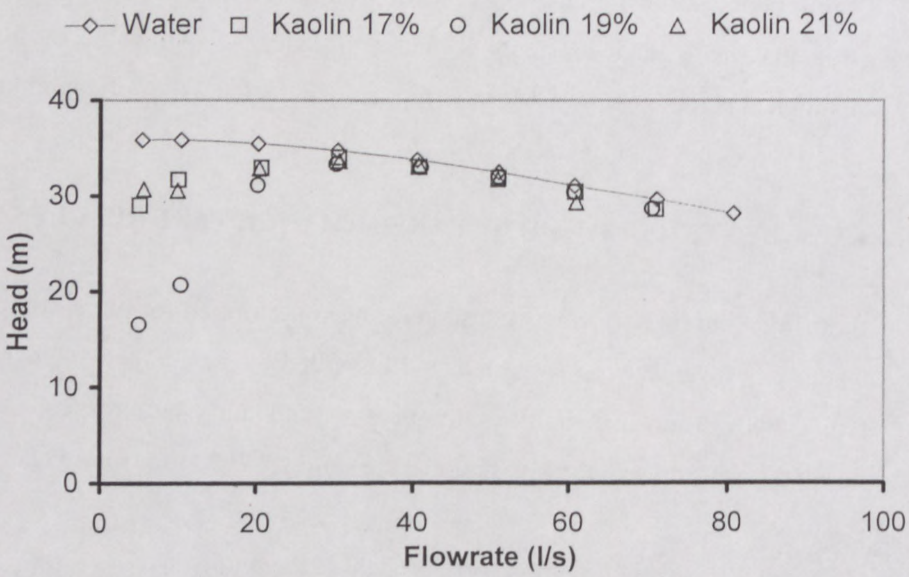

Figure 4.9: 6/4 Warman pump head curves for water and kaolin at 1200 rpm

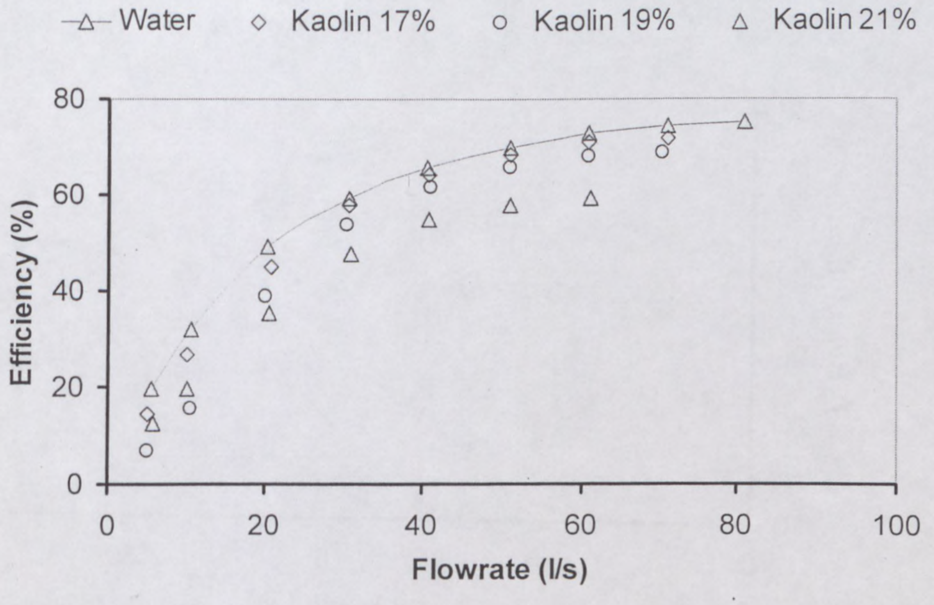

Figure 4.10: 6/4 Warman pump efficiency curves for water and kaolin at 1200 rpm

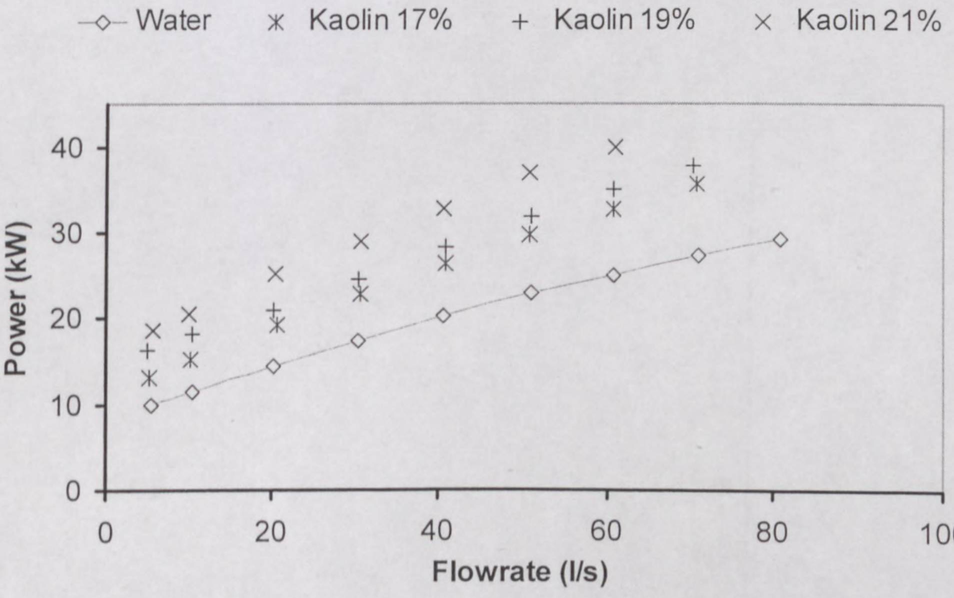

Figure 4.11: 6/4 Warman pump power curves for water and kaolin at 1200 rpm

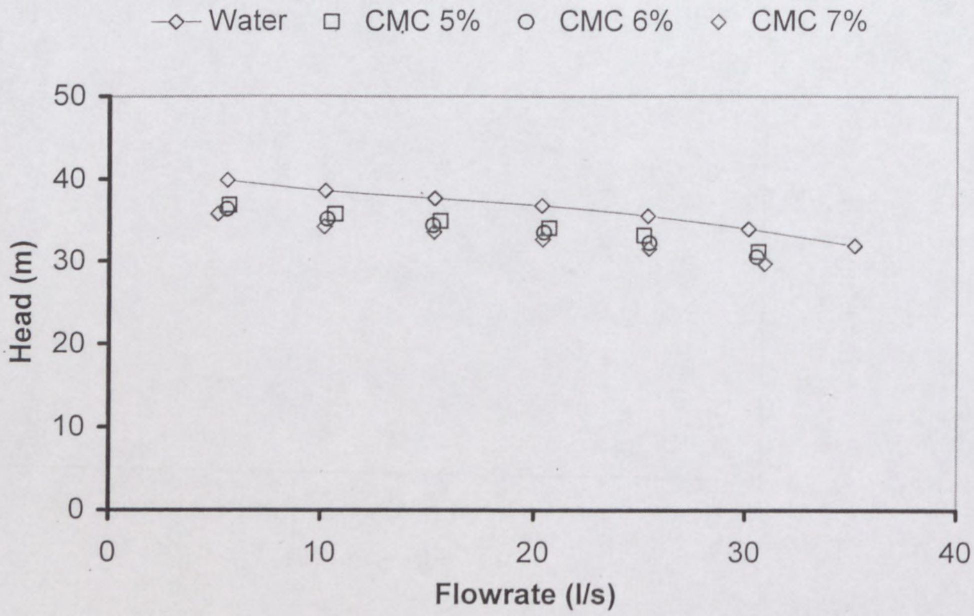

Figure 4.12: 4/3 GIW pump head curves for water and CMC at 1600 rpm

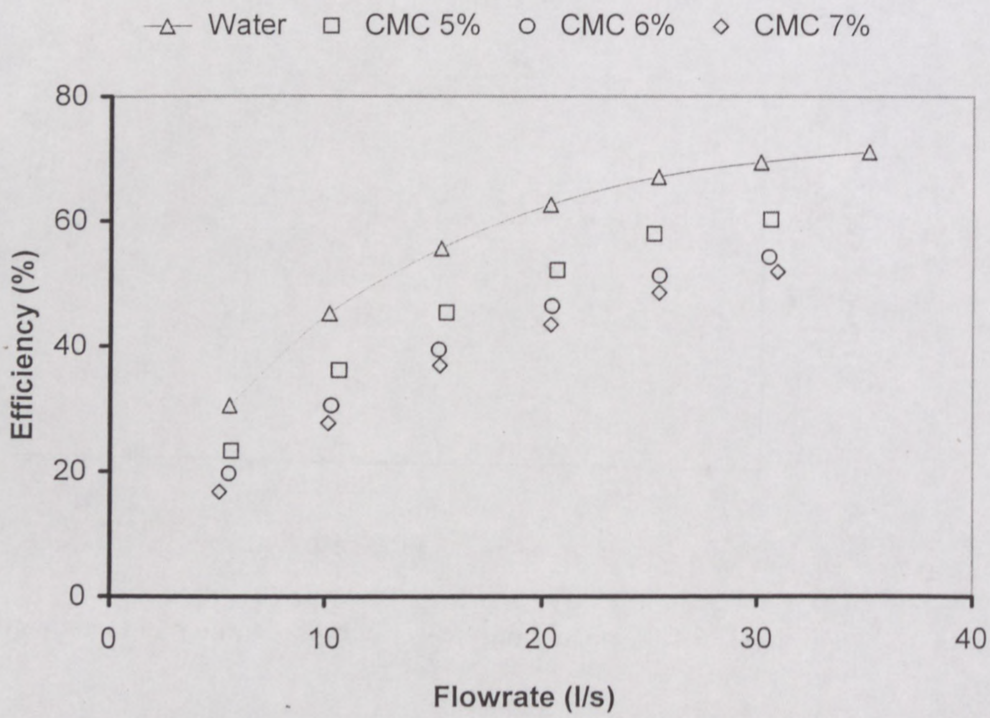

Figure 4.13: 4/3 GIW pump efficiency curves for water and CMC at 1600 rpm

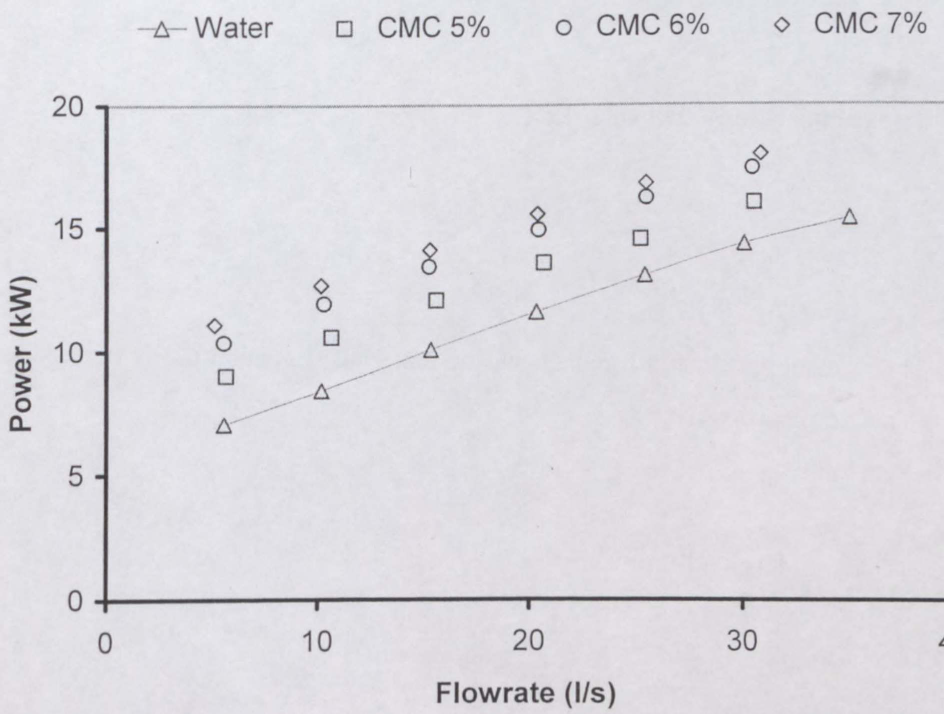

Figure 4.14: 4/3 GIW pump power curves for water and CMC at 1600 rpm

4.4 WALKER AND GOULAS DERATION PROCEDURE

The correlations of head and efficiency ratio with pump Reynolds numbers are obtained from experimental data. Results are presented by Figures 4.21 to Figure 4.28. The head and the efficiency reduction ratio are calculated from Equation 2.36 and Equation 2.37

4.4.1 Pump Reynolds number calculated using the apparent viscosity at shear rate=2ω

At this stage of the analysis, the pump Reynolds number is calculated using the modified pump Reynolds number expressed by Equation 2.39. The apparent viscosity μ_{app} at $\dot{\gamma} = 2\omega$ is valid only for low flow rates and is calculated using the general Equation 4.2. This general equation accommodates the rheological behaviour of the three materials tested.

$$\mu_{app} = \frac{\tau_y}{2\omega} + K(2\omega)^{(n-1)} \tag{4.2}$$

ω is obtained from Equation 4.3

$$\omega = \frac{2\pi}{60} * rpm \tag{4.3}$$

For pseudoplastic and Bingham plastic materials, Equation 4.2 is reduced to Equations 4.4 and 4.5 respectively.

$$\mu_{app} = K(2\omega)^{(n-1)} \tag{4.4}$$

$$\mu_{app} = \frac{\tau_y}{2\omega} + K \tag{4.5}$$

The next section will look at the use of the plastic viscosity for high flow rates.

4.4.2 Pump Reynolds number calculated using the plastic viscosity (μ_p) derived from the Bingham plastic model

Analysis using the plastic viscosity (μ_p) required that a Bingham model be forced to fit in to a different rheogram to obtain Bingham parameters (Slatter, 1994).

The plastic viscosity is defined in Paragraph 2.10. Since at high rates of shear, $\mu_p = \eta =$ K, in this work, the slope of the straight line fitted (K) is taken as the plastic viscosity.

Tables 4.3 and 4.4 show the rheological parameters from the Bingham analysis and Figures 4.14 to 4.18 depict the related rheogram. Table 3.17 gives the parameters of bentonite. In this case, the pump Reynolds number is calculated using Equation 2.40.

Table 4.3: CMC rheological parameters using the Bingham plastic fit

SAMPLE	DENSITY [Kg/m^3]	τ_y	K [Pa.s^n]	n
CMC 5 %	1028.3	19.807	0.159	1
CMC 6 %	1032.3	34.829	0.155	1
CMC 7 %	1036.8	50	0.1975	1

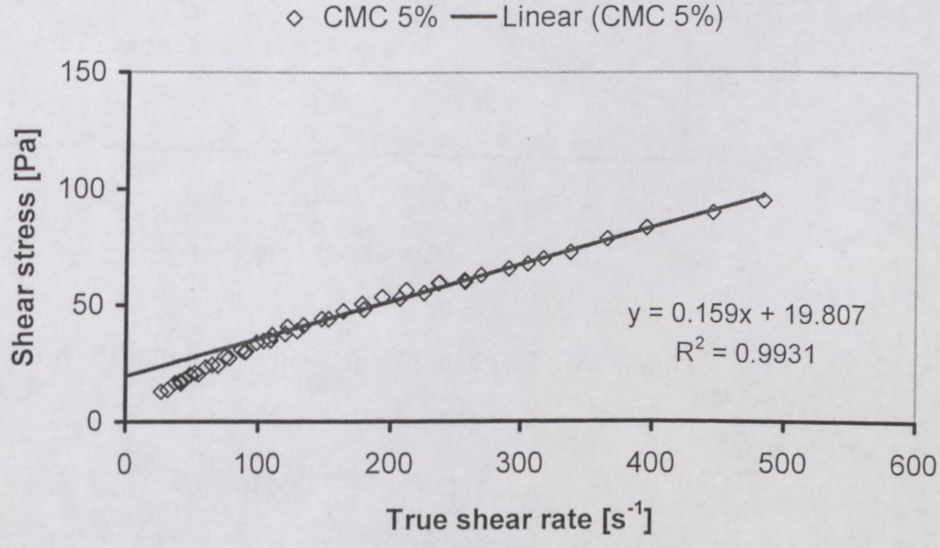

Figure 4.15: Bingham plastic model fitted to CMC 5 %

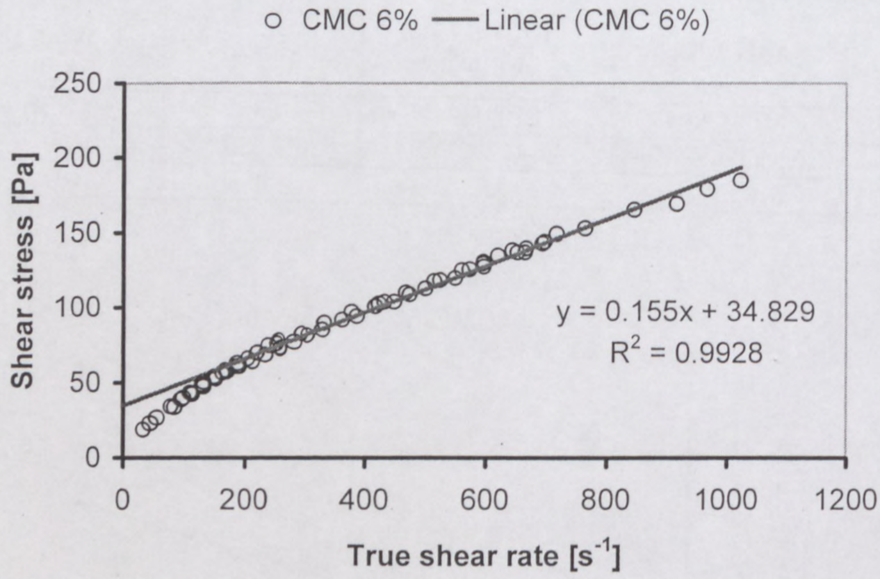

Figure 4.16: Bingham plastic model fitted to CMC 6 %

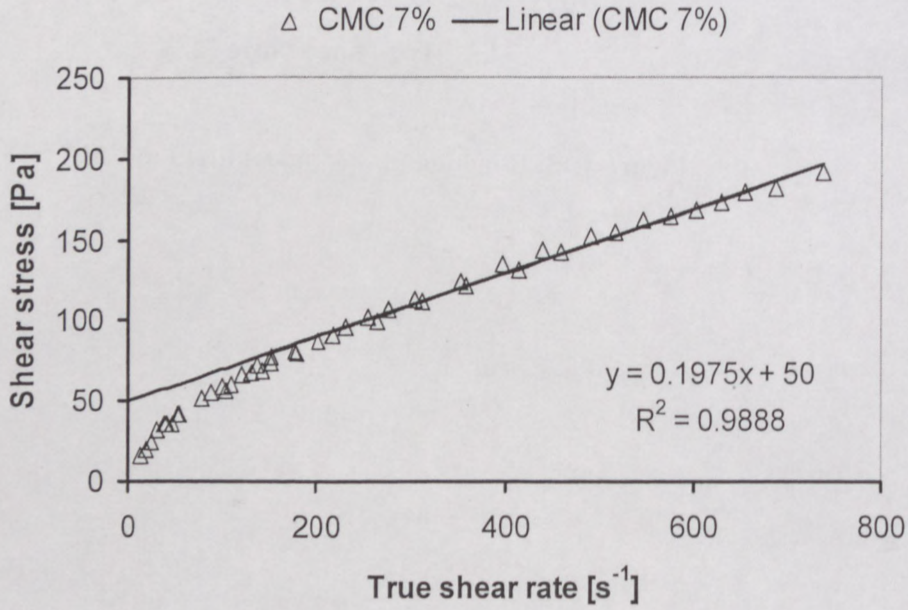

Figure 4. 17: Bingham plastic model fitted to CMC 7 %

Table 4.4: Kaolin rheological parameters using the Bingham plastic fit

SAMPLE	DENSITY [Kg/m^3]	τ_y [Pa]	K [Pa.s^n]	n
Kaolin 17 %	1284.0	124.05	0.0197	1
Kaolin 19 %	1315.9	171.05	0.0374	1
Kaolin 21 %	1351.1	239.87	0.0338	1

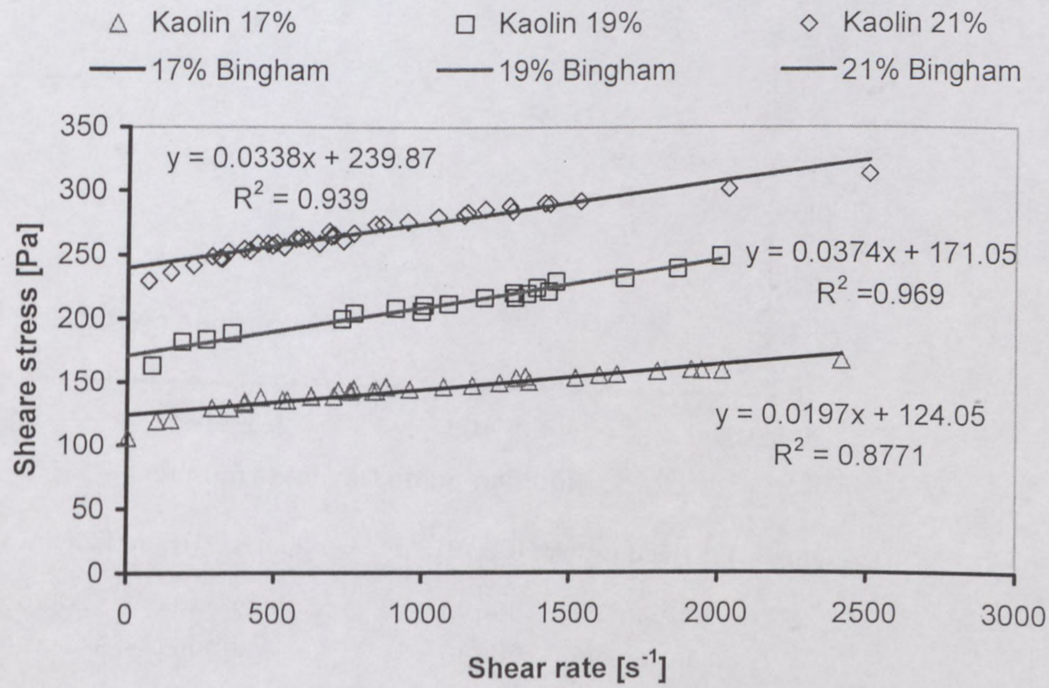

Figure 4.18: Bingham plastic model fitted to kaolin 17, 19 and 21 % data

4.4.3 Correlation of head and efficiency reduction ratio to the pump Reynolds number

Head and efficiency reduction ratios obtained for each material tested are correlated to the pump Reynolds number which is using the apparent viscosity calculated at 2ω for low flow rates or using the plastic viscosity K for high flow rates.

Figures 4.19 to 4.26 present the correlation of head and efficiency reduction ratio to the pump Reynolds number. A fitting trend reproduced from Walker and Goulas curves is also plotted. Results for both the 6/4 Warman and the 4/3 GIW centrifugal pumps are considered for low and high flow rate.

4.4.3.1 6/4 Warman pump results for bentonite, CMC and kaolin at 0.1QBEP

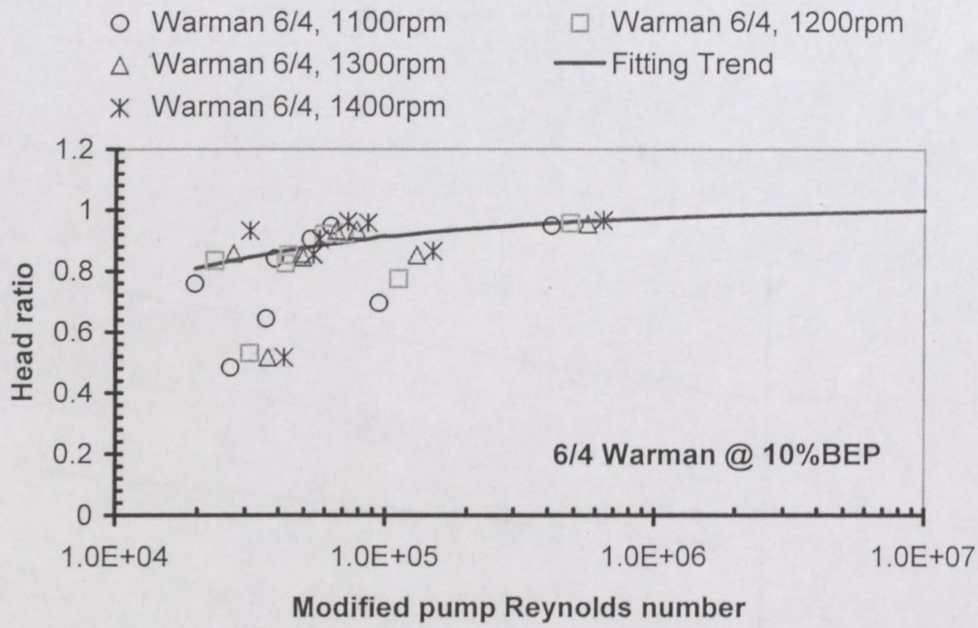

Figure 4.19: Head ratio at 0.1QBEP for bentonite, CMC and kaolin slurries

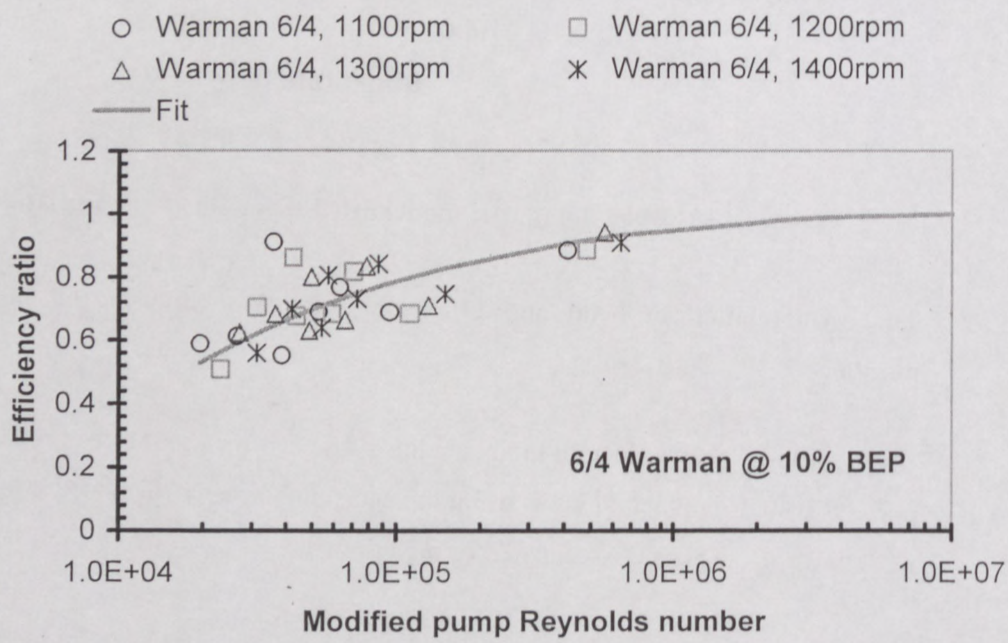

Figure 4.20: Efficiency ratio at 0.1QBEP for bentonite, CMC and kaolin slurries

4.4.3.2 6/4 Warman pump results for bentonite, CMC and kaolin at BEP

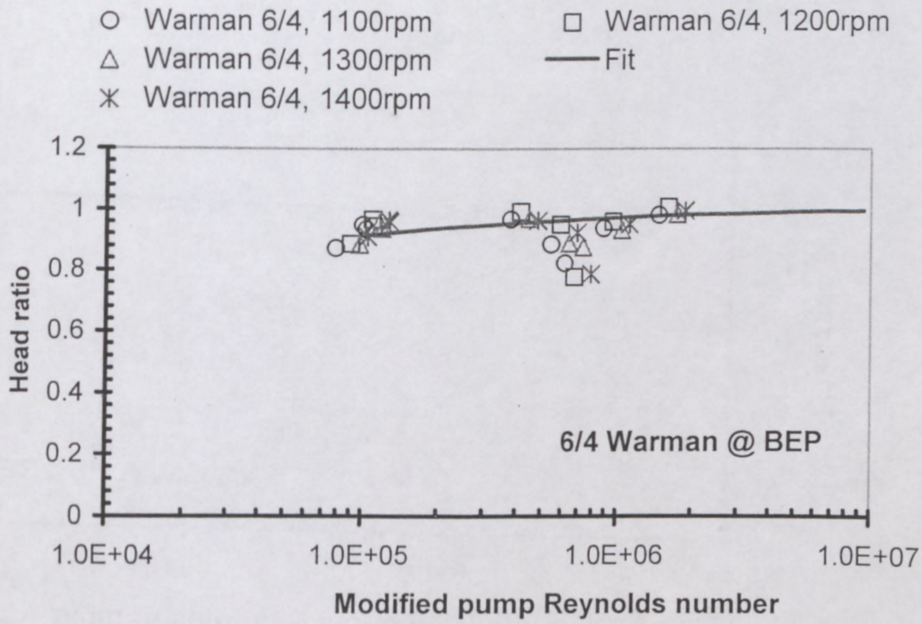

Figure 4.21: Head ratio at BEP for bentonite, CMC and kaolin slurries

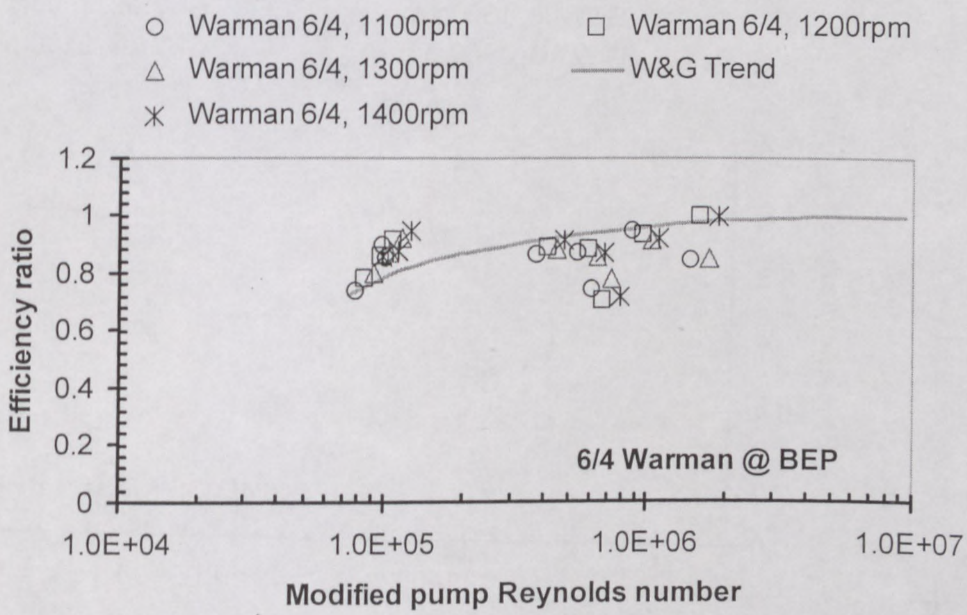

Figure 4.22: Efficiency ratio at BEP for bentonite, CMC and kaolin slurries

4.4.3.3 4/3 GIW pump results for bentonite, CMC and kaolin at 0.1QBEP

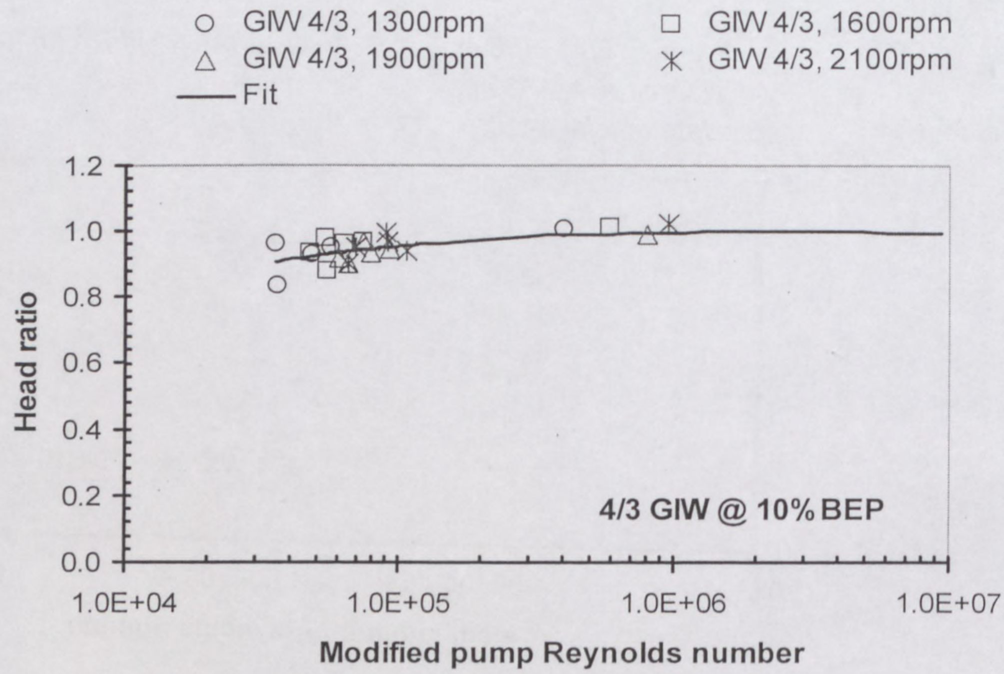

Figure 4.23: Head ratio at 0.1QBEP for bentonite, CMC and kaolin slurries

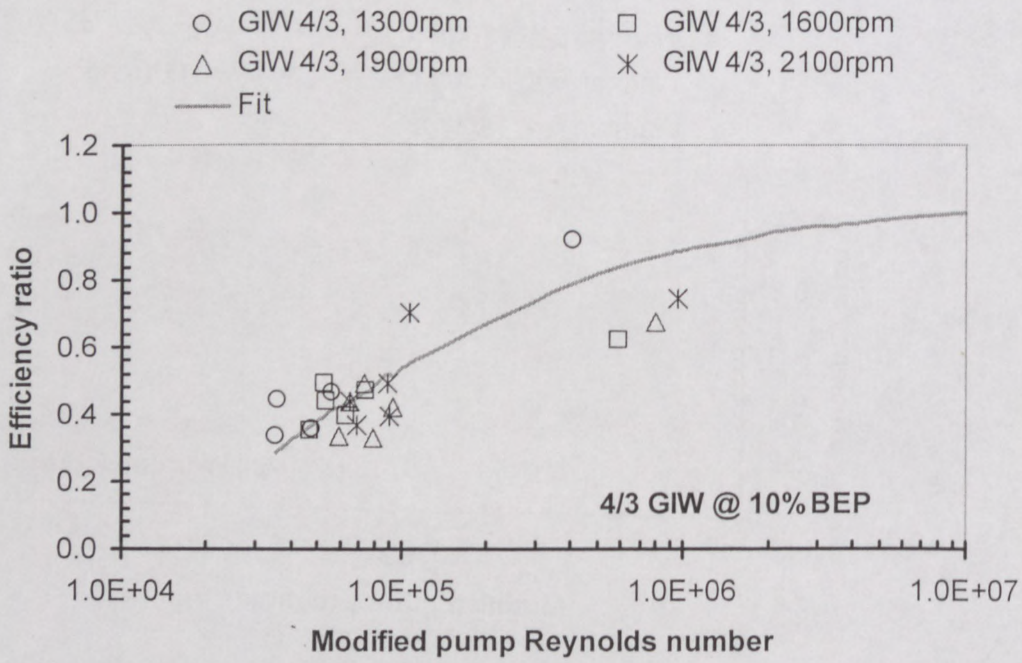

Figure 4.24: Efficiency ratio at 0.1QBEP for bentonite, CMC and kaolin slurries

4.4.3.4 4/3 GIW pump results for bentonite, CMC and kaolin at BEP

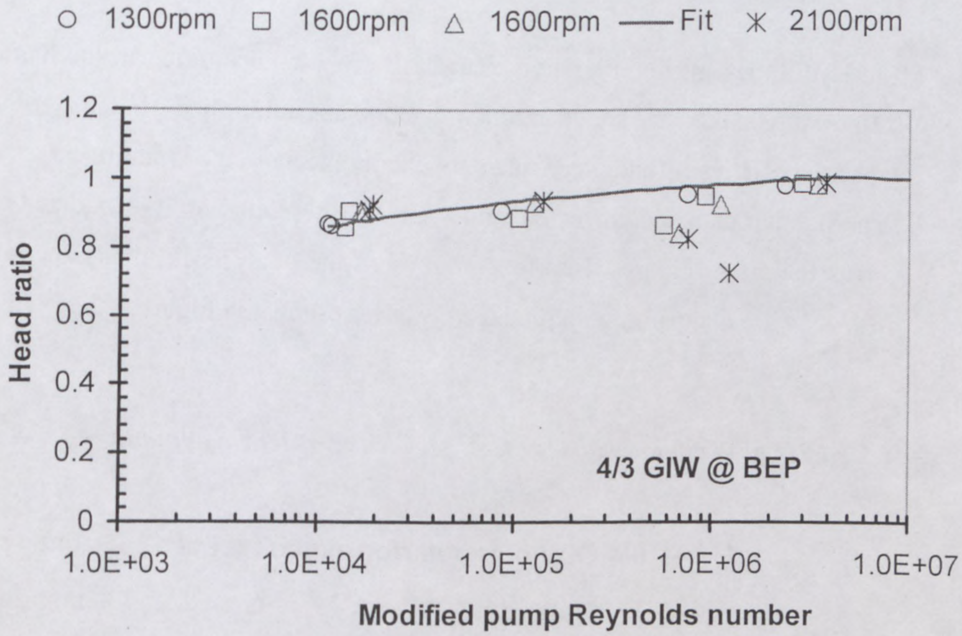

Figure 4.25: Head ratio at BEP for bentonite, CMC and kaolin slurries

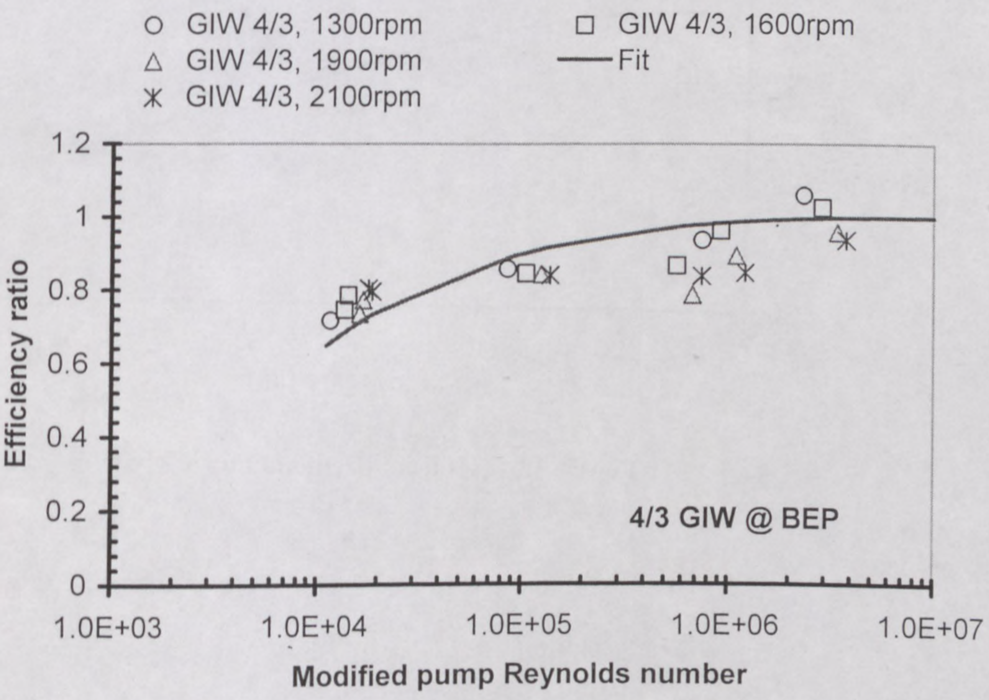

Figure 4.26: Efficiency ratio at QBEP for bentonite, CMC and kaolin slurries

4.5 PREDICTION OF CENTRIFUGAL PUMP PERFORMANCE USING THE HYDRAULICS INSTITUTE CHART

The Hydraulics Institute deration chart has been used according to the literature in Section 2.10.b of Chapter 2. The correction factors are multiplied to the corresponding water capacity, efficiency and head data to obtain the corrected pump curves for the slurry. Experimental data and corrected values are finally plotted on the head and efficiency graph versus the flow. Figures 4.27 to 4.32 present the analysis results. Experimental head and efficiency are compared with predicted values as shown in Figures 4.33 to Figure 4.36.

4.5.1.1 HI prediction results for CMC 7% with 6/4 Warman pump

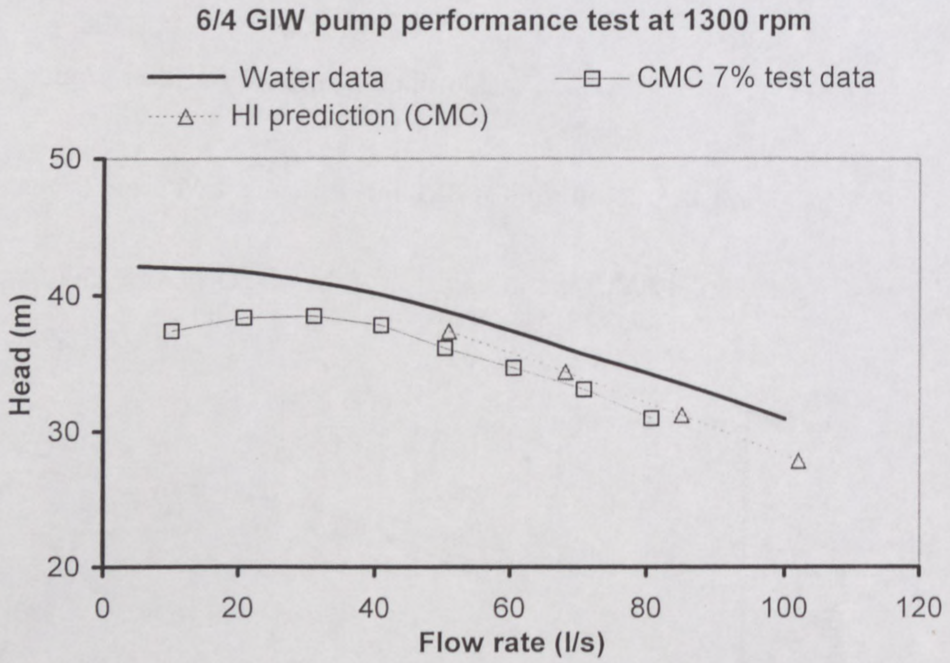

Figure 4.27: HI head prediction for CMC 7%

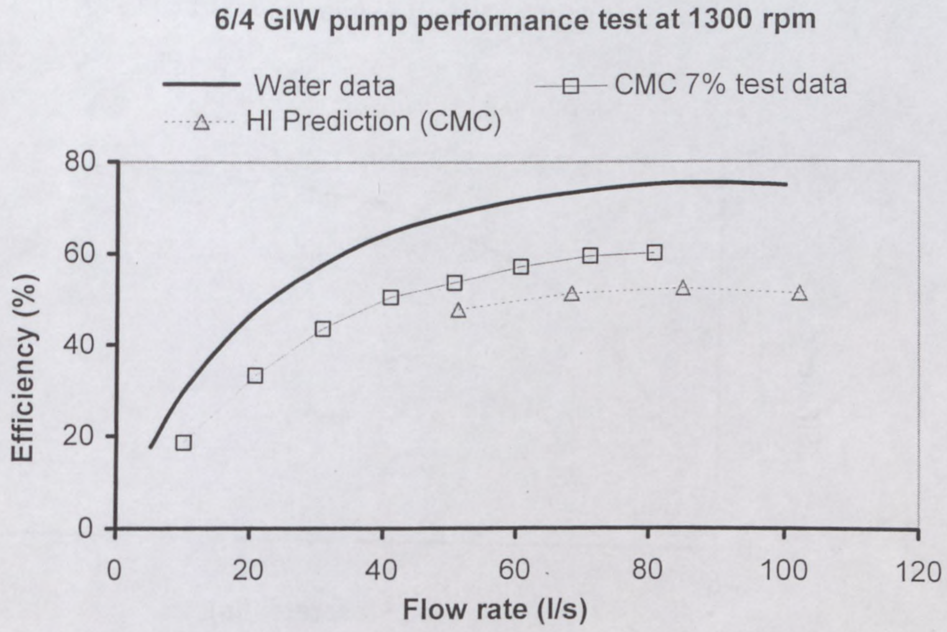

Figure 4.28: HI efficiency prediction for CMC 7%

4.5.1.2 HI predicted results for kaolin 21 % with 6/4 Warman pump

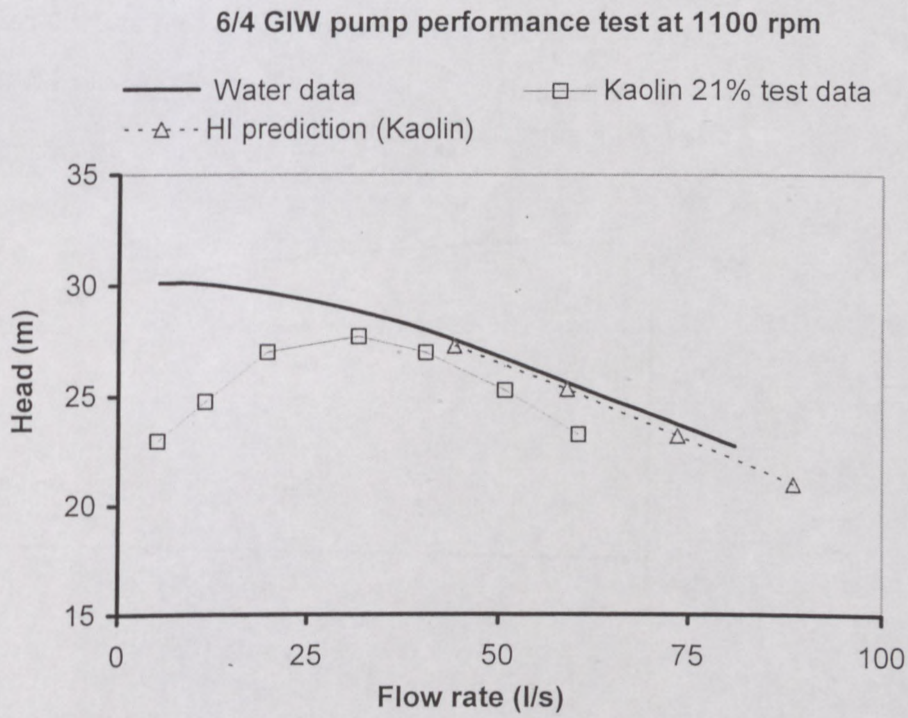

Figure 4.29: HI head prediction for kaolin 21%

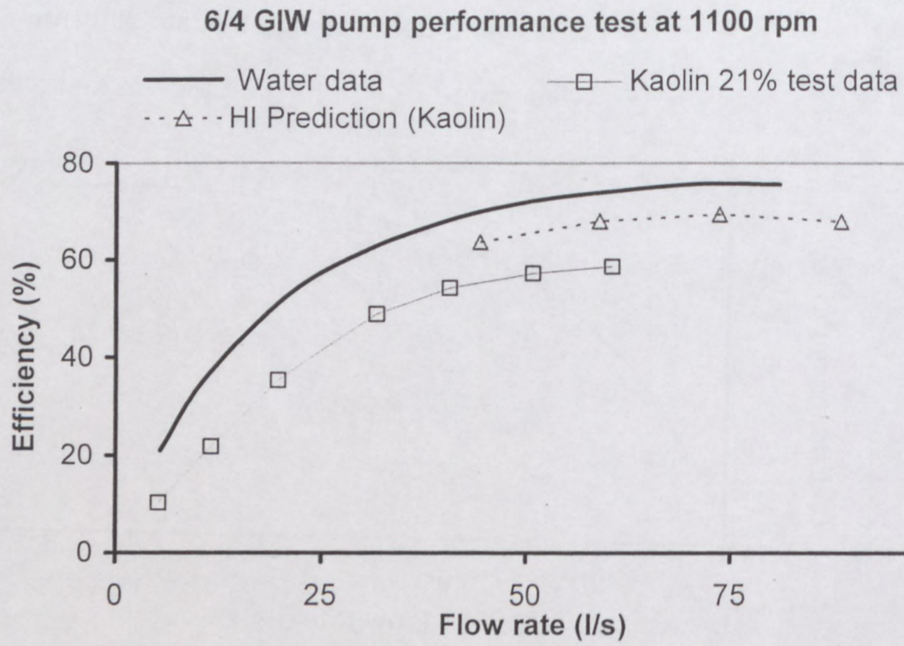

Figure 4.30: HI efficiency prediction for kaolin 21%

4.5.1.3 HI prediction results for bentonite 7% with the 4/3 GIW pump

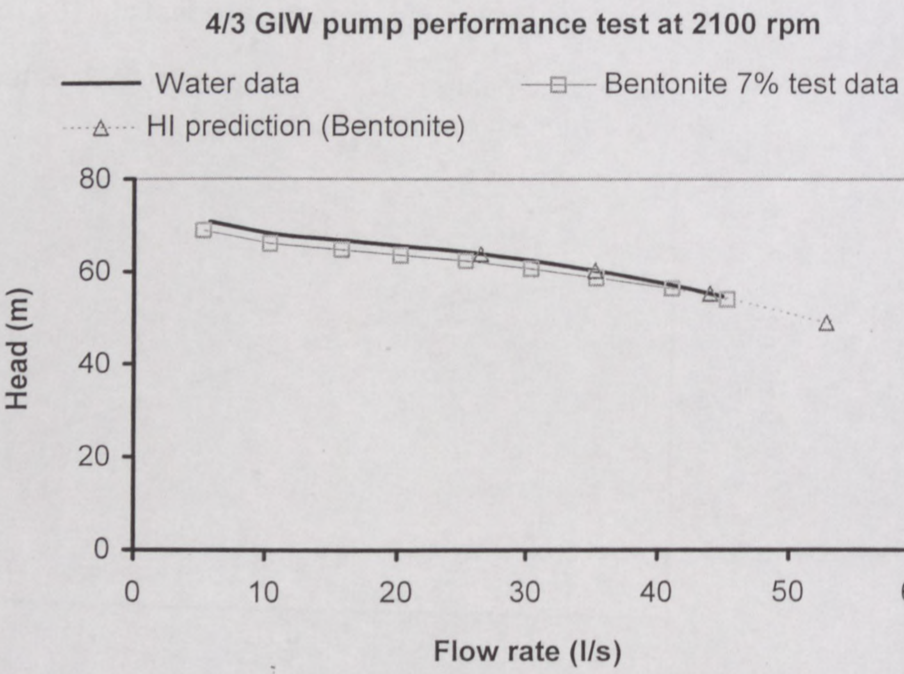

Figure 4.31: HI head prediction for bentonite 7 %

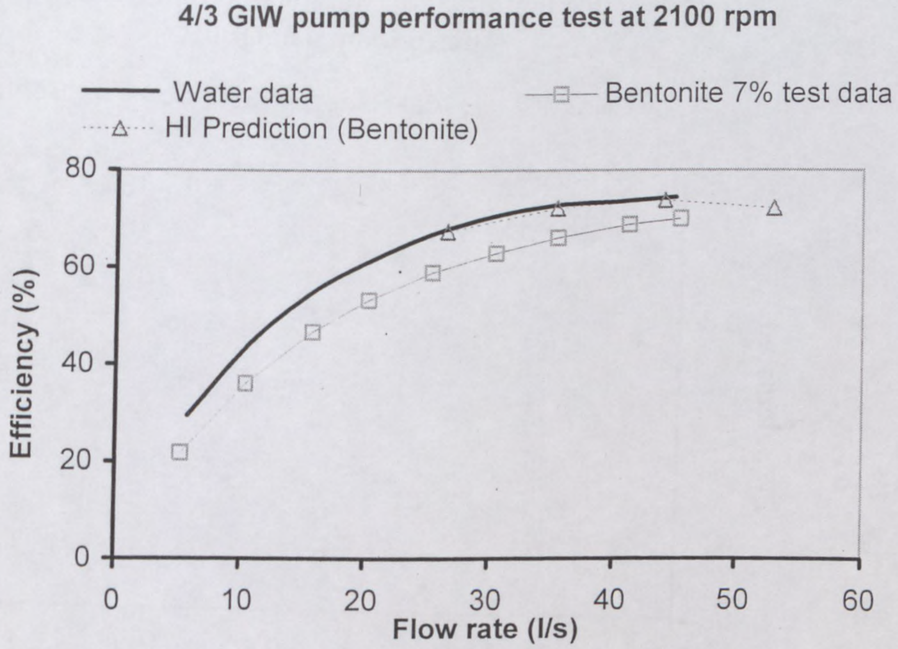

Figure 4.32: HI efficiency prediction for bentonite 7 %

4.5.1.4 Prediction error when using the Hydraulics Institute Chart for non-Newtonian slurries

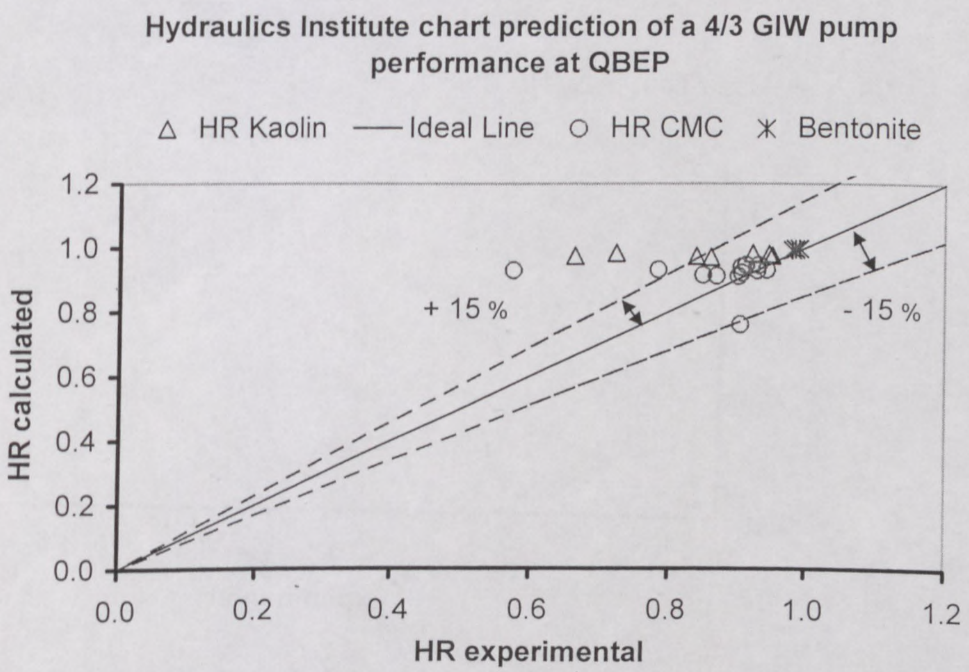

Figure 4.33: Experimental HR against calculated values from HI chart

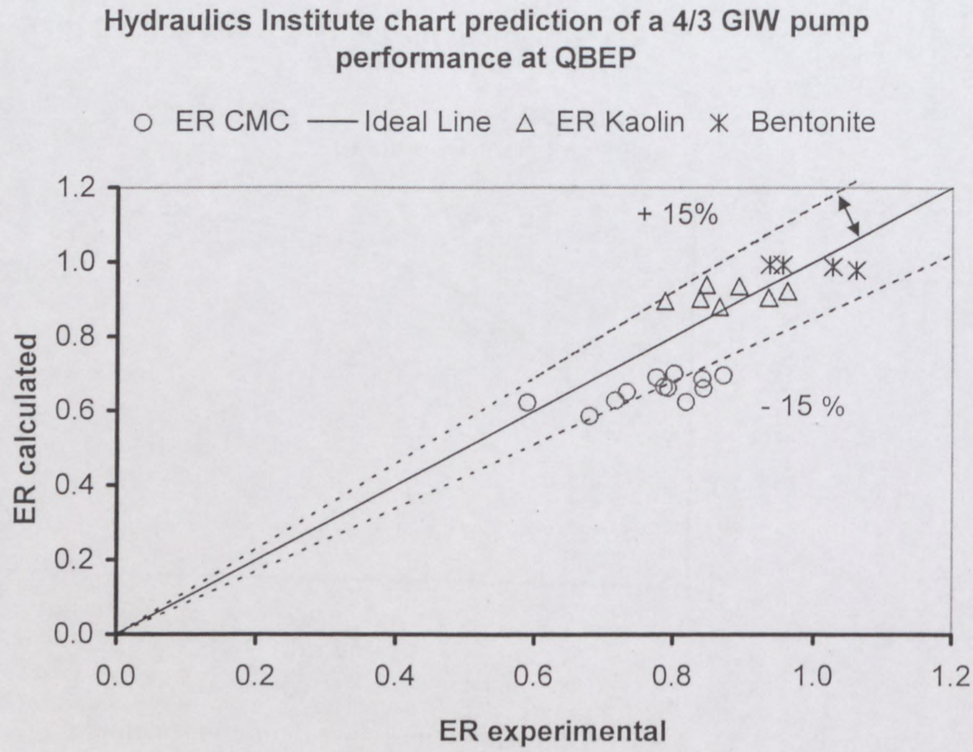

Figure 4.34: Experimental ER against calculated values from HI chart

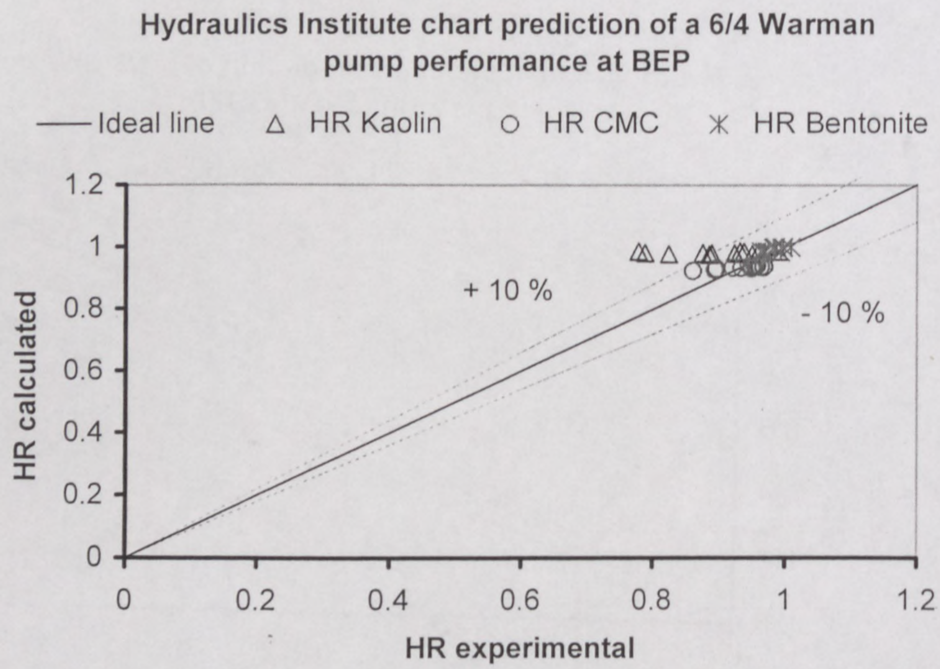

Figure 4.35: Experimental HR against calculated values from HI chart

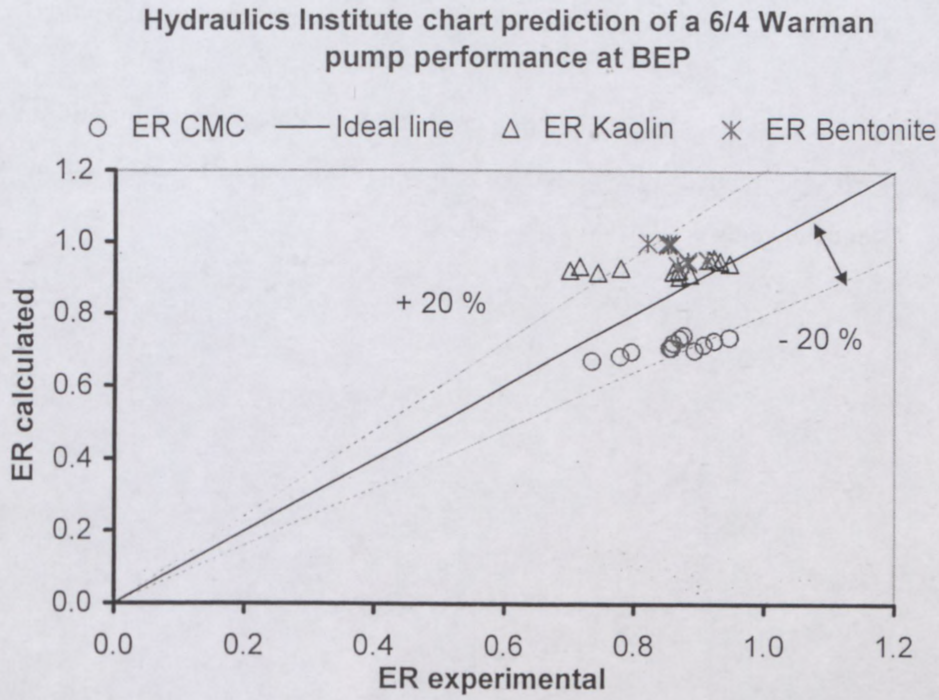

Figure 4.36: Experimental ER against calculated values from HI chart

Table 4.5: Error values in the prediction of pump performance at BEP using the HI chart

Using the plastic viscosity K		
Pump Type	**Error (%)**	
	HR	**ER**
4/3 GIW	±15	±15
6/4 Warman	±10	±20

4.6 CONCLUSIONS

The rheological characterisation procedure was presented. It showed that the materials tested, bentonite, CMC and kaolin belong to the Bingham plastic, pseudoplastic and yield pseudoplastic models respectively. The materials are also characterised using the Bingham plastic forced fit in order to determine the plastic viscosity.

Head and efficiency reduction ratio are calculated for the fluids tested at four speeds of rotation for each centrifugal pump. The HR and the ER are correlated to the pump Reynolds number as results of Walker and Goulas's deration procedure. The pump Reynolds number is calculated according to the flow rate as describe in the literature in Section 2.10.

Results of the HI charts prediction are presented. Values found for HR and ER from the HI charts are plotted against the experimental HR and ER data and an error margin is established between the two sets of data.

CHAPTER 5

EVALUATION AND DISCUSSION OF RESULTS

5.1 INTRODUCTION

This chapter discusses and evaluates the results presented in Chapter 4 and in the Appendices C, D and F. The objectives assigned to this project are also reviewed. The points for discussion are the following:

- the literature;
- the experimental test loop and instrumentation;
- the experimental method;
- material tested;
- rheological characterisation;
- pump Reynolds number deration procedure; and
- hydraulic Institute charts deration procedure.

5.2 THE LITERATURE

The existing literature was reviewed with the main goal of identifying some researchable areas related to centrifugal pump derating, and to establish the need for investigation.

Wilson *et al.,* (1997) documented that slurry does affect the performance of a centrifugal pump, forcing the system to operate in laminar flow conditions. Laminar flow slurry pumping has become a growing technology with much ongoing research in this regard (Bootle, 2006).

Centrifugal pump deration has to be well understood (Abulnaga, 2002). As an outcome of that knowledge, Bootle (2006) has suggested some of the possible benefits, especially for mine disposal, in the form of thickened tails or paste as a drop off in water consumption, fewer safety concerns, and reduction of environmental impact.

Two models available for centrifugal pump deration have been presented. They are the correlation of head and efficiency reduction ratios to the pump Reynolds number and the Hydraulics Institute deration chart for Newtonian fluids. Work based on the above deration procedures has been conducted only for yield pseudo plastic fluids characterised in terms of Bingham plastic fluid (Walker and Goulas, 1984; Sery & Slatter, 2002). Furthermore, there are no conclusive guidelines in the literature as to which procedure adequately predicts centrifugal pump performance for non-Newtonian slurries. The present project has covered Walker and Goulas's work and has extended it to pseudoplastic slurry.

5.3 THE EXPERIMENTAL TEST LOOP AND INSTRUMENTATION

The test loop used for experimental work was designed and built on a scale representing the industry reality. The loop construction has respected the recommendations written in the international standard ISO 9906 for rotodynamic pumps and followed the building pattern found in the literature. The main pieces of equipment used on the pipe rig to run either the pipe pressure gradient test or the centrifugal pump test are the flow meters, the speed-torque unit, the transducers and the centrifugal pumps.

The difficulties experienced during the test period are related to the operation of centrifugal pumps and the type of slurry being tested. Operating the pumps at high rotation speeds induces a vibration around the pump bay (mainly the suction pipes) that can disturb the suction pressure readings. Slurry with higher viscosity generates the heat probably owing to the friction in the pump.
The main inconvenience is that the rig requires a large quantity of material to be tested given its total volume.

5.4 EXPERIMENTAL METHOD

The experimental method used in this work is to perform multiple readings for all the measurable variables and to derive the computable variables thereafter. Using an Excel spreadsheet, the above operations are performed simultaneously; and averaged in order to record a single point. Three sets of thirty readings each are completed; the plots of head, efficiency and power versus flow rate are directly shown on the screen.

5.5 MATERIALS TESTED

The materials selected to complete this investigation were chosen to represent the three classes of non-Newtonian fluids.

- Water

Water was used as the test fluid during the apparatus calibration. to establish the actual performance of centrifugal pumps. The catalogue pump curves compared with water test results obtained in this project are within the permissible margin for both pumps (4/3 GIW and 6/4 Warman).

- CMC

This material has represented the power law fluids model. It displayed a pseudoplastic behaviour characterised by an absence of yield stress. However, CMC has shown a ready tendency to form lumps required a long mixing time. The rheological parameters changed slightly from day to day. Similar difficulties in moving the fluid were noticed for the CMC 7% mixture.

- Bentonite

Bentonite mixtures displayed a Bingham plastic behaviour as expected. Bentonite slurries have presented a moderate yield stress compare with kaolin slurries tested. The thickening properties of bentonite conferred on the mixture the susceptibility to change its rheology after a while. To avoid that drawback, all the tests were conducted in a short period of time. Bentonite (9%) mixed could not be pumped through the rig with the 4/3 GIW.

- Kaolin

This material is known to have a yield stress. It was selected to represent the yield pseudoplastic behaviour. Mixtures of kaolin prepared at different concentrations (17, 19 and 21%) displayed the yield pseudoplastic behaviour as expected. As reported in the literature, the pump performance tests have shown a significant drop in terms of head at low flow, rates and the efficiency was affected proportionally to the increase of the material's concentration. Some difficulties were observed with high concentrations of kaolin (19% and 21%). It was difficult to get the fluid to start flowing probably owing to the high yield stress. Kaolin at 21 % concentration could not be pumped at all with the 4/3 GIW pump.

5.6 RHEOLOGICAL CHARACTERISATION

Two types of characterisation have been completed:

- a simple fitting on laminar data with Excel power law model for pseudoplastic material, and an iterative process using the least error square method on the Herschel-Bulkley equation for yield pseudoplastic or Bingham plastic materials; and.
- the forcing of a straight line (best fit) on laminar data to obtain the Bingham plastic parameters for all the fluids tested.

5.7 PUMP REYNOLDS NUMBER DERATION PROCEDURE

The pump Reynolds number was calculated using the apparent viscosity at 2ω for low-flow rates and the plastic viscosity K at high-flow rates. The plots of head and efficiency reduction ratio versus the pump Reynolds number are presented at 0.1QBEP and BEP for both pumps.

On HR and ER versus NRep graphs data are scattered, but follow the Walker and Goulas trend for all the material tested. The reduction of head and efficiency ratios is observed to decrease with pump Reynolds number values below 10^6 as presented in the literature review on Figure 2.9.

This project has reproduced centrifugal pump data from the literature (Walker and Goulas, 1984) for different specific speeds. Figures 5.1 and 5.2 show the HR and ER curves for NS values of 0.27, 0.43, 0.53 and 0.74 respectively.

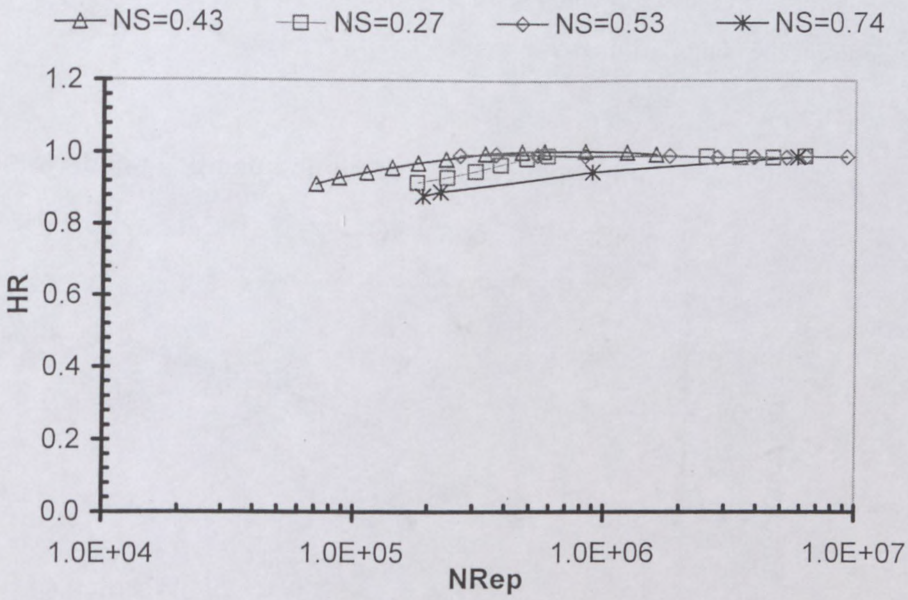

Figure 5.1: Pumps results (HR vs NRep) at BEP for different pump specific speeds

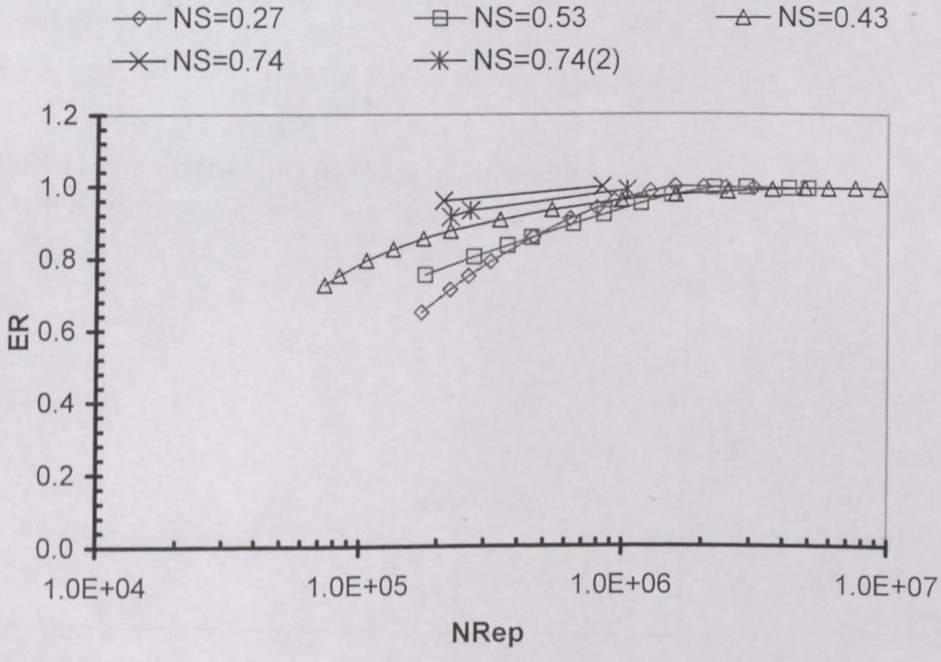

Figure 5.2: Pumps results (ER vs NRep) at BEP for different pump specific speeds

Test data for bentonite, CMC and kaolin tested with a 6/4 Warman NS=0.52 and a 4/3 GIW NS=0.43, are plotted on the above graphs (Figure 5.1 and Figure 5.2). Comparisons of literature specific speeds NS=0.53 and NS=0.43 with this project's test data are illustrated in

Figure 5.3, Figure 5.5 and Figure 5.7. In addition, Figure 5.4, Figure 5.6 and Figure 5.8 present the comparison error margins.

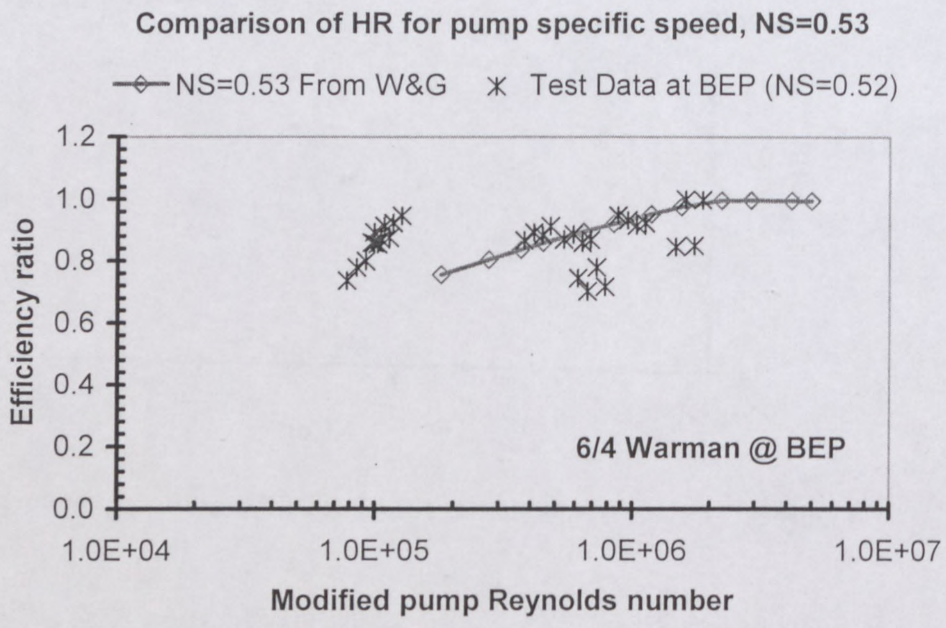

Figure 5.3: Specific speeds (NS=0.53) vs test data for the 6/4 Warman

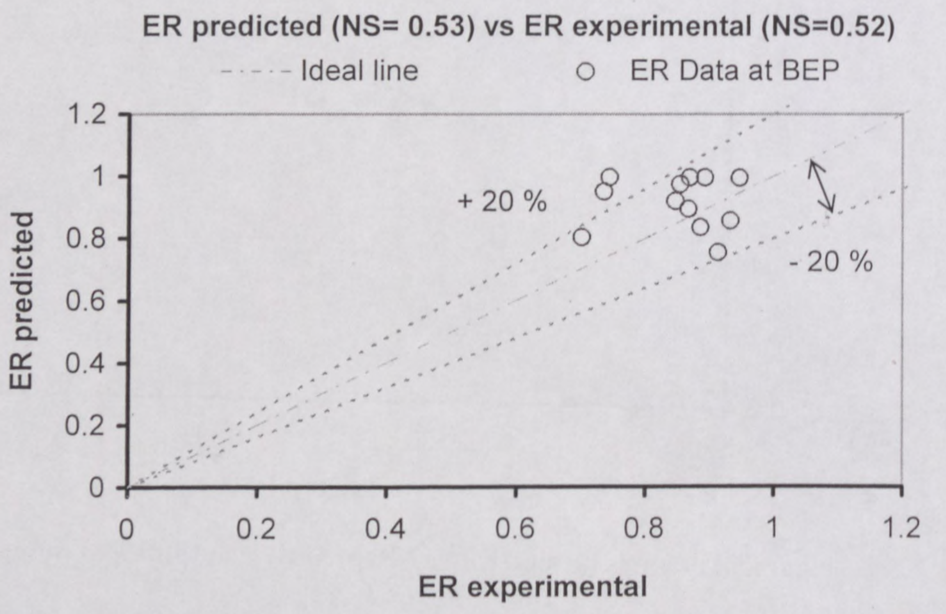

Figure 5.4: Error margin between ER predicted (NS=0.53) and ER experimental (NS= 0.52) for the 6/4 Warman

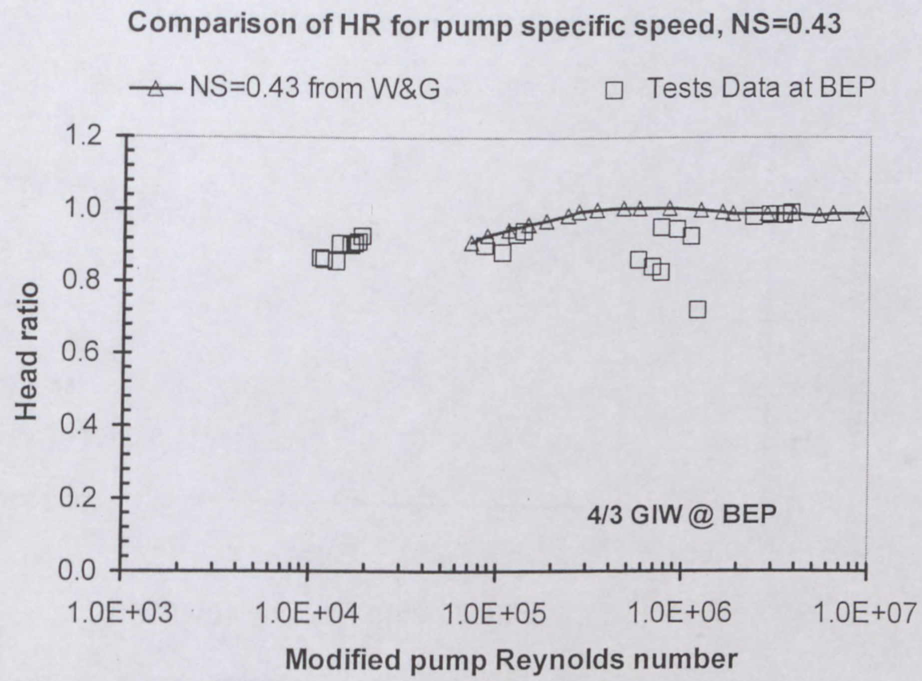

Figure 5.5: Comparison of the predicted HR (specific speed, NS=0.43) and the experimental HR (Ns=0.43) for the 4/3 GIW

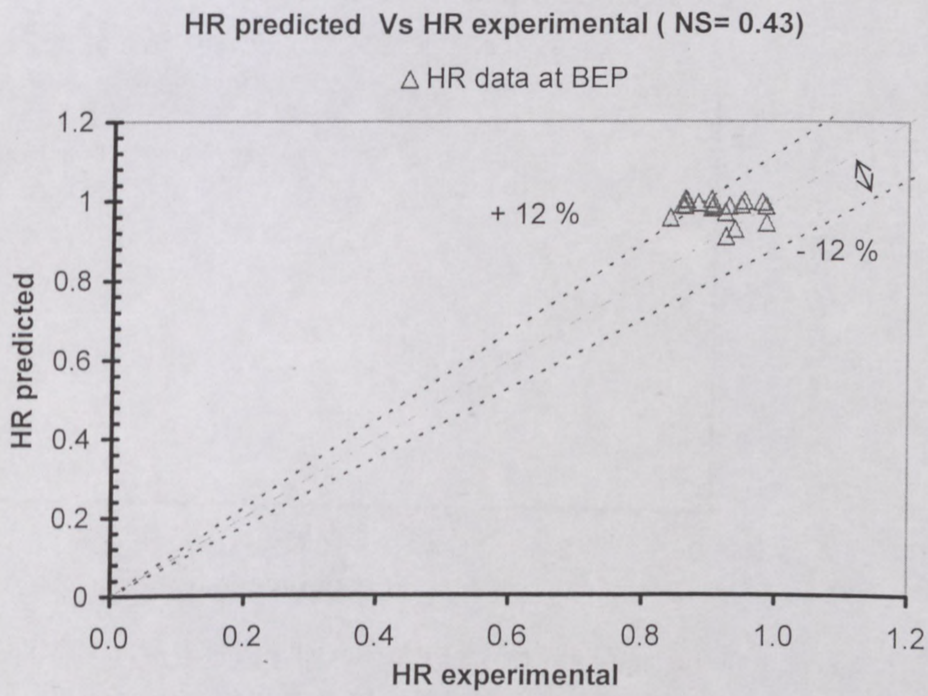

Figure 5.6: Error margin between HR predicted vs HR experimental (NS= 0.43) for the 4/3 GIW

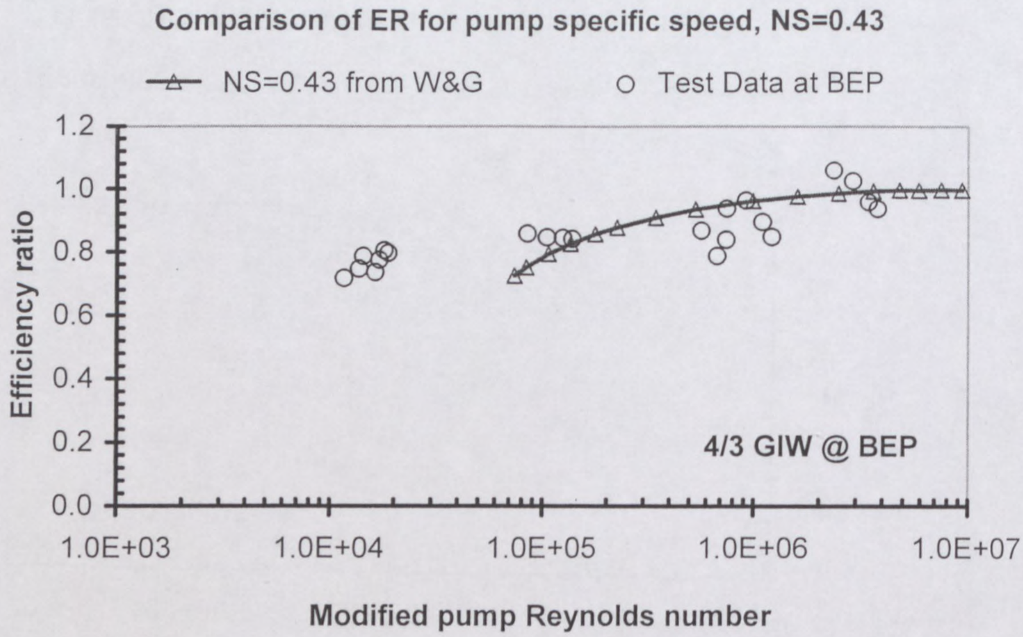

Figure 5.7: Comparison of the predicted ER (specific speed, NS=0.43) and the experimental ER (Ns=0.43) for the 4/3 GIW

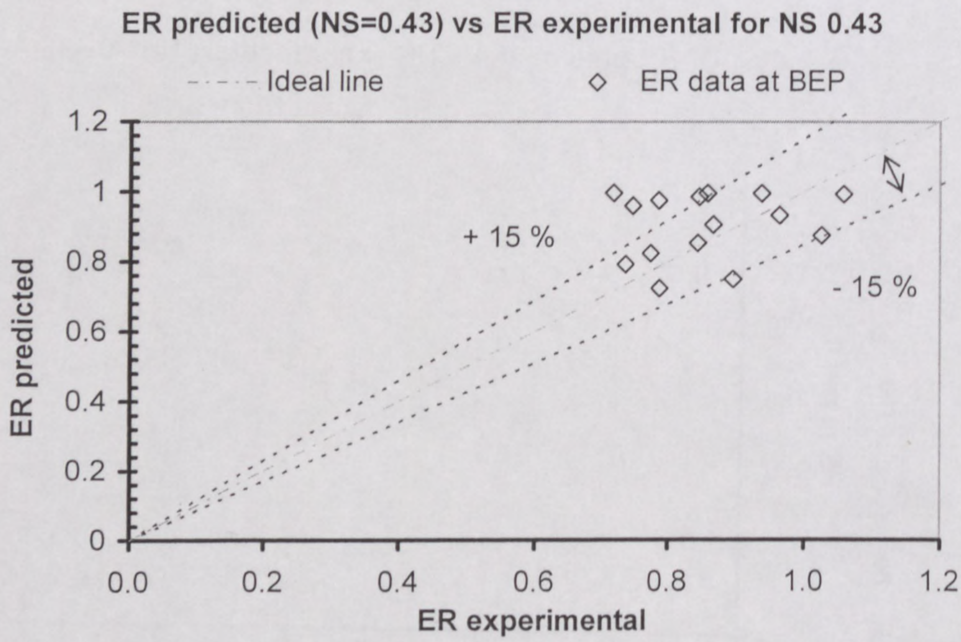

Figure 5.8: Error margin between ER predicted (NS=0.43) and ER experimental (NS= 0.43) for the 4/3 GIW

Test data (HR and ER) for the 4/3 GIW pump (NS=0.43) are compared with the trend reported in the literature for the same specific speed. An error margin of ± 12 % and ± 15 % are found for the head ratio and the efficiency ratio respectively.

Walker and Goulas (1984) have performed pump tests with a Hazelton 3-in (NS=0.27) and a Warman 4/3 DAH fitted with respectively a 5-vanes closed impeller (NS=0.51) and a 3 vanes open impeller (NS=0.56). However, the literature presents a curve for specific speed NS=0.53. This project presents test results for the 6/4 Warman pump (NS=0.52). Error margin of ± 20% for the ER and ± 10% for the HR are established between the experimental data (NS= 0.52) and the trend line from Walker and Goulas for NS=0.53.

These error values can be viewed as falling within permissible margins (± 20%) and may therefore confirm Walker and Goulas's (1984) contention that the reduction of the pump performance (HR and ER) experienced by higher specific speed pumps are lesser than those found in low specific speed pumps.

5.8 HYDRAULICS INSTITUTE CHART DERATION PROCEDURE

The error margins found in this work are two to three times higher than those presented in the literature for head reduction, and three to four times higher for efficiency reduction. The plastic viscosity is used in the nomogram for the prediction calculations. Table 5.1 presents both the results from the literature and those obtained in the current work.

Table 5.1: Prediction error from the HI chart at BEP

Present work			Walker and Goulas (1984)		
Error (%)			Error (%)		
Pump type	**HR**	**ER**	**Pump type**	**HR**	**ER**
4/3 GIW	± 15	± 15	4/3 Warman DAH	± 5	± 5
6/4 Warman	± 10	± 20	Hazleton 3 in B CTL	± 5	± 5

Possible reasons to justify the discrepancies are:

- the rheology of the fluids tested. Walker and Goulas (1984) have altered the viscosity of the material tested by adding an aqueous solution of sodium silicate. This practice has not been applied for the present work; and

- the value of the kinematic viscosity used in the HI chart.

The Bingham plastic forced fit may also have generated some errors. Given that the HI prediction depends on the plastic viscosity from the Bingham forced fit, the error margin found here must be interpreted with care. Figures 4.32 to 4.35 have presented the results for the HI evaluation.

5.9 CONCLUSION

- Derating procedures are evaluated with data from the materials tested. A 4/3 GIW and a 6/4 Warman are the motive machines of the slurry in the pipe system. It is shown that all data followed the literature Walker trend.

- Walker and Goulas's (1984) statement regarding a correlation between the pump performance (HR and ER) and the pump specific speed is corroborated by the present work.

- Error margins found in this work using the HI deration chart to predict the performance of the 4/3 GIW are ± 15 % for the head and ± 15 % for the efficiency. Performance prediction for the 6/4 Warman gives ± 10% and ± 20% for the head and the efficiency respectively.

  The use of HI deration procedures in the prediction of centrifugal pump for non-Newtonian materials must be considered with care, as neither the work conducted by Sery and Slatter (2002), nor the present work, has come to the same conclusions as the original work carried out by Walker and Goulas (1984).

CHAPTER 6

SUMMARY, CONTRIBUTIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

Walker and Goulas (1984) have introduced a centrifugal pump deration procedure from test conducted on yield pseudoplastic materials. Sery and Slatter (2002) have carried out experimental work on the same materials.

This work seeks to contribute to the understanding of the effect of slurry on centrifugal pump performance. The reason for repeating the work is to corroborate previous findings and to extend the evaluation of deration procedures to other materials as presented in the literature. In particular pseudoplastic fluids are also studied.

This chapter presents a summary of the current work and conclusions together with some recommendations.

6.2 SUMMARY

Vast tonnages of non-Newtonian slurries are hydraulically transported each year in diverse industries (Wilson *et al.*, 1997). Centrifugal pumps have become the most commonly used pumps in the slurry transport systems (Abulnaga, 2002). However, their performance is different for slurry or viscous materials (Stepanoff, 1969) and this need to be accounted for. Usually, slurry pumps are designed differently; their design is governed by different hydraulic relationships than conventional water pumps although they are universally tested on water as a reference fluid (Abulnaga, 2002).

The centrifugal pump deration procedures introduced by Walker and Goulas's work (1984) are based on yield pseudoplastic slurries characterised in terms of the Bingham plastic model. The aim of this thesis is to evaluate the existing deration procedures and to demonstrate their reliability.

The test work was conducted in the Flow Process Research Centre laboratory of the Cape Peninsula University of Technology. Two centrifugal pumps, a Warman 6/4 and a GIW 4/3 were used to move different slurries through 60 mm, 80 mm and 150 mm recirculating pipes. The experimental investigations are described in Chapter 3 and the results analysed in Chapter 4.

It is concluded that the findings in this work corroborate the results found in the literature for the correlation of head and efficiency to the pump Reynolds number. The head reduction ratio (HR) and the efficiency reduction ratio (ER) decreased for NRe_p less than 10^6.
The present work has also compared the head and efficiency reduction experienced in centrifugal pumps of 0.53 and 0.43 specific speed to those calculated from a Warman 6/4 and a GIW 4/3.

Error margin found in this work using the HI deration chart to predict the performance of the 4/3 GIW are ± 15 % for both the head and the efficiency. Performance prediction for the 6/4 Warman gives ± 10% for the head and ± 20% for the efficiency respectively.

The use of HI deration procedure in the prediction of centrifugal pumps for non-Newtonian material must be considered with care, as neither the work conducted by Sery and Slatter (2002), nor the present work, has come to the same conclusions as the original work carried out by Walker and Goulas (1984).

6.3 CONTRIBUTIONS

The present work has confirmed the effect of viscous non-Newtonian fluids on the performance of centrifugal pumps. It has highlighted and confirmed certain other hypotheses as listed below:

- pump efficiency is reduced significantly for all the three materials tested;
- the total head at low flow rate dropped severely for material with yield stress compared to the pseudoplastic material (without yield stress);

- the analysis with the Walker and Goulas procedure for material with yield stress has come to the same conclusion as in the literature. The head reduction ratio (HR) and the efficiency reduction ratio (ER) decreased for pump Reynolds number (NRep) less than 10^6;

- for the first time CMC pump data have been analysed with the Walker and Goulas procedure. Again, deration is noticed for pump Reynolds numbers less than 10^6.

- trends for 2 pump specific speeds from the literature were compared with experimental data. The error margins found are within permissible limits thus confirming again that the pump performance (HR and ER) experienced in centrifugal pumps depend on the pump specific speed.

- the use of the HI deration chart in the prediction of centrifugal pump performance handling non-Newtonian slurries has shown the following values as error margins: for the GIW 4/3 pump: ± 15 % for both the head and the efficiency, and for the Warman 6/4 pump: ± 10% for the head and ± 20% for the efficiency: and.

- the HI deration procedure primarily meant for Newtonian material should be used with caution in the prediction of centrifugal pump for non-Newtonian material, as neither the work conducted by Sery and Slatter (2002), nor the present work has come to the same conclusions as the original work carried out by Walker and Goulas (1984).

6.4 RECOMMENDATIONS

Additional experimental work needs to be carried out, as some controversies still exist between the literature and the results of this project.

- The rheological characterisation is one of the issues: data analysis for both deration procedures depends on the rheological values (τ_y, K and n).

- The plastic viscosity derived from the rheological characterisation needs to be correctly interpreted. The plastic viscosity affects the value of the pump Reynolds number at BEP.

- The use of Hydraulic Institute chart deration procedures in the prediction of non-Newtonian materials needs to be investigated further to confirm its applicability.

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APPENDIX A

PHOTOGRAPHS OF THE EXPERIMENTAL TEST LOOP AND INSTRUMENTATION

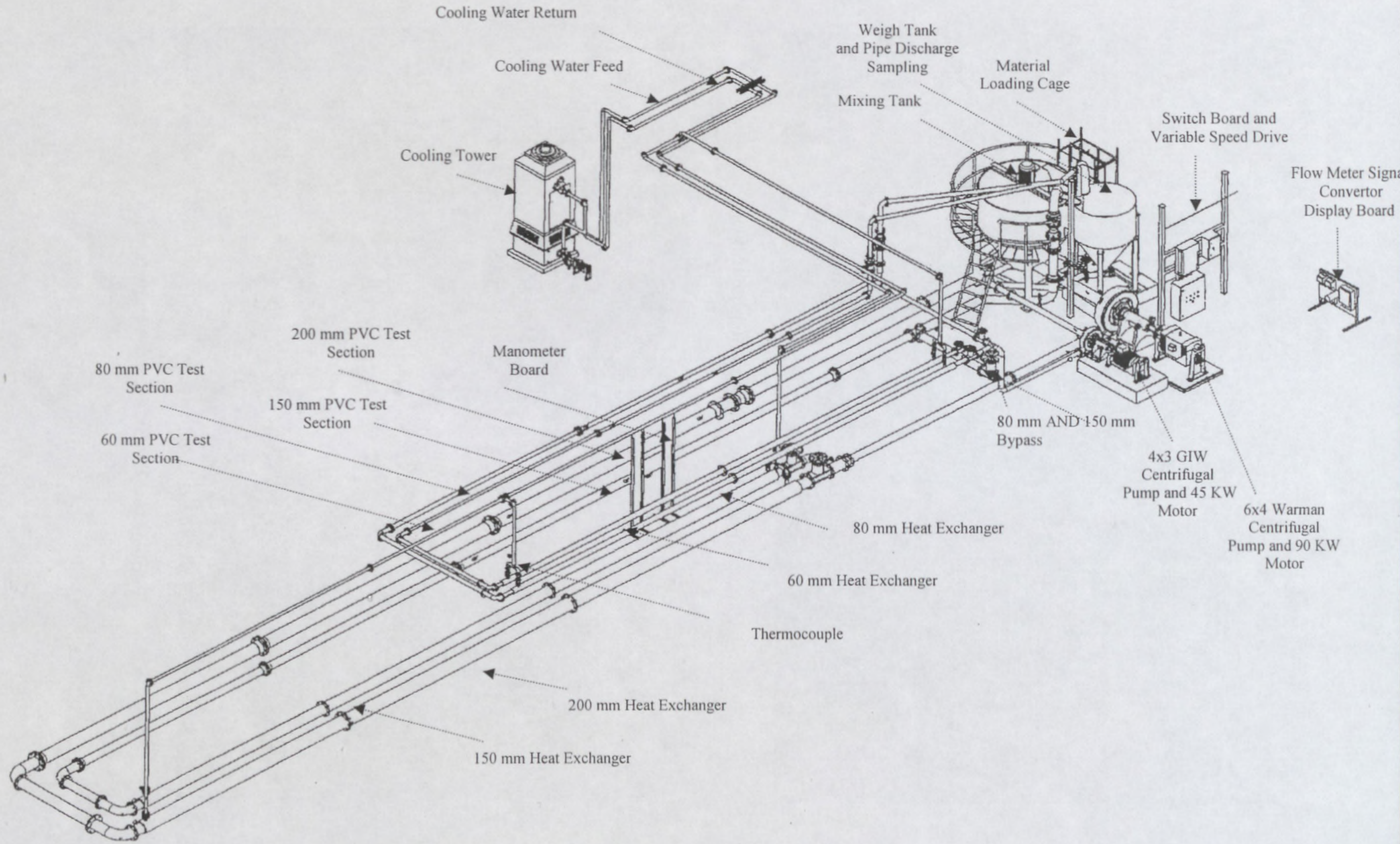
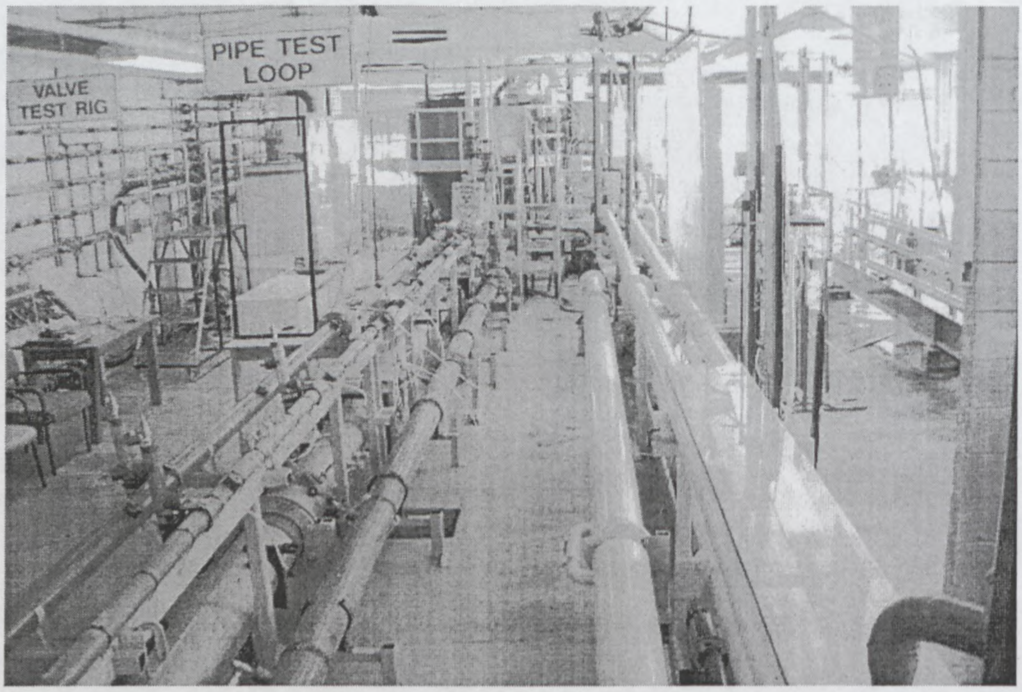
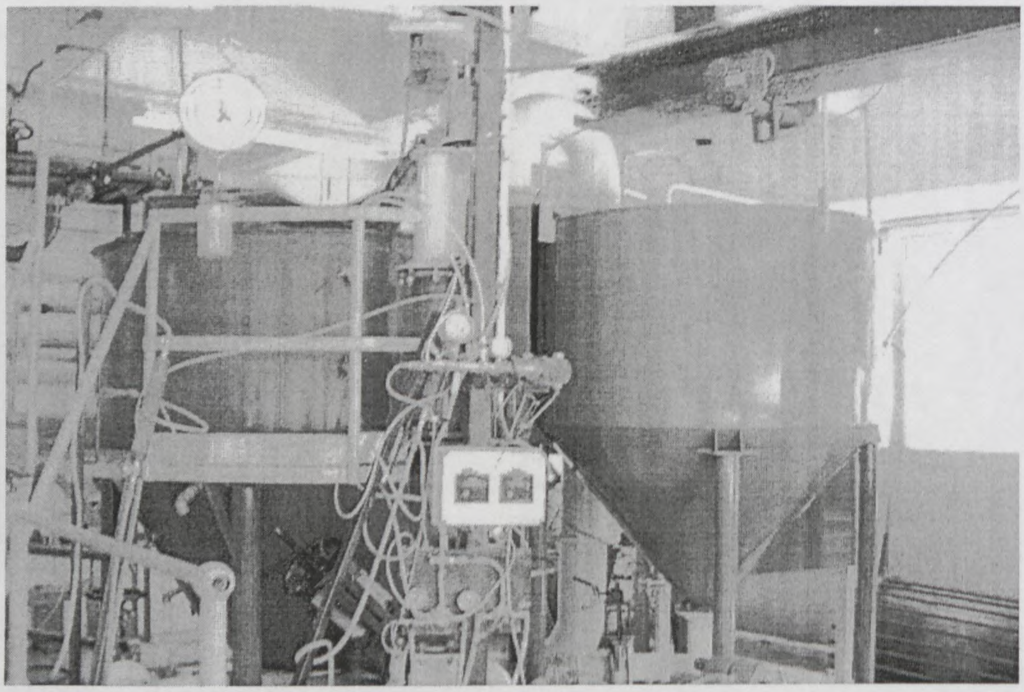


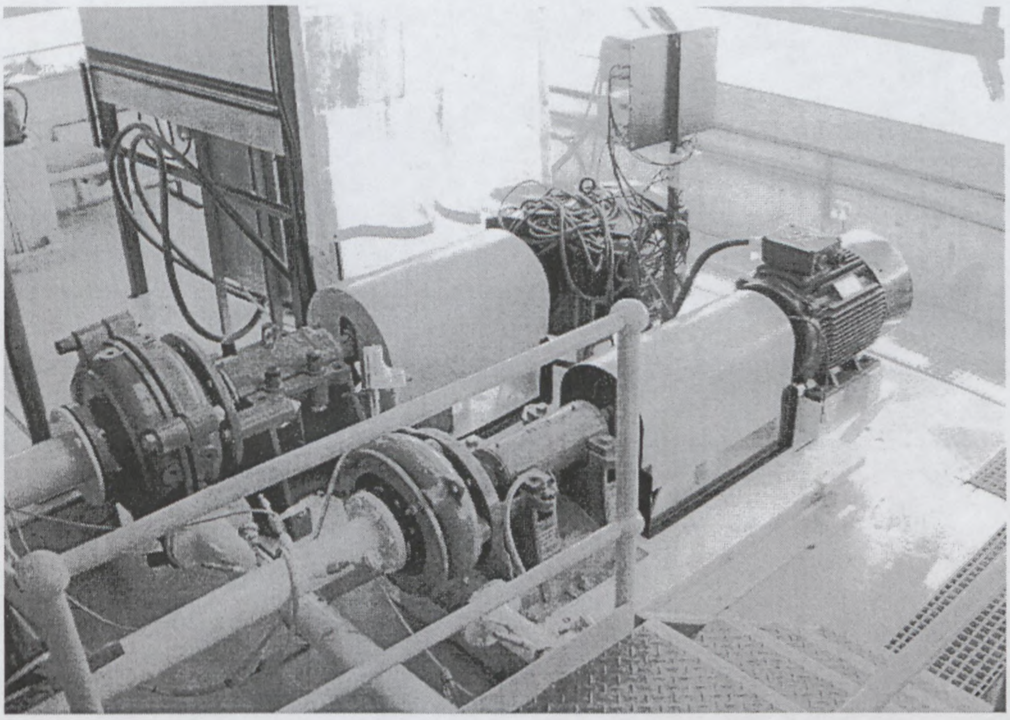
Figure 1: Schematic diagram of the pipe test rig



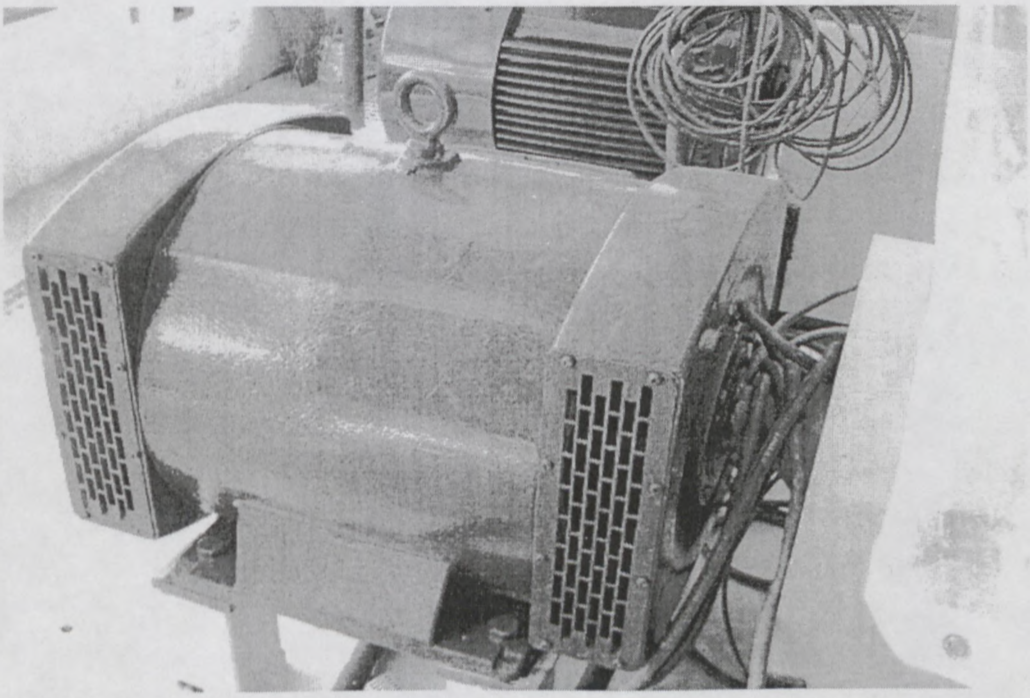
Photograph 1: Over view of the pipe test rig



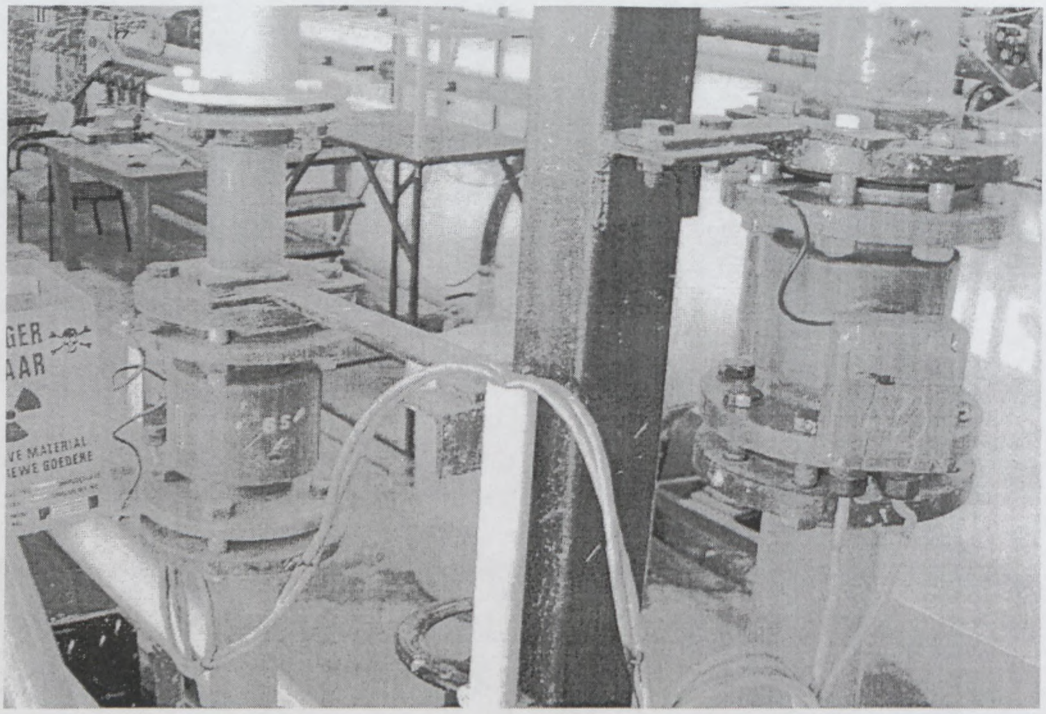
Photograph 2: Mixing and weight tank



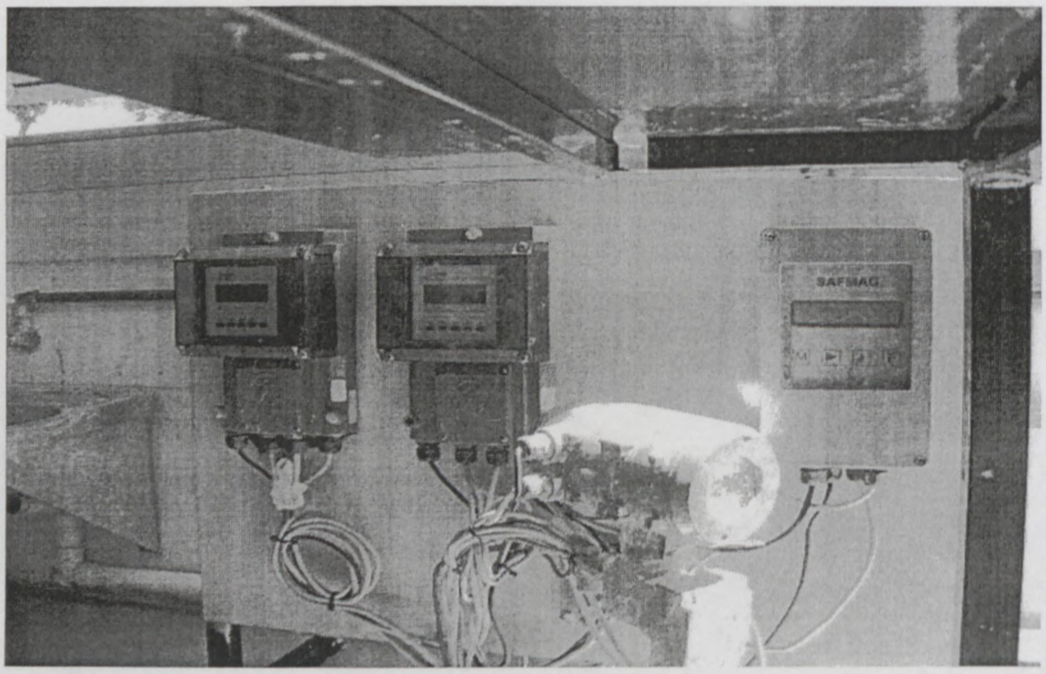
Photograph 3: 6/4 Warman and 4/3 GIW centrifugal pumps



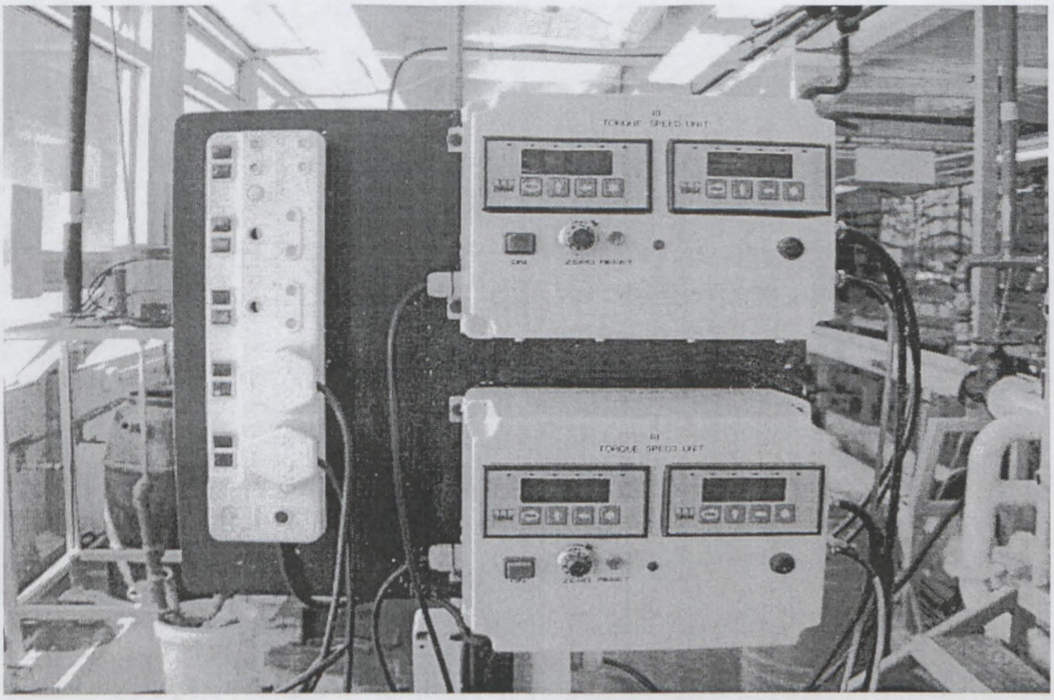
Photograph 4: 90 kW and 45 kW electric motors



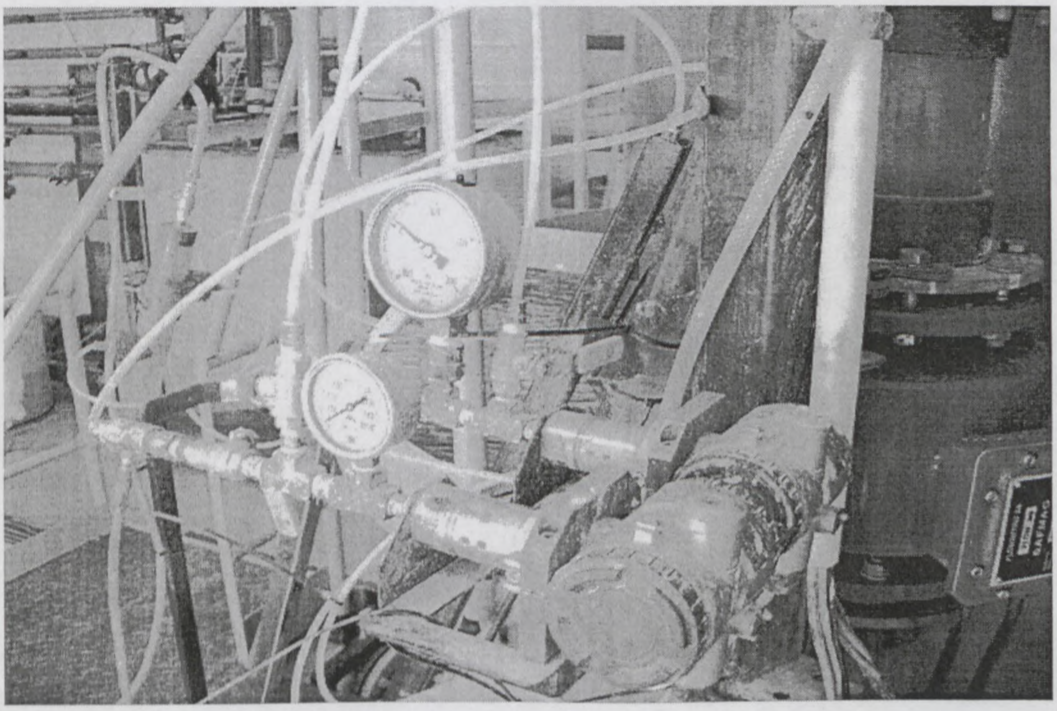
Photograph 5: 60 mm and 80 mm Flow meters



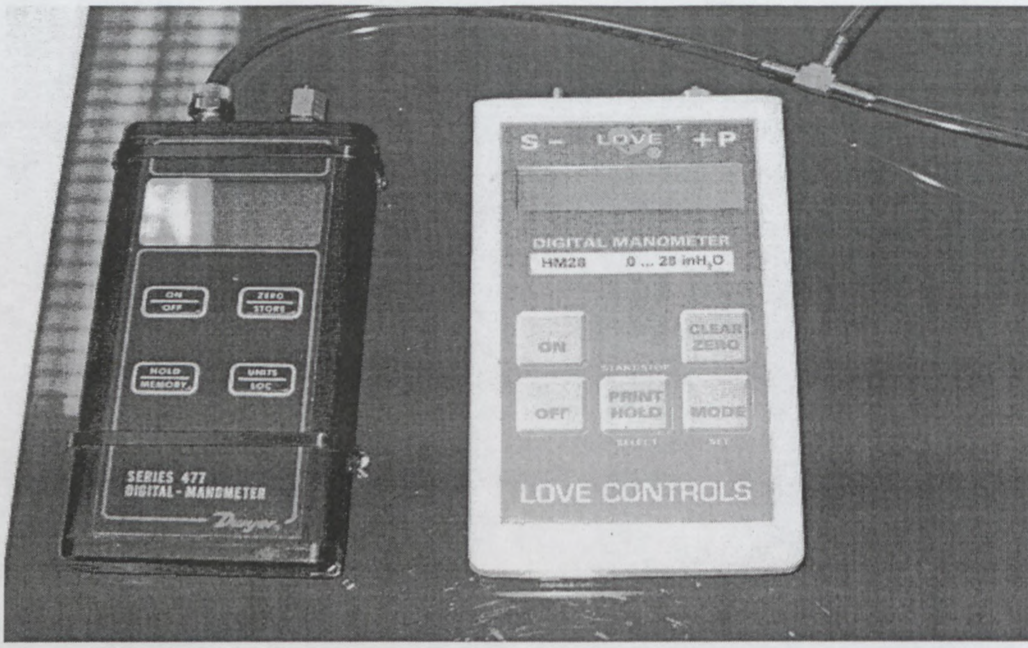
Photograph 6: 60 mm, 80 mm, 150 mm and 200 mm Flow meters displayers



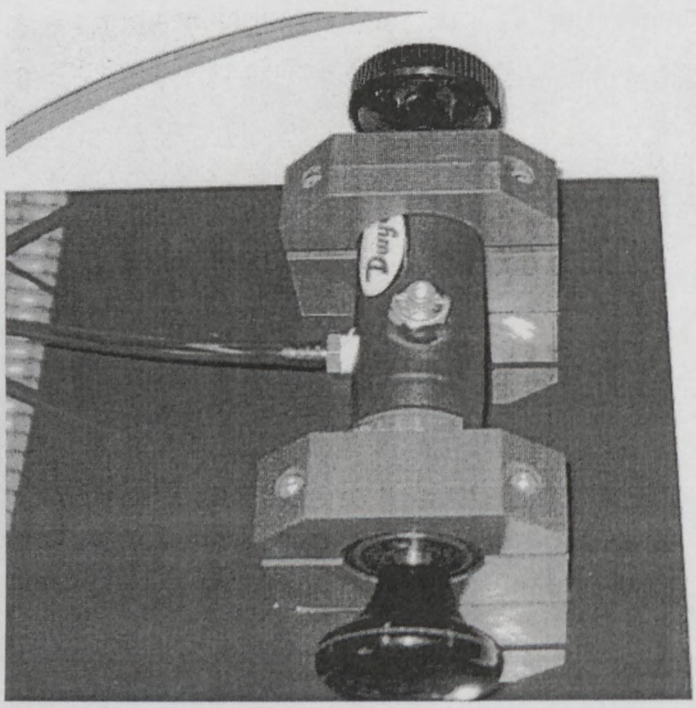
Photograph 7: Torque speed unit displayer



Photograph 8: Pressure point transducers

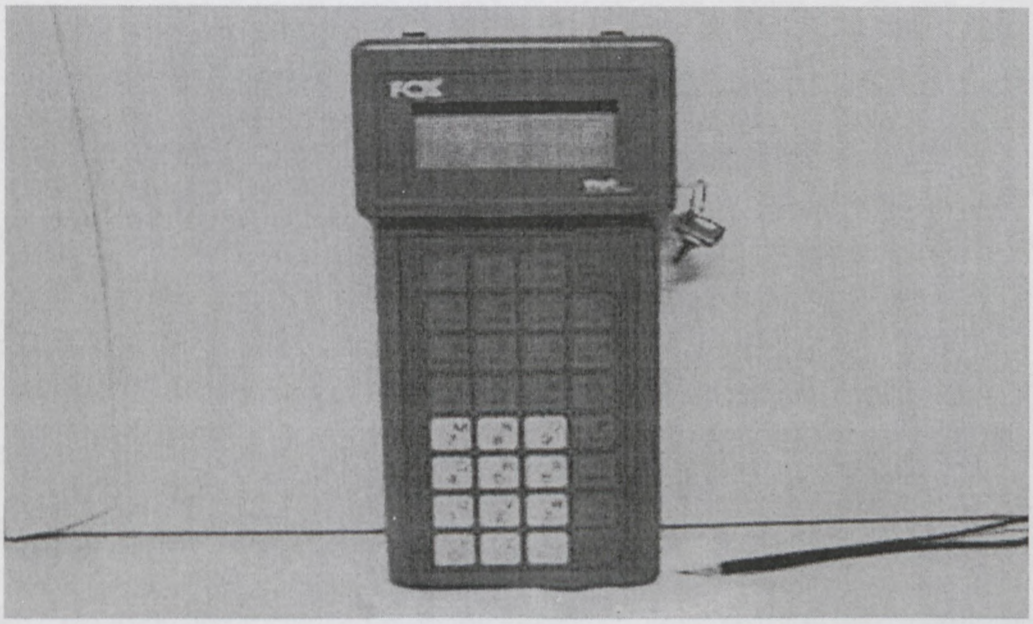


Photograph 9: Digital manometers

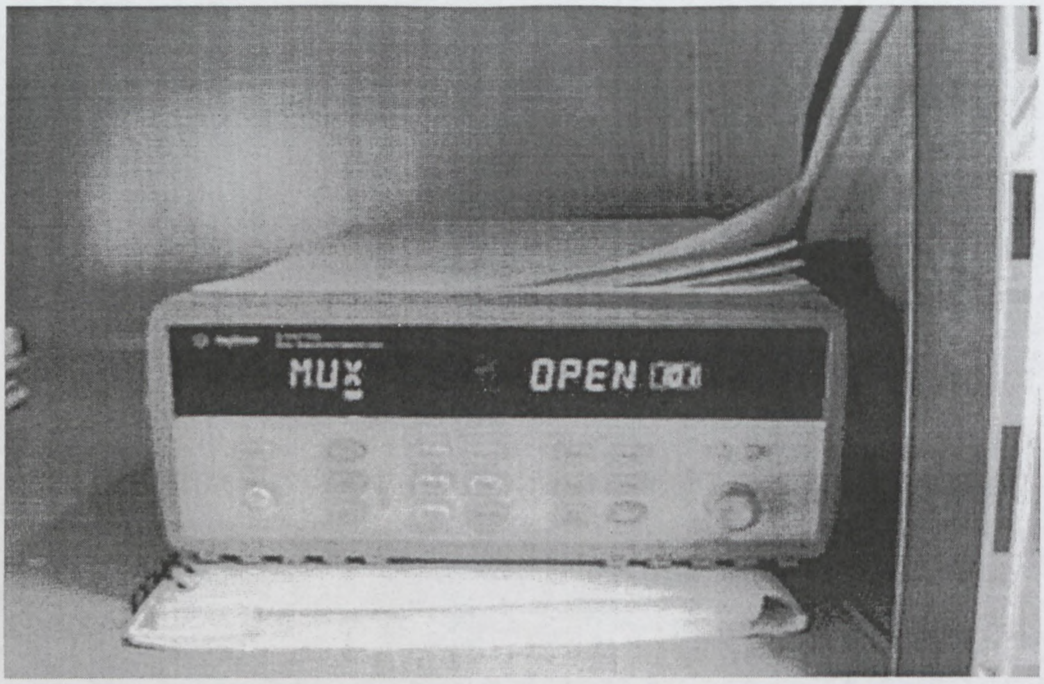


Photograph 10: Piston pump for the manometer

Photograph 11: Digital tachometer



Photograph 12: Hand held communicator



Photograph 13: Data log acquisition unit

APPENDIX B

CLEAR WATER PIPE TEST DATA AND COLEBROOK-WHITE WATER TEST ANALYSIS

Table 1: Water test data in 57.68 mm straight pipe

Clear Water Test Analysis

28-Jan-05

D = 57.68 mm k = 08.0 um

Sum(Diff^2) 323.13109

8E-06 8E-06

D =	0.05768	m	m
L =	3.00	m	m
Temp =	27.22	deg C	deg C
A =	0.00261301	m^2	m^2

						8V/D	($f\rho V^2/2$)				($D\Delta P/4L$)	($\tau_o - \tau_{o\,obs}$)		($4fLV^2/2Dg$)	($\rho g\Delta h$)	($\Delta H/L$)	($D\Delta P/4L$)
Temperature	V	(stddev)	ρ	D	μ	i_w/m	τ_o (k=0)	ΔP (obs)		Δp Sdev	τ_o (obs)	Diff(erence)	Diff^2	ΔH (calc)	ΔP (calc)	i_m	τ_o (calc)
26.382	9.685	0.010	996.729	0.058	0.000868	1.204	169.731	34281.164	H	0.353	164.778	4.953	24.532	3.611	35311.593	1.204	169.731
26.445	9.735	0.008	996.712	0.058	0.000867	1.213	170.966	34288.211	H	0.169	164.812	6.154	37.867	3.638	35568.438	1.213	170.966
26.483	9.744	0.004	996.702	0.058	0.000866	1.214	171.223	33546.020	H	0.264	161.245	9.979	99.579	3.643	35622.075	1.214	171.223
26.611	9.114	0.002	996.668	0.058	0.000864	1.069	150.698	30679.748	H	0.160	147.467	3.231	10.438	3.207	31351.907	1.069	150.698
26.713	9.125	0.005	996.641	0.058	0.000862	1.071	151.020	31541.529	H	0.210	151.610	-0.590	0.348	3.214	31418.851	1.071	151.020
26.767	9.136	0.004	996.627	0.058	0.000861	1.074	151.349	30328.012	H	0.213	145.777	5.572	31.050	3.221	31487.282	1.074	151.349
26.869	8.567	0.005	996.600	0.058	0.000859	0.950	133.883	27234.879	H	0.211	130.909	2.974	8.847	2.849	27853.700	0.950	133.883
26.923	8.554	0.004	996.585	0.058	0.000858	0.947	133.465	26349.615	H	0.189	126.654	6.811	46.391	2.840	27766.631	0.947	133.465
26.947	8.564	0.006	996.579	0.058	0.000857	0.949	133.771	27180.162	H	0.202	130.646	3.125	9.767	2.847	27830.348	0.949	133.771
27.014	8.023	0.006	996.561	0.058	0.000856	0.838	118.144	24151.676	H	0.071	116.089	2.055	4.225	2.514	24579.289	0.838	118.144
27.044	8.009	0.004	996.553	0.058	0.000856	0.835	117.764	24438.240	H	0.163	117.466	0.297	0.088	2.506	24500.036	0.835	117.764
27.083	8.032	0.004	996.542	0.058	0.000855	0.840	118.374	24060.893	H	0.134	115.653	2.721	7.406	2.519	24627.048	0.840	118.374
27.135	7.431	0.007	996.528	0.058	0.000854	0.725	102.135	20858.285	H	0.120	100.259	1.876	3.520	2.174	21248.614	0.725	102.135
27.155	7.444	0.003	996.523	0.058	0.000854	0.727	102.468	21165.709	H	0.141	101.737	0.731	0.535	2.181	21317.839	0.727	102.468
27.168	7.442	0.003	996.519	0.058	0.000853	0.726	102.408	20634.451	H	0.143	99.183	3.225	10.398	2.179	21305.323	0.726	102.408
27.212	6.911	0.002	996.507	0.058	0.000852	0.631	89.010	18353.701	H	0.150	88.220	0.790	0.625	1.894	18518.128	0.631	89.010
27.231	6.908	0.002	996.502	0.058	0.000852	0.631	88.940	18171.174	H	0.092	87.343	1.597	2.551	1.893	18503.437	0.631	88.940
27.254	6.911	0.003	996.496	0.058	0.000852	0.631	88.994	18208.113	H	0.125	87.520	1.474	2.172	1.894	18514.709	0.631	88.994
27.309	6.354	0.002	996.481	0.058	0.000851	0.539	75.924	15911.341	H	0.115	76.481	-0.556	0.309	1.616	15795.660	0.539	75.924
27.331	6.361	0.003	996.475	0.058	0.000850	0.540	76.076	15809.651	H	0.079	75.992	0.084	0.007	1.619	15827.152	0.540	76.076
27.344	6.357	0.002	996.471	0.058	0.000850	0.539	75.982	15110.649	H	0.132	72.632	3.350	11.224	1.617	15807.654	0.539	75.982
27.361	5.800	0.001	996.467	0.058	0.000850	0.453	63.910	13515.905	H	0.134	64.966	-1.057	1.116	1.360	13296.101	0.453	63.910
27.372	5.789	0.002	996.464	0.058	0.000850	0.452	63.694	13005.833	H	0.068	62.515	1.180	1.392	1.356	13251.276	0.452	63.694
27.382	5.788	0.003	996.461	0.058	0.000849	0.452	63.661	13083.076	H	0.105	62.886	0.775	0.600	1.355	13244.210	0.452	63.661
27.396	5.257	0.002	996.457	0.058	0.000849	0.377	53.115	11057.330	H	0.064	53.149	-0.034	0.001	1.130	11050.258	0.377	53.115
27.402	5.259	0.003	996.455	0.058	0.000849	0.377	53.173	11064.590	H	0.072	53.184	-0.010	0.000	1.132	11062.420	0.377	53.173
27.407	5.262	0.001	996.454	0.058	0.000849	0.378	53.231	11149.334	H	0.062	53.591	-0.360	0.130	1.133	11074.390	0.378	53.231
27.413	4.691	0.002	996.452	0.058	0.000849	0.304	42.910	8905.648	H	0.099	42.806	0.103	0.011	0.913	8927.096	0.304	42.910
27.416	4.689	0.002	996.452	0.058	0.000849	0.304	42.874	9146.919	H	0.064	43.966	-1.093	1.194	0.912	8919.596	0.304	42.874
27.420	4.682	0.002	996.451	0.058	0.000849	0.303	42.757	9100.188	H	0.061	43.742	-0.985	0.969	0.910	8895.367	0.303	42.757
27.424	4.144	0.003	996.449	0.058	0.000849	0.241	34.025	7382.205	H	0.076	35.484	-1.459	2.129	0.724	7078.612	0.241	34.025
27.427	4.158	0.001	996.449	0.058	0.000849	0.243	34.247	7213.395	H	0.050	34.672	-0.426	0.181	0.729	7124.802	0.243	34.247
27.430	4.148	0.001	996.448	0.058	0.000848	0.242	34.088	7311.213	H	0.056	35.143	-1.055	1.113	0.725	7091.757	0.242	34.088
27.434	4.157	0.001	996.447	0.058	0.000848	0.243	34.234	7339.591	H	0.044	35.279	-1.045	1.092	0.729	7122.200	0.243	34.234
27.437	4.151	0.002	996.446	0.058	0.000848	0.242	34.133	7250.846	H	0.037	34.852	-0.719	0.518	0.726	7101.164	0.242	34.133
27.441	3.596	0.001	996.445	0.058	0.000848	0.185	26.125	5481.135	L	0.025	26.346	-0.221	0.049	0.556	5435.152	0.185	26.125
27.448	3.600	0.001	996.443	0.058	0.000848	0.186	26.183	5497.199	L	0.020	26.423	-0.241	0.058	0.557	5447.146	0.186	26.183
27.450	3.597	0.001	996.442	0.058	0.000848	0.185	26.143	5498.055	L	0.024	26.427	-0.285	0.081	0.556	5438.831	0.185	26.143
27.453	3.051	0.000	996.442	0.058	0.000848	0.137	19.254	4087.129	L	0.035	19.645	-0.391	0.153	0.410	4005.683	0.137	19.254
27.451	3.049	0.001	996.442	0.058	0.000848	0.136	19.235	4079.974	L	0.030	19.611	-0.376	0.141	0.409	4001.809	0.136	19.235
27.454	3.049	0.001	996.441	0.058	0.000848	0.137	19.242	4077.068	L	0.031	19.597	-0.355	0.126	0.410	4003.211	0.137	19.242
27.449	2.549	0.001	996.443	0.058	0.000848	0.098	13.819	2967.750	L	0.053	14.265	-0.446	0.199	0.294	2874.968	0.098	13.819
27.448	2.551	0.001	996.443	0.058	0.000848	0.098	13.841	2972.844	L	0.052	14.289	-0.449	0.201	0.295	2879.466	0.098	13.841
27.450	2.547	0.001	996.442	0.058	0.000848	0.098	13.802	2972.336	L	0.058	14.287	-0.485	0.236	0.294	2871.367	0.098	13.802
27.448	1.129	0.002	996.443	0.058	0.000848	0.022	3.117	548.982	L	0.027	2.639	0.478	0.229	0.066	648.436	0.022	3.117
27.448	1.133	0.000	996.443	0.058	0.000848	0.022	3.141	694.933	L	0.064	3.340	-0.199	0.040	0.067	653.449	0.022	3.141
27.446	1.132	0.000	996.443	0.058	0.000848	0.022	3.140	717.501	L	0.071	3.449	-0.309	0.095	0.067	653.283	0.022	3.140

Table 2: Water test data in 81.20 mm straight pipe

Clear Water
Test Analysis

27-Jan-05

D = 81.20 mm
k = 08.0 um

Sum(Diff^2) 122.98935

8E-06 8E-06

D =	0.0812	m
L =	3.65	m
Temp =	29.21	deg C
A =	0.0051785	m^2

						8V/D	$(f\rho V^2/2)$				$(D\Delta P/4L)$	$(\tau_o - \tau_{o\,obs})$		$(4fLV^2/2Dg)$	$(\rho g\Delta h)$	$\Delta H/L)$	$(D\Delta P/4L)$
Temperature	V	(stddev)	ρ	Δ	μ	i_m/m	τ_o (k=0)	ΔP (obs)		Δp Sdev	τ_o (obs)	Diff(erence)	Diff^2	ΔH (calc)	ΔP (calc)	i_m	τ_o (calc)
29.522	3.562	0.001	995.855	0.081	0.000812	0.120	23.846	4561.536	L	0.016	25.370	-1.524	2.322	0.439	4287.578	0.120	23.846
29.435	3.190	0.001	995.880	0.081	0.000813	0.098	19.380	3733.914	L	0.021	20.767	-1.387	1.923	0.357	3484.563	0.098	19.380
29.397	2.829	0.000	995.892	0.081	0.000814	0.078	15.514	3011.869	L	0.022	16.751	-1.237	1.529	0.286	2789.520	0.078	15.514
29.353	2.457	0.000	995.904	0.081	0.000814	0.060	11.950	2333.082	L	0.032	12.976	-1.026	1.053	0.220	2148.565	0.060	11.950
29.314	2.113	0.000	995.916	0.081	0.000815	0.046	9.051	1784.811	L	0.031	9.926	-0.876	0.767	0.167	1627.348	0.046	9.051
29.274	1.756	0.000	995.927	0.081	0.000816	0.032	6.445	1285.017	L	0.050	7.147	-0.702	0.493	0.119	1158.821	0.032	6.445
29.232	1.411	0.001	995.940	0.081	0.000817	0.022	4.319	848.087	L	0.062	4.717	-0.398	0.158	0.079	776.554	0.022	4.319
29.203	1.037	0.001	995.948	0.081	0.000817	0.012	2.467	517.228	L	0.063	2.877	-0.410	0.168	0.045	443.531	0.012	2.467
29.173	0.707	0.001	995.957	0.081	0.000818	0.006	1.235	267.768	L	0.054	1.489	-0.254	0.065	0.023	222.073	0.006	1.235
29.138	0.299	0.001	995.967	0.081	0.000818	0.001	0.265	71.653	L	0.002	0.399	-0.133	0.018	0.005	47.680	0.001	0.265
29.090	4.295	0.001	995.981	0.081	0.000819	0.171	33.888	6679.137	H	0.110	37.147	-3.259	10.624	0.624	6093.082	0.171	33.888
29.068	4.661	0.002	995.987	0.081	0.000819	0.199	39.403	7698.956	H	0.113	42.819	-3.416	11.667	0.725	7084.801	0.199	39.403
29.065	5.021	0.001	995.988	0.081	0.000819	0.228	45.320	8451.603	H	0.148	47.005	-1.684	2.837	0.834	8148.728	0.228	45.320
29.063	5.400	0.002	995.989	0.081	0.000819	0.262	51.961	10119.400	H	0.150	56.281	-4.319	18.655	0.956	9342.801	0.262	51.961
29.066	5.769	0.003	995.988	0.081	0.000819	0.297	58.848	10735.964	H	0.202	59.710	-0.862	0.743	1.083	10581.028	0.297	58.848
29.080	6.132	0.002	995.984	0.081	0.000819	0.333	66.041	12757.792	H	0.187	70.954	-4.913	24.139	1.215	11874.399	0.333	66.041
29.102	6.495	0.002	995.977	0.081	0.000819	0.371	73.614	14023.361	H	0.196	77.993	-4.379	19.179	1.355	13235.943	0.371	73.614
29.140	6.858	0.002	995.966	0.081	0.000818	0.411	81.596	15447.306	H	0.274	85.912	-4.317	18.635	1.502	14671.127	0.411	81.596
29.185	7.242	0.003	995.953	0.081	0.000817	0.456	90.463	16774.561	H	0.326	93.294	-2.831	8.015	1.665	16265.509	0.456	90.463

Table 3: Water test data in 150.60 mm straight pipe

Clear Water Test Analysis 28-Jan-05 D = 150.60 mm k = 08.0 um		
D =	0.15060	m
L =	5.35	m
Temp =	3.48	deg C
A =	0.0178131	m^2

Sum(Diff^2) 8.9114

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						8V/D	$(f\rho V^2/2)$				$(D\Delta P/4L)$	$(\tau_o - \tau_{o\,obs})$		$(4fLV^2/2Dg)$	$(\rho g\Delta h)$	$(\Delta H/L)$	$(D\Delta P/4L)$
Temperature	V	(stddev)	ρ	D	μ	i_m/m	τ_o (k=0)	ΔP (obs)		Δp Sdev	τ_o (obs)	Diff(erence)	Diff^2	ΔH (calc)	ΔP (calc)	i_m	τ_o (calc)
27.655	4.131	0.004	996.386	0.151	0.000844	0.076	28.100	4165.278	L	0.080	29.313	-1.212	1.470	0.409	3992.989	0.076	28.100
27.663	6.788	0.005	996.384	0.151	0.000844	0.194	71.508	10211.551	H	0.186	71.863	-0.355	0.126	1.040	10161.167	0.194	71.508
27.760	7.305	0.005	996.357	0.151	0.000843	0.223	82.130	11923.542	H	0.155	83.911	-1.781	3.170	1.194	11670.533	0.223	82.130
27.865	6.248	0.006	996.328	0.151	0.000841	0.166	61.039	8686.438	H	0.200	61.130	-0.091	0.008	0.887	8673.482	0.166	61.039
27.937	5.713	0.006	996.308	0.151	0.000839	0.140	51.539	7734.860	H	0.123	54.433	-2.894	8.375	0.749	7323.640	0.140	51.539
27.999	5.192	0.003	996.291	0.151	0.000838	0.117	43.024	6438.418	H	0.126	45.310	-2.286	5.226	0.626	6113.568	0.117	43.024
28.034	4.647	0.004	996.281	0.151	0.000838	0.095	34.908	5156.037	L	0.061	36.285	-1.377	1.897	0.508	4960.347	0.095	34.908
28.108	4.095	0.002	996.260	0.151	0.000836	0.075	27.536	4073.936	L	0.054	28.670	-1.133	1.285	0.400	3912.879	0.075	27.536
28.121	4.089	0.004	996.257	0.151	0.000836	0.075	27.458	4075.316	L	0.077	28.680	-1.221	1.491	0.399	3901.781	0.075	27.458
28.129	4.085	0.004	996.254	0.151	0.000836	0.074	27.411	4085.806	L	0.075	28.753	-1.342	1.802	0.399	3895.063	0.074	27.411
28.136	3.527	0.003	996.252	0.151	0.000836	0.057	20.824	3140.933	L	0.047	22.104	-1.280	1.639	0.303	2959.007	0.057	20.824
28.134	3.523	0.001	996.253	0.151	0.000836	0.056	20.775	3124.450	L	0.061	21.988	-1.213	1.472	0.302	2952.023	0.056	20.775
28.133	3.523	0.004	996.253	0.151	0.000836	0.056	20.777	3128.336	L	0.055	22.015	-1.239	1.535	0.302	2952.309	0.056	20.777
28.132	2.902	0.003	996.254	0.151	0.000836	0.039	14.473	2250.015	L	0.043	15.834	-1.361	1.852	0.210	2056.633	0.039	14.473
28.127	2.902	0.003	996.255	0.151	0.000836	0.039	14.476	2252.081	L	0.047	15.849	-1.373	1.885	0.210	2056.972	0.039	14.476
28.126	2.898	0.004	996.255	0.151	0.000836	0.039	14.444	2208.224	L	0.034	15.540	-1.096	1.201	0.210	2052.484	0.039	14.444
28.115	2.332	0.003	996.258	0.151	0.000836	0.026	9.645	1540.697	L	0.031	10.842	-1.197	1.433	0.140	1370.587	0.026	9.645
27.867	2.324	0.002	996.327	0.151	0.000841	0.026	9.602	1533.789	L	0.036	10.794	-1.192	1.422	0.140	1364.368	0.026	9.602
27.834	2.330	0.002	996.337	0.151	0.000841	0.026	9.647	1539.482	L	0.036	10.834	-1.187	1.409	0.140	1370.789	0.026	9.647
27.776	1.723	0.002	996.353	0.151	0.000842	0.015	5.524	923.471	L	0.031	6.499	-0.974	0.950	0.080	785.004	0.015	5.524
27.729	1.719	0.001	996.366	0.151	0.000843	0.015	5.507	926.181	L	0.032	6.518	-1.011	1.022	0.080	782.504	0.015	5.507
27.686	1.721	0.001	996.378	0.151	0.000844	0.015	5.516	924.584	L	0.041	6.507	-0.990	0.981	0.080	783.869	0.015	5.516
27.609	1.083	0.001	996.399	0.151	0.000845	0.006	2.361	458.688	L	0.013	3.228	-0.867	0.752	0.034	335.478	0.006	2.361
27.533	1.081	0.001	996.420	0.151	0.000847	0.006	2.358	449.350	L	0.013	3.162	-0.804	0.647	0.034	335.061	0.006	2.358
27.503	1.083	0.001	996.428	0.151	0.000847	0.006	2.364	452.900	L	0.010	3.187	-0.823	0.677	0.034	335.961	0.006	2.364

Table 4: Water test analysis (Colebrook-White equation solver) in 57.68 mm straight pipe

COLEBROOK-WHITE Clear Water Test Analysis 19-Jan-06			
D =	0.05768		
V_{max} =	10.00	L(m) =	3.00
V_{step} =	0.40	Temp =	27.22
V_{crit} =	0.0311		

Test of sensitivity for Newtonian flow

COLEBROOK-WHITE EQUATION SOLVER (Newton-Raphson)

k 8E-06

V	Temperature	ρ	D	μ	i_m/m	τ_o (k=0)	ΔH	ΔP	i_m	τ_o	f (= f7)	Re	k/D	f1	F(f1)
					8V/D	($f\rho V^2/2$)	($4fLV^2/2Dg$) (Darcy)	($\rho g\Delta h$)	ΔH/L)	(DΔP/4L)	(f)				
0.00	27.22	996.5	0.05768	0.000852	0.540	0.000					0.061	262.500	0.000	0.061	Laminar flow
0.01	27.22	996.5	0.05768	0.000852	1.080	0.001					0.030	525.000	0.000	0.030	Laminar flow
0.02	27.22	996.5	0.05768	0.000852	2.159	0.002					0.015	1050.000	0.000	0.015	Laminar flow
0.03	27.22	996.5	0.05768	0.000852	4.319	0.004					0.008	2100.000	0.000	0.008	
0.03	27.22	996.5	0.05768	0.000852	0.000	0.006	0.000	1.226	0.000	0.006	0.012	2100.000	0.000	0.010	1.123
0.43	27.22	996.5	0.05768	0.000852	0.004	0.554	0.012	115.300	0.004	0.554	0.006	28993.066	0.000	0.012	-4.408
0.83	27.22	996.5	0.05768	0.000852	0.013	1.791	0.038	372.602	0.013	1.791	0.005	55886.131	0.000	0.006	-1.046
1.23	27.22	996.5	0.05768	0.000852	0.026	3.639	0.077	757.102	0.026	3.639	0.005	82779.197	0.000	0.005	-0.602
1.63	27.22	996.5	0.05768	0.000852	0.043	6.069	0.129	1262.541	0.043	6.069	0.005	109672.263	0.000	0.005	-0.413
2.02	27.22	996.5	0.05768	0.000852	0.064	9.062	0.193	1885.205	0.064	9.062	0.004	136565.329	0.000	0.005	-0.309
2.42	27.22	996.5	0.05768	0.000852	0.089	12.606	0.268	2622.647	0.089	12.606	0.004	163458.394	0.000	0.004	-0.244
2.82	27.22	996.5	0.05768	0.000852	0.118	16.694	0.355	3473.131	0.118	16.694	0.004	190351.460	0.000	0.004	-0.199
3.22	27.22	996.5	0.05768	0.000852	0.151	21.319	0.454	4435.366	0.151	21.319	0.004	217244.526	0.000	0.004	-0.167
3.62	27.22	996.5	0.05768	0.000852	0.188	26.477	0.563	5508.361	0.188	26.477	0.004	244137.591	0.000	0.004	-0.142
4.02	27.22	996.5	0.05768	0.000852	0.228	32.163	0.684	6691.333	0.228	32.163	0.004	271030.657	0.000	0.004	-0.123
4.42	27.22	996.5	0.05768	0.000852	0.272	38.375	0.817	7983.651	0.272	38.375	0.004	297923.723	0.000	0.004	-0.108
4.82	27.22	996.5	0.05768	0.000852	0.320	45.110	0.960	9384.798	0.320	45.110	0.004	324816.788	0.000	0.004	-0.096
5.21	27.22	996.5	0.05768	0.000852	0.371	52.365	1.114	10894.347	0.371	52.365	0.004	351709.854	0.000	0.004	-0.086
5.61	27.22	996.5	0.05768	0.000852	0.427	60.141	1.280	12511.936	0.427	60.141	0.004	378602.920	0.000	0.004	-0.077
6.01	27.22	996.5	0.05768	0.000852	0.485	68.434	1.456	14237.262	0.485	68.434	0.004	405495.986	0.000	0.004	-0.070
6.41	27.22	996.5	0.05768	0.000852	0.548	77.243	1.644	16070.062	0.548	77.243	0.004	432389.051	0.000	0.004	-0.064
6.81	27.22	996.5	0.05768	0.000852	0.614	86.569	1.842	18010.113	0.614	86.569	0.004	459282.117	0.000	0.004	-0.058
7.21	27.22	996.5	0.05768	0.000852	0.684	96.408	2.052	20057.218	0.684	96.408	0.004	486175.183	0.000	0.004	-0.054
7.61	27.22	996.5	0.05768	0.000852	0.757	106.762	2.272	22211.206	0.757	106.762	0.004	513068.248	0.000	0.004	-0.050
8.01	27.22	996.5	0.05768	0.000852	0.834	117.628	2.503	24471.929	0.834	117.628	0.004	539961.314	0.000	0.004	-0.046
8.40	27.22	996.5	0.05768	0.000852	0.915	129.007	2.746	26839.254	0.915	129.007	0.004	566854.380	0.000	0.004	-0.043
8.80	27.22	996.5	0.05768	0.000852	1.000	140.898	2.999	29313.063	1.000	140.898	0.004	593747.445	0.000	0.004	-0.040
9.20	27.22	996.5	0.05768	0.000852	1.088	153.300	3.263	31893.252	1.088	153.300	0.004	620640.511	0.000	0.004	-0.037
9.60	27.22	996.5	0.05768	0.000852	1.179	166.213	3.537	34579.729	1.179	166.213	0.004	647533.577	0.000	0.004	-0.035
10.00	27.22	996.5	0.05768	0.000852	1.274	179.637	3.823	37372.409	1.274	179.637	0.004	674426.643	0.000	0.004	-0.033

Table 5: Water test analysis (Colebrook-White equation solver) in 81.20 mm straight pipe

COLEBROOK-WHITE

Clear Water Test Analysis

19-Jan-06

D = 0.08120

V_{max} = 10.00 L(m) = 3.65

V_{step} = 0.40 Temp = 29.21

V_{crit} = 0.0212

Test of sensitivity for Newtonian flow

COLEBROOK-WHITE EQUATION SOLVER (Newton-Raphson)

k 8E-06

V	Temperature	ρ	D	μ	i_m/m (8V/D)	τ_o (k=0) ($f\rho V^2/2$)	ΔH ($4fLV^2/2Dg$) (Darcy)	ΔP (ρgΔh)	i_m (_H/L)	τ_o (DΔP/4L)	f (= f7) (f)	Re	k/D	f1	F(f1)
0.003	29.205	995.947	0.081	0.000817	0.261	0.000					0.061	262.500	0.0000	0.061	Laminar flow
0.005	29.205	995.947	0.081	0.000817	0.523	0.000					0.030	525.000	0.0000	0.030	Laminar flow
0.011	29.205	995.947	0.081	0.000817	1.045	0.001					0.015	1050.000	0.0000	0.015	Laminar flow
0.021	29.205	995.947	0.081	0.000817	2.090	0.002					0.008	2100.000	0.0000	0.008	
0.021	29.205	995.947	0.081	0.000817	0.000	0.003	0.000	0.491	0.000	0.003	0.012	2100.000	0.0001	0.010	1.120
0.420	29.205	995.947	0.081	0.000817	0.002	0.486	0.009	87.429	0.002	0.486	0.006	41609.281	0.0001	0.012	-5.029
0.820	29.205	995.947	0.081	0.000817	0.008	1.613	0.030	290.038	0.008	1.613	0.005	81118.562	0.0001	0.006	-1.059
1.219	29.205	995.947	0.081	0.000817	0.017	3.310	0.061	595.147	0.017	3.310	0.004	120627.843	0.0001	0.005	-0.609
1.618	29.205	995.947	0.081	0.000817	0.028	5.550	0.102	997.867	0.028	5.550	0.004	160137.124	0.0001	0.004	-0.416
2.017	29.205	995.947	0.081	0.000817	0.042	8.316	0.153	1495.264	0.042	8.316	0.004	199646.405	0.0001	0.004	-0.311
2.416	29.205	995.947	0.081	0.000817	0.058	11.598	0.213	2085.404	0.058	11.598	0.004	239155.686	0.0001	0.004	-0.245
2.815	29.205	995.947	0.081	0.000817	0.078	15.389	0.283	2766.920	0.078	15.389	0.004	278664.967	0.0001	0.004	-0.200
3.214	29.205	995.947	0.081	0.000817	0.099	19.682	0.362	3538.796	0.099	19.682	0.004	318174.248	0.0001	0.004	-0.167
3.614	29.205	995.947	0.081	0.000817	0.123	24.473	0.450	4400.251	0.123	24.473	0.004	357683.530	0.0001	0.004	-0.143
4.013	29.205	995.947	0.081	0.000817	0.150	29.759	0.548	5350.670	0.150	29.759	0.004	397192.811	0.0001	0.004	-0.124
4.412	29.205	995.947	0.081	0.000817	0.179	35.536	0.654	6389.558	0.179	35.536	0.004	436702.092	0.0001	0.004	-0.108
4.811	29.205	995.947	0.081	0.000817	0.211	41.804	0.769	7516.509	0.211	41.804	0.004	476211.373	0.0001	0.004	-0.096
5.210	29.205	995.947	0.081	0.000817	0.245	48.560	0.894	8731.189	0.245	48.560	0.004	515720.654	0.0001	0.004	-0.086
5.609	29.205	995.947	0.081	0.000817	0.281	55.802	1.027	10033.314	0.281	55.802	0.004	555229.935	0.0001	0.004	-0.077
6.008	29.205	995.947	0.081	0.000817	0.320	63.529	1.169	11422.646	0.320	63.529	0.004	594739.216	0.0001	0.004	-0.070
6.408	29.205	995.947	0.081	0.000817	0.362	71.740	1.320	12898.981	0.362	71.740	0.004	634248.497	0.0001	0.004	-0.064
6.807	29.205	995.947	0.081	0.000817	0.406	80.433	1.480	14462.143	0.406	80.433	0.003	673757.778	0.0001	0.004	-0.058
7.206	29.205	995.947	0.081	0.000817	0.452	89.609	1.649	16111.978	0.452	89.609	0.003	713267.059	0.0001	0.003	-0.054
7.605	29.205	995.947	0.081	0.000817	0.500	99.266	1.827	17848.354	0.500	99.266	0.003	752776.340	0.0001	0.003	-0.050
8.004	29.205	995.947	0.081	0.000817	0.552	109.404	2.013	19671.154	0.552	109.404	0.003	792285.621	0.0001	0.003	-0.046
8.403	29.205	995.947	0.081	0.000817	0.605	120.022	2.209	21580.274	0.605	120.022	0.003	831794.902	0.0001	0.003	-0.043
8.803	29.205	995.947	0.081	0.000817	0.661	131.119	2.413	23575.624	0.661	131.119	0.003	871304.183	0.0001	0.003	-0.040
9.202	29.205	995.947	0.081	0.000817	0.719	142.696	2.626	25657.121	0.719	142.696	0.003	910813.464	0.0001	0.003	-0.037
9.601	29.205	995.947	0.081	0.000817	0.780	154.751	2.848	27824.693	0.780	154.751	0.003	950322.745	0.0001	0.003	-0.035
10.000	29.205	995.947	0.081	0.000817	0.843	167.285	3.079	30078.274	0.843	167.285	0.003	989832.026	0.0001	0.003	-0.033

Table 6: Water test analysis (Colebrook-White equation solver) in 150.60 mm straight pipe

COLEBROOK-WHITE Clear Water Test Analysis 19-Jan-06			
D =	0.15060		
V_{max} =	10.00	L(m) =	5.35
V_{step} =	0.40	Temp =	27.91
V_{crit} =	0.0118		

Test of sensitivity for Newtonian flow

COLEBROOK-WHITE EQUATION SOLVER (Newton-Raphson)

k 8E-06

V	Temperature	ρ	D	μ	i_w/m	τ_o (k=0)	ΔH	ΔP	i_m	τ_o	f (= f7)	Re	k/D	f1	F(f1)
					8V/D	($f\rho V^2/2$)	($4fLV^2/2Dg$) (Darcy)	($\rho g\Delta h$)	ΔH/L)	(DΔP/4L)	(f)				
0.001	27.908	996.316	0.151	0.000840	0.078	0.000					0.061	262.500	0.0000	0.061	Laminar flow
0.003	27.908	996.316	0.151	0.000840	0.156	0.000					0.030	525.000	0.0000	0.030	Laminar flow
0.006	27.908	996.316	0.151	0.000840	0.312	0.000					0.015	1050.000	0.0000	0.015	Laminar flow
0.012	27.908	996.316	0.151	0.000840	0.624	0.001					0.008	2100.000	0.0000	0.008	
0.012	27.908	996.316	0.151	0.000840	0.000	0.001	0.000	0.119	0.000	0.001	0.012	2100.000	0.0001	0.010	1.117
0.411	27.908	996.316	0.151	0.000840	0.001	0.408	0.006	58.030	0.001	0.408	0.005	73478.347	0.0001	0.012	-6.021
0.811	27.908	996.316	0.151	0.000840	0.004	1.396	0.020	198.377	0.004	1.396	0.004	144856.693	0.0001	0.005	-1.059
1.210	27.908	996.316	0.151	0.000840	0.008	2.894	0.042	411.253	0.008	2.894	0.004	216235.040	0.0001	0.004	-0.622
1.610	27.908	996.316	0.151	0.000840	0.013	4.880	0.071	693.379	0.013	4.880	0.004	287613.386	0.0001	0.004	-0.425
2.009	27.908	996.316	0.151	0.000840	0.020	7.338	0.107	1042.674	0.020	7.338	0.004	358991.733	0.0001	0.004	-0.318
2.409	27.908	996.316	0.151	0.000840	0.028	10.259	0.149	1457.756	0.028	10.259	0.004	430370.079	0.0001	0.004	-0.251
2.808	27.908	996.316	0.151	0.000840	0.037	13.636	0.198	1937.640	0.037	13.636	0.003	501748.426	0.0001	0.004	-0.205
3.208	27.908	996.316	0.151	0.000840	0.047	17.464	0.254	2481.593	0.047	17.464	0.003	573126.772	0.0001	0.003	-0.172
3.608	27.908	996.316	0.151	0.000840	0.059	21.739	0.316	3089.047	0.059	21.739	0.003	644505.119	0.0001	0.003	-0.147
4.007	27.908	996.316	0.151	0.000840	0.072	26.457	0.385	3759.554	0.072	26.457	0.003	715883.465	0.0001	0.003	-0.127
4.407	27.908	996.316	0.151	0.000840	0.086	31.617	0.460	4492.749	0.086	31.617	0.003	787261.812	0.0001	0.003	-0.112
4.806	27.908	996.316	0.151	0.000840	0.101	37.216	0.541	5288.336	0.101	37.216	0.003	858640.158	0.0001	0.003	-0.099
5.206	27.908	996.316	0.151	0.000840	0.118	43.252	0.629	6146.065	0.118	43.252	0.003	930018.505	0.0001	0.003	-0.089
5.605	27.908	996.316	0.151	0.000840	0.135	49.724	0.723	7065.727	0.135	49.724	0.003	1001396.851	0.0001	0.003	-0.080
6.005	27.908	996.316	0.151	0.000840	0.154	56.631	0.823	8047.145	0.154	56.631	0.003	1072775.198	0.0001	0.003	-0.073
6.404	27.908	996.316	0.151	0.000840	0.174	63.971	0.930	9090.165	0.174	63.971	0.003	1144153.544	0.0001	0.003	-0.066
6.804	27.908	996.316	0.151	0.000840	0.195	71.744	1.043	10194.656	0.195	71.744	0.003	1215531.891	0.0001	0.003	-0.061
7.203	27.908	996.316	0.151	0.000840	0.217	79.948	1.162	11360.503	0.217	79.948	0.003	1286910.237	0.0001	0.003	-0.056
7.603	27.908	996.316	0.151	0.000840	0.241	88.584	1.288	12587.606	0.241	88.584	0.003	1358288.584	0.0001	0.003	-0.052
8.002	27.908	996.316	0.151	0.000840	0.265	97.650	1.420	13875.875	0.265	97.650	0.003	1429666.930	0.0001	0.003	-0.048
8.402	27.908	996.316	0.151	0.000840	0.291	107.146	1.558	15225.233	0.291	107.146	0.003	1501045.277	0.0001	0.003	-0.045
8.801	27.908	996.316	0.151	0.000840	0.318	117.071	1.702	16635.610	0.318	117.071	0.003	1572423.623	0.0001	0.003	-0.042
9.201	27.908	996.316	0.151	0.000840	0.346	127.426	1.853	18106.945	0.346	127.426	0.003	1643801.970	0.0001	0.003	-0.039
9.600	27.908	996.316	0.151	0.000840	0.376	138.208	2.009	19639.181	0.376	138.208	0.003	1715180.316	0.0001	0.003	-0.036
10.000	27.908	996.316	0.151	0.000840	0.406	149.420	2.172	21232.270	0.406	149.420	0.003	1786558.663	0.0001	0.003	-0.034

APPENDIX C

WATER PUMP TEST RESULTS

6/4 WARMAN CENTRIFUGAL PUMP

Table 7: Standard installation measurements of the 6/4 Warman pump

Description	ISO9906: 1999 Nomenclature	spreadsheet Nomenclature	Value	Unit
Inlet pipe diameter	D1	D1Inlet	0.1570	m
Inlet pipe area	A1	A1Inlet	0.0194	m^2
Inlet pipe length: tappings to pump flange	l1'-l1	L1Inlet	0.4202	m
Inlet pipe C/L reference height above floor	z1	Z1inlet	0.4635	m
Inlet tapping height above inlet C/L	H1m	Z1t	0.0695	m
Inlet water column height above inlet tapping	H1w	Z1w inlet	1.2250	m
Inlet head transducer port height above floor		Z1IH	1.7580	m
Outlet pipe diameter	D2	D2outlet	0.1060	m
Outlet pipe area	A2	A2Outlet	0.0088	m^2
Outlet pipe length: tappings to pump flange	l2-l2'	L2Outlet	0.3152	m
Outlet pipe C/L reference height above floor	z2	Z2outlet	0.2285	m
Outlet tapping height above outlet C/L	H2m	Z2t	0.0485	m
Outlet water column height above outlet tapping	H2w	Z2w outlet	1.4810	m
Outlet head transducer port height above floor		Z2IH	1.7580	m

Table 8: Characteristic of water tested

WATER PROPERTIES		
Material type:	Water	
Pump	6/4 Warman	
Date:	15-Feb-05	
Density of Water at 4°C	1000	kg/m3
Density of Material	998.000	kg/m3
Rheological parameters		
Ty	0	Pa
K	0	Pa.s^n
n	0	

Table 9: Water test results for 6/4 Warman centrifugal pump at 1400 and 1300 rpm

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe pressure (P1) kPa	discharge pipe pressure (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output W	Pump shaft torque N.m	Pump power in W	Pump efficiency %
1404.55	33.750	33.654	132.858	-37.260	152.987	167.990	0.355	29.005	28.650	37265.554	419.349	61679.834	60.418
1404.54	34.971	34.874	131.048	-37.109	165.410	180.413	0.305	29.959	29.654	38046.003	415.754	61150.465	62.217
1404.54	35.411	35.313	121.172	-31.616	211.684	226.688	0.528	33.046	32.519	38577.498	399.793	58802.959	65.605
1404.90	36.051	35.943	111.010	-25.861	249.562	264.565	0.795	35.362	34.567	37569.112	383.416	56408.733	66.602
1405.65	36.527	36.418	100.674	-21.078	283.235	298.238	0.986	37.362	36.376	35853.421	365.434	53791.986	66.652
1405.65	36.894	36.780	91.055	-17.309	316.256	331.260	1.120	39.521	38.401	34232.580	347.459	51145.918	66.931
1406.34	37.538	37.424	81.658	-13.797	344.921	359.924	1.258	41.380	40.122	32076.147	330.092	48613.403	65.982
1406.39	37.893	37.780	70.880	-10.300	376.096	391.100	1.392	43.482	42.091	29208.823	308.649	45456.938	64.256
1407.37	38.237	38.138	60.530	-7.478	403.066	418.069	1.495	45.342	43.847	25984.453	285.847	42128.230	61.679
1407.51	39.366	39.283	50.454	-5.174	426.452	441.456	1.578	46.995	45.417	22434.147	259.908	38309.077	58.561
1408.58	39.762	39.688	40.601	-3.191	443.900	458.903	1.659	48.186	46.528	18494.871	233.247	34405.390	53.756
1408.63	40.012	39.964	30.490	-1.654	458.534	473.538	1.718	49.208	47.490	14176.269	206.332	30436.528	46.576
1409.38	40.205	40.208	20.506	-0.587	469.556	484.560	1.758	49.999	48.241	9684.855	177.622	26215.254	36.944
1409.37	40.355	40.510	10.455	0.172	474.658	489.662	1.793	50.315	48.522	4966.827	148.259	21881.466	22.699
1410.20	40.468	40.818	5.497	0.995	475.764	490.768	1.866	50.376	48.510	2610.671	135.713	20041.567	13.026
1304.04	41.011	40.921	124.637	-33.421	135.512	150.516	0.459	25.827	25.367	30954.360	356.539	48688.568	63.576
1304.04	41.467	41.374	120.520	-30.633	152.914	167.917	0.607	26.940	26.333	31071.268	351.815	48043.347	64.673
1304.04	41.749	41.651	110.751	-25.660	190.265	205.268	0.807	29.268	28.460	30859.368	338.127	46174.240	66.832
1305.15	42.106	42.006	100.027	-21.049	225.074	240.077	0.971	31.336	30.364	29736.080	321.543	43947.171	67.663
1305.15	42.408	42.305	90.358	-17.190	255.367	270.370	1.115	33.218	32.103	28399.495	305.588	41766.309	67.996
1305.15	42.666	42.561	80.766	-13.723	282.841	297.845	1.246	34.944	33.698	26646.356	289.085	39510.917	67.440
1306.29	42.922	42.817	70.558	-10.377	310.866	325.870	1.378	36.790	35.412	24462.489	270.421	36992.147	66.129
1306.29	40.978	40.884	60.524	-7.552	336.450	351.454	1.487	38.537	37.050	21953.985	251.665	34426.367	63.771
1306.29	41.028	40.935	50.658	-5.282	358.607	373.611	1.570	40.078	38.509	19098.673	230.903	31586.185	60.465
1307.05	41.070	40.988	40.526	-3.320	377.735	392.739	1.645	41.424	39.780	15783.219	206.911	28320.745	55.730
1307.04	41.080	41.017	30.415	-1.783	392.094	407.098	1.704	42.419	40.715	12123.753	182.945	25040.334	48.417
1308.15	41.067	41.054	20.148	-0.679	403.173	418.176	1.746	43.209	41.462	8178.744	155.660	21323.860	38.355
1308.15	41.043	41.148	10.590	-0.060	407.878	422.882	1.770	43.496	41.726	4326.086	130.361	17858.137	24.225
1308.95	41.058	41.352	5.200	0.722	410.176	425.180	1.838	43.675	41.837	2130.078	116.061	15908.846	13.389

Table 10: Water test results for 6/4 Warman centrifugal pump at 1200 and 1100 rpm

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe pressure (P1) kPa	discharge pipe pressure (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output W	Pump shaft torque N.m	Pump power in W	Pump efficiency %
1203.57	41.412	41.320	115.504	-28.247	117.519	132.522	0.689	22.545	21.856	24715.089	306.356	38612.568	64.008
1203.58	41.805	41.705	110.517	-25.798	136.963	151.967	0.786	23.789	23.003	24889.393	301.161	37957.900	65.571
1203.63	42.099	41.993	100.523	-21.364	167.693	182.696	0.952	25.540	24.587	24197.891	288.791	36400.551	66.477
1204.70	42.361	42.246	90.030	-17.257	199.532	214.535	1.100	27.476	26.376	23248.679	273.142	34458.633	67.468
1204.71	41.841	41.724	80.777	-14.066	224.122	239.126	1.211	28.948	27.737	21934.985	259.938	32793.044	66.889
1204.71	41.837	41.718	71.012	-10.917	249.791	264.794	1.331	30.594	29.263	20344.366	244.865	30891.556	65.857
1205.83	41.834	41.713	60.762	-7.879	274.966	289.969	1.458	32.276	30.819	18333.487	226.917	28653.852	63.983
1205.83	41.819	41.702	50.924	-5.499	296.823	311.826	1.551	33.786	32.234	16070.683	209.643	26472.701	60.707
1205.99	41.788	41.676	40.509	-3.511	316.526	331.529	1.625	35.171	33.546	13304.496	187.404	23667.553	56.214
1206.97	41.745	41.646	30.553	-2.003	330.955	345.959	1.683	36.179	34.497	10318.751	164.687	20815.343	49.573
1206.97	41.689	41.627	20.284	-0.834	342.040	357.043	1.731	36.968	35.237	6997.742	140.170	17716.699	39.498
1207.72	41.635	41.672	10.446	-0.190	347.673	362.676	1.756	37.344	35.589	3639.701	117.516	14862.610	24.489
1207.73	41.620	41.771	5.489	0.204	348.440	363.444	1.785	37.371	35.585	1912.396	104.972	13276.088	14.405
1103.53	42.324	42.194	106.074	-24.035	99.656	114.659	0.836	19.345	18.510	19222.515	262.614	30348.298	63.340
1103.54	42.735	42.601	100.586	-21.673	118.063	133.066	0.923	20.479	19.557	19258.859	257.116	29712.968	64.816
1103.54	42.983	42.844	90.150	-17.753	147.563	162.566	1.052	22.182	21.130	18649.140	243.541	28144.186	66.263
1103.54	42.109	41.966	80.822	-14.426	171.231	186.234	1.175	23.550	22.375	17704.481	230.669	26656.810	66.416
1104.07	42.056	41.908	71.364	-11.431	194.733	209.736	1.285	25.003	23.718	16571.088	216.768	25062.417	66.119
1104.28	42.002	41.860	61.015	-8.372	219.047	234.050	1.412	26.585	25.173	15037.696	201.346	23283.884	64.584
1104.28	41.957	41.811	50.677	-5.742	241.079	256.082	1.523	28.075	26.552	13173.877	184.226	21304.051	61.837
1104.80	41.900	41.763	40.585	-3.804	259.869	274.872	1.596	29.388	27.792	11043.047	165.915	19195.402	57.530
1105.41	41.816	41.686	30.701	-2.502	273.842	288.846	1.633	30.352	28.719	8632.268	146.152	16918.375	51.023
1105.41	41.717	41.624	20.989	-1.869	283.757	298.761	1.629	31.034	29.405	6042.400	125.165	14488.929	41.704
1106.53	41.631	41.620	10.823	-1.184	290.701	305.704	1.655	31.531	29.875	3165.518	102.596	11888.364	26.627
1106.53	41.604	41.699	5.364	-0.667	292.051	307.055	1.696	31.610	29.914	1570.830	91.010	10545.900	14.895

4/3 GIW CENTRIFUGAL PUMP

Table 11: Standard measurements done after the installation of the 4/3 GIW pump

Description	ISO9906: 1999 Nomenclature	spreadsheet Nomenclature	Value	Unit
Inlet pipe diameter	D1	D1Inlet	0.1016	m
Inlet pipe area	A1	A1Inlet	0.0081	m^2
Inlet pipe length: tappings to pump flange	l1'-l1	L1Inlet	0.2032	m
Inlet pipe C/L reference height above floor	z1	Z1inlet	0.3742	m
Inlet tapping height above inlet C/L	H1m	Z1t	0.0508	m
Inlet water column height above inlet tapping	H1w	Z1w inlet	1.1210	m
Inlet head transducer port height above floor		Z1IH	1.5460	m
Outlet pipe diameter.	D2	D2outlet	0.0762	m
Outlet pipe area	A2	A2Outlet	0.0046	m^2
Outlet pipe length: tappings to pump flange	l2-l2'	L2Outlet	0.1524	m
Outlet pipe C/L reference height above floor	z2	Z2outlet	0.1809	m
Outlet tapping height above outlet C/L	H2m	Z2t	0.0381	m
Outlet water column height above outlet tapping	H2w	Z2w outlet	1.3270	m
Outlet head transducer port height above floor		Z2IH	1.5460	m

Table 12: Characteristic of water tested

WATER PROPERTIES		
Material type:	Water	
Pump	4/3 GIW	
Date:	16-Feb-05	
Density of Water at 4°C	1000	kg/m3
Density of Material	998.000	kg/m3
Rheological parameters		
Ty	0	Pa
K	0	Pa.s^n
n	0	

Table 13: Water test results for 4/3 GIW centrifugal pump at 2100 and 1900 rpm

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe pressure (P1) kPa	discharge pipe pressure (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output W	Pump shaft torque N.m	Pump power in W	Pump efficiency %
2099.17	42.757	43.457	51.335	-50.704	326.689	340.080	-1.587	41.375	42.963	21592.597	150.180	33013.404	65.406
2098.66	44.360	45.082	50.682	-49.446	383.036	396.427	-1.510	46.967	48.478	24054.377	155.532	34181.614	70.372
2097.48	44.655	45.316	44.957	-38.838	459.978	473.369	-0.851	53.485	54.336	23915.813	147.192	32330.562	73.973
2104.15	44.781	45.450	44.989	-38.569	462.823	476.214	-0.822	53.782	54.604	24050.807	146.825	32352.352	74.340
2108.67	44.945	45.725	40.047	-30.618	506.748	520.139	-0.336	57.239	57.574	22573.763	138.939	30680.582	73.577
2111.07	45.216	45.886	35.254	-23.963	543.330	556.721	0.064	60.091	60.027	20718.474	128.463	28399.526	72.954
2113.97	45.356	46.017	30.275	-17.943	576.091	589.482	0.426	62.637	62.211	18439.501	117.819	26082.154	70.698
2116.97	45.428	46.128	25.073	-12.700	603.798	617.189	0,739	64.762	64.023	15716.113	106.020	23503.523	66.867
2120.30	45.557	46.274	20.264	-8.680	623.377	636.768	0.980	66.227	65.247	12944.863	94.905	21072.502	61.430
2122.89	45.604	46.348	15.748	-5.765	640.490	653.881	1.152	67.577	66.425	10241.186	83.793	18627.804	54.978
2126.11	45.603	46.471	10.658	-3.199	658.117	671.507	1.310	69.048	67.738	7068.219	71.571	15934.935	44.357
2128.86	45.536	46.685	5.681	-1.800	686.778	700.169	1.389	71.776	70.387	3915.172	59.432	13249.521	29.550
1900.53	45.460	46.817	49.164	-46.057	301.000	314.391	-1.282	38.217	39.499	19012.200	130.403	25953.297	73.255
1902.06	46.310	47.246	44.824	-38.407	346.664	360.055	-0.817	41.881	42.698	18737.580	124.524	24803.125	75.545
1904.29	46.584	47.398	40.435	-31.303	383.323	396.714	-0.381	44.709	45.090	17850.148	118.404	23611.805	75.598
1905.83	46.463	47.266	35.099	-23.665	423.622	437.013	0.086	47.837	47.751	16408.699	110.483	22050.135	74.415
1908.75	46.642	47.479	30.600	-18.225	453.063	466.454	0.413	50.120	49.707	14891.563	101.872	20362.498	73.132
1911.09	46.826	47.565	25.733	-13.183	477.970	491.360	0.715	51.992	51.277	12918.282	92.487	18509.464	69.793
1914.04	46.442	47.170	20.626	-8.839	496.525	509.916	0.975	53.307	52.332	10567.424	81.647	16365.283	64.572
1917.03	45.589	46.339	15.297	-5.321	517.337	530.728	1.186	54.964	53.777	8053.749	70.046	14061.849	57.274
1919.74	45.258	46.108	10.694	-3.059	531.581	544.972	1.324	56.125	54.801	5737.468	59.336	11928.676	48.098
1922.23	45.050	46.122	5.458	-1.549	556.560	569.950	1.413	58.469	57.056	3048.739	48.380	9738.689	31.305

Table 14: Water test results for 4/3 GIW centrifugal pump at 1600 and 1300 rpm

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe pressure (P1) kPa	discharge pipe pressure (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output W	Pump shaft torque N.m	Pump power in W	Pump efficiency %
1601.49	38.999	39.611	42.035	-30.391	219.501	232.892	-0.186	28.299	28.485	11722.486	99.955	16763.19 6	69.930
1601.50	38.996	39.771	40.595	-28.152	230.962	244.353	-0.049	29.178	29.228	11616.218	98.456	16512.06 8	70.350
1602.90	39.188	39.795	35.125	-20.968	268.428	281.818	0.363	31.990	31.627	10875.990	91.532	15364.11 9	70.788
1603.72	39.287	39.797	30.121	-14.497	301.034	314.425	0.771	34.520	33.749	9952.584	85.310	14327.09 3	69.467
1605.94	39.301	39.797	25.403	-9.796	325.274	338.664	1.048	36.354	35.306	8780.768	77.774	13079.67 7	67.133
1608.13	39.284	39.787	20.330	-5.522	345.492	358.882	1.305	37.850	36.546	7273.861	68.894	11601.98 0	62.695
1610.42	39.254	39.781	15.335	-2.334	360.104	373.495	1.492	38.906	37.414	5617.338	59.822	10088.61 4	55.680
1611.91	39.216	39.773	10.173	0.040	373.692	387.083	1.633	39.972	38.339	3818.517	49.993	8438.791	45.250
1614.16	39.179	39.824	5.552	1.369	388.843	402.234	1.712	41.341	39.629	2154.062	41.750	7057.138	30.523
1300.81	39.072	39.909	34.042	-19.392	146.398	159.789	0.466	19.342	18.876	6291.081	65.911	8978.464	70.069
1302.31	39.148	39.882	30.371	-14.759	167.963	181.354	0.756	20.965	20.209	6009.071	62.573	8533.534	70.417
1303.05	39.166	39.814	25.292	-9.720	195.096	208.487	1.052	23.044	21.992	5445.651	57.350	7825.692	69.587
1304.54	39.167	39.768	20.436	-5.697	215.771	229.162	1.290	24.611	23.321	4666.016	51.404	7022.313	66.446
1306.02	39.194	39.730	15.132	-2.289	231.391	244.782	1.492	25.744	24.252	3592.837	43.792	5989.295	59.988
1307.59	39.184	39.701	10.562	-0.140	241.278	254.669	1.620	26.466	24.846	2569.126	36.956	5060.492	50.768
1309.05	39.115	39.716	5.163	1.443	252.915	266.306	1.716	27.447	25.731	1300.654	29.228	4006.668	32.462

APPENDIX D

PUMP TEST RESULTS FOR DIFFERENT MATERIALS TESTED

CMC 5%

SLURRY PROPERTIES		
Material type	CMC 5%	
Pump	6/4 Warman	
Date	11-Feb-05	
Density of Water	1000	kg/m3
Density of Material	1028.3	kg/m3
Rheological parameters		
Ty	0	Pa
K	1.3745	Pa.s^n
n	0.6875	

Table 15: 6/4 Warman pump test at 1400 and 1300 rpm for CMC 5%

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1404.8	44.8	44.8	108.2	-27.5	233.7	248.7	0.6	32.6	32.0	34945.2	391.6	57611.9	60.7
1405.7	46.5	46.5	108.0	-27.2	230.6	245.7	0.6	32.3	31.7	34492.7	389.9	57396.1	60.1
1405.7	46.4	46.4	100.9	-23.8	271.2	286.2	0.7	35.3	34.6	35164.2	377.5	55568.2	63.3
1405.7	46.2	46.2	91.0	-19.4	310.8	325.8	0.9	38.0	37.1	34030.3	364.4	53643.3	63.4
1406.4	46.1	46.0	80.9	-15.3	346.7	361.8	1.1	40.4	39.3	32093.2	345.9	50949.2	63.0
1406.4	45.9	45.8	70.8	-11.8	379.3	394.3	1.2	42.6	41.4	29531.8	325.1	47875.8	61.7
1407.4	45.7	45.6	60.9	-8.7	407.4	422.4	1.4	44.5	43.2	26503.9	302.3	44559.1	59.5
1407.6	45.6	45.5	50.6	-5.8	432.1	447.1	1.5	46.2	44.7	22819.6	276.2	40707.0	56.1
1408.7	45.5	45.4	40.7	-3.6	451.3	466.3	1.6	47.5	46.0	18855.7	248.9	36713.5	51.4
1408.7	45.3	45.3	30.2	-1.8	467.0	482.0	1.7	48.6	46.9	14309.9	221.7	32704.4	43.8
1409.4	45.2	45.3	20.7	-0.5	474.8	489.8	1.7	49.1	47.3	9904.1	195.4	28833.3	34.3
1409.4	44.9	45.3	10.1	0.7	478.9	493.9	1.8	49.3	47.4	4855.6	165.5	24421.0	19.9
1410.4	44.9	45.6	5.3	1.0	483.6	498.6	1.8	49.7	47.8	2571.3	152.8	22560.8	11.4
1304.1	44.5	44.5	100.0	-23.6	209.4	224.4	0.7	29.0	28.3	28546.0	340.1	46447.7	61.5
1304.1	44.4	44.3	90.6	-19.5	246.6	261.7	0.9	31.6	30.7	28035.3	327.5	44722.6	62.7
1305.2	44.3	44.2	80.9	-15.6	279.7	294.7	1.1	33.8	32.7	26684.1	312.1	42653.6	62.6
1305.2	44.2	44.1	70.9	-11.9	311.0	326.0	1.2	35.8	34.6	24746.5	294.0	40190.6	61.6
1305.3	44.1	44.0	61.1	-8.8	338.6	353.6	1.4	37.7	36.4	22407.9	273.8	37418.7	59.9
1306.4	44.0	44.0	50.5	-5.9	363.9	378.9	1.5	39.5	38.0	19335.3	250.3	34235.0	56.5
1306.4	44.0	43.9	40.5	-3.8	383.2	398.3	1.6	40.8	39.2	16035.1	225.9	30908.0	51.9
1307.1	43.9	43.8	30.6	-2.0	397.4	412.5	1.7	41.7	40.1	12355.3	201.1	27521.9	44.9
1307.1	43.8	43.8	20.3	-0.5	404.3	419.3	1.7	42.1	40.3	8248.7	174.4	23875.6	34.5
1308.2	43.6	43.8	10.5	0.6	408.5	423.5	1.8	42.3	40.5	4285.8	151.1	20698.6	20.7
1308.2	43.5	44.0	5.5	1.0	409.7	424.7	1.8	42.3	40.5	2238.8	137.3	18816.2	11.9

Table 16: 6/4 Warman pump test at 1200 and 1100 rpm for CMC 5%

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1203.7	43.3	43.2	90.6	-19.5	184.9	199.9	0.9	25.4	24.5	22420.7	293.3	36967.7	60.6
1203.7	43.2	43.2	80.5	-15.5	219.1	234.2	1.1	27.7	26.6	21629.3	280.5	35350.7	61.2
1203.7	43.2	43.1	70.6	-11.8	249.4	264.4	1.2	29.7	28.5	20302.7	264.1	33294.0	61.0
1204.7	43.2	43.1	60.7	-8.8	276.4	291.4	1.4	31.5	30.2	18478.0	246.1	31047.3	59.5
1204.8	43.2	43.1	50.5	-6.0	300.4	315.4	1.5	33.2	31.7	16165.8	225.9	28505.7	56.7
1204.8	43.2	43.1	40.4	-3.8	320.7	335.7	1.6	34.6	33.0	13467.7	203.5	25677.4	52.4
1205.9	43.1	43.1	30.3	-1.9	334.9	350.0	1.7	35.5	33.9	10368.1	179.8	22711.0	45.7
1205.9	43.1	43.1	20.6	-0.6	340.4	355.4	1.7	35.7	34.0	7084.6	156.0	19699.3	36.0
1207.0	43.0	43.1	10.4	0.7	342.9	357.9	1.8	35.8	34.0	3569.0	134.3	16972.0	21.0
1207.0	42.8	43.3	5.8	1.0	344.3	359.3	1.8	35.9	34.0	1984.6	122.8	15522.8	12.8
1103.7	40.4	40.4	94.7	-21.2	116.0	131.0	0.8	19.1	18.3	17466.1	267.6	30924.3	56.5
1103.7	40.7	40.7	90.6	-19.5	131.2	146.2	0.9	20.1	19.2	17560.9	262.3	30311.9	57.9
1103.9	41.0	41.0	80.8	-15.4	164.4	179.4	1.1	22.3	21.2	17286.7	251.0	29014.0	59.6
1104.4	41.4	41.3	70.8	-12.0	192.9	207.9	1.2	24.1	22.9	16363.9	236.8	27384.8	59.8
1104.4	41.7	41.6	60.7	-8.8	219.8	234.8	1.4	25.9	24.6	15052.0	219.4	25368.6	59.3
1104.4	41.9	41.7	50.4	-5.9	243.7	258.7	1.5	27.5	26.1	13249.8	200.6	23198.6	57.1
1105.5	42.0	41.9	40.9	-3.8	262.2	277.2	1.6	28.8	27.2	11250.2	182.6	21136.8	53.2
1105.5	42.2	42.1	30.5	-1.9	277.6	292.7	1.7	29.9	28.2	8677.2	160.3	18562.9	46.7
1105.6	42.4	42.3	20.5	-0.6	287.2	302.2	1.7	30.5	28.7	5950.5	138.6	16048.9	37.1
1106.6	42.5	42.5	10.5	0.6	297.2	312.2	1.8	31.2	29.4	3104.5	118.0	13675.0	22.7

SLURRY PROPERTIES		
Material type	CMC 5%	
Pump	4/3 GIW	
Date	10-Feb-05	
Density of Water	1000	kg/m^3
Density of Material	1028.3	kg/m^3
Rheological parameters		
Ty	0	Pa
K	1.3745	$Pa.s^n$
n	0.6875	

Table 17: 4/3 GIW pump test at 2100 and 1900 rpm for CMC 5%

Pump speed	Temperature suction pipe (T1)	Temperature discharge pipe (T2)	Pump discharge flow	Suction pipe vel press (P1)	discharge pipe vel press (P2)	P2 Adjusted	Pump Suction head	Pump Discharge head	Pump Total head	Pump power output rho.q.g.H	Pump shaft torque	Pump power in 2.Pi.n.T	Pump effy
rpm	°C	°C	l/s	kPa	kPa		m	m	m	W	N.m	W	%
2101.3	41.1	44.6	49.5	-49.0	344.0	357.4	-1.4	41.6	43.1	21500.6	165.5	36424.1	59.0
2101.3	41.4	44.9	45.8	-42.3	430.1	443.5	-1.0	49.3	50.3	23255.4	165.6	36447.4	63.8
2104.1	41.8	45.5	40.4	-33.8	481.6	495.0	-0.6	53.3	53.8	21960.7	155.9	34347.8	63.9
2105.8	42.1	45.8	35.3	-26.6	522.8	536.2	-0.2	56.4	56.6	20162.9	147.4	32505.9	62.0
2108.4	42.3	46.1	30.2	-20.1	558.1	571.5	0.2	59.1	58.8	17923.8	136.9	30233.9	59.3
2111.0	42.4	46.3	25.8	-15.2	581.8	595.2	0.5	60.8	60.3	15690.0	128.1	28308.6	55.4
2114.0	42.5	46.5	20.8	-10.3	603.3	616.7	0.8	62.4	61.5	12901.3	115.6	25601.1	50.4
2117.1	42.5	46.7	15.3	-5.8	624.4	637.8	1.1	64.0	62.9	9675.1	102.6	22743.7	42.5
2120.0	42.6	47.0	10.6	-2.9	638.7	652.1	1.3	65.1	63.8	6847.9	91.0	20195.7	33.9
2122.9	42.7	47.4	6.3	-0.6	658.6	672.0	1.5	66.9	65.4	4186.5	80.5	17885.1	23.4
1899.9	38.7	41.0	45.9	-43.5	311.5	324.9	-1.2	37.6	38.7	17940.3	144.8	28800.9	62.3
1899.9	38.8	41.2	45.3	-42.3	317.6	331.0	-1.1	38.0	39.1	17886.5	143.4	28538.8	62.7
1901.3	39.0	41.5	40.5	-34.6	360.7	374.1	-0.6	41.3	41.9	17149.6	136.5	27169.5	63.1
1902.9	39.2	41.7	35.3	-27.4	401.8	415.2	-0.2	44.4	44.6	15906.0	128.5	25605.3	62.1
1905.1	39.3	41.9	30.5	-21.0	434.4	447.8	0.2	46.9	46.7	14378.4	121.1	24160.8	59.5
1906.9	39.5	42.1	25.5	-15.5	461.4	474.8	0.5	48.8	48.4	12459.2	111.6	22290.2	55.9
1910.4	39.6	42.3	20.3	-10.2	483.0	496.4	0.8	50.4	49.6	10158.3	101.0	20207.9	50.3
1912.6	39.6	42.5	15.3	-6.1	500.1	513.5	1.1	51.7	50.6	7805.6	90.2	18058.5	43.2
1914.8	39.7	42.7	10.8	-3.2	514.8	528.2	1.3	52.8	51.5	5605.2	79.9	16029.7	35.0
1917.3	39.8	43.0	5.8	-0.6	533.8	547.2	1.5	54.5	53.0	3111.4	69.2	13891.3	22.4

Table 18: 4/3 GIW pump test at 1600 and 1300 rpm for CMC 5%

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1600.3	37.8	39.5	37.5	-31.0	227.2	240.6	-0.5	27.5	27.9	10572.1	103.6	17356.9	60.9
1601.5	37.9	39.7	35.6	-28.2	240.6	254.0	-0.3	28.5	28.8	10336.4	101.6	17041.3	60.7
1602.2	38.0	39.8	30.6	-21.7	274.9	288.3	0.1	31.1	31.0	9556.8	95.3	15992.5	59.8
1604.3	40.5	43.4	25.2	-14.9	306.6	320.0	0.5	33.5	32.9	8374.0	86.5	14528.8	57.6
1605.9	38.0	40.0	20.7	-10.8	325.0	338.4	0.8	34.8	34.0	7088.1	80.7	13579.2	52.2
1608.2	38.1	40.1	15.6	-6.5	341.5	354.9	1.1	36.0	34.9	5489.7	71.8	12091.8	45.4
1610.4	38.1	40.2	10.6	-3.2	355.5	368.9	1.3	37.0	35.7	3832.1	62.9	10603.2	36.1
1611.9	38.1	40.5	5.6	-0.5	370.3	383.7	1.5	38.3	36.8	2096.9	53.5	9032.7	23.2
1300.9	37.5	39.0	28.9	-19.6	155.4	168.8	0.2	19.0	18.7	5459.0	69.9	9528.0	57.3
1301.5	37.6	39.2	25.8	-16.2	172.1	185.5	0.4	20.2	19.8	5148.7	67.2	9152.0	56.3
1303.1	37.6	39.3	20.2	-10.5	198.8	212.2	0.8	22.2	21.4	4374.0	60.7	8277.2	52.8
1304.5	37.6	39.4	15.6	-6.6	213.9	227.3	1.0	23.3	22.3	3501.2	54.7	7468.1	46.9
1306.0	37.6	39.5	10.5	-3.2	226.2	239.6	1.3	24.2	22.9	2435.2	47.4	6486.1	37.5
1307.9	37.7	39.6	5.5	-0.5	238.8	252.2	1.5	25.3	23.8	1307.2	40.0	5474.6	23.9

CMC 6 %

SLURRY PROPERTIES		
Material type	CMC 6 %	
Pump	6/4 Warman	
Date	08-Feb-05	
Density of Water	1000	kg/m3
Density of Material	1032.3	kg/m3
Rheological parameters		
Ty	0	Pa
K	1.9702	Pa.s^n
n	0.655	

Table 19: 6/4 Warman pump test at 1400 and 1300 rpm for CMC 6 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1404.6	47.5	47.6	95.3	-22.3	126.7	141.7	0.8	20.2	19.4	18771.6	349.9	51470.3	36.5
1404.6	48.8	48.8	90.6	-20.2	309.3	324.3	0.8	37.6	36.8	33755.6	385.0	56628.9	59.6
1404.6	49.2	49.2	80.8	-16.2	344.5	359.5	1.0	40.0	39.0	31937.7	372.1	54733.8	58.4
1405.7	49.7	49.7	70.9	-12.4	375.8	390.8	1.2	42.1	41.0	29416.7	351.8	51789.5	56.8
1405.7	50.1	50.1	60.5	-9.1	405.9	420.9	1.3	44.2	42.9	26277.4	327.4	48194.6	54.5
1406.4	50.5	50.4	50.7	-6.4	429.6	444.7	1.4	45.8	44.4	22771.1	300.9	44315.8	51.4
1406.4	50.8	50.8	40.8	-4.1	448.7	463.8	1.5	47.1	45.6	18818.4	274.0	40355.9	46.6
1407.6	51.1	51.1	30.5	-2.2	462.1	477.1	1.6	48.0	46.3	14304.0	245.1	36121.3	39.6
1408.6	51.2	51.4	19.0	-0.3	474.4	489.4	1.7	48.8	47.1	9039.9	213.7	31519.4	28.7
1408.7	51.4	51.8	10.4	0.7	484.9	499.9	1.8	49.7	47.9	5053.6	190.1	28043.2	18.0
1305.2	52.3	52.3	89.7	-19.4	113.7	128.7	0.9	18.2	17.3	15731.9	305.4	41748.6	37.7
1305.2	52.8	52.7	80.1	-15.6	279.3	294.4	1.0	33.5	32.5	26352.5	324.9	44406.5	59.3
1305.2	53.2	53.1	70.7	-12.1	310.3	325.3	1.2	35.6	34.4	24640.8	311.0	42503.0	58.0
1305.2	53.5	53.4	60.6	-8.8	338.2	353.2	1.3	37.5	36.2	22217.5	289.9	39616.8	56.1
1306.3	51.3	51.2	51.0	-6.4	358.4	373.4	1.4	38.8	37.4	19293.1	268.7	36753.3	52.5
1306.3	51.3	51.2	40.6	-4.2	377.9	392.9	1.5	40.1	38.6	15847.4	244.8	33485.2	47.3
1307.1	51.3	51.3	30.7	-2.2	391.8	406.9	1.6	41.0	39.4	12256.5	218.7	29934.9	40.9
1307.1	51.3	51.3	20.5	-0.5	399.2	414.2	1.7	41.4	39.7	8252.7	192.5	26352.0	31.3
1308.2	51.3	51.5	10.3	0.8	409.3	424.3	1.8	42.2	40.4	4232.2	166.4	22799.9	18.6

Table 20: 6/4 Warman pump test at 1200 and 1100 rpm for CMC 6 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1203.6	51.2	51.2	83.4	-16.9	105.8	120.8	1.0	16.7	15.7	13292.4	267.0	33648.7	39.5
1203.5	51.6	51.5	70.9	-12.3	244.1	259.1	1.2	29.1	27.9	20039.4	276.5	34840.8	57.5
1203.6	51.8	51.7	60.7	-8.9	273.2	288.2	1.3	31.1	29.8	18290.4	258.1	32527.6	56.2
1203.6	51.2	51.1	51.0	-6.4	291.5	306.5	1.4	32.2	30.8	15892.2	239.1	30136.7	52.7
1204.7	51.2	51.1	40.8	-4.2	312.8	327.8	1.5	33.7	32.2	13287.7	217.4	27428.6	48.4
1204.7	51.2	51.1	30.8	-2.2	327.9	342.9	1.6	34.7	33.1	10325.8	193.8	24443.2	42.2
1205.6	51.1	51.1	20.9	-0.5	335.3	350.4	1.7	35.1	33.4	7049.7	169.9	21453.4	32.9
1205.8	51.1	51.3	10.2	0.9	343.9	358.9	1.8	35.7	33.9	3502.9	145.9	18429.4	19.0
1103.5	51.1	51.0	91.0	-20.0	117.9	133.0	0.9	18.8	17.9	16519.8	269.8	31180.2	53.0
1103.5	51.3	51.2	80.6	-15.8	157.7	172.7	1.0	21.6	20.5	16747.6	256.6	29647.7	56.5
1104.1	50.9	50.9	70.9	-12.4	185.8	200.9	1.2	23.4	22.2	15926.2	243.7	28180.3	56.5
1104.2	50.9	50.8	60.9	-9.1	213.1	228.1	1.3	25.2	23.9	14712.0	228.8	26463.0	55.6
1104.2	50.8	50.8	50.6	-6.2	235.2	250.3	1.5	26.6	25.2	12890.3	210.5	24342.3	53.0
1105.0	50.8	50.7	40.6	-4.1	254.8	269.8	1.5	28.0	26.4	10857.0	192.5	22271.1	48.7
1105.4	50.8	50.7	30.6	-2.2	268.8	283.9	1.6	28.9	27.2	8445.5	170.9	19783.4	42.7
1105.4	50.7	50.7	20.8	-0.4	278.8	293.8	1.7	29.5	27.8	5862.1	149.3	17282.6	33.9
1106.5	50.7	50.8	10.7	0.9	286.3	301.3	1.8	30.1	28.2	3045.5	128.8	14923.3	20.4

SLURRY PROPERTIES		
Material type	CMC 6 %	
Pump	4/3 GIW	
Date	08-Feb-05	
Density of Water	1000	kg/m3
Density of Material	1032.3	kg/m3
Rheological parameters		
Ty	0	Pa
K	1.9702	$Pa.s^n$
n	0.655	

Table 21: 4/3 GIW pump test at 2100 and 1900 rpm for CMC 6 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
2100.4	39.1	41.9	47.9	-51.9	361.1	374.5	-1.8	42.8	44.6	21642.9	177.2	38978.4	55.5
2099.8	39.5	42.4	45.7	-48.0	410.3	423.7	-1.6	47.1	48.8	22574.7	177.7	39084.5	57.8
2102.1	39.7	42.7	40.6	-39.6	469.9	483.3	-1.1	51.9	53.1	21797.5	168.4	37072.3	58.8
2104.4	39.9	43.0	35.2	-31.4	514.7	528.1	-0.6	55.4	56.0	19954.9	157.3	34670.9	57.6
2106.5	40.1	43.2	30.3	-24.6	548.0	561.4	-0.2	57.9	58.1	17829.4	147.1	32453.7	54.9
2109.9	40.4	43.8	25.4	-18.6	575.0	588.4	0.2	59.9	59.7	15337.1	137.1	30285.1	50.6
2113.2	40.6	44.1	20.1	-13.0	596.8	610.2	0.5	61.4	60.9	12425.1	124.9	27633.0	45.0
2116.2	40.7	44.4	15.3	-8.7	615.2	628.6	0.8	62.8	62.0	9586.5	113.0	25035.2	38.3
2119.2	40.8	44.7	10.4	-4.7	633.0	646.4	1.1	64.3	63.1	6645.2	100.1	22224.7	29.9
1899.8	37.4	39.5	43.6	-45.6	322.7	336.1	-1.5	38.0	39.6	17467.5	150.7	29973.5	58.3
1900.4	37.7	39.9	40.6	-40.4	350.0	363.4	-1.2	40.1	41.3	16970.9	145.5	28963.3	58.6
1902.1	37.9	40.2	35.3	-32.3	391.3	404.7	-0.7	43.2	43.9	15698.3	138.4	27567.9	56.9
1904.3	38.0	40.4	30.3	-25.3	424.8	438.2	-0.3	45.7	46.0	14129.1	130.2	25962.0	54.4
1905.8	38.1	40.6	25.2	-19.1	453.1	466.5	0.1	47.8	47.7	12161.4	120.9	24122.9	50.4
1908.4	38.3	40.8	20.6	-14.0	473.2	486.6	0.5	49.3	48.8	10165.9	111.6	22312.6	45.6
1911.1	38.4	41.0	15.1	-9.0	491.6	505.0	0.8	50.6	49.8	7632.6	99.8	19972.7	38.2
1914.1	38.5	41.2	10.2	-5.0	508.3	521.8	1.1	52.0	50.9	5274.2	88.8	17804.4	29.6
1916.3	38.5	41.6	5.6	-1.9	528.8	542.2	1.3	53.8	52.5	2975.4	78.4	15737.2	18.9
1899.8	37.4	39.5	43.6	-45.6	322.7	336.1	-1.5	38.0	39.6	17467.5	150.7	29973.5	58.3

Table 22: 4/3 GIW pump test at 1600 and 1300 rpm for CMC 6 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1600.0	36.4	38.4	34.7	-31.9	237.3	250.7	-0.7	27.9	28.6	10040.2	108.6	18191.5	55.2
1601.5	36.6	38.6	30.5	-26.1	264.8	278.2	-0.3	29.9	30.3	9356.5	103.7	17396.8	53.8
1602.9	36.7	38.7	25.5	-19.8	293.6	307.0	0.1	32.1	32.0	8261.2	96.5	16199.9	51.0
1605.1	36.9	38.9	20.4	-14.3	315.9	329.3	0.4	33.7	33.3	6888.5	88.7	14910.3	46.2
1607.4	37.0	39.0	15.2	-9.3	334.9	348.3	0.8	35.1	34.4	5306.6	79.9	13443.6	39.5
1608.9	37.0	39.2	10.3	-5.2	348.5	361.9	1.1	36.2	35.1	3653.0	71.1	11970.8	30.5
1611.1	37.1	39.5	5.5	-2.1	365.4	378.8	1.3	37.7	36.3	2036.3	61.5	10380.4	19.6
1300.8	35.5	37.6	25.9	-20.6	162.7	176.1	0.0	19.2	19.2	5031.0	74.5	10151.0	49.6
1302.3	35.3	37.8	20.4	-14.4	190.4	203.8	0.4	21.3	20.9	4309.1	68.6	9359.6	46.0
1303.4	35.4	37.9	15.5	-9.8	207.1	220.5	0.7	22.5	21.8	3432.8	62.5	8531.7	40.2
1305.2	35.6	38.1	10.3	-5.4	221.4	234.8	1.1	23.6	22.6	2357.0	55.1	7537.8	31.3
1306.7	35.7	38.3	5.4	-2.1	232.7	246.1	1.3	24.6	23.2	1281.7	47.9	6560.7	19.5

CMC 7 %

SLURRY PROPERTIES		
Material type	CMC 7 %	
Pump	6/4 Warman	
Date	02-Feb-05	
Density of Water	1000	kg/m3
Density of Material	1036.8	kg/m3
Rheological parameters		
Ty	0	Pa
K	3.6886	$Pa.s^n$
n	0.5978	

Table 23: 6/4 Warman pump test at 1400 and 1300 rpm for CMC 7 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1404.7	44.8	44.8	91.0	-23.2	285.6	300.6	0.6	35.2	34.7	32111.0	386.9	56905.5	56.4
1404.7	44.4	44.3	81.0	-18.9	325.9	340.9	0.7	38.1	37.3	30729.9	367.5	54066.7	56.8
1405.8	44.2	44.1	70.9	-14.9	359.5	374.5	0.9	40.4	39.4	28449.4	347.3	51128.4	55.6
1405.9	43.9	43.9	60.6	-11.7	386.5	401.5	1.1	42.1	41.1	25303.7	332.1	48887.3	51.8
1406.6	43.6	43.6	51.1	-8.9	412.9	427.9	1.2	44.0	42.8	22272.1	310.3	45699.5	48.7
1406.6	43.3	43.3	40.5	-5.8	438.1	453.2	1.4	45.9	44.5	18309.0	280.5	41311.7	44.3
1407.8	43.1	43.2	30.5	-3.5	451.4	466.4	1.5	46.7	45.2	14021.6	255.2	37625.4	37.3
1407.8	42.2	43.1	20.5	-1.7	454.6	469.6	1.6	46.7	45.1	9404.0	228.3	33657.1	27.9
1408.9	42.5	42.8	11.1	-0.1	435.8	450.8	1.7	44.6	42.9	4845.2	207.0	30548.0	15.9
1299.9	48.0	48.0	91.4	-21.9	215.7	230.7	0.7	28.4	27.7	25751.1	353.0	48056.5	53.6
1301.0	47.8	47.8	80.7	-17.7	258.7	273.8	0.9	31.4	30.6	25100.8	338.1	46065.7	54.5
1301.0	47.7	47.6	70.8	-13.7	292.9	307.9	1.0	33.8	32.8	23579.2	321.5	43802.6	53.8
1301.1	47.6	47.5	60.5	-10.5	319.8	334.9	1.2	35.6	34.4	21145.7	301.4	41066.2	51.5
1302.1	47.5	47.4	50.4	-7.8	345.5	360.5	1.3	37.3	36.0	18498.0	280.8	38291.3	48.3
1302.1	47.3	47.2	40.9	-5.0	370.2	385.2	1.4	39.2	37.8	15699.4	256.1	34922.0	45.0
1303.3	47.1	47.1	30.9	-2.6	383.3	398.3	1.6	40.0	38.4	12079.1	231.0	31523.1	38.3
1303.3	47.0	47.1	20.8	-0.7	386.7	401.8	1.7	40.0	38.3	8091.7	205.9	28096.1	28.8
1304.0	46.8	47.2	10.2	0.8	380.4	395.4	1.8	39.2	37.4	3861.0	180.1	24600.2	15.7

Table 24: 6/4 Warman pump test at 1200 and 1100 rpm for CMC 7 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1202.8	46.5	46.5	90.7	-21.7	154.9	170.0	0.7	22.4	21.7	19982.7	317.0	39928.6	50.0
1203.6	46.3	46.3	80.4	-17.4	198.2	213.2	0.9	25.4	24.6	20074.0	301.2	37964.9	52.9
1203.6	46.2	46.1	70.5	-13.9	228.9	243.9	1.0	27.5	26.5	18982.0	291.1	36694.6	51.7
1203.6	46.0	46.0	60.8	-10.6	257.6	272.6	1.2	29.5	28.3	17497.9	273.8	34505.1	50.7
1204.7	45.6	45.5	50.8	-7.9	280.3	295.4	1.3	31.0	29.7	15327.6	254.2	32068.6	47.8
1204.7	44.7	45.4	40.6	-6.2	310.1	325.1	1.3	33.3	31.9	13194.5	232.3	29306.5	45.0
1205.2	44.8	45.3	30.8	-3.1	323.1	338.1	1.5	34.1	32.6	10210.1	209.1	26394.2	38.7
1205.8	44.9	45.2	20.8	-0.7	327.7	342.7	1.7	34.2	32.5	6861.0	186.9	23599.8	29.1
1205.8	45.0	45.3	10.2	0.9	324.0	339.1	1.8	33.6	31.8	3294.6	164.4	20758.3	15.9
1103.5	44.8	44.8	81.8	-18.0	137.4	152.4	0.9	19.6	18.8	15606.1	273.4	31589.6	49.4
1103.5	44.6	44.6	70.8	-13.7	172.3	187.3	1.0	21.9	20.9	15040.7	260.2	30063.1	50.0
1103.5	44.3	44.2	61.1	-10.8	197.5	212.5	1.2	23.6	22.4	13932.7	246.8	28516.6	48.9
1104.0	44.2	44.1	50.2	-7.7	227.1	242.1	1.3	25.7	24.4	12444.3	227.7	26320.1	47.3
1104.3	44.1	44.1	40.6	-5.9	251.6	266.6	1.4	27.5	26.2	10816.2	210.5	24342.5	44.4
1104.3	44.0	44.1	30.8	-3.1	265.1	280.1	1.5	28.4	26.9	8404.8	191.0	22089.1	38.0
1105.4	44.1	44.3	9.9	0.8	273.8	288.8	1.8	28.7	26.9	2694.4	147.6	17082.0	15.8
1105.4	43.5	44.5	5.3	1.4	281.9	296.9	1.9	29.4	27.6	1474.8	138.7	16056.1	9.2

KAOLIN 17 %

SLURRY PROPERTIES		
Material type	KAOLIN 17 %	
Pump	6/4 Warman	
Date	20-Feb-05	
Density of Water	1000	kg/m^3
Density of Material	1284	kg/m^3
Rheological parameters		
Ty	104.85	Pa
K	2.126	$Pa.s^n$
n	0.430	

Table 25: 6/4 Warman pump test at 1400 and 1300 rpm for kaolin 17 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1405.1	54.9	54.9	96.1	-24.2	122.2	137.3	0.8	17.2	16.4	19835.4	376.7	55432.5	35.8
1403.5	54.3	54.2	90.4	-21.3	363.9	379.0	0.9	35.7	34.8	39642.2	435.8	64050.3	61.9
1404.5	53.4	53.2	81.0	-16.9	428.5	443.7	1.0	39.8	38.7	39509.3	418.6	61559.3	64.2
1404.5	52.5	52.4	70.8	-12.9	472.3	487.4	1.1	42.2	41.1	36636.9	393.6	57886.9	63.3
1405.6	51.6	51.4	61.1	-9.8	505.3	520.4	1.2	44.0	42.8	32932.8	365.9	53863.4	61.1
1406.1	50.6	50.5	51.4	-7.1	535.2	550.3	1.3	45.7	44.4	28709.6	337.9	49751.4	57.7
1406.4	48.7	49.5	40.8	-6.5	559.6	574.8	1.2	47.0	45.8	23516.0	303.7	44724..	52.6
1407.5	48.3	48.6	30.9	-4.2	580.8	595.9	1.3	48.2	46.9	18232.5	270.9	39921.4	45.7
1408.6	49.7	49.5	20.2	-1.1	577.7	592.9	1.5	47.6	46.1	11744.5	232.4	34281.1	34.3
1408.7	49.9	49.5	10.1	-0.1	568.8	584.0	1.5	46.7	45.2	5757.5	195.5	28845.0	20.0
1409.4	49.6	49.8	5.4	0.2	557.1	572.2	1.5	45.7	44.2	3006.5	178.0	26275.6	11.4
1304.0	53.0	52.9	90.2	-21.1	113.3	128.4	0.9	15.8	14.9	16872.5	328.1	44803.5	37.7
1303.3	52.2	52.1	80.9	-17.0	346.4	361.5	1.0	33.2	32.2	32826.7	372.8	50878.2	64.5
1303.3	51.2	51.1	71.0	-13.0	388.5	403.6	1.1	35.6	34.4	30819.3	350.2	47801.8	64.5
1304.0	51.2	51.1	61.3	-9.8	421.6	436.7	1.2	37.4	36.2	27926.9	326.0	44519.0	62.7
1304.5	51.3	51.1	50.8	-7.1	452.7	467.9	1.3	39.1	37.8	24189.0	297.5	40646.0	59.5
1305.1	50.8	51.1	41.0	-4.1	476.1	491.2	1.4	40.3	38.9	20090.4	268.7	36727.6	54.7
1306.3	51.1	51.3	30.4	-2.5	496.3	511.4	1.4	41.4	40.0	15336.0	236.0	32277.8	47.5
1306.3	51.3	51.5	20.4	-1.1	490.1	505.2	1.5	40.6	39.2	10040.9	204.0	27904.7	36.0
1307.0	51.7	52.0	10.6	0.0	479.7	494.8	1.5	39.6	38.1	5061.3	169.5	23203.4	21.8
1307.0	50.7	52.5	5.0	-0.1	438.1	453.2	1.5	36.2	34.7	2206.6	155.1	21232.0	10.4

Table 26: 6/4 Warman pump test at 1200 and 1100 rpm for kaolin 17 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1202.8	51.8	51.6	80.7	-16.8	269.7	284.9	1.0	27.1	26.1	26535.3	328.0	41316.8	64.2
1202.8	50.9	50.9	70.9	-12.8	312.2	327.3	1.2	29.5	28.4	25342.0	310.4	39093.2	64.8
1203.5	51.0	50.9	60.8	-9.7	346.5	361.7	1.2	31.4	30.2	23111.4	287.5	36234.9	63.8
1203.5	51.2	51.1	60.8	-9.6	347.1	362.2	1.2	31.4	30.2	23113.3	287.6	36245.5	63.8
1203.5	51.3	51.1	50.9	-6.9	375.1	390.2	1.3	32.9	31.6	20260.5	263.7	33241.4	60.9
1204.7	51.1	51.3	40.8	-3.6	399.7	414.8	1.4	34.3	32.8	16851.1	236.8	29868.2	56.4
1204.7	51.4	51.4	30.7	-2.5	418.0	433.1	1.4	35.2	33.8	13072.3	208.2	26268.8	49.8
1205.8	51.6	51.8	20.7	-1.2	409.3	424.5	1.4	34.2	32.8	8544.0	179.4	22658.5	37.7
1206.5	52.4	52.5	10.1	-0.1	396.7	411.8	1.5	33.0	31.5	4021.2	147.0	18570.5	21.7
1206.9	53.6	53.8	5.1	-1.2	362.4	377.5	1.4	30.2	28.8	1861.7	131.6	16635.[illegible]	11.2
1103.4	52.4	52.2	77.6	-15.5	98.5	113.6	1.1	13.2	12.1	11860.7	246.7	28506.3	41.6
1102.3	51.9	51.7	71.1	-12.9	240.8	255.9	1.2	23.9	22.7	20339.3	272.3	31431.0	64.7
1103.5	51.1	51.0	60.8	-9.7	275.2	290.3	1.2	25.7	24.5	18773.6	251.6	29076.6	64.6
1103.5	50.5	50.4	51.6	-7.1	302.6	317.7	1.3	27.2	25.9	16828.7	233.7	27002.6	62.3
1104.1	50.4	50.5	40.7	-4.4	328.4	343.5	1.4	28.6	27.2	13951.8	207.4	23978.3	58.2
1104.2	50.7	50.7	30.7	-3.1	346.9	362.1	1.4	29.6	28.2	10909.4	181.6	20999.9	51.9
1105.1	51.0	51.0	20.6	-1.1	335.3	350.4	1.5	28.3	26.9	6960.4	156.5	18108.2	38.4
1105.3	51.1	51.2	13.0	-0.3	287.1	302.2	1.5	24.3	22.8	3749.6	134.7	15595.9	24.0
1105.3	50.9	51.6	3.7	0.4	217.3	232.4	1.5	18.7	17.2	798.4	115.8	13407.2	6.0

SLURRY PROPERTIES		
Material type	KAOLIN 17 %	
Pump	4/3 GIW	
Date	21-Feb-05	
Density of Water	1000	kg/m3
Density of Material	1284	kg/m3
Rheological parameters		
Ty	104.85	Pa
K	2.126	$Pa.s^n$
n	0.430	

Table 27: 4/3 GIW pump test at 2100 and 1900 rpm for kaolin 17 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
2125.1	50.4	56.6	6.9	2.4	829.7	843.2	0.6	67.2	66.6	5829.7	98.1	21841.6	26.7
2121.8	50.2	56.6	10.1	1.3	813.1	826.6	0.6	66.1	65.5	8319.6	107.4	23854.3	34.9
2117.7	50.3	56.4	15.7	-1.4	788.9	802.4	0.5	64.5	64.0	12674.6	124.7	27656.0	45.8
2114.0	50.4	56.3	20.8	-4.9	764.8	778.3	0.3	63.0	62.7	16390.9	138.5	30669.5	53.4
2110.2	50.3	56.4	25.4	-8.8	738.1	751.6	0.2	61.4	61.3	19588.0	153.5	33919.5	57.7
2105.8	50.3	56.4	30.4	-14.0	703.7	717.2	0.0	59.4	59.4	22712.3	164.3	36225.8	62.7
2102.1	50.3	56.5	35.2	-20.0	661.5	675.0	-0.3	56.8	57.1	25290.6	177.7	39107.9	64.7
2097.9	50.4	56.5	40.4	-27.6	593.7	607.2	-0.6	52.4	52.9	26964.7	189.8	41697.9	64.7
2100.5	50.5	57.0	46.2	-37.0	341.5	355.0	-0.9	33.6	34.5	20077.1	179.3	39444.0	50.9
1923.3	51.8	57.6	6.0	2.8	675.1	688.6	0.6	54.9	54.3	4130.4	78.0	15716.5	26.3
1920.3	51.6	57.4	10.4	1.2	656.7	670.2	0.6	53.7	53.1	6930.4	89.0	17897.9	38.7
1917.1	51.5	57.2	15.4	-1.3	638.3	651.7	0.5	52.5	52.0	10079.4	103.4	20753.3	48.6
1913.6	51.4	57.0	20.4	-4.6	618.1	631.6	0.3	51.3	51.0	13077.6	116.6	23366.1	56.0
1910.4	51.3	57.0	25.4	-9.1	589.9	603.4	0.2	49.7	49.5	15872.5	129.7	25937.2	61.2
1906.1	51.1	56.8	30.4	-14.4	555.7	569.1	-0.1	47.6	47.7	18236.9	141.4	28220.0	64.6
1904.3	51.0	56.6	35.1	-19.6	519.8	533.3	-0.2	45.5	45.8	20203.0	149.6	29838.7	67.7
1900.0	50.9	56.7	40.7	-27.7	455.9	469.4	-0.5	41.5	42.0	21568.8	160.2	31878.7	67.7
1899.8	50.9	57.1	44.1	-34.1	357.5	371.0	-0.8	34.4	35.2	19585.5	161.5	32130.4	61.0

Table 28: 4/3 GIW pump test at 1600 and 1300 rpm for kaolin 17 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1619.1	51.8	57.1	5.0	3.1	463.6	477.1	0.6	38.1	37.5	2366.5	56.0	9499.6	24.9
1616.1	51.4	57.1	10.7	1.0	453.5	467.0	0.5	37.5	37.0	4968.2	68.4	11579.0	42.9
1613.4	51.2	56.6	15.4	-1.2	439.7	453.2	0.5	36.7	36.3	7053.1	79.4	13409.9	52.6
1610.4	51.1	56.3	20.5	-4.5	421.8	435.3	0.3	35.8	35.4	9141.6	90.7	15301.1	59.7
1607.5	50.9	56.0	25.4	-9.0	396.2	409.7	0.2	34.3	34.1	10932.3	100.7	16953.0	64.5
1605.2	50.8	55.9	30.5	-14.3	363.1	376.6	0.0	32.4	32.4	12469.7	109.7	18431.7	67.7
1602.9	50.7	56.0	35.2	-20.1	323.5	337.0	-0.3	30.0	30.2	13409.2	117.0	19633.7	68.3
1601.5	50.8	56.2	41.2	-28.7	260.5	274.0	-0.6	26.1	26.7	13834.6	125.5	21042.9	65.7
1311.3	51.8	57.2	6.2	3.0	264.1	277.6	0.6	22.3	21.7	1678.5	44.1	6061.8	27.7
1309.0	51.6	57.1	10.3	1.6	282.3	295.8	0.6	23.9	23.3	3041.1	51.5	7061.8	43.1
1306.8	51.5	56.8	15.8	-1.0	273.3	286.8	0.5	23.6	23.1	4603.9	60.9	8339.4	55.2
1305.3	51.4	56.9	20.4	-4.3	256.2	269.7	0.4	22.6	22.2	5703.7	68.3	9331.0	61.1
1303.0	51.4	57.0	26.0	-9.2	226.7	240.1	0.2	20.9	20.7	6796.8	76.5	10435.1	65.1
1300.9	51.5	57.1	30.3	-14.2	196.4	209.9	0.0	19.1	19.1	7297.5	82.4	11228.2	65.0

KAOLIN 19 %

SLURRY PROPERTIES		
Material type	KAOLIN 19 %	
Pump	6/4 Warman	
Date	24-Feb-05	
Density of Water	1000	kg/m^3
Density of Material	1315.9	kg/m^3
Rheological parameters		
Ty	152.779	Pa
K	0.791	Pa.s^n
n	0.623	

Table 29: 6/4 Warman pump test at 1400 and 1300 rpm for kaolin 19 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1404.6	55.1	55.1	90.9	-27.3	130.3	145.4	0.5	16.9	16.5	19300.6	379.3	55783.2	34.6
1403.4	56.7	56.6	81.3	-22.6	415.5	430.7	0.6	37.9	37.3	39174.3	433.2	63669.5	61.5
1403.5	52.0	52.0	70.7	-18.5	475.4	490.5	0.7	41.5	40.8	37246.7	411.5	60475.6	61.6
1404.6	52.5	52.4	60.7	-15.3	514.3	529.4	0.8	43.7	42.9	33601.7	382.9	56326.3	59.7
1405.3	52.6	52.5	50.7	-12.4	545.0	560.2	0.9	45.3	44.5	29081.1	350.9	51647.1	56.3
1405.7	52.5	52.7	40.9	-11.1	567.8	582.9	0.8	46.5	45.7	24079.3	318.4	46873.2	51.4
1406.4	52.7	52.8	30.7	-7.7	584.3	599.5	1.0	47.3	46.3	18353.6	283.2	41704.7	44.0
1407.6	52.9	52.8	20.6	-5.9	557.7	572.9	1.1	44.9	43.8	11644.8	250.2	36877.3	31.6
1407.6	53.0	53.4	10.5	-4.6	290.1	305.2	1.1	23.9	22.8	3106.2	225.2	33198.8	9.4
1408.6	53.4	54.2	5.9	-4.0	283.1	298.3	1.2	23.4	22.2	1680.8	207.6	30621.6	5.5
1304.8	52.8	52.6	85.1	-24.4	127.8	143.0	0.6	16.1	15.5	17045.3	337.6	46127.4	37.0
1304.4	54.0	53.9	80.4	-22.2	191.2	206.3	0.6	20.5	19.8	20587.7	340.9	46565.4	44.2
1304.1	54.8	54.7	70.4	-18.5	390.6	405.7	0.7	34.9	34.2	31085.9	367.4	50174.8	62.0
1304.1	51.0	50.9	60.7	-15.4	429.3	444.4	0.8	37.1	36.3	28452.3	344.8	47086.8	60.4
1305.2	51.0	51.0	50.7	-13.5	459.9	475.1	0.8	38.7	38.0	24845.3	315.9	43171.9	57.5
1305.7	50.8	51.1	40.6	-11.2	482.3	497.5	0.8	39.8	39.0	20442.8	283.5	38769.0	52.7
1306.3	51.2	51.2	31.1	-7.7	495.0	510.2	1.0	40.4	39.4	15805.6	253.6	34690.2	45.6
1307.1	51.3	51.2	20.2	-6.0	454.1	469.3	1.1	36.8	35.8	9343.4	217.9	29822.7	31.3
1307.1	51.3	51.5	11.0	-4.8	276.5	291.7	1.1	22.9	21.8	3086.1	198.1	27120.2	11.4
1307.4	51.5	52.2	5.3	-4.0	243.7	258.8	1.2	20.3	19.1	1313.1	181.4	24833.5	5.3

Table 30: 6/4 Warman pump test at 1200 and 1100 rpm for kaolin 19 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1204.8	48.5	48.4	79.0	-21.7	127.5	142.6	0.6	15.4	14.8	15037.0	297.8	37570.5	40.0
1203.7	49.9	49.8	70.4	-18.2	315.1	330.2	0.7	29.1	28.3	25761.6	327.4	41274.6	62.4
1203.7	50.5	50.3	60.7	-15.2	348.9	364.0	0.8	30.9	30.1	23553.7	305.3	38489.0	61.2
1204.8	50.8	50.7	50.9	-12.8	379.3	394.5	0.8	32.5	31.7	20809.2	280.1	35343.0	58.9
1204.8	50.6	50.9	40.9	-11.3	400.1	415.2	0.8	33.5	32.7	17263.6	251.8	31769.3	54.3
1205.9	51.2	51.1	30.4	-7.6	413.6	428.7	1.0	34.0	33.0	12956.5	220.7	27873.5	46.5
1206.3	51.3	51.0	20.2	-5.8	390.8	406.0	1.1	31.9	30.9	8049.3	192.6	24330.4	33.1
1207.0	51.3	51.3	10.4	-4.7	259.1	274.3	1.1	21.5	20.4	2746.8	170.3	21524.2	12.8
1207.0	51.4	51.8	5.1	-3.8	207.5	222.7	1.2	17.5	16.3	1064.8	156.1	19729.3	5.4
1103.6	51.1	51.0	72.4	-18.9	122.0	137.1	0.7	14.3	13.6	12703.4	256.1	29590.3	42.9
1103.6	52.0	51.8	61.1	-15.5	270.2	285.3	0.8	24.8	24.0	18925.4	267.2	30878.9	61.3
1103.5	52.1	52.3	50.9	-13.9	302.5	317.6	0.7	26.5	25.8	16969.5	245.7	28399.1	59.8
1104.1	51.7	52.6	40.8	-10.9	326.4	341.6	0.8	27.8	26.9	14202.3	221.3	25585.9	55.5
1104.3	52.9	52.8	30.9	-7.7	338.5	353.6	1.0	28.3	27.3	10870.1	195.0	22545.6	48.2
1105.2	53.1	52.9	19.7	-5.8	294.6	309.7	1.1	24.5	23.4	5941.1	160.0	18514.8	32.1
1105.4	53.1	53.1	10.7	-4.8	213.2	228.3	1.1	18.0	16.9	2329.4	145.3	16820.7	13.8
1105.4	53.3	53.5	5.9	-4.2	177.9	193.0	1.1	15.2	14.1	1077.9	134.2	15532.5	6.9

KAOLIN 19 %

SLURRY PROPERTIES		
Material type	KAOLIN 19 %	
Pump	4/3 GIW	
Date	24-Feb-05	
Density of Water	1000	kg/m3
Density of Material	1315.9	kg/m3
Rheological parameters		
Ty	152.779	Pa
K	0.791	$Pa.s^n$
n	0.623	

Table 31: 4/3 GIW pump test at 2100 and 1900 rpm for kaolin 19 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
2097.0	47.7	55.2	42.4	-52.8	281.2	294.7	-1.4	27.4	28.8	15797.0	164.3	36071.5	43.8
2098.6	48.3	55.9	40.8	-50.2	364.0	377.5	-1.3	33.5	34.8	18341.7	167.3	36769.7	49.9
2093.6	48.4	55.0	35.6	-42.4	627.7	641.2	-1.0	53.0	54.0	24776.8	178.5	39144.3	63.3
2102.8	48.5	55.1	30.8	-36.5	689.5	703.0	-0.8	57.0	57.8	22937.0	170.5	37552.3	61.1
2106.5	48.5	55.2	25.7	-30.4	735.2	748.8	-0.6	59.8	60.4	19998.8	153.8	33938.5	58.9
2111.7	48.5	55.4	20.2	-25.3	769.2	782.7	-0.4	61.8	62.2	16238.7	139.6	30881.0	52.6
2116.1	48.6	55.4	15.8	-21.9	787.6	801.1	-0.2	62.8	63.1	12825.0	126.2	27970.5	45.9
2120.1	48.4	55.5	10.8	-19.0	799.0	812.5	-0.1	63.4	63.5	8884.9	110.3	24493.6	36.3
2125.1	48.3	55.9	5.2	-16.6	760.0	773.5	0.0	60.2	60.2	4029.0	94.0	20913.7	19.3
1900.4	48.5	55.8	41.2	-50.4	270.0	283.6	-1.3	26.3	27.6	14668.1	147.4	29334.1	50.0
1898.4	49.1	55.4	35.4	-41.9	494.7	508.2	-1.0	42.6	43.6	19901.6	157.1	31226.6	63.7
1900.6	49.0	55.3	30.4	-35.4	549.6	563.1	-0.8	46.1	46.8	18352.2	145.6	28979.5	63.3
1904.3	49.0	55.1	25.4	-29.8	588.6	602.1	-0.5	48.4	48.9	16026.1	134.1	26743.0	59.9
1908.0	48.9	55.0	20.8	-25.8	613.5	627.0	-0.4	49.8	50.2	13486.2	122.7	24513.8	55.0
1908.0	48.7	54.9	20.8	-25.5	614.2	627.7	-0.4	49.9	50.2	13510.7	122.8	24527.7	55.1
1911.8	48.6	54.8	15.6	-21.7	633.5	647.0	-0.2	50.9	51.1	10296.9	108.6	21734.7	47.4
1916.3	48.5	54.9	10.3	-18.7	632.3	645.8	-0.1	50.5	50.6	6733.1	94.0	18861.1	35.7
1920.0	48.4	55.1	4.8	-16.4	613.0	626.5	0.0	48.8	48.7	3028.7	78.8	15839.8	19.1

Table 32: 4/3 GIW pump test at 1600 rpm for kaolin 19 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1602.0	46.1	54.8	38.0	-45.9	246.7	260.2	-1.2	23.9	25.0	12276.6	123.2	20669.5	59.4
1602.3	46.7	55.1	35.2	-41.9	298.7	312.2	-1.0	27.4	28.4	12900.6	121.3	20357.7	63.4
1603.7	47.2	55.1	30.6	-35.8	350.7	364.2	-0.8	30.7	31.5	12422.6	114.3	19197.9	64.7
1603.7	47.0	54.1	30.5	-35.2	351.7	365.2	-0.7	30.7	31.5	12374.6	113.9	19126.3	64.7
1605.9	46.9	53.6	25.6	-29.6	389.5	403.0	-0.5	33.0	33.5	11053.3	106.2	17861.4	61.9
1608.9	47.1	53.6	20.3	-25.0	418.4	431.9	-0.3	34.7	35.0	9185.4	95.2	16045.4	57.2
1611.2	47.0	53.5	15.3	-21.4	434.4	447.9	-0.2	35.5	35.6	7062.8	84.3	14229.1	49.6
1614.2	47.1	53.5	10.3	-18.5	434.6	448.1	-0.1	35.1	35.2	4663.9	73.1	12356.3	37.7
1617.1	47.0	53.7	5.2	-16.4	420.4	433.9	0.0	33.9	33.8	2281.8	61.5	10416.9	21.9

KAOLIN 21 %

SLURRY PROPERTIES		
Material type	KAOLIN 21 %	
Pump	6/4 Warman	
Date	27-Feb-05	
Density of Water	1000	kg/m^3
Density of Material	1351.1	kg/m^3
Rheological parameters		
Ty	218.04	Pa
K	1.479	Pa.s^n
n	0.534	

Table 33: 6/4 Warman pump test at 1400 and 1300 rpm for kaolin 21 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1405.7	47.0	47.0	82.8	-28.7	158.8	173.9	0.2	17.9	17.7	19370.2	405.0	59620.9	32.5
1404.6	48.4	48.4	70.3	-23.7	461.6	476.8	0.3	39.5	39.1	36445.5	449.1	66060.3	55.2
1405.7	49.5	49.5	60.7	-20.5	518.6	533.8	0.4	42.9	42.5	34226.1	426.6	62796.9	54.5
1405.7	49.7	50.6	50.9	-19.2	553.0	568.2	0.3	44.8	44.5	30020.6	389.7	57367.7	52.3
1406.4	51.0	51.5	40.8	-14.7	581.5	596.7	0.6	46.3	45.8	24732.6	353.0	51988.6	47.6
1407.5	52.7	52.7	30.7	-11.5	602.7	617.8	0.7	47.5	46.8	19041.3	318.3	46915.6	40.6
1408.3	53.5	53.6	20.6	-9.7	609.1	624.3	0.8	47.6	46.8	12800.0	281.1	41450.1	30.9
1408.7	54.1	54.4	10.7	-8.1	601.5	616.7	0.8	46.8	46.0	6516.4	239.8	35370.3	18.4
1409.4	54.5	55.4	5.1	-7.5	599.8	615.0	0.9	46.6	45.8	3093.4	216.1	31887.4	9.7
1305.2	55.5	55.5	77.6	-26.6	151.5	166.7	0.3	16.8	16.5	16974.8	358.5	48995.2	34.6
1304.2	56.9	56.9	71.2	-23.9	293.7	308.9	0.3	26.9	26.5	25048.0	384.7	52538.8	47.7
1304.0	57.8	57.7	60.2	-20.7	429.9	445.1	0.4	36.2	35.8	28580.9	380.6	51972.5	55.0
1305.2	52.2	52.6	50.4	-19.2	461.7	476.9	0.3	37.9	37.5	25103.0	354.1	48396.2	51.9
1305.1	52.7	52.8	40.8	-14.9	490.5	505.7	0.5	39.5	38.9	21072.0	320.8	43849.7	48.1
1306.3	52.9	52.9	31.0	-11.7	509.0	524.1	0.7	40.4	39.7	16315.9	286.8	39235.3	41.6
1306.9	53.0	53.1	21.0	-9.8	504.8	519.9	0.8	39.7	39.0	10862.0	254.5	34834.6	31.2
1307.0	53.1	53.3	11.1	-8.2	485.1	500.3	0.8	38.1	37.2	5500.5	218.7	29928.2	18.4
1308.1	53.2	53.8	5.7	-7.5	472.7	487.8	0.9	37.1	36.2	2745.7	197.6	27072.7	10.1

Table 34: 6/4 Warman pump test at 1200 and 1100 rpm for kaolin 21 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1204.7	54.1	54.0	71.6	-24.6	142.4	157.5	0.3	15.5	15.2	14427.7	316.8	39970.4	36.1
1204.4	53.5	53.8	60.9	-22.6	335.7	350.8	0.2	29.1	28.9	23339.7	343.4	43316.9	53.9
1204.7	53.1	53.6	50.8	-20.6	377.5	392.6	0.2	31.6	31.3	21100.2	319.6	40318.6	52.3
1205.8	53.4	53.6	40.7	-18.1	406.6	421.8	0.3	33.1	32.8	17711.4	287.2	36268.0	48.8
1205.8	53.7	53.7	30.7	-11.6	424.2	439.4	0.7	34.0	33.3	13575.3	256.5	32388.1	41.9
1206.9	53.8	53.8	20.4	-9.8	419.0	434.2	0.8	33.3	32.5	8807.0	225.5	28495.2	30.9
1207.1	53.8	54.1	10.0	-8.4	392.1	407.3	0.8	31.0	30.2	4008.2	190.2	24038.7	16.7
1207.7	54.1	54.5	5.7	-7.9	395.0	410.2	0.9	31.2	30.3	2275.8	174.8	22102.8	10.3
1104.2	55.1	55.0	65.8	-22.8	136.0	151.2	0.3	14.5	14.2	12349.8	280.0	32382.1	38.1
1104.0	55.4	55.8	60.4	-22.2	256.4	271.6	0.3	23.1	22.9	18316.0	301.3	34838.1	52.6
1104.2	55.5	55.8	50.8	-15.5	297.4	312.6	0.6	25.5	24.9	16755.6	283.7	32808.4	51.1
1104.5	55.0	55.0	40.4	-14.8	327.6	342.8	0.5	27.2	26.6	14238.8	256.7	29695.2	47.9
1105.3	54.9	54.8	31.5	-12.1	344.3	359.4	0.7	28.0	27.3	11422.1	231.3	26778.0	42.7
1106.3	54.6	54.6	19.7	-9.7	341.7	356.9	0.8	27.4	26.6	6952.5	198.6	23005.2	30.2
1106.4	54.7	54.8	11.5	-8.9	314.7	329.8	0.8	25.2	24.4	3706.8	174.9	20260.9	18.3
1106.4	54.7	55.1	5.2	-8.7	292.1	307.2	0.8	23.4	22.6	1556.2	158.1	18317.3	8.5

BENTONITE 7 %

SLURRY PROPERTIES		
Material type	BENTONITE 7 %	
Pump	6/4 Warman	
Date	07-Mar-05	
Density of Water	1000	kg/m3
Density of Material	1046.4	kg/m3
Rheological parameters		
Ty	7.685	Pa
K	0.0058	$Pa.s^n$
n	1	

Table 35: 6/4 Warman pump test at 1400 rpm for bentonite 7 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1410.7	36.5	36.9	5.5	-1.4	491.9	506.9	1.6	49.6	48.1	2691.4	187.0	27623.2	9.7
1410.7	36.0	36.3	10.5	-2.4	491.4	506.4	1.5	49.6	48.2	5196.5	200.0	29548.3	17.6
1409.5	36.1	36.2	20.8	-3.3	485.3	500.4	1.4	49.3	47.8	10184.7	231.6	34190.3	29.8
1409.5	36.3	36.3	31.0	-4.5	473.5	488.5	1.4	48.5	47.1	14980.5	260.3	38424.7	39.0
1408.8	36.3	36.2	41.1	-6.0	458.0	473.0	1.4	47.4	46.1	19416.6	287.7	42450.9	45.7
1408.5	36.4	36.4	50.8	-7.8	440.0	455.0	1.3	46.3	45.0	23445.3	314.5	46396.5	50.5
1407.7	36.6	36.5	60.9	-10.4	414.8	429.8	1.2	44.5	43.3	27117.0	340.3	50166.2	54.1
1406.6	36.7	36.7	71.3	-13.2	386.6	401.6	1.1	42.7	41.6	30419.1	363.0	53463.9	56.9
1406.5	36.9	36.8	80.8	-16.3	357.2	372.3	1.0	40.8	39.8	32996.6	383.4	56470.4	58.4
1406.4	37.1	37.0	90.9	-20.2	324.4	339.4	0.9	38.7	37.9	35340.9	403.8	59470.2	59.4
1405.8	37.3	37.2	101.1	-24.8	289.7	304.7	0.7	36.6	36.0	37322.2	422.2	62155.7	60.0
1405.8	37.5	37.5	111.2	-29.9	252.0	267.0	0.5	34.4	33.9	38711.2	442.8	65191.2	59.4
1404.7	37.8	37.7	121.2	-36.3	208.2	223.2	0.2	31.6	31.5	39167.6	460.2	67697.6	57.9
1404.7	38.0	38.0	131.3	-41.8	163.8	178.9	0.0	29.0	29.0	39138.4	476.1	70029.9	55.9

Table 36: 6/4 Warman pump test at 1300 rpm for bentonite 7 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1308.3	37.2	37.5	5.6	-1.6	422.1	437.1	1.5	42.8	41.3	2363.5	145.9	19994.6	11.8
1308.3	35.2	35.0	10.7	-2.5	421.7	436.7	1.5	42.8	41.4	4528.9	158.9	21764.8	20.8
1308.3	35.8	35.9	20.4	-3.3	416.5	431.5	1.4	42.5	41.1	8625.6	184.1	25218.8	34.2
1307.2	36.2	36.1	30.7	-4.3	405.4	420.4	1.4	41.8	40.4	12722.4	210.6	28828.9	44.1
1307.2	36.2	36.2	40.7	-5.9	390.0	405.0	1.4	40.8	39.4	16448.6	236.8	32418.6	50.7
1306.4	36.3	36.3	50.9	-7.9	370.4	385.4	1.3	39.5	38.2	19948.5	261.1	35727.1	55.8
1306.4	36.5	36.4	60.8	-10.2	346.7	361.8	1.2	37.9	36.7	22911.7	283.7	38813.2	59.0
1305.6	36.6	36.5	70.7	-13.0	319.9	334.9	1.1	36.1	35.0	25408.1	303.3	41465.6	61.3
1305.3	36.7	36.6	80.9	-16.1	290.8	305.8	1.0	34.3	33.3	27657.0	322.7	44103.7	62.7
1305.3	36.8	36.7	91.0	-20.1	260.0	275.0	0.9	32.5	31.6	29510.7	340.5	46544.2	63.4
1304.2	37.0	36.9	100.9	-24.4	227.6	242.7	0.7	30.6	29.9	30918.3	356.8	48732.5	63.4
1304.2	37.2	37.1	111.1	-29.8	190.7	205.7	0.5	28.4	27.9	31854.7	372.9	50922.8	62.6
1304.2	37.4	37.3	121.4	-35.8	152.7	167.7	0.2	26.3	26.0	32471.0	389.2	53152.1	61.1
1303.5	37.6	37.5	131.1	-41.9	100.5	115.5	0.0	22.8	22.8	30715.7	402.9	54990.8	55.9

Table 37: 6/4 Warman pump test at 1100 and 1200 rpm for bentonite 7 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1106.6	38.5	38.6	5.5	-2.0	301.9	316.9	1.5	31.1	29.6	1684.9	102.0	11825.4	14.2
1106.6	38.4	38.4	10.9	-2.6	300.7	315.8	1.5	31.1	29.6	3303.2	115.3	13357.1	24.7
1106.6	38.3	38.3	21.5	-3.3	293.6	308.7	1.4	30.6	29.2	6421.2	139.0	16101.8	39.9
1105.5	38.4	38.2	31.0	-4.4	282.7	297.8	1.4	29.9	28.5	9044.5	161.1	18652.5	48.5
1105.5	38.2	38.1	41.0	-6.0	267.8	282.8	1.4	28.9	27.5	11576.7	182.2	21089.2	54.9
1105.4	38.2	38.1	50.4	-7.8	249.7	264.7	1.3	27.7	26.4	13661.0	200.0	23150.7	59.0
1104.3	38.2	38.0	61.4	-10.5	224.8	239.9	1.2	26.1	24.9	15678.3	218.9	25311.6	61.9
1104.3	38.2	38.0	71.4	-13.3	200.4	215.4	1.1	24.6	23.5	17209.2	235.4	27221.0	63.2
1104.3	38.2	38.0	80.9	-16.2	176.3	191.3	1.0	23.2	22.2	18406.3	249.9	28901.6	63.7
1103.6	38.2	38.1	90.9	-19.7	151.2	166.2	0.9	21.9	20.9	19535.7	263.4	30436.0	64.2
1103.6	38.2	38.1	101.7	-24.7	117.0	132.0	0.7	19.9	19.2	20020.3	278.1	32141.4	62.3
1208.4	38.0	38.2	5.4	-1.9	360.0	375.0	1.5	36.8	35.3	1946.0	122.1	15453.0	12.6
1207.8	37.8	37.9	10.7	-2.6	359.0	374.0	1.5	36.7	35.3	3877.5	135.6	17149.6	22.6
1207.8	37.9	37.9	20.5	-3.3	353.2	368.3	1.4	36.4	34.9	7343.8	159.8	20216.4	36.3
1207.1	38.0	37.9	30.4	-4.4	342.2	357.3	1.4	35.6	34.2	10700.4	183.4	23179.7	46.2
1207.1	38.0	37.8	41.1	-6.0	326.2	341.3	1.3	34.6	33.2	14026.4	208.6	26368.4	53.2
1206.5	37.9	37.8	50.8	-8.0	307.3	322.3	1.3	33.3	32.1	16710.9	229.9	29042.6	57.5
1205.9	38.0	37.8	60.9	-10.3	284.0	299.0	1.2	31.8	30.6	19128.7	250.0	31573.4	60.6
1205.9	38.0	37.9	71.3	-13.4	256.6	271.7	1.1	30.0	28.9	21200.9	268.8	33942.9	62.5
1204.8	38.0	37.9	80.7	-16.2	231.4	246.4	1.0	28.5	27.5	22782.9	285.2	35982.8	63.3
1204.8	38.1	38.0	91.1	-20.3	200.6	215.6	0.9	26.7	25.8	24179.0	301.7	38062.3	63.5
1204.8	38.2	38.1	100.9	-24.0	174.2	189.3	0.7	25.4	24.6	25485.7	314.2	39639.0	64.3
1204.6	38.2	38.1	111.3	-30.1	135.0	150.1	0.5	23.0	22.5	25760.7	329.4	41552.5	62.0

BENTONITE 9 %

SLURRY PROPERTIES		
Material type	BENTONITE 9 %	
Pump	6/4 Warman	
Date	16-Mar-05	
Density of Water	1000	kg/m3
Density of Material	1064.7	kg/m3
Rheological parameters		
Ty	35.1796	Pa
K	0.02	$Pa.s^n$
n	1	

Table 38: 6/4 Warman pump test at 1400 rpm for bentonite 9 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1408.7	51.9	52.2	6.0	-4.8	434.2	449.3	1.2	43.3	42.0	2631.0	146.1	21554.8	12.2
1408.7	50.7	51.4	10.4	-5.1	447.0	462.1	1.2	44.5	43.3	4726.5	157.3	23204.3	20.4
1407.5	50.9	51.5	20.4	-5.6	467.3	482.3	1.2	46.7	45.5	9703.4	186.8	27539.8	35.2
1407.4	50.7	51.8	30.9	-7.3	469.9	485.0	1.1	47.3	46.2	14887.3	216.6	31916.5	46.6
1406.4	52.2	52.1	40.8	-8.3	455.7	470.7	1.1	46.4	45.3	19269.7	242.9	35771.5	53.9
1405.7	52.6	52.5	50.8	-10.1	437.1	452.1	1.1	45.2	44.2	23423.2	269.4	39658.3	59.1
1405.7	52.7	52.6	60.8	-12.5	412.8	427.9	1.0	43.6	42.6	27079.7	295.7	43528.2	62.2
1404.5	52.9	52.8	72.3	-16.0	377.2	392.2	0.9	41.2	40.4	30462.3	323.6	47589.8	64.0
1404.5	53.2	53.1	81.2	-18.6	351.8	366.8	0.8	39.7	38.9	32959.7	341.2	50182.5	65.7
1403.4	53.8	53.7	91.2	-22.1	318.6	333.6	0.7	37.6	36.9	35210.9	360.6	52988.5	66.5
1403.4	54.2	54.2	101.5	-26.1	281.7	296.8	0.6	35.4	34.8	36902.8	380.9	55982.9	65.9
1403.3	54.9	54.8	110.9	-30.5	234.9	249.9	0.4	32.3	31.8	36862.2	396.4	58247.1	63.3

Table 39 : 6/4 Warman pump test at 1300 rpm for bentonite 9 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1308.2	47.5	48.1	5.9	-4.7	382.2	397.2	1.2	38.3	37.0	2296.2	130.0	17809.7	12.9
1307.1	47.0	47.4	10.9	-5.1	376.3	391.3	1.2	37.8	36.6	4150.3	147.3	20159.2	20.6
1307.1	47.1	47.7	21.0	-5.6	392.4	407.4	1.2	39.5	38.3	8402.4	172.1	23561.2	35.7
1306.4	46.9	47.9	30.9	-6.6	401.5	416.5	1.2	40.7	39.6	12774.0	195.5	26751.1	47.8
1306.3	48.3	48.2	41.2	-8.2	387.4	402.4	1.1	39.9	38.7	16679.1	223.3	30543.0	54.6
1305.5	48.5	48.3	51.1	-10.1	369.3	384.3	1.1	38.7	37.7	20109.6	246.5	33697.6	59.7
1305.2	48.5	48.3	60.8	-12.4	346.2	361.2	1.0	37.2	36.2	23009.0	270.2	36931.7	62.3
1305.1	48.7	48.6	71.6	-15.4	316.3	331.3	0.9	35.3	34.4	25718.7	291.2	39794.6	64.6
1304.1	49.1	49.0	81.2	-18.7	286.7	301.8	0.8	33.5	32.7	27708.8	310.5	42399.3	65.4
1304.1	49.4	49.3	91.0	-21.8	255.8	270.9	0.7	31.6	30.9	29359.8	327.9	44772.7	65.6
1303.3	49.9	49.8	102.2	-26.4	218.1	233.1	0.6	29.4	28.9	30811.2	346.5	47285.8	65.2
1303.3	50.4	50.3	110.9	-30.4	178.4	193.5	0.4	26.8	26.4	30565.7	358.8	48975.2	62.4
1303.3	51.1	51.1	111.2	-30.6	173.8	188.8	0.4	26.4	26.0	30211.2	359.0	49003.8	61.7

Table 40: 6/4 Warman pump test at 1200 and 1100 rpm for bentonite 9 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1207.8	45.3	45.5	5.6	-4.4	316.0	331.0	1.3	31.9	30.7	1807.1	116.6	14747.7	12.3
1207.4	44.6	44.9	10.6	-4.8	257.0	272.0	1.2	26.3	25.1	2776.9	130.0	16441.4	16.9
1207.0	44.7	45.0	21.1	-5.5	324.7	339.8	1.2	33.1	31.8	7028.7	154.8	19571.6	35.9
1207.0	44.6	45.2	30.7	-7.7	338.4	353.5	1.1	34.7	33.6	10792.5	176.9	22358.7	48.3
1205.9	45.6	45.5	41.0	-8.1	324.8	339.8	1.1	33.9	32.7	14020.0	200.2	25275.0	55.5
1205.9	45.8	45.7	51.0	-10.0	306.8	321.9	1.1	32.8	31.7	16863.9	220.7	27873.8	60.5
1204.8	45.9	45.7	61.2	-12.6	282.5	297.5	1.0	31.2	30.2	19287.6	242.1	30548.1	63.1
1204.8	46.1	46.0	71.2	-15.2	255.8	270.8	0.9	29.5	28.6	21253.6	261.0	32925.6	64.6
1204.8	46.1	46.2	81.5	-18.8	225.1	240.1	0.8	27.6	26.8	22815.4	279.2	35229.7	64.8
1203.6	46.4	46.3	91.5	-22.1	196.5	211.6	0.7	26.0	25.3	24164.3	295.7	37276.0	64.8
1203.6	46.9	46.8	101.7	-26.3	163.1	178.2	0.6	24.1	23.5	24971.7	312.9	39432.9	63.3
1106.5	42.5	42.8	5.4	-4.5	233.8	248.9	1.3	24.1	22.8	1296.7	103.1	11952.1	10.8
1106.5	42.4	42.7	10.5	-4.9	204.0	219.0	1.2	21.3	20.0	2196.1	114.1	13222.7	16.6
1106.5	42.3	42.7	20.7	-5.6	261.4	276.4	1.2	27.0	25.8	5577.6	136.2	15787.1	35.3
1105.4	42.7	42.8	30.9	-7.5	280.3	295.3	1.1	29.1	28.0	9041.5	155.0	17947.1	50.4
1105.4	43.1	43.0	40.7	-8.2	267.1	282.1	1.1	28.3	27.2	11574.8	176.5	20430.0	56.7
1105.0	43.2	42.9	51.0	-10.1	248.7	263.7	1.1	27.2	26.1	13911.3	196.9	22784.1	61.1
1104.3	43.2	43.0	61.2	-12.7	223.7	238.8	1.0	25.6	24.6	15708.9	215.8	24956.2	62.9
1104.3	43.4	43.3	71.1	-15.5	199.3	214.4	0.9	24.1	23.2	17237.2	231.1	26722.0	64.5
1104.2	43.6	43.5	81.5	-18.9	169.9	184.9	0.8	22.3	21.5	18315.6	246.8	28535.0	64.2
1103.6	44.3	44.2	91.4	-22.2	142.1	157.2	0.7	20.8	20.1	19165.8	261.2	30186.0	63.5
1103.6	44.5	44.4	101.8	-26.3	103.5	118.5	0.6	18.4	17.8	18949.0	275.5	31840.6	59.5

BENTONITE 9 %

SLURRY PROPERTIES		
Material type	BENTONITE 7 %	
Pump	4/3 GIW	
Date	08-Mar-05	
Density of Water	1000	kg/m3
Density of Material	1046.4	kg/m3
Rheological parameters		
Ty	7.685	Pa
K	0.0058	$Pa.s^n$
n	1	

Table 41: 4/3 GIW pump test at 2100 and 1900 rpm for bentonite 7 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
2124.9	37.0	38.6	5.2	-3.5	703.3	708.7	1.2	70.1	68.9	3681.4	75.7	16844.2	21.9
2121.3	36.5	38.6	10.4	-5.0	671.3	678.2	1.1	67.1	66.1	7021.9	87.6	19469.3	36.1
2119.0	36.5	38.7	15.8	-7.2	653.1	662.2	1.0	65.7	64.7	10507.2	101.3	22477.4	46.7
2116.3	37.6	39.0	20.2	-9.7	636.3	647.9	0.9	64.5	63.6	13202.6	111.9	24802.5	53.2
2113.5	38.1	39.1	25.3	-13.7	616.0	631.6	0.7	63.1	62.4	16184.4	124.0	27443.5	59.0
2110.2	38.4	39.3	30.4	-18.6	589.0	609.5	0.4	61.1	60.7	18940.6	136.3	30120.3	62.9
2107.6	38.6	39.4	35.3	-24.0	558.5	584.4	0.1	58.9	58.8	21332.3	146.3	32288.7	66.1
2104.4	38.9	39.7	41.1	-31.7	516.3	549.8	-0.3	55.9	56.2	23736.2	157.5	34712.5	68.4
2098.6	39.1	40.0	45.4	-38.5	478.4	518.8	-0.7	53.1	53.8	25066.6	164.2	36090.1	69.5
2098.5	39.3	40.2	50.3	-47.2	430.6	479.7	-1.1	49.6	50.8	26206.5	172.6	37933.7	69.1
2095.4	39.5	40.4	54.9	-56.5	349.8	408.1	-1.7	43.0	44.6	25153.7	177.2	38886.2	64.7
1919.2	33.2	35.0	5.5	-2.7	567.7	572.3	1.3	56.9	55.6	3113.3	60.0	12054.5	25.8
1916.6	32.7	34.9	10.4	-4.3	542.7	549.0	1.2	54.6	53.5	5730.8	70.3	14101.3	40.6
1914.1	32.7	35.0	15.8	-6.6	526.6	535.1	1.0	53.4	52.4	8499.2	82.3	16493.0	51.5
1911.5	33.7	35.1	20.5	-9.8	510.5	522.1	0.9	52.2	51.4	10820.5	92.7	18547.8	58.3
1908.8	34.3	35.4	25.5	-14.0	489.9	505.9	0.6	50.8	50.2	13147.4	103.0	20584.9	63.9
1906.6	34.6	35.6	30.3	-19.4	464.6	485.9	0.3	49.0	48.7	15154.5	112.2	22400.5	67.7
1904.5	35.1	35.9	35.2	-25.3	433.6	460.8	0.0	46.8	46.8	16908.5	120.8	24082.4	70.2
1902.1	35.5	36.3	40.8	-33.5	391.5	426.9	-0.5	43.7	44.2	18516.0	129.7	25828.9	71.7
1899.8	35.8	36.5	45.4	-40.4	354.6	396.9	-0.8	41.1	41.9	19549.2	136.4	27132.6	72.1
1898.3	35.9	36.8	51.2	-52.4	293.0	347.3	-1.6	36.5	38.0	20012.3	144.1	28648.2	69.9

Table 42: 4/3 GIW pump test at 1600 and 1300 rpm for bentonite 7 %

Pump speed rpm	Temperature suction pipe (T1) °C	Temperature discharge pipe (T2) °C	Pump discharge flow l/s	Suction pipe vel press (P1) kPa	discharge pipe vel press (P2) kPa	P2 Adjusted	Pump Suction head m	Pump Discharge head m	Pump Total head m	Pump power output rho.q.g.H W	Pump shaft torque N.m	Pump power in 2.Pi.n.T W	Pump effy %
1614.1	35.5	37.3	5.4	-2.8	394.8	399.5	1.2	40.0	38.8	2147.6	41.3	6980.3	30.8
1611.8	35.2	37.3	10.1	-4.2	379.4	385.6	1.2	38.7	37.5	3907.2	50.5	8518.7	45.9
1610.3	35.2	37.2	15.3	-6.5	366.3	374.7	1.0	37.7	36.7	5761.1	60.6	10215.6	56.4
1608.1	35.2	37.3	20.2	-9.6	351.2	362.7	0.9	36.7	35.8	7410.9	69.5	11703.5	63.3
1605.7	35.8	37.4	25.9	-14.2	327.6	343.6	0.6	35.0	34.4	9163.7	79.6	13384.5	68.5
1603.6	35.7	37.4	30.7	-18.7	302.3	322.9	0.4	33.2	32.8	10340.7	86.9	14595.8	70.8
1602.5	35.9	37.5	35.4	-24.0	272.3	298.3	0.1	31.1	31.0	11257.9	92.8	15571.1	72.3
1601.4	36.3	37.6	40.3	-30.7	237.3	269.9	-0.2	28.6	28.8	11919.6	98.9	16582.9	71.9
1599.9	36.6	37.7	43.9	-36.3	208.7	246.9	-0.5	26.6	27.1	12220.8	102.7	17205.0	71.0
1308.3	35.9	37.9	5.3	-3.6	253.8	259.3	1.2	26.3	25.1	1363.9	28.5	3899.8	35.0
1306.7	35.6	37.6	10.4	-5.0	243.6	250.4	1.1	25.5	24.4	2604.0	35.9	4907.6	53.1
1305.2	35.5	37.6	15.8	-7.2	231.6	240.7	1.0	24.7	23.7	3836.8	43.8	5986.3	64.1
1304.1	35.6	37.7	20.5	-9.9	217.1	228.9	0.9	23.7	22.8	4808.7	50.5	6901.4	69.7
1302.2	35.7	37.8	25.6	-14.0	194.9	210.8	0.6	22.1	21.4	5627.2	56.4	7691.2	73.2
1300.7	36.0	37.8	30.3	-18.3	169.7	189.9	0.4	20.3	19.9	6178.0	61.1	8326.4	74.2
1299.9	36.3	37.8	35.1	-23.8	140.5	166.2	0.1	18.2	18.1	6509.2	65.8	8954.4	72.7

APPENDIX E

CENTRIFUGAL PUMPS ERROR CALCULATION VALUES

Table 43: Errors of computed variables for the 6/4 Warman at 800 rpm

6/4 Warman 800 RPM									
Variables	Measurements average	Standard deviation	Absolute error at 95% conf.	Relative error [±%]	EXPECTED HIGHEST ERROR [± %]				
					Velocity	Head	Pump power out	Pump power in	Efficiency
Pump flow rate [l/s]	71.687	0.161	0.322	0.449					
Pump speed [rpm]	801.782	0.351	0.702	0.088					
Pressure suction [kPa]	-9.238	0.062	0.124	-1.339	0.979	1.958			
Pressure discharge [kPa]	65.965	0.667	1.331	2.018	1.340	2.532			
Pump shaft torque [N.m]	132.913	1.239	2.478	1.864			2.009	1.866	1.782

Table 44: Errors of computed variables for the 6/4 Warman at 1200 rpm

6/4 Warman at 1200RPM									
Variables	Measurements average	Standard deviation	Absolute error at 95% conf.	Relative error [±%]	EXPECTED HIGHEST ERROR [± %]				
					Velocity	Head	Pump power out	Pump power in	Efficiency
Pump flow rate [l/s]	110.115	0.577	1.153	1.047					
Pump speed [rpm]	1203.438	0.0293	0.0587	0.005					
Pressure suction [kPa]	-25.105	0.360	0.7202	-2.869	1.361	2.723			
Pressure discharge [kPa]	125.483	2.525	5.0505	4.025	1.641	2.5261			
Pump shaft torque [N.m]	294.004	2.227	4.454	1.515			2.917	1.515	2.137

Table 45: Errors of computed variables for the 4/3 GIW at 900rpm

4/3 GIW at 900RPM									
Variables	Measurements average	Standard deviation	Absolute error at 95% conf.	Relative error [±%]	EXPECTED HIGHEST ERROR [± %]				
					Velocity	Head	Pump power out	Pump power in	Efficiency
Pump flow rate [l/s]	16.163	0.021	0.041	0.254					
Pump speed [rpm]	901.086	0.972	1.944	0.216					
Pressure suction [kPa]	-4.1413	0.032	0.064	-1.556	0.254	0.3599			
Pressure discharge [kPa]	101.379	2.412	4.825	4.759	0.254	0.305			
Pump shaft torque [N.m]	28.638	5.626	11.252	39.289			0.440	39.290	25.540

Table 46: Errors of computed variables for the 4/3 GIW at 1300 rpm

4/3 GIW at 1300 RPM									
Variables	Measurements average	Standard deviation	Absolute error at 95% conf.	Relative error [±%]	EXPECTED HIGHEST ERROR [± %]				
					Velocity	Head	Pump power out	Pump power in	Efficiency
Pump flow rate [l/s]	23.901	0.0352	0.070	0.294					
Pump speed [rpm]	1300.416	0.372	0.744	0.0572					
Pressure suction [kPa]	-9.591	0.122	0.245	-2.553	0.294	0.416			
Pressure discharge [kPa]	202.997	0.934	1.868	0.920	0.295	0.0815			
Pump shaft torque [N.m]	53.107	2.250	4.500	8.473			0.510	8.473	5.517

APPENDIX F

ANALYSIS WITH HYDRAULICS INSTITUTE CHART

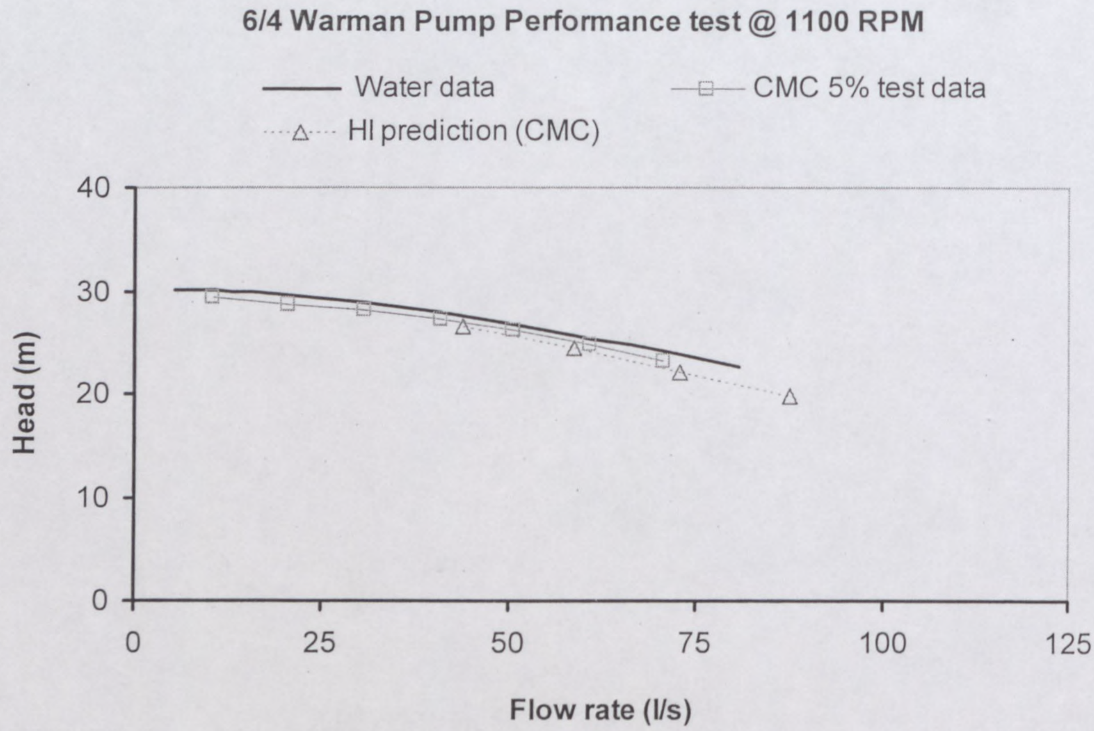

Figure 2: HI head prediction for CMC 5% at 1100 rpm

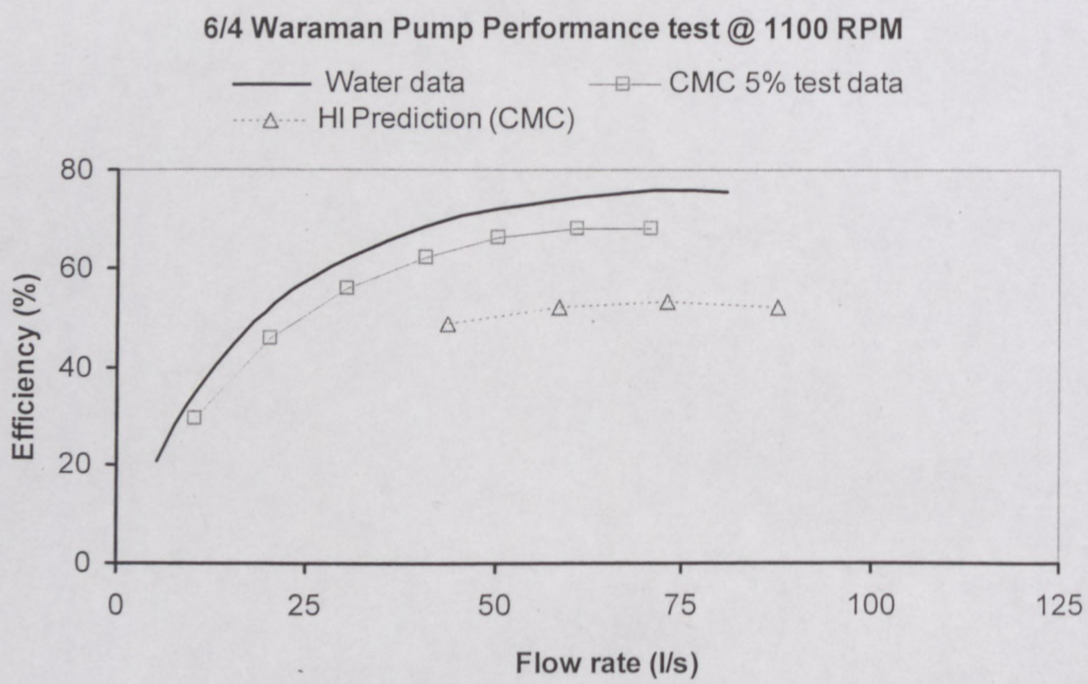

Figure 3: HI efficiency prediction for CMC 5% at 1100 rpm

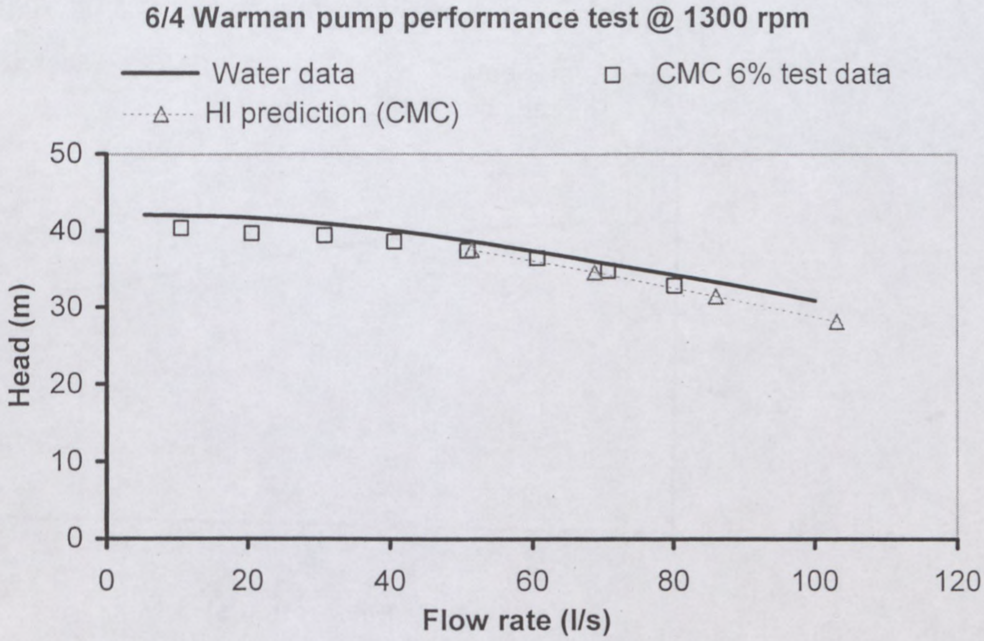

Figure 4: HI head prediction for CMC 6 % at 1300 rpm

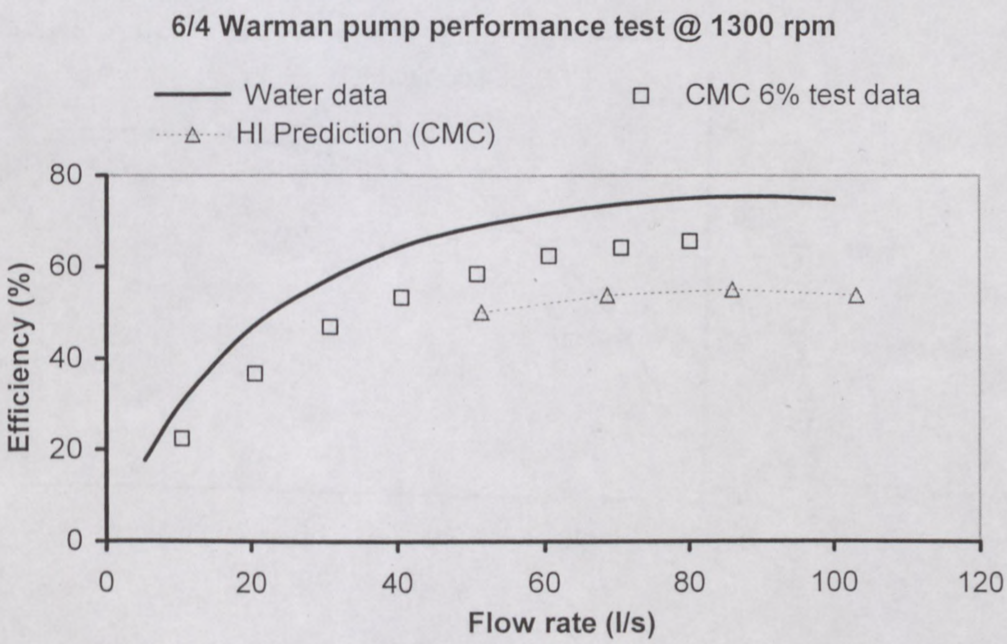

Figure 5: HI efficiency prediction for CMC 6 % at 1300 rpm

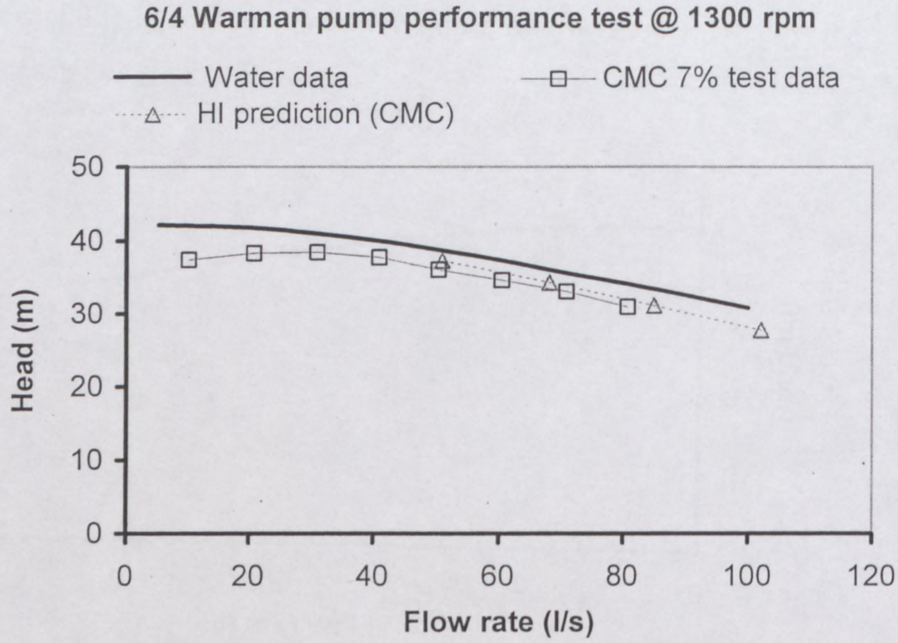

Figure 6: HI head prediction for CMC 7 % at 1300 rpm

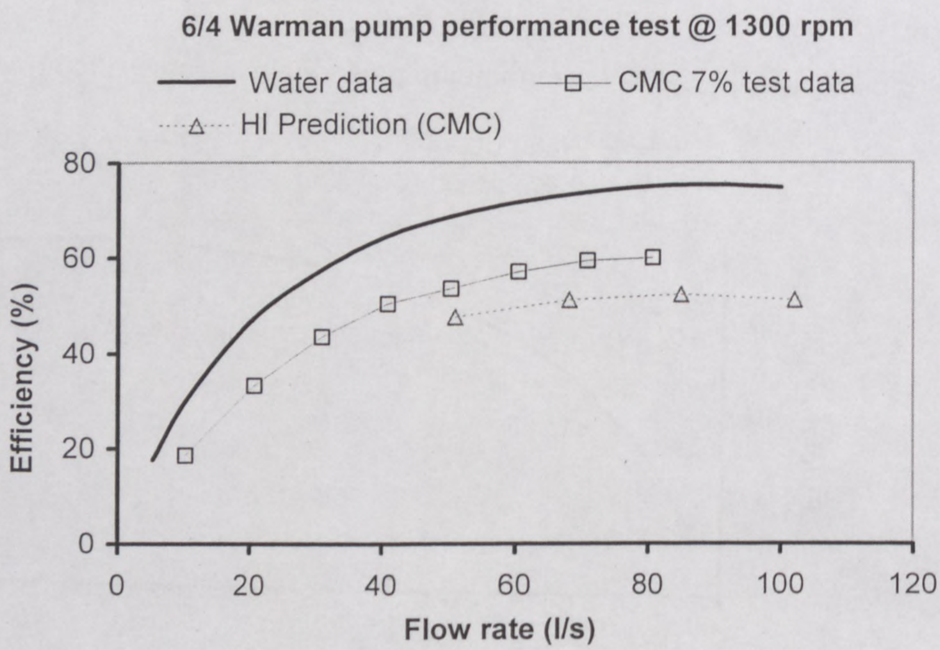

Figure 7: HI efficiency prediction for CMC 7 % at 1300 rpm

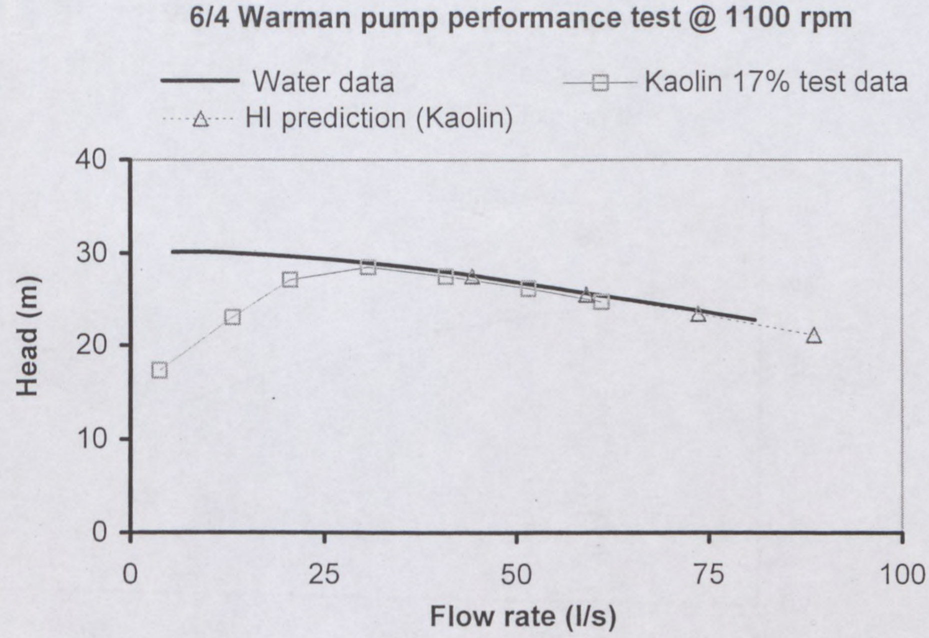

Figure 8: HI head prediction for kaolin 17 % at 1100 rpm

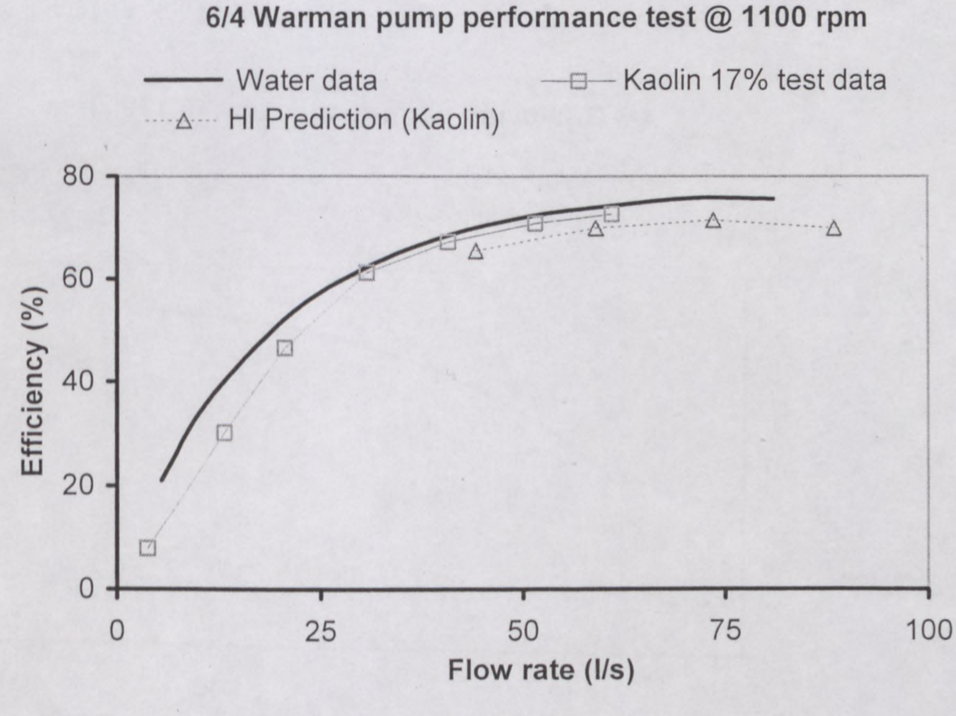

Figure 9: HI efficiency prediction for kaolin 17 % at 1100 rpm

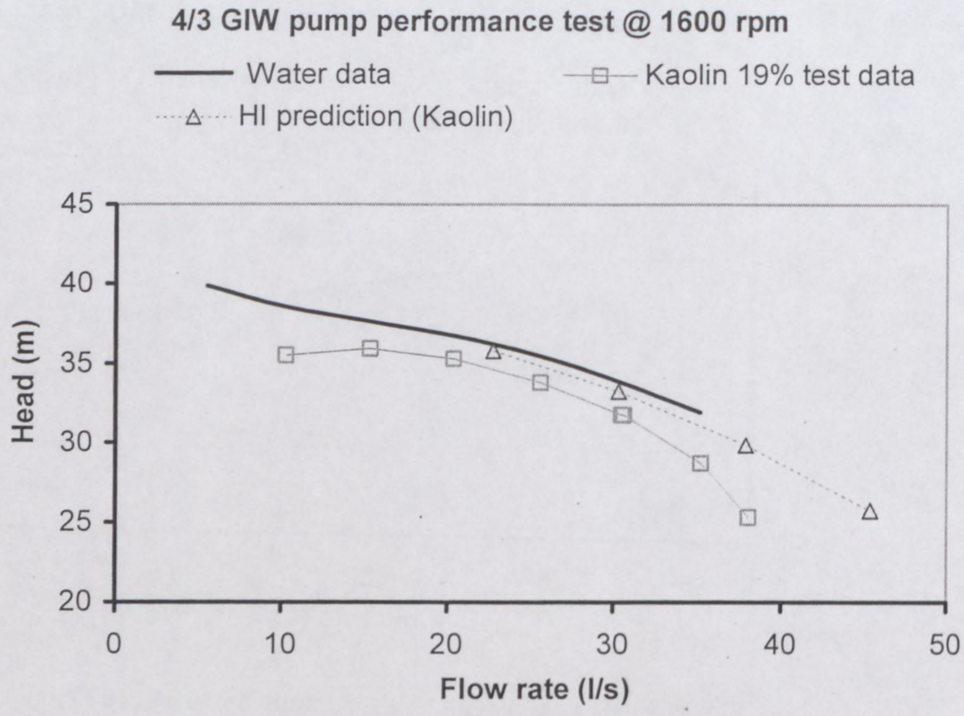

Figure 10: HI head prediction for kaolin 19 % at 1600 rpm

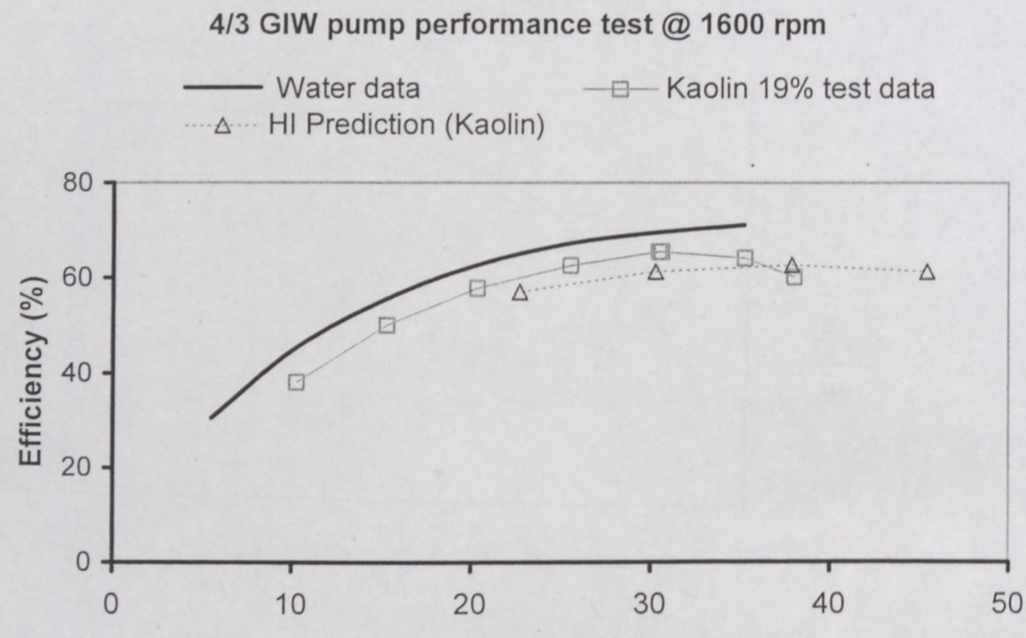

Figure 11: HI efficiency prediction for kaolin 19 % at 1600 rpm

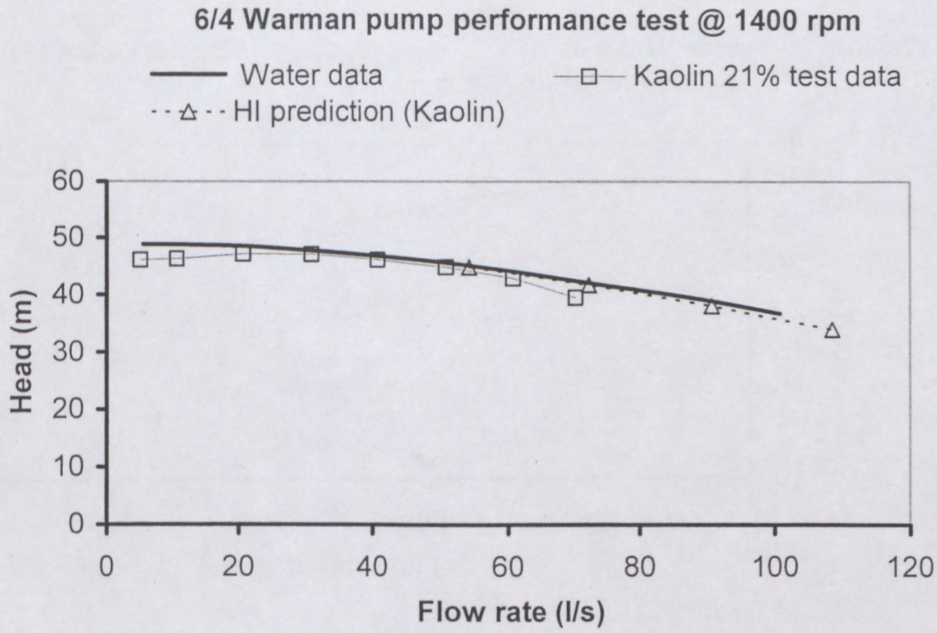

Figure 12: HI head prediction for kaolin 21 % at 1400 rpm

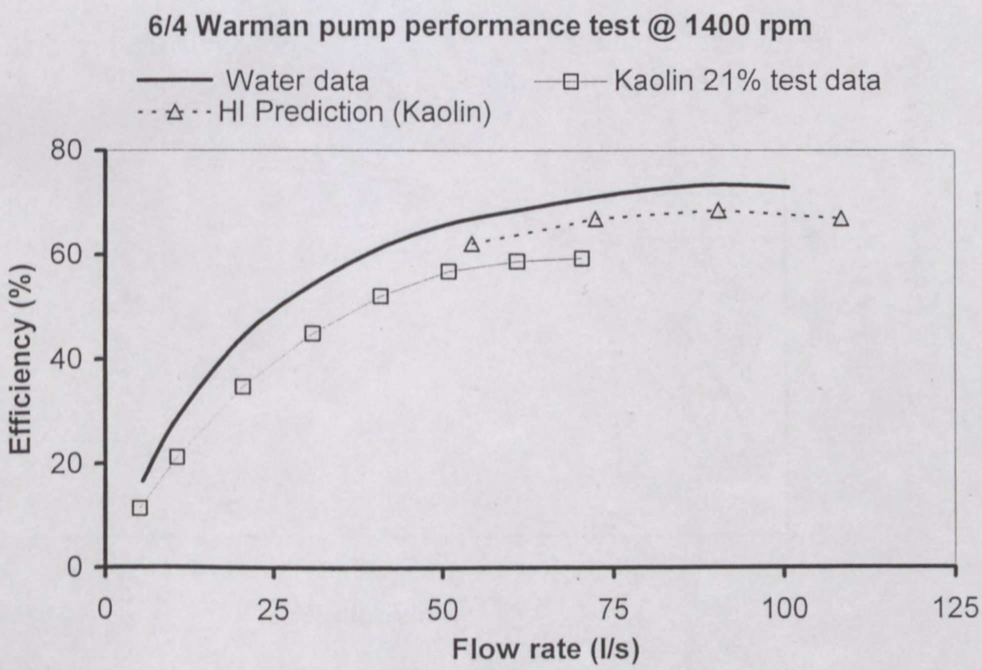

Figure 13: HI efficiency prediction for kaolin 21 % at 1400 rpm

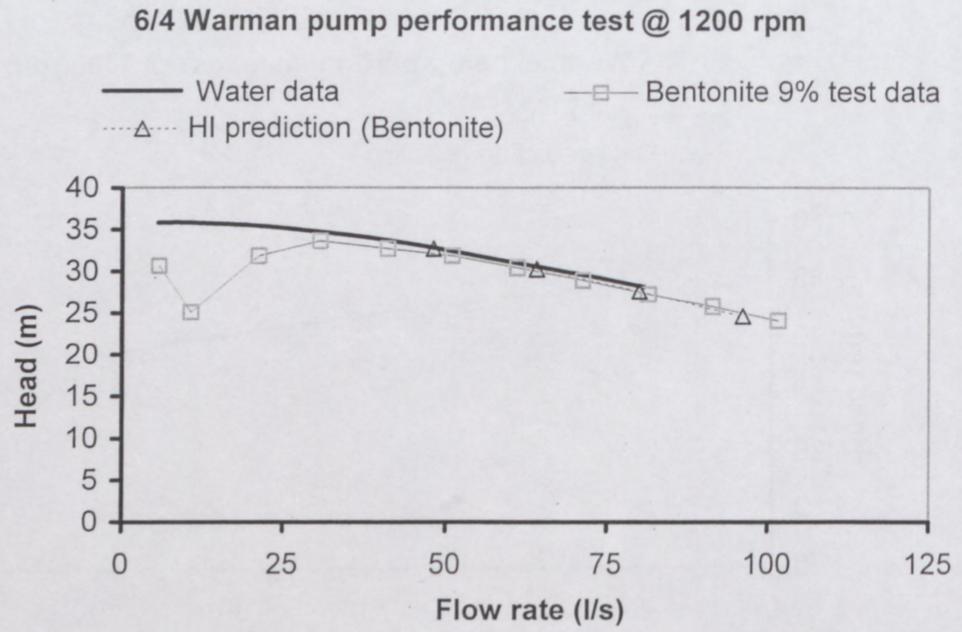

Figure 14: HI head prediction for bentonite 9 % at 1200 rpm

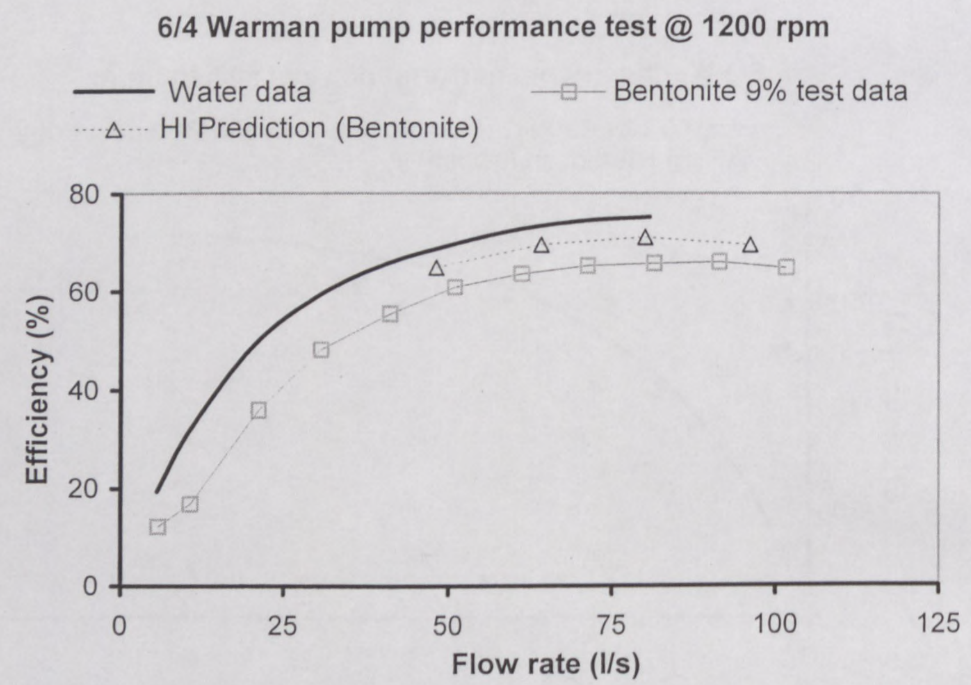

Figure 15: HI efficiency prediction for bentonite 9 % at 1200 rpm

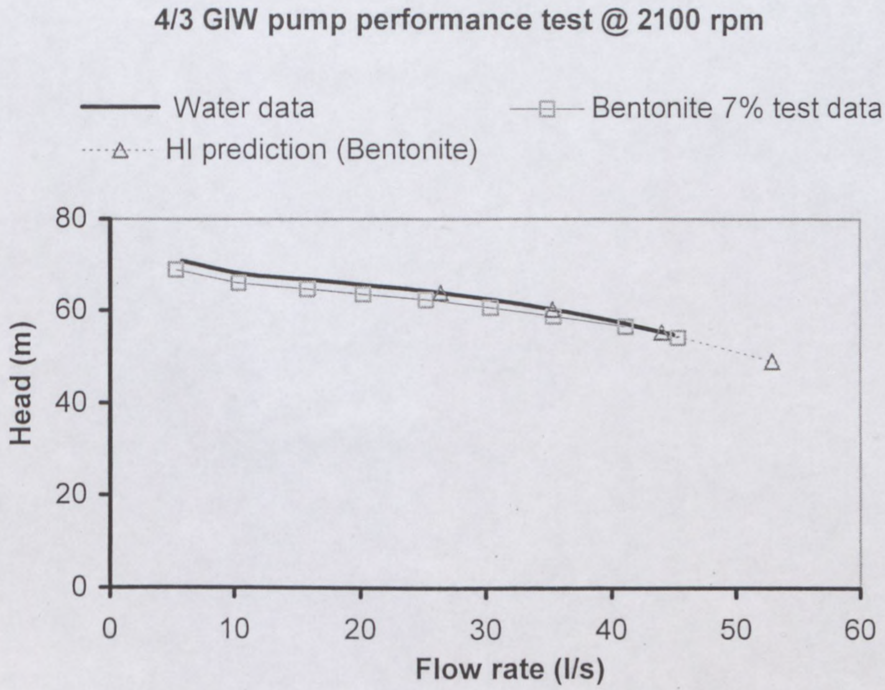

Figure 16: HI head prediction for bentonite 7 % at 2100 rpm

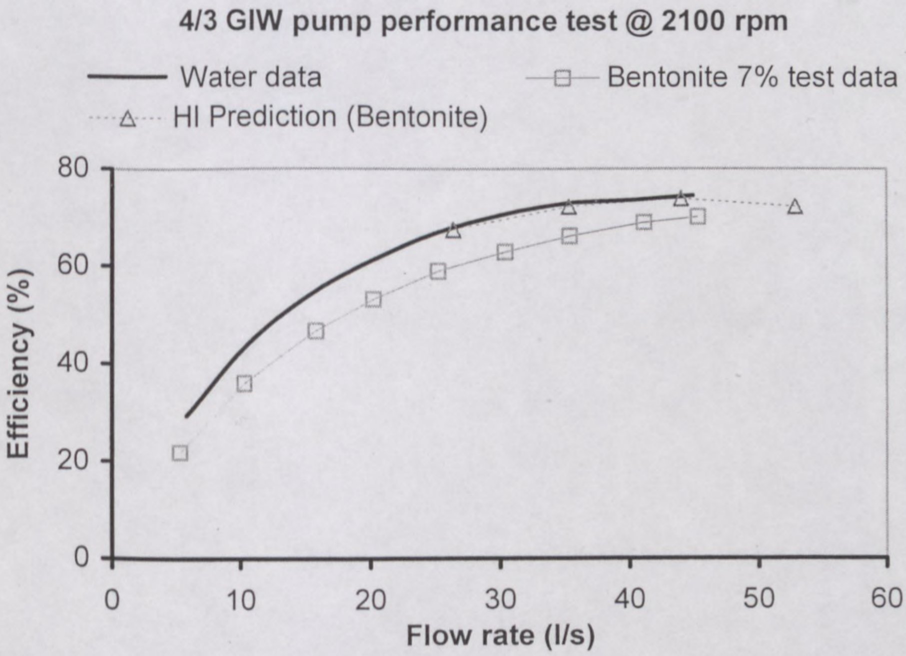

Figure 17: HI efficiency prediction for bentonite 7 % at 2100 rpm

APPENDIX G

RELATIVE DENSITY TEST

6.4.1 Relative density test procedure (RD Test)

A quantity of approximatively one liter of sample is collected in a plastic bottle in order to measure the relative density:

- An electronic balance, type Explorer with an accuracy of ± 0.001g is connected to a computer to allow for the readings of any weighed value.
- Three volumetric flasks are cleaned, dried and weighed. This operation is named M1.
- The tested fluid is poured in each flask at approximatively half the volume of the container and weighed. This operation is called M2.
- The M3 operation consists of reading the weight of the flasks where water is added to the tested fluid up to the graduated mark. Water is carefully added and flasks gently shaken to prevent and remove any air bubbles.
- In the last step, M4 is measured. The flasks are emptied and rinsed with water and alcohol thereafter to dry. They are then filled with water up to the graduated mark and weighed.

RD Calculations

The mass of the tested fluid was found by: M2-M1
The mass of water was expressed by: M4-M1
The mass of water filling the space left by the tested fluid was given by: M3-M2
The mass of water that had a volume equal to that of the tested fluid was expressed by: (M4-M1) - (M3-M2).
Therefore by definition the RD of the tested fluids is expressed by

$$RD = \frac{M2 - M1}{(M4 - M1) - (M3 - M2)}$$

The RD calculation per material tested was done on three samples. The final RD value used in calculation was the average of the three. An example of such a test is given in Appendix G.

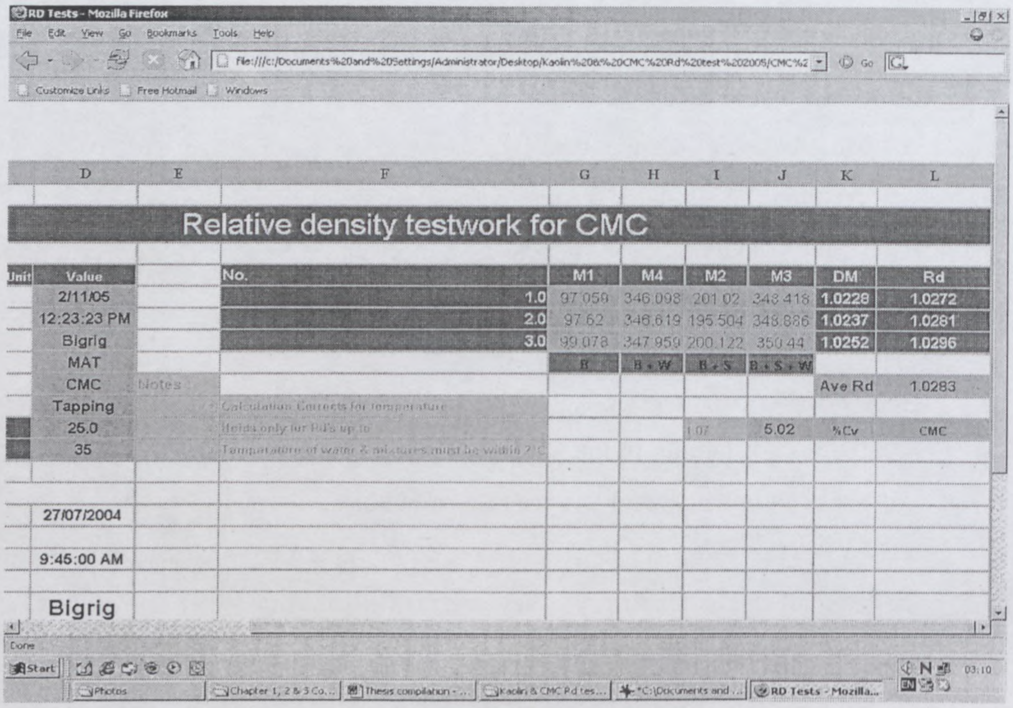

Figure 18: Relative density test for CMC 5%

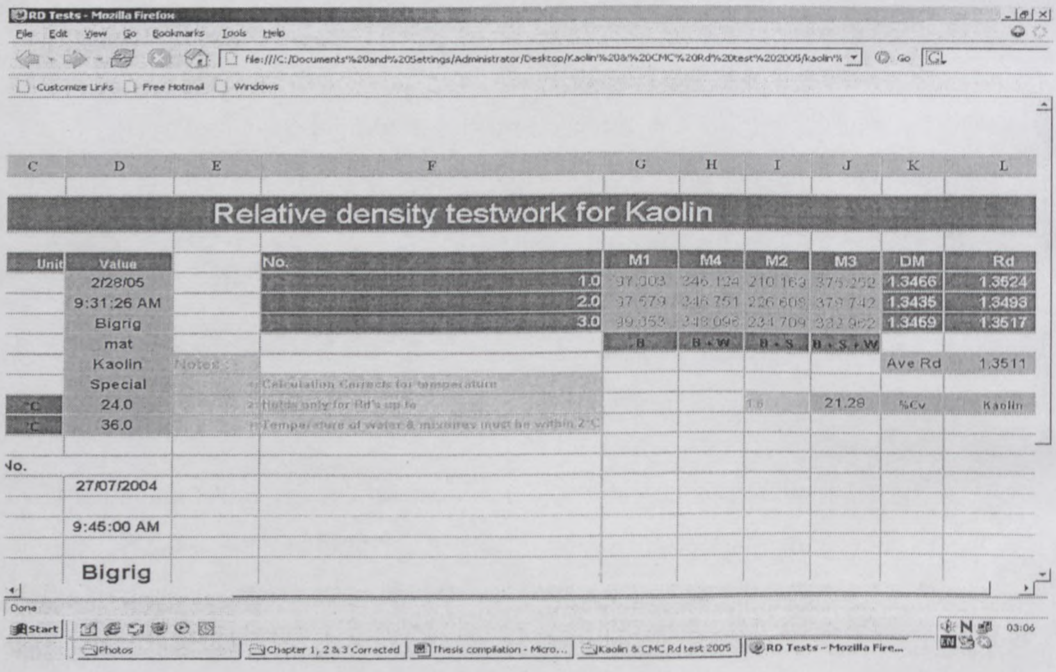

Figure 19 : Relative density test for kaolin 21 %