

Solids Effect On The Performance Of Centrifugal Slurry Pumps

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SOLIDS EFFECT ON THE PERFORMANCE OF CENTRIFUGAL SLURRY PUMPS

by

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Preface

Before you lies the thesis "Solids effect on the performance of centrifugal pumps", which is the last chapter of my master study at the Delft University of Technology for the offshore and dredging engineering master. The research for this thesis is conducted from November 2017 to April 2020.

This research is undertaken at the request of the SSB, a joint research institute funded by the Delft University of Technology, Royal Boskalis Westminster and Royal Van Oord. This research took longer than expected due to the practical nature of the assignment and because of personal circumstances. Experiments tend to take longer than planned and unexpected wear caused delays.

I would like to thank my supervisors; Michel de Nijs, Chris van den Berg, Arno Talmon and Cees van Rhee, for their guidance and patience during this process. I learned valuable lessons about conducting experiments, reporting and analysis of experimental data. I also want to thank the staff from the lab, Ed Stok and Freek Brakel, for their assistance and help during the experiments.

I hope you enjoy your reading.

*Wesley Pont
Delft, April 2020*

December 2025,

I finished my thesis during the corona pandemic in 2020 thanks to Van Oord, while I was already full time working abroad onboard of dredging vessels. Due to this and the pandemic I lost contact with my professor Arno Talmon to finalise this officially at the TU Delft.

I want to express my gratitude to Pim van der Male for reaching out and after a few talks with Rudy Helmons and Geert Keetels I was able to officially finish my thesis and my study.

Summary

In the slurry transport industry, such as the dredging industry, the clear water pump curves are not applicable for transport calculations. This is due to the decrease in pump performance, expressed in meter mixture head, during the hydraulic transport of the mixture. This decrease occurs due to the presence of solids in the mixture. In the past 60 years, lots of researchers have investigated the effect of solids in centrifugal pumps. Each researcher formed a formulation which described a specific data set of particles with certain particle size and density with a specific pump size.

The purpose of this thesis is to determine which formulation is the best formulation for the dredging industry. This industry is characterised by pumping quartz particle size ranging from $d_{50} = 0.1 - 2$ mm, with a density around 2650 kg/m^3 , using pump impellers ranging from $D_{impeller} = 0.4 - 2.5$ m. These specific characteristics are evaluated with scaled experiments in this thesis.

An extensive literature study is conducted, where all known formulations are evaluated and checked against each other. After analysing this comparison, the most relevant formulations are selected to be evaluated deeper by conducting experiments at the dredging lab of the Delft University of Technology.

The experiments took place from August 2018 till February 2019 and were performed at the dredging lab. During the experiments three narrow graded quartz materials are tested with d_{50} values of: 0.139 mm, 0.285 mm and 0.859 mm. The test set up uses a centrifugal pump with $D_{impeller} = 0.4$ m. Each material is tested over the range from 0 - 40% concentration by volume for three different flow rates at constant RPM. With the help of a butterfly valve, the flow rate is tested over the range from 60 % to 140 % Q/Q_{BEP} . Q/Q_{BEP} is the ratio of the actual flow rate to the best efficiency flow rate of the pump, for the selected RPM setting. The range 60% to 140% is the usual operating windows for the dredging industry.

This is the first research known in the literature that varied the Q/Q_{BEP} ratio, at constant RPM. The test duration of 1 minute for each configuration provide a solid and very accurate data set. This data set is used to evaluate the "solids effect" for each material, concentration and flow rate. The results provide new insights into this "solids effect" and help the industry better understand this effect.

After the literature study and experiments, several conclusions are drawn. First, it is found that the solids effect is best described by a non-linear relation to the volumetric concentration for fine materials, while the coarser material is better described with a non-linear relation of the concentration by weight. Secondly, the relation with the d_{50} is observed and it appears the effect of the d_{50} is best described with a power-law. Furthermore, the influence of the Q/Q_{BEP} ratio is determined and an addition is provided to improve the accuracy of the Stepanoff formulation from 1965 for the conducted experiments. After this, a new formulation is formed based on the observations made in Chapter 6. Finally, it is found that the Stepanoff 1965 formulation is the best existing theory for this data set with and without the new Q/Q_{BEP} effect formulation, while the newly formed formulation, together with the modified Stepanoff, is the most accurate.

Based on the literature study, the Wilson and Sellgren 2017 formulation was presumed to be the most accurate. This because the formulation is the most recent and fitted against large data sets. However, this formulation was only accurate for the Q_{BEP} flow rate while pumping fine materials. An explanation for this could be the impeller size. This formulation is developed with larger pumps than available in the current test set up.

Based on everything above, the experiments were successful and new insights are provided with new data available for further research.

Nomenclature

Acronyms

Symbol	Description	Unit
BEP	Best efficiency point	
PSD	Particle Size Distribution	
SSB	Stichting Speurwerk Baggertechniek	

Greek Symbols

Symbol	Description	Unit
α	Coefficient used to correct formulas	[-]
β	Coefficient used to correct formulas	[-]
Δ	Submersed Specific gravity	[-]
η	Efficiency of the centrifugal pump	[-]
γ	Additional effect factor	[-]
λ_f	Darcy-Weisbach friction coefficient	[-]
μ	Dynamic viscosity	kg/ms
ν	Kinematic viscosity	m ² /s
ρ	Density	kg/m ³
ζ	additional losses due to flow obstructions	[-]

Roman Symbols

Symbol	Description	Unit
A	Area	m ²
C_D	Drag coefficient	[-]
C_v	Volumetric concentration of solids in the mixture - $\frac{\text{Volume Solids}}{\text{Total Volume}}$	[-]
C_w	Mass concentration of solids in the mixture - $\frac{\text{Mass Solids}}{\text{Total Mass}}$	[-]
D	Diameter	m
d_{50}	Median particle size	m
d_w	Weighted particle size	m
E_r	Efficiency ratio	[-]
F	Force	N
g	Gravitational acceleration	m/s ²
H	Pressure Head	m
H_r	Head ratio	[-]
I	Gradient Frictional head loss	mH ₂ O/m
K	Coefficient for McElvain	[-]

k	Coefficient for Engine and Gur	[–]
L	Length of pipe section	m
m	Empirical coefficient hindered settling	[–]
N	Rotation speed	<i>RPM</i>
N_{sd}	Specific speed	[–]
P	Power	kW
p	Pressure	kpa
Q	Flow rate	m ³ /h
R^2	Coefficient of determination	[–]
R_H	Head reduction factor	[–]
Re	Reynolds number	[–]
S	Specific gravity	[–]
S_1	Coefficient Wilson and Sellgren	[–]
S_2	Coefficient Wilson and Sellgren	[–]
S_{kt}	The Furboter empirical coefficient dependent on solids properties	[–]
T	Time	s
u	Flow velocity	m/s
V	Velocity	m/s
w_t	Settling velocity	m/s
X_h	Fraction of fines in Wilson and Sellgren 2017 formulation	[–]

Subscripts

Symbol	Description	Unit
$discharge$	Discharge side of the pipe / pump	
f	Fluid	
$impeller$	Pump impeller	
$inlet$	inlet or suction side of pipe / pump	
m	Mixture	
man	Manometric	
new	Variables for the new formulation	
p	Particle	
$pump$	Pump	
s	Solids	
w	Water	
w_{salt}	Salt water	
$QBEP$	coefficients used for the Q/Q_{BEP} formula	

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1

Introduction of the research subject

Centrifugal slurry pumps are used extensively for slurry transport because of their capabilities to economically convey large size abrasive solids in large quantities. [Khalil *et al.*, 2013]

Slurry, or mixture, transport is an important subject of the dredging and mining industry. Within these industries the development of centrifugal pump and transport theories is of great importance. Dredging vessels are typically equipped with modified centrifugal pumps to transport large volumes of solids from the dredging site into hoppers or through pipelines to another destination. The effect of solids on the performance of the centrifugal pumps is investigated in this study and research conducted in the past is reviewed. Furthermore, knowledge and data gaps will be filled with data from experiments conducted at the Delft University of Technology. This is in collaboration with the SSB (Stichting Speurwerk Baggertechniek).

1.1. PROBLEM DEFINITION

Specifications of centrifugal pumps are determined while pumping clear water. Pump performances are measured and captured in so-called Q-H or Q-p curves. These curves are used to visualize respectively the manometric head or pressure at a given flow rate and RPM setting.

In the slurry transport industry, such as the mining and dredging industry, the clear water curves are not applicable in the transport calculations. This is because centrifugal dredge pump performance is affected by the solid particles in the slurry (Solids effect). The solids effect is a broad area of research where many researchers have conducted different researches, and the most important ones are reviewed in Chapter 3 while others are mentioned in Appendix B. There are lots of different ways of formulating a general equation to predict the solids effect. This is reviewed, discussed in a literature study and conclusions are made for the applicability of the equations in the dredging industry.

1.2. OBJECTIVES AND RESEARCH QUESTIONS

This study focusses on the solids effect with respect to the different properties of a slurry that affect the performance of the centrifugal pump. Some important parameters are: solid particle size, the density of the solid particles, the concentration of solids in the slurry and the impeller diameter of the pump.

The main objective of this research is:

"Verify & Improve an existing, or develop a new, formulation to estimate the solids effect on the centrifugal pump for the transported slurries. Furthermore, find knowledge or data gaps and perform experiments to fill these gaps."

This main objective is addressed by reviewing multiple theories available in the literature and gathering all the information concerning the experiments and the corresponding data. Additionally, small-scale experiments are performed to obtain a data set to evaluate known formulations and find answers for uncertainties concerning the solids effect.

1.3. OUTLINE OF THE REPORT

In Chapter 1 the graduation period is briefly explained. The problem statement and the main objective are stated, and the purpose of this thesis is clear. In Chapter 2 an introduction is given on the definition of the solids effect. A general definition is given which is the standard for this report. Also, the physical and mathematical formulations concerning the solids effect are explained.

In Chapter 3 the three most promising theories are reviewed. The models are analysed, and the experimental parameters are mentioned together with the important variables in the formulations. If available, the original experimental plots are inserted to illustrate the results of the researcher. If the researcher found interesting conclusions, this is also mentioned in the model section. At the end of Chapter 3 there is a discussion section (Section 3.7) where the different formulations are compared. More research is included in appendix A.

In Chapter 4 the small scale experiments and the test plan are explained. Here all the information regarding the test set-up and the calculations are covered. This ranges from the original test set up, Labview software scripts, first starting the slurry loop and the actual test plan for each material. In Chapter 5 the experiments are reported and described in terms of results and problems encountered. This chapter is followed by Chapter 6, here the data is analysed, preliminary conclusions are drawn, new formulations are formed and tested, and the best formulations are compared. Chapter 7 is the last chapter of this thesis report. Here the conclusions are provided together with some recommendations for the experimental test set-up and the general process. Also, ideas for follow up studies are mentioned.

After the conclusions, several appendixes are inserted. This ranges from background information regarding some parameters or variables, Appendix A, the inventory of signals and equipment used for the experiments in C, to errors in the slurry loop, Appendix D. The Particle size distributions and an overview of all the working points are included in Appendix E and G respectively. Appendix H contains all data points from the experiments used in the different figures of this thesis. And the last appendix, Appendix I, contains some pictures of the slurry loop, before and during the experiments.

2

The Solids effect

The basics of the solids effect are explained in this chapter. This information is based on the physical understanding of the process. This chapter starts with a physical explanation of fluid in a pump, followed by the physics of solids in the fluid. After this, an introduction to the term solids effect is provided with the mathematics of all the processes.

2.1. PHYSICAL EXPLANATION OF FLUID IN A PUMP

The principle of a centrifugal pump is explained in the basic elements in this section. At the heart of the pump lies the impeller. This impeller has curved vanes, that extend from the inner diameter out towards the outer diameter, between two shroud plates. When the centrifugal pump is started, the impeller will rotate and move the fluid through the pump with the curved vanes.

When the centrifugal pump is operating the pump converts the rotational (mechanical) power from the pump drive to energy in the moving fluid. A portion of the rotational energy is converted to kinetic energy of the fluid. The fluid enters the centrifugal pump, and the impeller, from the suction pipe in axial direction. From here the fluid is pushed outwards in both tangential and radial direction until it reaches the end of the impeller. This is due to the centrifugal forces acting on the fluid particles, hence the name centrifugal pump. While being transported through the impeller the fluid velocity and pressure are increasing. By leaving the pump at the discharge side, located in radial direction, the flow is decelerated by the diffuser and the pressure increases even further. The combination of velocity and pressure at the discharge side of the pump is characterised in the Q-H, or Q-p, curves and are different for each centrifugal pump design or impeller blade.

2.2. PHYSICAL EXPLANATION OF SOLIDS IN A FLUID

A. J. Stepanoff is one of the first researchers who studied the topic of slurry transport. He proposed to investigate the behaviour of centrifugal pumps and the effect of solid materials on the efficiency of the pump.

This section from [Stepanoff, 1965] is intended to provide a more theoretical insight to the physics behind the solids effect. Multiple researchers have observed the head reduction in measurements but only fit empirical formulas to the data without explaining the fundamental physics behind the head reduction.

"An important theoretical consideration is to realise the fact that solids suspended in a liquid cannot absorb, store, or transmit pressure energy. This is the property of fluids only. The pressure that a fluid exerts on the walls of a container is caused by the bombardment of molecules freely moving in a confined space. This is not the case for solids. The molecules of a solid are restricted in their movement by intermolecular cohesion and therefore unable to contribute in maintaining or transmitting pressure energy. It is also not possible due to this to increase their own kinetic energy (disregarding the energy of elastic compression) when surrounded with liquid carrying the pressure energy.

In a steady-flow process, solids cannot transmit their kinetic energy to the fluid since the fluid particles in every case move with a higher velocity. In a horizontal pipe carrying a solid-liquid mixture, solids do not acquire any net potential energy but only cause hydraulic losses due to obstruction of the flow of water. This energy loss is increased with increasing volumetric concentration, density of the solid and particle size.

An example to illustrate the information given above is a solid particle near the bottom of the pipe. Due to turbulence the particle is picked up and released near the top of the pipe. For this pick-up energy is used. After a while the particle is due to settling (gravitational forces) again near the bottom of the pipe. The potential energy of the solid particle is the same as before the pick-up, but the turbulence has lost some energy. Hence, the solids in the mixture do not acquire any net potential energy but only cause hydraulic losses."

2.3. INTRODUCTION TO THE SOLIDS EFFECT

When a centrifugal pump is pumping clear water, the velocity and pressure are corresponding to the Q-H or Q-p curves of the pump. When a centrifugal pump transports a mixture of solids and water, the pressure and velocity change according to the situation. The velocity will decrease due to the extra resistance in the pipe, while the pressure will increase due to the presence of the solid particles. To evaluate this understandably, the pressure is converted to the hydraulic head, expressed in meters of mixture. Doing so, it enables the researchers to compare the performances of the pump pumping water or mixture in a similar fashion.

Stepanoff developed a correction factor to connect the decrease in performance of the centrifugal pump to the concentration and the particle size of the transported solids. Because he was one of the first researchers to investigate this topic, the solids effect is sometimes called the Stepanoff factor. In this study we use the term head ratio factor when we speak about the factor to determine the solids effect on the pump performances. This will be explained in Section 2.5

2.4. DEFINITION OF THE SOLIDS EFFECT

All the researchers reviewed in the literature study are unanimous about the fact that there is a degrading effect or solids effect when pumping material other than clear water through the centrifugal pump. This so-called solids effect is stated as the "**head ratio factor**", H_r . This ratio factor is multiplied by the clear water head, expressed in m liquid water column, and the result is an estimated head of a centrifugal pump pumping a mixture of solids and water.

2.5. MATHEMATICAL EXPLANATION OF PUMPING MIXTURES

In this section the mathematical reasoning behind the theoretical models is explained and the preferred notations are introduced. Also, certain basic hydraulic equations are mentioned which are used in this report.

2.5.1. PRESSURE AND HEAD DURING CLEAR WATER TRANSPORT

The manometric pressure required for pumping a liquid with a density greater than water, for example a mixture with very fine solids, at the same flow rate is calculated with Equation 2.1. Here the ρ_2 represents the density of the mixture greater than water. This pressure is generated by the impeller but requires an increase in mechanical energy from the pump drive. This increase in required power is determined with Equation 2.2. When this power is not available the flow rate and pump pressure will change to a sustainable working point with the pressure and power available.

$$p_{\rho_2}(Q) = p_w(Q) \cdot \left(\frac{\rho_2}{\rho_w} \right) \quad (2.1)$$

$$P_{\rho_2}(Q) = P_w(Q) \cdot \left(\frac{\rho_2}{\rho_w} \right) \quad (2.2)$$

2.5.2. PRESSURE AND HEAD DURING MIXTURE TRANSPORT

When pumping coarser solid particles the same principle is applied. The energy that is required to keep the coarser solids in suspension and to transport the mixture through the pump is acquired from the impeller. The impeller applies the energy to the mixture, just as to clear water, as if the fluid is of uniform density. This influences the pump characteristics. For the constant RPM pump curves, given the flow rate, Q , the manometric pressure of the mixture is the same as that of an equivalent density, reduced only by the additional hydraulic losses caused by the presence of solids in the mixture, H_r . This is stated in Equation 2.3 rewritten to the pump pressure of water.

The studies from the literature study contained no information regarding the required power. Sellgren and Addie found an increase in required power, see Figure B.8 but didn't provide a formulation for this. From self performed experiments it is found that Equation 2.2 is still valid as shown in Figures 5.11, 5.19 and 5.27.

$$p_m(Q) = p_w(Q) \cdot \left(\frac{\rho_m}{\rho_w} \right) \cdot H_r(Q) \quad (2.3)$$

This H_r is better to understand when the pump pressures are converted to the hydraulic head parameters. For the constant RPM pump curves, given the identical flow rate, Q , the hydraulic head in meters of mixture column should be the same as that of clear water, reduced only by the additional hydraulic losses caused by the presence of solids in the pump. This is shown in Equations 2.4 and 2.5.

$$H_w(Q) = \frac{p_w(Q)}{\rho_w \cdot g} \quad (2.4)$$

$$H_m(Q) = \frac{p_w(Q) \cdot \left(\frac{\rho_m}{\rho_w} \right) \cdot H_r(Q)}{\rho_m \cdot g} = H_w(Q) \cdot H_r(Q) \quad (2.5)$$

The head ratio, H_r , which is used in equation 2.5 is formulated with the head reduction term, R_H :

$$H_r(Q) = 1 - R_H(Q) \quad (2.6)$$

This head reduction term, R_H , is by all researchers defined in a different way, which is reviewed in Chapter 3, but the principles are the same. The performances of a centrifugal pump are reduced with the presence of solid particles.

For low concentrations and/or small particles this results in a small head reduction term, so the H_r will be relatively high, which indicates that the pump behaves like pumping clear water. If the concentrations are higher and/or the particles are larger, the head reduction term will be more significant and the H_r value drops. And therefore the performance of the pump will be significantly lower than in the case of pumping clear water. Additionally to this, the size of the impeller also influences the solids reduction term. A larger impeller is less affected by the solids effect than a small impeller when pumping the same size material. So the ratio between the solid size and impeller has an important roll in this subject.

The researchers have performed experiments to check and/or fit their formulations. This is done with Equation 2.7. In this equation the manometric head of the mixture is compared with the manometric head of clear water. Important to note is that for this equation the flow rates need to be matched and the manometric head is in meter of mixture column. After all experiments are done the equation is used to determine the head ratio factor, H_r , and with the values obtained from the experiments the formulations are calibrated.

$$H_r(Q) = \frac{H_m(Q)}{H_w(Q)} \quad (2.7)$$

2.5.3. EFFICIENCY OF CENTRIFUGAL PUMPS

The efficiency of the centrifugal pump is obtained from hydraulic power divided by mechanical power, see Equation 2.8. The hydraulic power is pressure times flow rate, where the mechanical power is the output of the pump axle. This power output at the pump axle is determined with the R0032 parameter of the control unit of the frequency drive as shown in Figure C.1.

$$\eta_{Pump} = \frac{P_{Hydraulic}}{P_{Mechanical}} = \frac{Q \cdot p}{P_{Mechanical}} \quad (2.8)$$

The hydraulic power is affected by the solids effect, H_r . As stated before, the pressure will increase with increasing density, but there are also pressure losses due to the presence of the solids. The mechanical power is, as stated before, for both mixture and clear water transport formulated by Equation 2.2. Here the required power for the mixture transport is obtained by multiplying the power required for the clear water transport with the density ratio during mixture transport.

Due to this, the efficiency ratio, E_r , is equal to the head ratio, H_r . This is observed by most of the researchers. For very high concentrations the efficiency appears to behave differently than the head reduction factor [Sellgren, 1979], this effect is observed but not quantified in a formulation.

$$E_r(Q) = \frac{\eta_m(Q)}{\eta_w(Q)} \quad (2.9)$$

$$E_r(Q) = H_r(Q) \quad (2.10)$$

With the information provided above, it is concluded that the head ratio factor for the solids in a mixture is a correction factor on the hydraulic head of the centrifugal pump. This is also applicable for the manometric pressure since it is a dimensionless reduction factor. Almost all researchers have concluded that the efficiency reduction is the same as the head ratio. Therefore in Chapter 3, and Appendix B, the efficiency reduction is not mentioned, except if a relation other than the relation for the head reduction is given.

2.6. KNOWN RESEARCH FROM THE PAST

Many researchers have conducted experiments and produced new theories which fitted nicely on the experimental data. Most of these experiments are with relative small impeller diameters in the range of 300 to 800 mm. These datasets are large, see Table 3.2 with a broad range of different values for parameters such as; the particle sizes, particle density, solids concentration and pump diameters. Due to this broad range of different experimental setups, it is hard to indicate if one formulation is accurate enough to be used in a general manner. And additionally, if this formulation applies to full-size dredge pumps with impellers with a significantly larger diameter, even more than 2 m diameter.

Some of the researchers developed a formulation including an impeller diameter, see Equations 3.3, 3.4 and B.8. These formulations are particularly interesting to evaluate and see if these are accurate for present-day use with larger pumps. As mentioned in the previous section the impeller size has an important effect on the solids reduction term, because it is observed that the solid effect is smaller in larger dredge pumps than in the smaller pumps. Generally, the latest formulations are the most interesting, because these are constructed with the knowledge of many prior performed experiments and their data sets.

3

Previous research on the solids effect

The most promising formulations and interesting observations are discussed in this chapter, other formulations are added in Appendix B. The literature study focusses on the research ranging from one of the first studies by Stepanoff originating from 1965 till more recent studies from 2017.

The first formulation is from Stepanoff, dating back to 1965. This formulation is still used in small scale experiments and appears to be accurate enough in modern days. Second is the formulation of Engin and Gur from 2003. This formulation is fitted on research data from 1965 until 2001. This formula is based on research which is also summarised in Appendix B. The last formulation in this chapter is of Wilson and Sellgren. This formulation is based on experiments starting in 1979 until 2017. These three formulations are expected to be interesting to evaluate in small scale experiments at the Delft University of Technology. All three formulations are composited in different ways. The formulations are proven in the papers to be fairly accurate, yet differ from each other when compared for identical cases. Using the experiments, conducted for this thesis, it will be determined which formulation is the most accurate and best applicable for this test set up.

After this data from SSB could be compared with the formula's and a decision could be made if one of these is accurate enough to determine the solids effect for commercial dredging activities. If interested, it is recommended to observe the formulations in Appendix B for more information on the development of the different formulas for the solids effect. After the summary, all formulations are gathered in Table 3.3 to provide a clear overview of the different theories throughout the years. After this the formulations are compared for 2 specific cases in Section 3.4. Also, the differences in mathematical behaviour are shown and the accuracy of the most promising theories are checked with experimental data from various sources from the literature.

At last a discussion is formed in Section 3.7 to state some of the important facts found in the papers used for this literature study. The experimental plan is formed and motivated based on the discussion and the identified data and knowledge gaps.

3.1. PROMISING STUDIES ON SOLIDS EFFECT

The literature study is conducted on papers from several different researchers and institutes. Each paper is analysed and important information is summarised in the following sections. All sections are tried to be formatted in the same manner. First a short introduction or background information of the study. Second the experimental parameters of the study in a clear table. Then the variables where the formulation of the researcher is based on with the corresponding units. At last the formulation with graphs presented in the paper to back up the formulation. These graphs could also provide insight into the measured data from experiments. If required there are some equations included where the final formulation is based on and if important conclusions are drawn this will also be mentioned.

3.1.1. STEPANOFF, 1965

Stepanoff has developed a formulation based on research data obtained by different researchers. This data is gathered to determine the solids effect in small centrifugal pumps, this data is given in Table 3.1. The only known pump diameter is the pump Herbich et al used. This is an 10,5 inch diameter impeller dredge pump. Stepanoff used a 10 inch pump for his own research on pumps and slurry transport. It is assumed that a 10.5 inch pump is a good estimated for the impeller size used for the gathered data. Nowadays is Stepanoff still used for smaller pump sizes and several dredging companies are using this formulation with a self-determined correction factor for larger pump sizes.

Table 3.1: Experimental data used by Stepanoff [Stepanoff, 1965]

Solids	Grain size [mm]	Source	Remarks
Clay- Silt	<0.15	Herbich et al	$H_r = E_r$
Fly ash	<0.074	Hasegawa et al	$H_r = E_r$
Sand	0.5 & 1.3 & 2.5	Terada	$H_r = E_r$
Sand	0.8	Fairbanks	$H_r = E_r$
Sand / gravel	0.5 - 1.0 & 6 - 10	Hasegawa et al	$H_r = E_r$
Sand	<0.5	O' Brien et al	$H_r = E_r$
Coal	0 - 0.5 & 5 - 15	Sasaki et al	$H_r > E_r$

Variables

The following variables are used for the Stepanoff formulation:

- Particle size, d_{50} , in [mm].
- Volumetric concentration, C_v .

Formulation

The head ratio factor, H_r , for sand and gravel mixtures is according to Stepanoff related to the particle size, d_{50} , and is linearly dependent with the volumetric concentration, C_v . Stepanoff observed a reduction of manometric head and pump efficiency with an increase of solid size and concentration. This reduction is relatively small for fine sands but appears to be significant if mixtures with coarser sand or gravel are transported. Equation 3.1 is based on these observations. In Figure 3.1 the Stepanoff formulation is shown for multiple concentrations and solid sizes. In this graph f_c is the head ratio H_r and C_T is the volumetric concentration C_v .

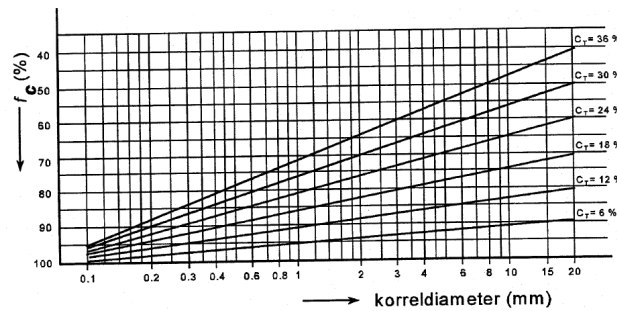


Figure 3.1: Parameter f_c giving reduction of the pump performance due to presence of sand / gravel particles in [Matousek, 2004]

The head ratio formulation of Stepanoff is:

$$H_r = 1 - C_v (0.8 + 0.6 \log d_{50}) \quad (3.1)$$

Conclusions

The Stepanoff formulation is an empirically fitted equation to experimental data and is based on the variables C_v and d_{50} . As seen in Table 3.1 there are several different materials used, but in the formulation of Stepanoff the density of the solids is not used as a variable. Because predominantly quartz materials, like sand and gravel, are tested this formulation is only valid for quartz materials.

3.1.2. ENGIN AND GUR, 2003

Engin and Gur developed a formulation based on a large number of available data from literature. This data is gathered from many different papers and researchers. This dataset is listed in Table 3.2. They also analysed several formulations of previous researchers and concluded that these formulations are only applicable to a restricted number of pumps and slurry types. This is due to the specific parameters of the experimental set up which would result in a case-specific formulation of the head ratio term. In [Engin & Gur, 2003] a formulation is provided which is, according to Engin and Gur, applicable to a much greater range of pumps and materials transported in a carrier liquid. This is due to the very large data set with lots of different solid densities, sizes and concentrations and also varying pumps sizes.

Variables

For the Engin and Gur formulation the following reformulated variables are used:

- Concentration by volume, C_v .
- Weighted particle size, d_w in [m].
- Impeller diameter, $D_{impeller}$ in [m].
- Density of the particle, ρ_s , and the corresponding specific gravity, S_s .
- Density of the mixture, ρ_m .

Engin and Gur's formulation from 2003 is a slightly modified version of [Engin & Gur, 2001]. Here, most of the variables were already determined. The influence of the solid-impeller ratio is implemented and fitted against the large dataset from Table 3.2.

Equations

In [Engin & Gur, 2001] the formulation was a function of the weighted diameter, d_w . In 2003 Engin and Gur decided to include the impeller diameter after the observations of [Sellgren & Addie, 1993], which stated that larger pumps are less influenced by the solids effect, and [Sellgren & Addie, 1989] where it was noticed that the reduction in head decreased exponentially with $D_{impeller}$ to the power 0.9.

Engin and Gur proposed the following form for the formulation of the solids effect term, R_H , with knowledge from [Engin & Gur, 2001]:

$$R_H = \left(C_v \frac{\rho_s}{\rho_m} \right) (S_s - 1)^k f \left(\frac{d_w}{D_{impeller}} \right) \quad (3.2)$$

After analysing all data available from Table 3.2 the resulting parameters are given in Equation 3.3. This solids effect formulation is formed with data covering a wide range of specific gravity (1.48 - 6.24), particle size (30 - 26,700 μm) and concentration by weight up to 65.7 %.

$$H_r = 1 - 2.705 \left(C_v \frac{\rho_s}{\rho_m} \right) (S_s - 1)^{0.64} \left(\frac{d_w}{D_{impeller}} \right)^{0.313} \quad (3.3)$$

Conclusion

Engin and Gur determined the accuracy of this formulation against many formulations from the past including; [Vocadlo *et al.*, 1974], [Cave, 1976], [Burgess & Reizes, 1976], [Sellgren, 1979], [Gahlot *et al.*, 1992], [Kazim *et al.*, 1997] and [Engin & Gur, 2001]. After analysing all formulations, it is observed that each formulation shows a reasonable agreement with their data. But the formulation provided by Engin and Gur, Equation 3.3, is the best fitted equation overall. The deviations are minimal compared to the large dataset, no formulation is ever tested against such a large dataset. Engin and Gur have done an extensive literature study until 2003, so this formulation is assumed to be the most accurate approach for further studies. The accuracy of this solids effect formulation is shown in Figure 3.2. Almost all data points are within +/- 15 % of the predicted value.

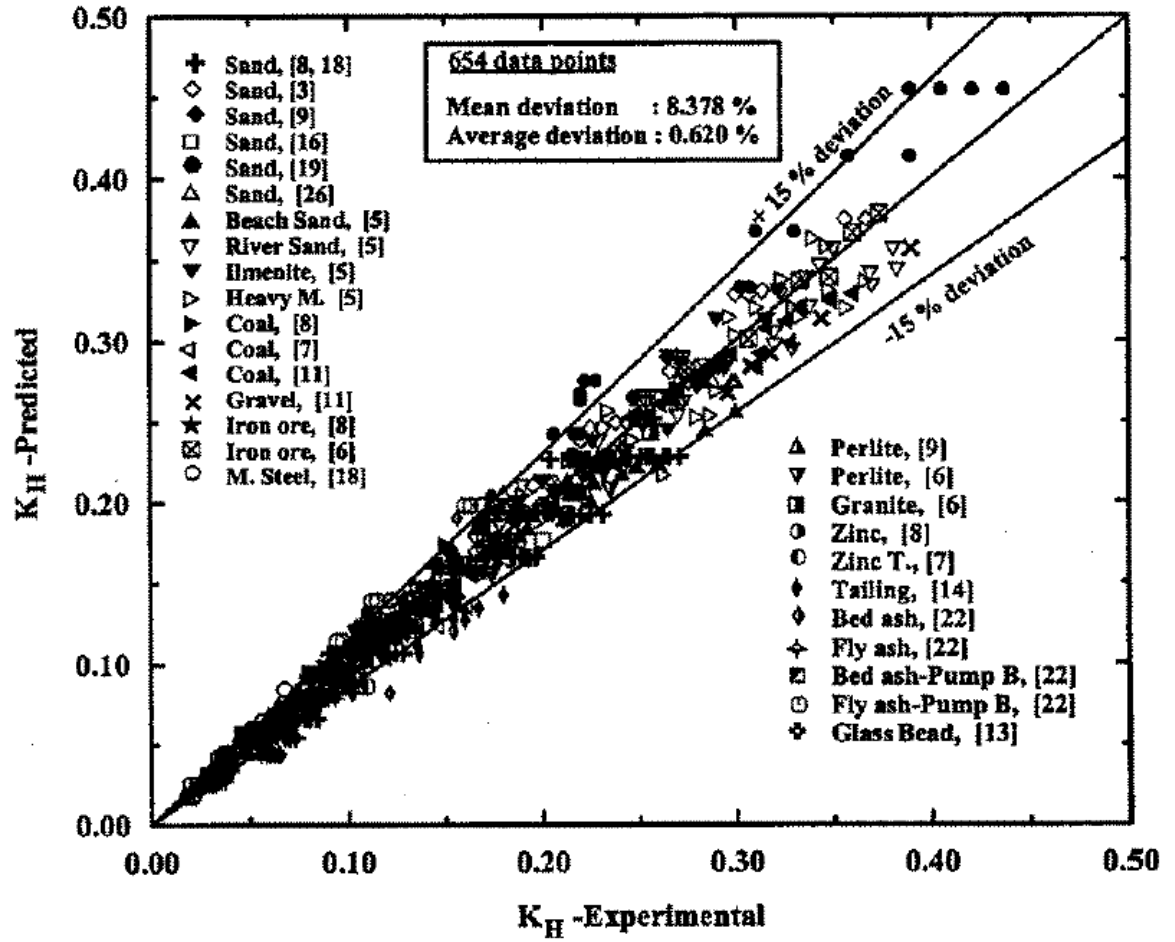


Figure 3.2: Accuracy of the Engin and Gur's formulation with materials from table 3.2 where the values for R_H are shown as K_H .

Table 3.2: Engin and Gur's experimental data collection from various sources [Engin & Gur, 2003]

Source	Solid	S_s	Particle diameter		C_w [%]		Flow rate	Impeller diameter	pump speed
			d_{50} [μm]	d_w [μm]	Min.	Max.	Q/Q_{BEP}	D [mm]	N [RPM]
*Kazim, 1997	Sand-A	2.65	180	180	9.053	32.775	0.25 - 1.00	270 (ML)	1000
[Kazim <i>et al.</i> , 1997]	Sand-B	2.65	230	230	6.511	27.906	AV	270 (ML)	1000
[Kazim <i>et al.</i> , 1997]	Sand-C	2.65	460	460	6.714	24.72	AV	270 (ML)	1000
*Kazim, 1997	Sand-D	2.65	230	230	6.644	56.02	0.25 - 1.00	270 (ML)	1000
*Kazim, 1997	Sand-E	2.65	230	328	10.778	55.205	0.25 - 1.00	270 (ML)	1000
[Kazim <i>et al.</i> , 1997]	Sand-F	2.65	362	400	6.72	44.602	AV	270 (ML)	1000
[Vocadlo <i>et al.</i> , 1974]	Sand-G	2.64	105	-	12.19	53.08	1	280 (RL)	1780
[Vocadlo <i>et al.</i> , 1974]	Sand-H	2.64	330	-	22.68	53.08	1	280 (RL)	1780
[Vocadlo <i>et al.</i> , 1974]	Sand-I	2.64	570	-	22.68	53.08	1	280 (RL)	1780
[Vocadlo <i>et al.</i> , 1974]	Sand-J	2.64	920	-	22.68	53.08	1	280 (RL)	1780
[Vocadlo <i>et al.</i> , 1974]	Sand-K	2.64	1400	-	22.68	53.08	1	280 (RL)	1780
[Vocadlo <i>et al.</i> , 1974]	Sand-L (=G)	2.64	105	-	22.68	53.08	1	280 (RL)	1180
[Vocadlo <i>et al.</i> , 1974]	Sand-M (=I)	2.64	570	-	39.76	46.81	1	280 (RL)	1180
[Vocadlo <i>et al.</i> , 1974]	Sand-N (=J)	2.64	920	-	22.68	46.81	1	280 (RL)	1180
[Vocadlo <i>et al.</i> , 1974]	Sand-O (=K)	2.64	1400	-	22.68	46.81	1	280 (RL)	1180
[Engin & Gur, 2001]	+ Sand-P	2.1	400	400	5.54	28.5	1	210 (ML)	1250
[Engin & Gur, 2001]	+ Sand-Q	2.64	413	440	11.6	21.4	1	210 (ML)	1250
*Walker, 1992	Sand-R	2.65	400	-	20	60	0.50 - 1.10	365 (ML)	1000
[Vlasblom <i>et al.</i> , 1999]	Sand-S	2.65	1840	-	15.556	65.713	0.60 - 1.40	400 (ML)	1200
[Vlasblom <i>et al.</i> , 1999]	Sand-T	2.65	372	-	14.467	65.743	0.60 - 1.40	400 (ML)	1200
*Not mentioned	Sand-U	2.64	270	-	22.68	39.759	0.30 - 0.65	810 (ML)	590
*Not mentioned	Sand-V	2.64	1500	-	22.68	53.083	0.30 - 1.00	810 (ML)	590
[Burgess & Reizes, 1976]	Beach sand	2.67	295	-	8.85	63.86	0.40 - 1.00	371 (ML)	1300
[Burgess & Reizes, 1976]	River sand	2.64	1290	-	13.93	56.45	0.40 - 1.00	371 (ML)	1300
[Burgess & Reizes, 1976]	Ilmenite	4.63	170	-	16.11	61.57	0.40 - 1.00	371 (ML)	1300
[Burgess & Reizes, 1976]	Heavy min.	4.35	290	-	14.77	58.16	0.40 - 1.00	371 (ML)	1300
[Kazim <i>et al.</i> , 1997]	Coal-A	1.49	185	377	9.01	57.8	AV	270 (ML)	1000
[Gahlot <i>et al.</i> , 1992]	Coal-B	1.48	-	900	33.943	47.743	AV	270 (ML)	1450
[Mez, 1984]	Coal-C1	1.625	-	14900	15.84	20.67	1	825 (ML)	-
[Mez, 1984]	Coal-C2	1.562	-	15500	25.31	29.25	1	825 (ML)	-
[Mez, 1984]	Coal-C3	1.716	-	15300	27.23	36.15	1	825 (ML)	-
[Mez, 1984]	Coal-D1	1.52	-	16700	23.58	29.66	1	825 (ML)	-
[Mez, 1984]	Coal-D2	1.756	-	17600	38.46	42.68	1	825 (ML)	-
[Mez, 1984]	Coal-D3	1.759	-	17300	43.17	48.67	1	825 (ML)	-
[Mez, 1984]	Coal-E1	1.827	-	17300	-	18.87	1	825 (ML)	-
[Mez, 1984]	Coal-E2	1.772	-	16600	30.72	33.12	1	825 (ML)	-
[Mez, 1984]	Coal-E3	1.754	-	15900	42.16	45.57	1	825 (ML)	-
[Mez, 1984]	Gravel	2.6	-	26700	21.44	28.59	1	825 (ML)	-
[Kazim <i>et al.</i> , 1997]	Iron ore-A	4.35	663	663	2.511	12.558	AV	270 (ML)	1000
[Sellgren, 1979]	Iron ore-B	4.15	1800	-	27.93	37.27	0.50 - 0.80	430 (RL)	800
*Kazim, 1997	Mild Steel	6.24	230	230	5.332	23.2	AV	270 (ML)	1000
[Engin & Gur, 2001]	+ Perlite-A	2.34	270	211	8.47	20.42	1	210 (ML)	1250
[Engin & Gur, 2001]	+ Perlite-B	2.34	1390	1147	8.45	23.39	1	210 (ML)	1250
[Sellgren, 1979]	Perlite-C	2.34	350	-	33.06	54.93	0.50 - 0.80	430 (RL)	1160
[Sellgren, 1979]	Granite	2.67	3000	-	17.31	30.71	0.50 - 0.80	430 (RL)	800
[Gahlot <i>et al.</i> , 1992]	Zinc tailing	2.85	-	170.4	13.617	56.17	AV	270 (ML)	1450
[Kazim <i>et al.</i> , 1997]	Zinc	5.51	455	482	3.665	9.47	AV	270 (ML)	1000
*Sellgren and Vappling, 1989	Tailing	2.75	30	-	55.9	62.15	0.25 - 0.70	450 (RL)	800
[Gandhi <i>et al.</i> , 2001]	Bed ash	2.44	135	209	12.1	52.1	0.30 - 1.00	264 (ML)	1450
[Gandhi <i>et al.</i> , 2001]	Fly ash	2.08	42	59	13.27	60.52	0.30 - 1.00	264 (ML)	1450
[Gandhi <i>et al.</i> , 2001]	Bed ash	2.44	135	209	10.07	31.8	0.25 - 0.70	400 (ML)	1250
[Gandhi <i>et al.</i> , 2001]	Fly ash	2.08	42	59	14.1	48	0.25 - 0.70	400 (ML)	1250
*Shet, K.K. Morison, 1987	Glass bead	2.42	90	-	10	50	1	267 (ML)	1200

(ML): Metal Lined, (RL): Rubber Lined, AV : averaged value over full range of flowrate

+ = 5% tip clearance ratio (Unshrouded impeller), * = paper not in the bibliography

3.1.3. WILSON & SELLGREN, 2017

Wilson and Sellgren conducted lots of research on the solids effect in centrifugal pumps. Many of these researches are conducted in combination with GIW Industries located in Georgia, USA. In the paper of [Visintainer *et al.*, 2017] the Wilson and Sellgren 2017 formulation is given. Before this paper, only the graph from this formulation shown in Figure 3.3 was available in [Wilson *et al.*, 2006]. This formulation is called the mono-sized pump solids effect model.

In this section, the mono-sized formulation of Wilson and Sellgren is discussed. Also, the study on the 4 component model from Wilson and Sellgren is mentioned, which is studied by Visintainer and Sellgren.

Variables

For the mono-sized formulation the following variables are used:

- Concentration by volume, C_v .
- Median particle size, d_{50} in [mm].
- Impeller diameter, $D_{impeller}$ in [m].
- Specific gravity of the solid, S_s .
- Fraction of solids smaller than 0.075 mm, X_h .

The mono-sized formulation of Wilson and Sellgren is developed after lots of experiments at GIW. As a pump supplier, GIW is capable of providing lots of different sized pumps which are used to determine the formulation. This formulation is empirically fitted with the d_{50} , $D_{impeller}$ and the specific gravity, concentration and the fraction of fines in the mixture.

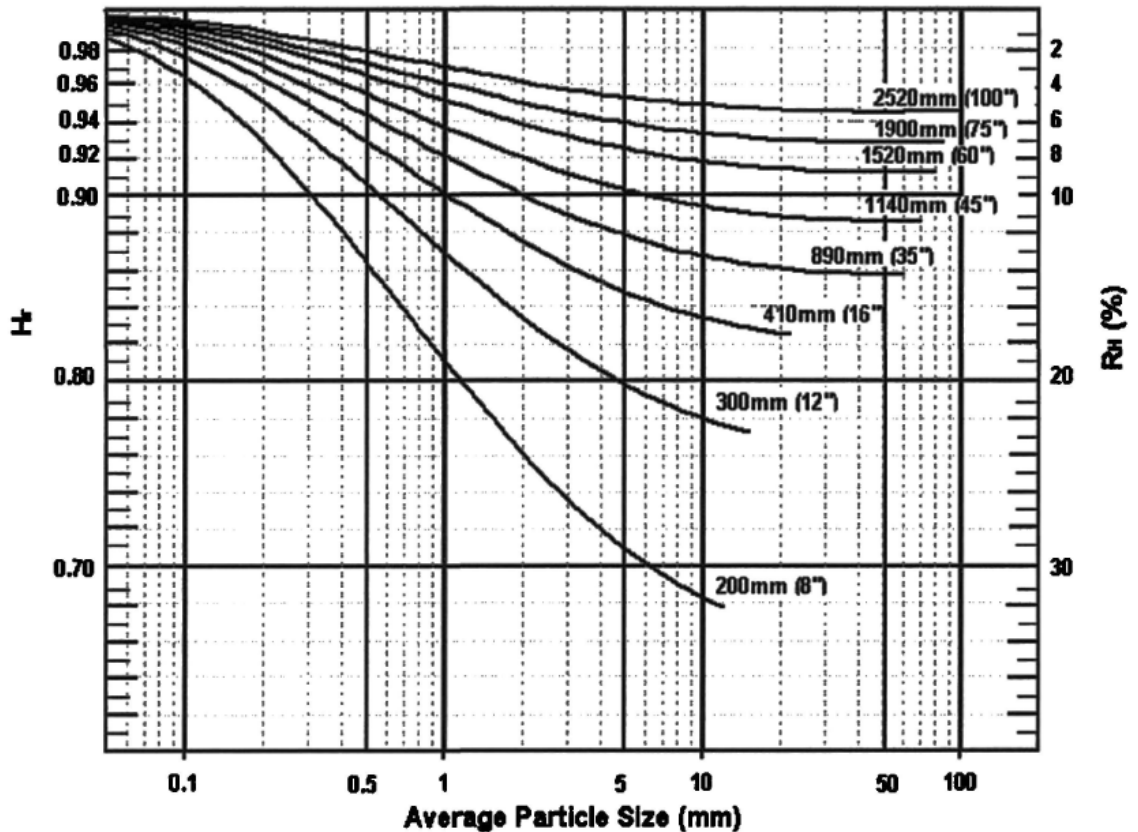


Figure 3.3: Solids effect graph for various pump sizes based on test at the GIW Hydraulic Laboratory. $C_v = 15\%$ with $S_s = 2.65$

Equations

The mono-sized head ratio of Wilson and Sellgren 2017 is:

$$H_r = 1 - \left[S_1 \left(\frac{1.11}{D_{impeller}} \right)^{0.9} (d_{50})^{S_2} \left(\frac{S_S - 1}{1.65} \right)^{0.65} \left(\frac{C_v}{0.15} \right) (1 - X_h)^2 \right] \quad (3.4)$$

with S_1 and S_2 as:

$$S_1 = 0.0404 \quad \text{If } D_{impeller} < 0.41m \quad (3.5)$$

$$S_1 = \left[\frac{4.04 + (6.5 - 4.04) \left(\frac{D_{impeller} - 0.41}{0.89 - 0.41} \right)}{100} \right] \quad \text{If } 0.41m < D_{impeller} < 0.89m \quad (3.6)$$

$$S_1 = 0.065 \quad \text{If } D_{impeller} > 0.89m \quad (3.7)$$

$$S_2 = 0.4d_{50}^{-0.25} \quad (3.8)$$

And X_h as the fraction of fines.

Conclusion

With the formulation of Wilson and Sellgren 2017, it is possible to determine the solids effect accurately using the parameters d_{50} , C_v , S_S and X_h . This formulation is applicable for a large range of centrifugal pumps ranging from small pumps ($D_{impeller} < 0.5$ m) to large pumps $D_{impeller} \approx 2.5$ m.

4 component model

The 4 component model follows the same strategy. But instead of 1 characteristic particle size d_{50} , the mixture is divided into 4 fractions.

- The carrier fluid fraction, X_f , included all particles $< 40 \mu\text{m}$.
- The Pseudo-homogeneous fraction, X_p , includes all particles $> 40 \mu\text{m}$, up to a limit of $0.2 v_r$ (mm), where v_r is the relative kinematic viscosity of the carrier fluid to that of water at 20°C .
- The Heterogeneous fraction, X_h , includes all particles larger than the upper limit of X_p and smaller than the lower limit of X_s .
- The Stratified fraction, X_s includes all particles larger than 0.015 times the pump discharge diameter.

This is also illustrated in Figure 3.4. Note that the fractions are defined relative to the total volume of particles, so that:

$$X_f + X_p + X_h + X_s = 1 \quad (3.9)$$

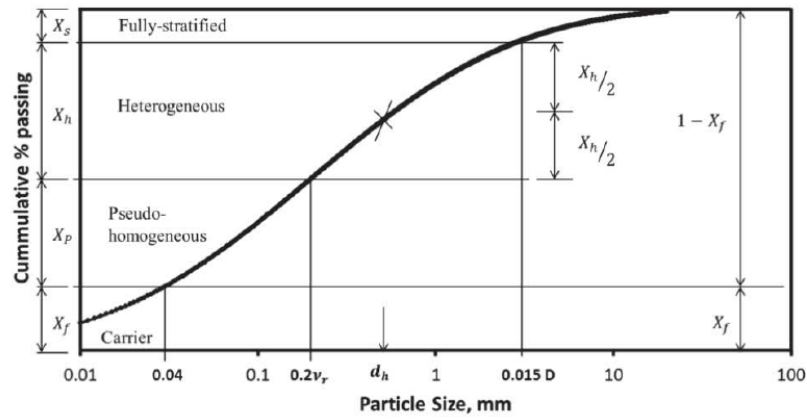


Figure 3.4: Representation of the four component fractions and their particle sizes

After determining all fractions, and additional steps which are not included in this section, the proposed 4 component model is described as:

$$R_H = R_{H,p} + R_{H,h} + R_{H,s} \quad (3.10)$$

Conclusions

The calculated head ratio for narrow graded material is similar when comparing the mono-sized model against the 4 component model. Although the improvement is not large using the 4 component model, it demonstrates the viability of the approach. Better results are obtained when broadly graded and bi-modal slurries are pumped. In those cases, the 4 component model is more accurate than the mono-sized variant.

An additional conclusion is that the pump size term in the equation needs to be adjusted when using the 4 component model. This is the focus of a future study by Visintainer and GIW.

3.2. VLASBLOM ET AL, 1999

Due to the increasing interest of many engineering fields into the performance of slurry pumps, Professor Vlasblom led a research on the effect of high solids concentration on characteristics of a slurry pump. The experiments are conducted by Dr. Fusheng Ni and this research paper is published in Hydrotransport 14, [Vlasblom *et al.*, 1999]. An additional report with measurement data is published in [Ni, 1999].

In this paper the effect of high delivered volumetric concentration on the characteristics of a slurry pump is presented. The experiments were focused on the observation of pump and pipeline characteristics, but the solids effect is also observed as a side product and some data regarding the solids effect is presented. For this research, three narrow graded quartz sand materials listed below are tested in the laboratory set-up. This slurry loop set-up contains a 400 mm pump, powered by a 164 kW diesel indirect drive, with an RPM range from 500 to 1500 RPM. The slurry loop pipe diameter is 150 mm.

The tested materials are;

- Fine sand (0.1-0.15mm), $d_{50} = 0.123$ mm
- Medium sand (0.2-0.5 mm), $d_{50} = 0.372$ mm
- Coarse sand (1.4-2.0 mm), $d_{50} = 1.840$ mm

Each material is for a broad range of concentrations tested at frequencies of 13.33 Hz (800 rpm), 16.67 Hz (1000 rpm) and 20 Hz (1200 rpm).

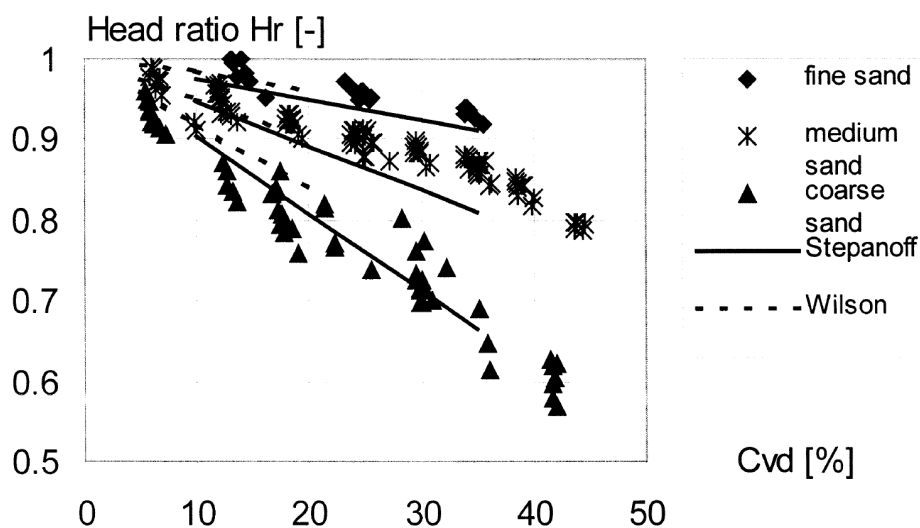


Figure 3.5: H_r overview with different concentrations and materials from paper

The experiment results are presented in Figure 3.5 for an undefined flow rate. Here the solids effect is shown for all three materials with a broad range of concentrations. Also, the theories of Stepanoff and Wilson are shown in this figure, but no information concerning which formulation is used. The head ratio in H_r is shown in Figure 3.6 for the coarsest material for multiple concentrations, Q/Q_{BEP} ratios and RPM settings.

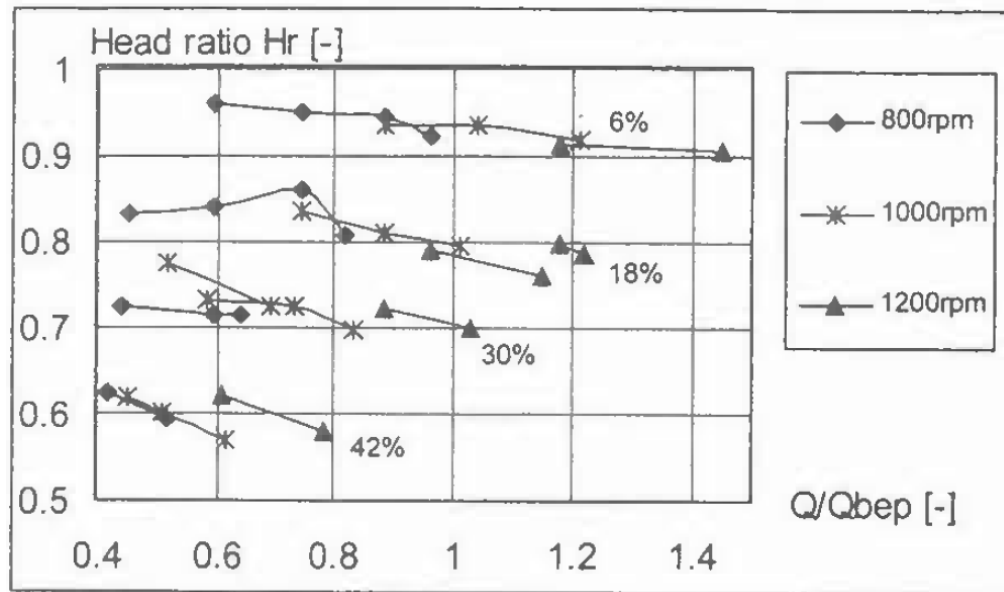


Figure 3.6: Dependence of H_r on flow rate and rpm while pumping coarse material ($d_{50}=1.84\text{mm}$) with different C_v from [Vlasblom *et al.*, 1999]

From Figure 3.6 it appears that the solids effect losses are increasing when the ratio Q/Q_{BEP} is increased. In Figure 3.6 three different symbols are applied, for different RPM settings, which all follow the same decreasing trend.

The decreasing trend for increasing Q/Q_{BEP} ratios could illustrate the influence of the flow rate on the solids effect term H_r , while the influence of the different RPM settings appears to be negligible. When combining all the observations it may be concluded that the flow field inside the specific pump influences the solids effect, this is strengthened by the scatter around the correlation lines in Figure 3.5 which could indicate a dependency on the flow rate. The solid effect is affected by the Q/Q_{BEP} ratio which represents the pumped flow rate against the best efficiency flow rate of this specific pump.

While the conclusions above are interesting. It is based on only two figures, from a side product of the research of Dr Ni and Professor Vlasblom. The main research was regarding the effect of high delivered volumetric concentration on the characteristics of a slurry pump. No information is provided of the H_r terms for the smaller sized particles which are also tested. So, the question remains if the observed trends are also applicable for the other particle sizes tested. This will be investigated in this thesis and conclusions will be drawn for all particle sizes tested.

3.3. SUMMARY OF SOLIDS EFFECT FORMULATIONS FROM LITERATURE STUDY

All formulas reviewed are listed in Table 3.3, these formulations are standardised with the corresponding units and changes as stated below:

- Particle size, d_{50} or d_w in [m].
- Impeller diameter, $D_{impeller}$ in [m].
- Concentration, C_v , in fractions.
- Specific gravity, S_s , S_f , S_m are dimensionless.
- Ratios ρ_s/ρ_f are changed to S_s .
- Densities ρ_s and ρ_m are in [kg/m³].

Table 3.3: Overview of solids effect formulations from the literature study

#	year	Researchers	Head ratio formulation	List of Variables
1	1965	Stepanoff	$H_r = 1 - C_v (0.8 + 0.6 \log(d_{50} \cdot 10^3))$	C_v, d_{50}
2	1968	Frazier	$H_r = \frac{1 - C_v}{1 - C_v + S_s C_v}$	C_v, S_s
3	1974	Vocadlo	$H_r = 1 - C_v (S_s - 1) \left[0.167 + 6.02 \sqrt{\frac{d_{50}}{D_{impeller}}} (S_s - 1) \right]$	$C_v, d_{50}, S_s, D_{impeller}$
4	1974	McElvain	$H_r = 1 - \frac{K C_v}{20}$	C_v, K
5	1976	Burgess and Reizes	$H_r = \left(1 - \left(C_v \frac{\rho_s}{\rho_m} \right)^n \right)^n$, $n = (S_{s0}, d_{50})$ (Burgess and Reizes), $n = (0.21 + 0.066 \ln(d_{50} \cdot 10^3)) \cdot S_s$ (Peng Cheng)	C_v, d_{50}, S_s, S_m
6	1976	Cave	$H_r = 1 - 0.0385 (S_s - 1) \left(\frac{S_s + 4}{S_s} \right) \left(C_v \frac{\rho_s}{\rho_m} \right) \ln \left(\frac{d_{50} \cdot 10^6}{22.7} \right)$	C_v, d_{50}, S_s, S_m
7	1979	Sellgren	$H_r = 1 - 0.32 \left(C_v \frac{\rho_s}{\rho_m} \right)^{0.7} (S_s - 1)^{0.7} C_d^{-0.25}$	C_v, S_s, S_m, C_d
8	1987	Wilson	$H_r = 1 - 0.075 \left(C_v \frac{\rho_s}{\rho_m} \right)^{0.7} (S_s - 1)^{0.45} w_t^{0.5} d_{50}^{-0.25}$	$C_v, d_{50}, S_s, S_m, w_t$
9	1992	Gahlot et al	$H_r = 1 - 0.056 (S_s - 1)^{0.72} \left(\frac{S_s + 3}{S_s} \right) \left(C_v \frac{\rho_s}{\rho_m} \right) \ln \left(\frac{d_w \cdot 10^6}{20} \right)$	C_v, d_w, S_s, S_m
10	1997	Kazim et al	$H_r = 1 - 0.13 \left(C_v \frac{\rho_s}{\rho_m} \right) \sqrt{S_s - 1} \ln \left(\frac{d_w \cdot 10^6}{20} \right)$	C_v, d_w, S_s, S_m
11	1998	He Xijie	$H_r = 1 - \left(\frac{1}{57} + 169.23 \frac{d_{50}}{D_{impeller}} S_s \right) C_v$	$C_v, d_{50}, D_{impeller}, S_s$
12	1999	Miedema	$H_r = 1 - \left(\frac{C_v (0.466 + 0.4 \log(d_{50} \cdot 10^3))}{D_{impeller}} \right)$	$C_v, d_{50}, D_{impeller}$
13	2001	Engin and Gur	$H_r = 1 - 0.11 \left(C_v \frac{\rho_s}{\rho_m} \right) (S_s - 1)^{0.64} \ln \left(\frac{d_w \cdot 10^6}{22.7} \right)^{0.313}$	C_v, d_w, S_s, S_m
14	2003	Engin and Gur	$H_r = 1 - 2.705 \left(C_v \frac{\rho_s}{\rho_m} \right) (S_s - 1)^{0.64} \left(\frac{d_w}{D_{impeller}} \right)^{0.313}$	$C_v, d_w, S_s, S_m, D_{impeller}$
15	2017	Wilson and Sellgren	$H_r = 1 - \left[S_1 \left(\frac{1.11}{D_{impeller}} \right)^{0.9} (d_{50} \cdot 10^3)^{S_2} \left(\frac{S_s - 1}{1.65} \right)^{0.65} \left(\frac{C_v}{0.15} \right) (1 - X_h)^2 \right]$	$C_v, d_{50}, S_s, S_m, D_{impeller}, X_h$

3.4. EVALUATION OF KNOWN SOLIDS EFFECT FORMULA'S

In this section the behaviour of the different formulas are compared against each other. This is done with the help of Table 3.4 where the parameters are given for an imaginary case. To illustrate the effect of impeller size it is chosen to compare this case for two different impeller sizes. The formulations with the impeller size included are all in agreement that the solids effect reduces for larger pumps, as expected.

Table 3.4: Input parameters for specific comparison case

Variables	Mixture
ρ_s [kg/m ³]	2650
ρ_f [kg/m ³]	1000
C_v [-]	0.2
d_{50} or d_w [m]	1×10^{-3}

Case 1 is pumping this mixture with an impeller of 0.4 m diameter. In case 2 the same mixture is pumped with an impeller of 2.5m diameter. As shown in Table 3.5 the different formulations all produce different values for the head ratio. All formulas are based on experiments and it is expected that the latest formulations are more accurate than the older ones. This, because the more recent formulations are based on larger experimental data sets including data sets from previous studies.

Table 3.5: Case specific comparison of head ratios from different solid effect formulations

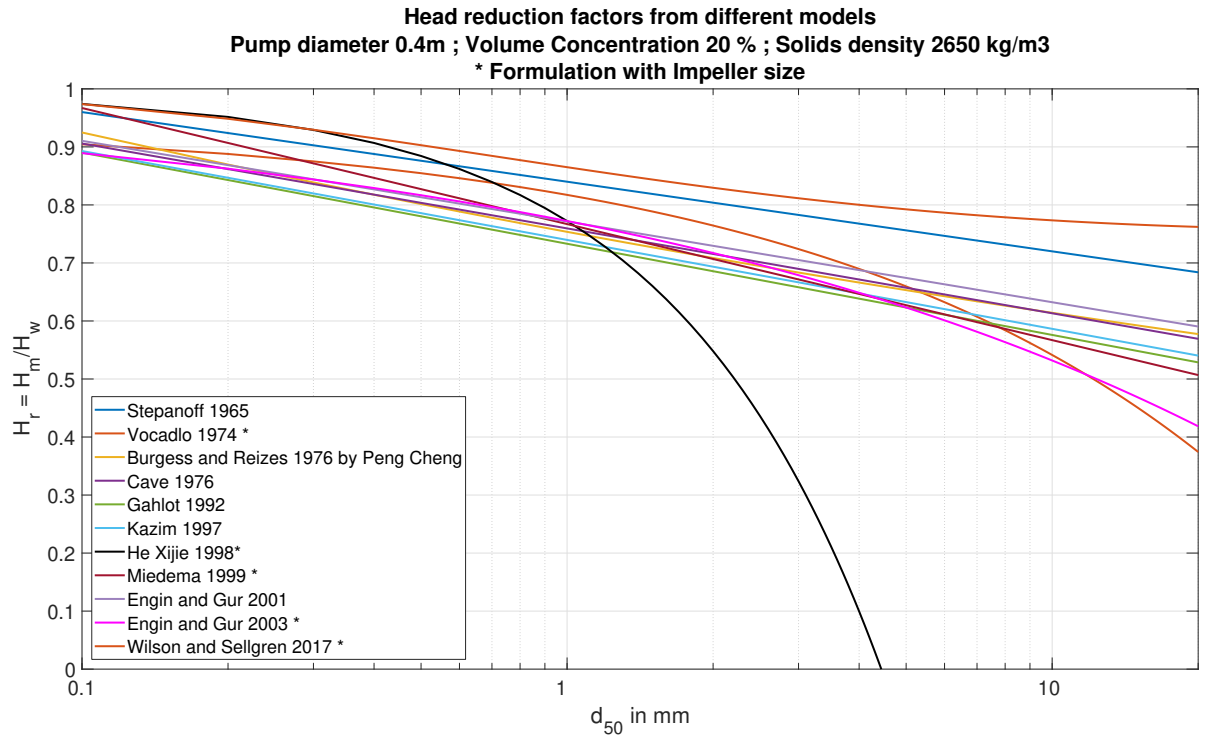
year	Researcher	Equation number	H_r case 1	H_r case 2
1965	Stepanoff	3.1	0.84	0.84
1968	Frazier	B.53	0.60	0.60
1970	Widenroth	B.5	0.99	0.99
1974	Vocadlo	B.8	0.82	0.89
1974	McElvain	B.9	0.75	0.75
1976	Burgess & Reizes	B.14 with B.15	0.75	0.75
1976	Peng Cheng	B.14 with B.17	0.75	0.75
1976	Cave	B.19	0.76	0.76
1979	Sellgren	B.24 with $C_D = 0.07^*$	0.54	0.54
1987	Wilson	B.32 using graphs	0.82	0.82
1992	Gahlot	B.43	0.73	0.73
1997	Kazim	B.44	0.74	0.74
1998	Xijie	B.54	0.77	0.96
1999	Miedema	B.45	0.77	0.96
2001	Engin and Gur	B.52	0.77	0.77
2002	Weir	Figure B.20	0.76	0.90
2003	Engin and Gur	3.3	0.77	0.87
2017	Wilson and Sellgren	3.4	0.87	0.96

*) The C_D value of [Sellgren, 1979] is corresponding to the C_D value used by [Wilson, 1987], this is the minimum drag coefficient given for spheres.

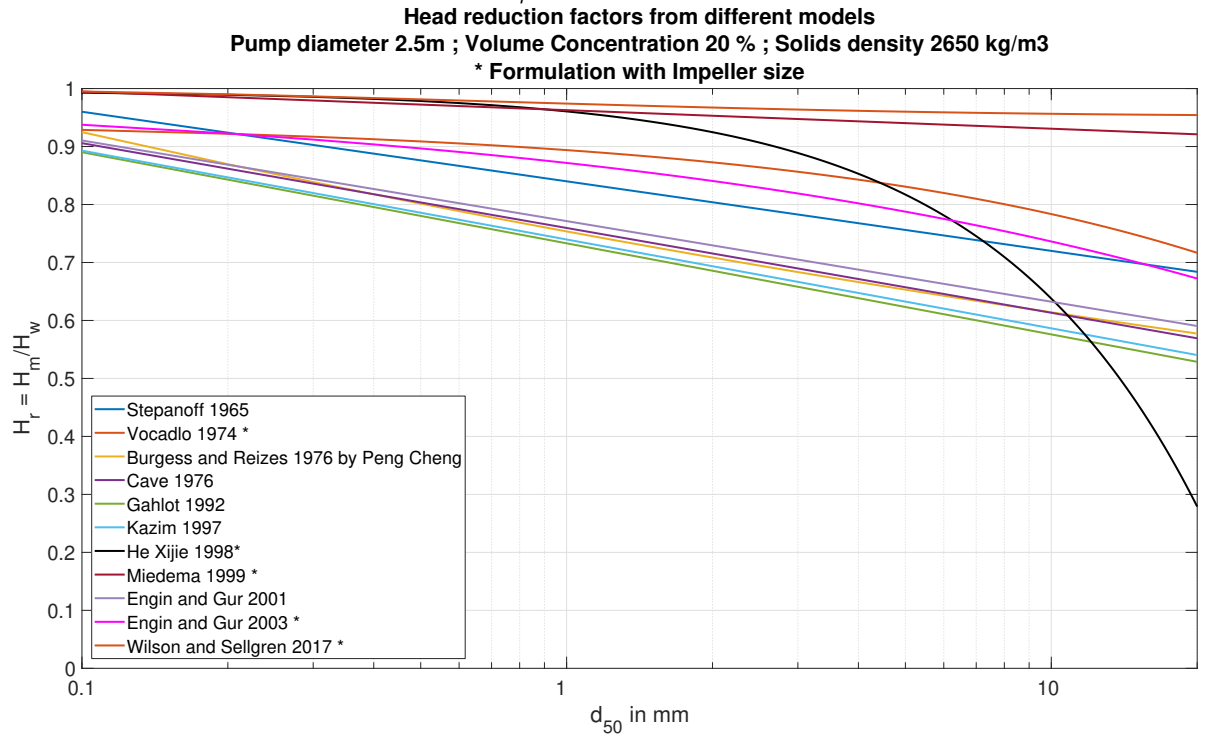
On the next pages the theories are presented with different variables mentioned in the title of the graphs. Figure 3.7a shows the different models for a small slurry pump. It is visible that most of the formulations are within the same range of head ratios.

Figure 3.7b shows the same models for a larger pump. In this plot the differences with Figure 3.7a are clear. The models which include an impeller size are shifting to a higher head ratio. Or in other words, the solids effect is smaller in larger pumps when pumping the same material as in the first graph.

Figures 3.8a, 3.8b, 3.9a and 3.9b show the head ratios for varying particle-impeller ratios. The difference in mathematical behaviour is clearly visible.

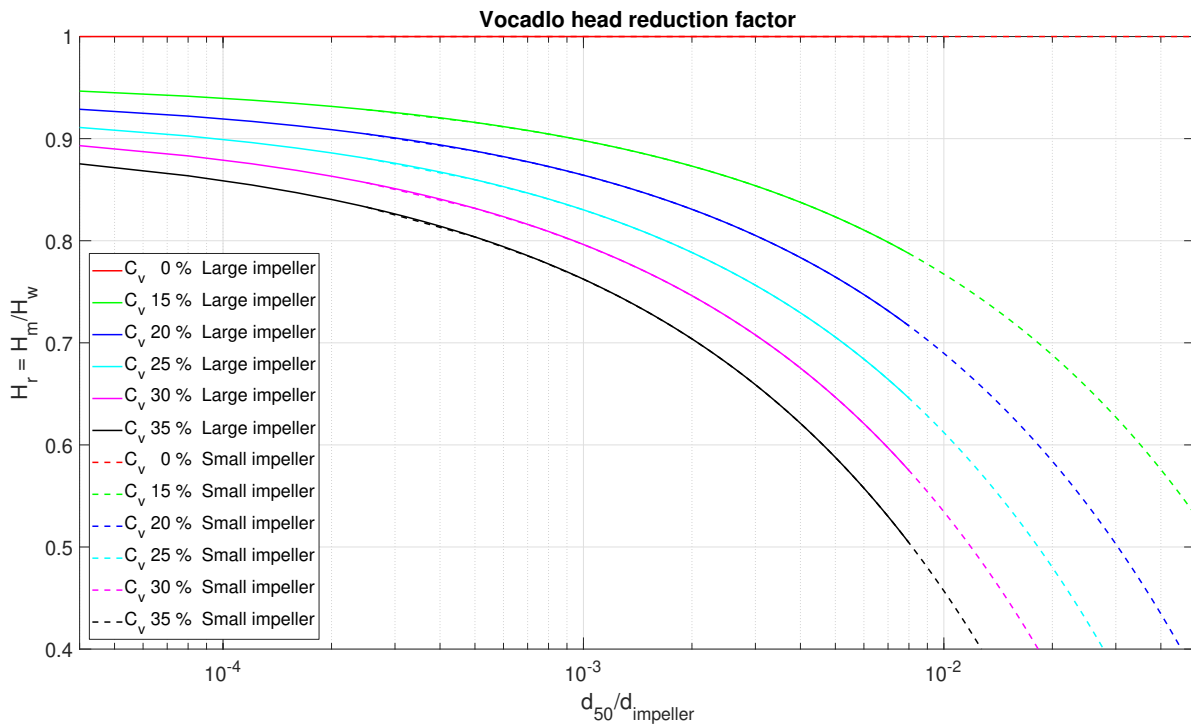


(a) Plot for multiple models given $C_v = 0.2$ and $D_{impeller} = 0.4m$

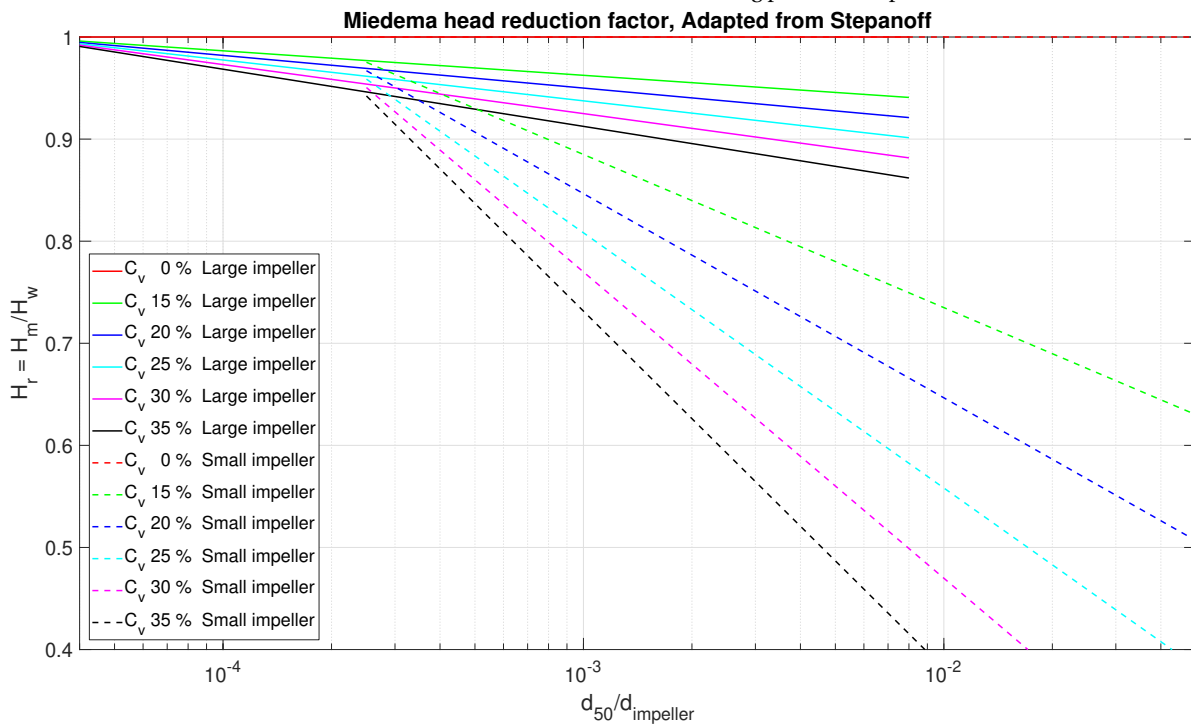


(b) Matlab plot for multiple models given $C_v = 0.2$ and $D_{impeller} = 2.5m$

Figure 3.7: Plot for comparing different pump sizes with multiple models

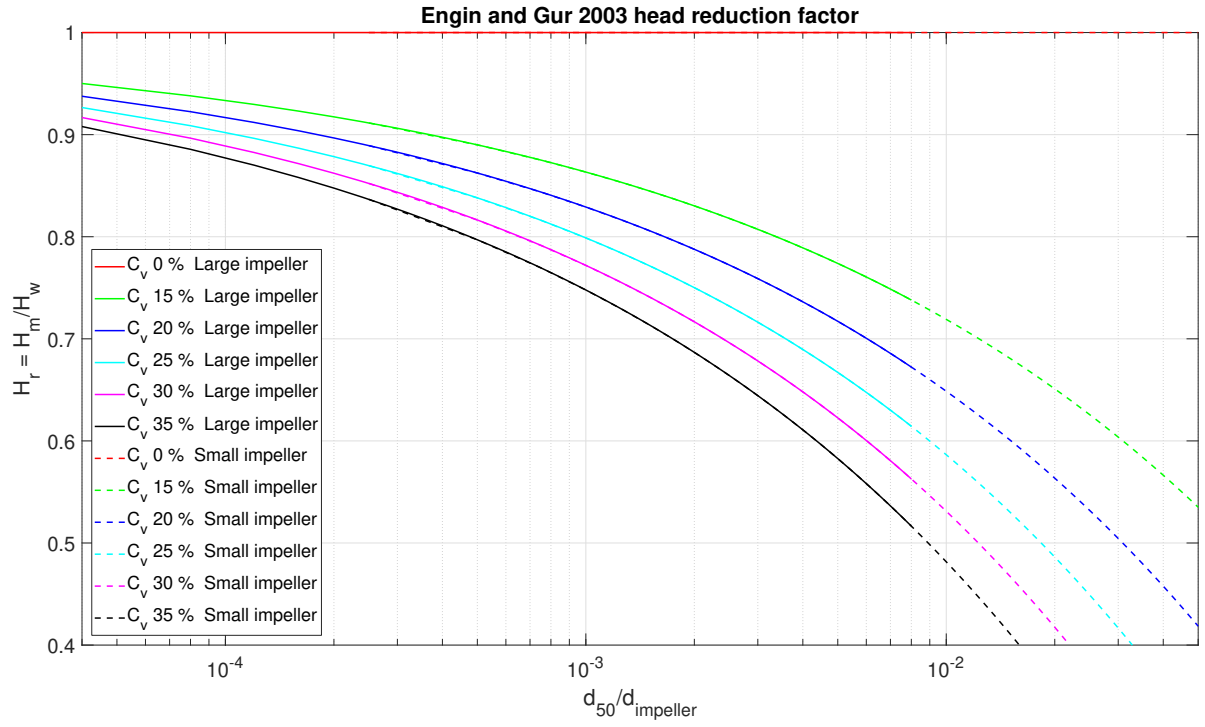


(a) Plot for the Vocadlo formulation, different concentrations and increasing particle - impeller ratios

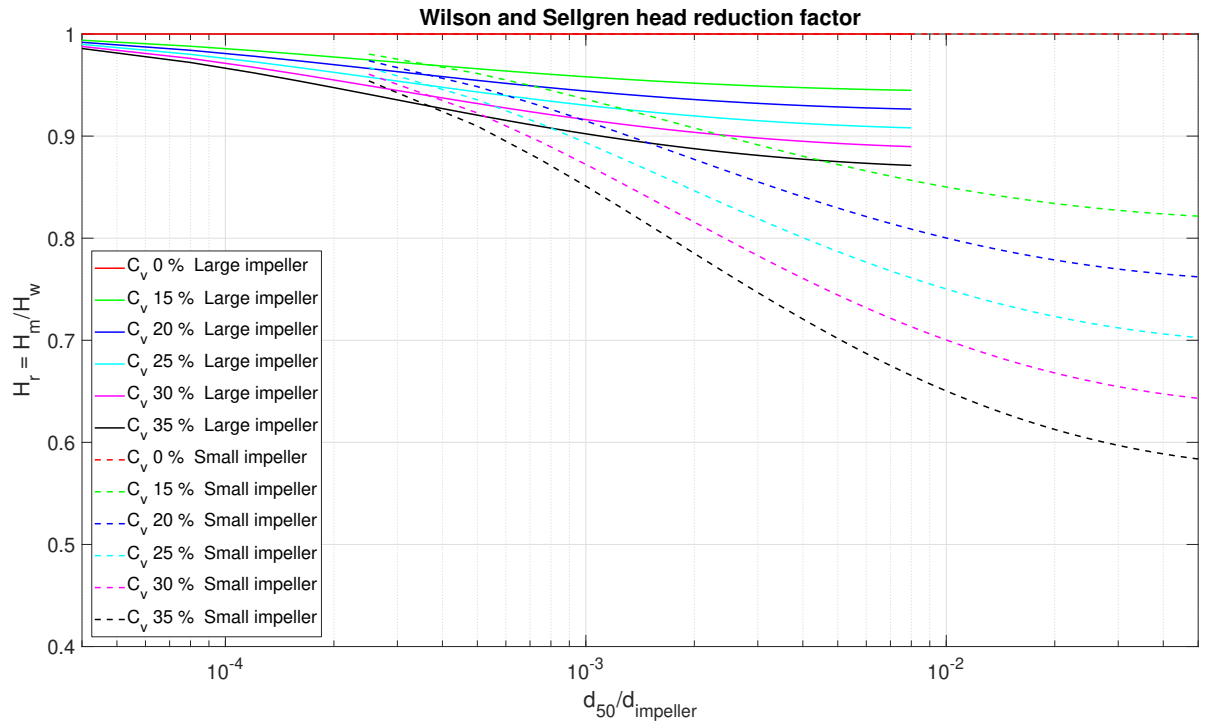


(b) Plot for the Miedema formulation, different concentrations and increasing particle - impeller ratios

Figure 3.8: Vocadlo and Miedema - head ratio against d_{50} with 2 impeller sizes, 0.4m and 2.5m



(a) Plot for the Engin and Gur 2003 formulation, different concentrations and increasing particle - impeller ratios



(b) Plot for the Wilson and Sellgren formulation, different concentrations and increasing particle - impeller ratios

Figure 3.9: Engin and Gur and Wilson - head ratio against d_{50} with 2 impeller sizes, 0.4m and 2.5m

3.5. HEAD RATIO VERSUS CONCENTRATION

The concentration has a large contribution to the solids effect. In Figures 3.10, 3.11 and 3.12 the head ratio is determined for different concentrations for three different particle sizes. The formulations of both Stepanoff 1965 and Wilson and Sellgren 2017 are linearly proportional to the volumetric concentration. While the formulation Engin and Gur 2003 is linearly proportional to the concentration by weight, resulting in a non-linear relation with C_v .

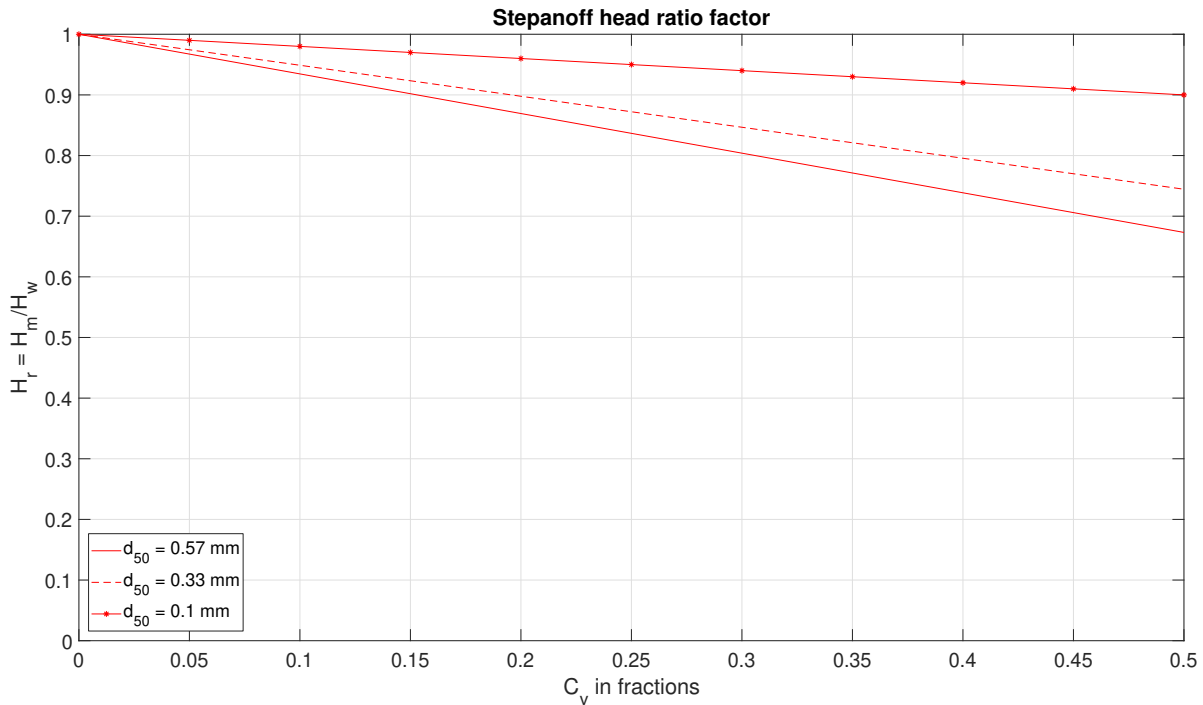
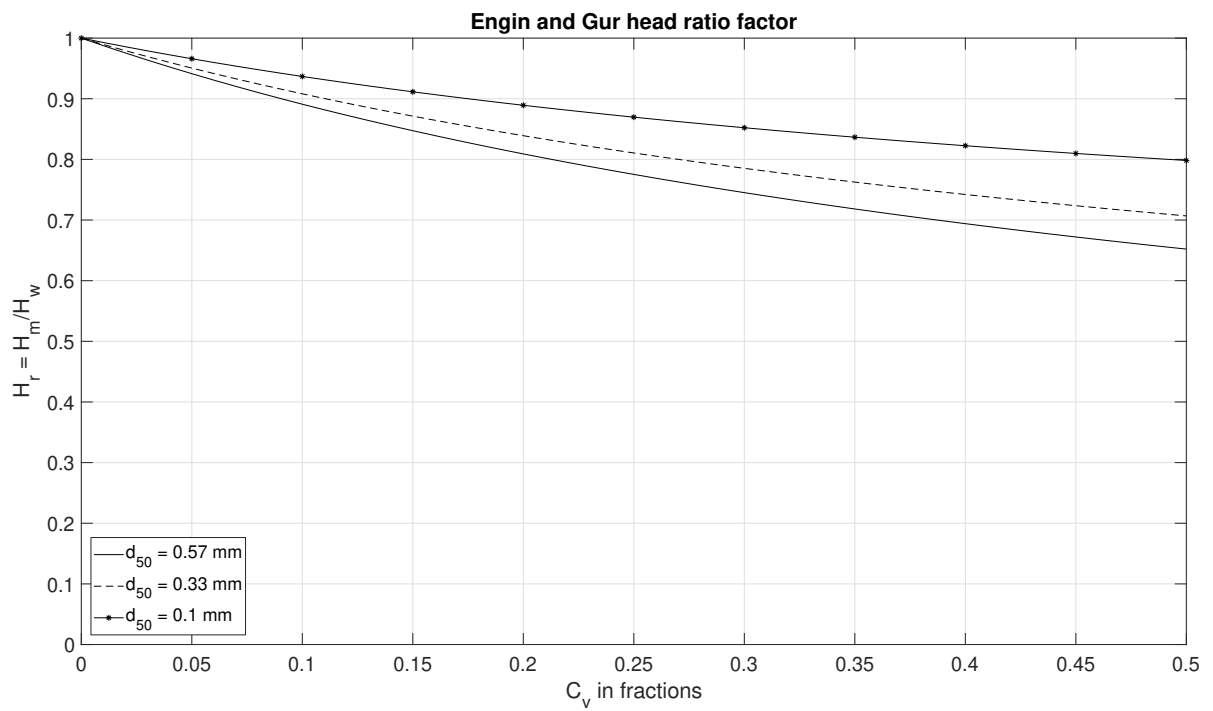
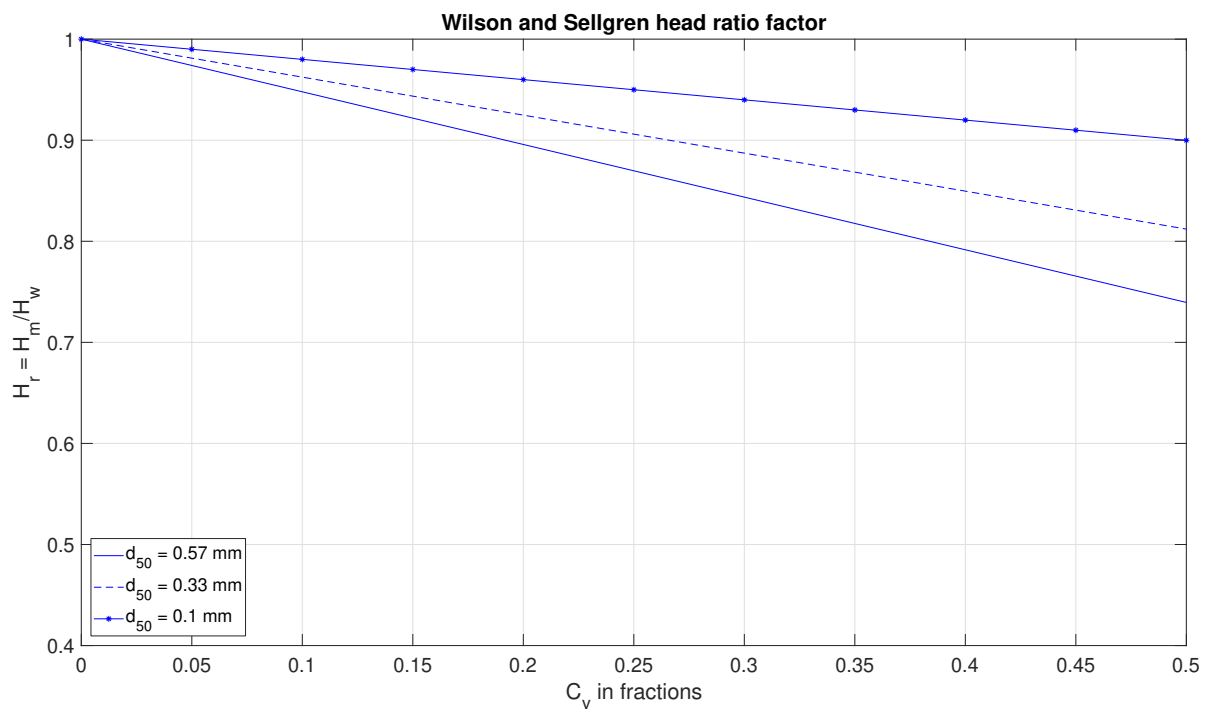


Figure 3.10: Stepanoff formulation - H_r values for given d_{50} and C_v

Figure 3.11: Engin and Gur - H_r values for given d_{50} and C_v Figure 3.12: Wilson and Sellgren - H_r values for given d_{50} and C_v

3.6. ACCURACY OF PROMISING FORMULATIONS

To determine the accuracy of the formulations, research data is gathered from [Vlasblom *et al.*, 1999], [Wilson *et al.*, 2006] and [Sellgren *et al.*, 2016], with particle diameters ranging from 0.123 mm to 1.840 mm, pumped with impeller diameters ranging from 0.4 to 1.38 m. Contact with Prof. Engin was made but unfortunately, Prof. Engin lost his copy of the data set mentioned in Table 3.2, this would provide much more data. All available data is sorted in Excel, where for each data point all conditions are stated. After this, the most promising formulations are applied to calculate the head ratio for these conditions. All data, experimental and calculated are imported in Matlab where the Root Mean Square Error (RMSE) and the coefficient of determination, R^2 , is determined.

The RMSE is a frequently used method to determine the differences between values. A RMSE value of 0 indicates a perfect fit of the model compared to the experimental data. The R^2 is a statistic which will provide some information about the goodness of fit of a model compared with measured data. A R^2 value of 1 indicates a perfect fit of the model compared to the experimental data. The R^2 value is shown in the plot title for the corresponding theory to indicate the accuracy of the theory for these data points from the literature.

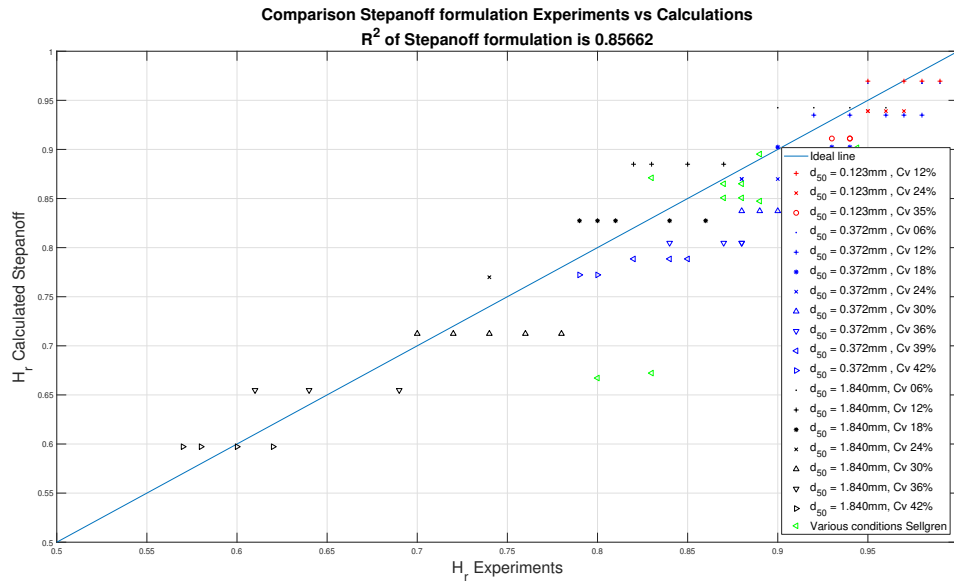


Figure 3.13: Scatter plot of Stepanoff 1965 formulation compared with experimental data from [Vlasblom *et al.*, 1999], [Wilson *et al.*, 2006] and [Sellgren *et al.*, 2016]

As shown in the Figures 3.13, 3.14 and 3.15 the RMSE and R^2 values are not optimal. To determine the best fit, the calculated values are altered with a coefficient β . This β coefficient is applied at the R_H term of each formulation as indicated in Equation 3.11. The coefficient for the best R^2 value is shown in Table 3.6.

$$Hr = 1 - R_H \times \beta \quad (3.11)$$

Table 3.6: Accuracy of the promising formulations

Formulation	RMSE	R2
Stepanoff	0.03960	0.8566
Engin and Gur	0.09100	0.2413
Wilson and Sellgren	0.03530	0.8857
Stepanoff with $\beta_{Stepanoff} = 0.91$	0.03560	0.8841
Engin and Gur with $\beta_{Engin} = 0.68$	0.04700	0.7982
Wilson and Sellgren with $\beta_{Wilson} = 1.13$	0.02960	0.9196

After applying this β coefficient the formulations are better fitted against the dataset. The coefficient increases the accuracy of this particular data set slightly for Stepanoff and Wilson, Engin and Gur is significantly increased. The risk of overfitting is present because this is a small dataset. With more experimental data from multiple sources, a better understanding of the accuracy of the formulations could be provided. With and without the β , the formulation of Wilson and Sellgren is the most accurate according to this dataset.

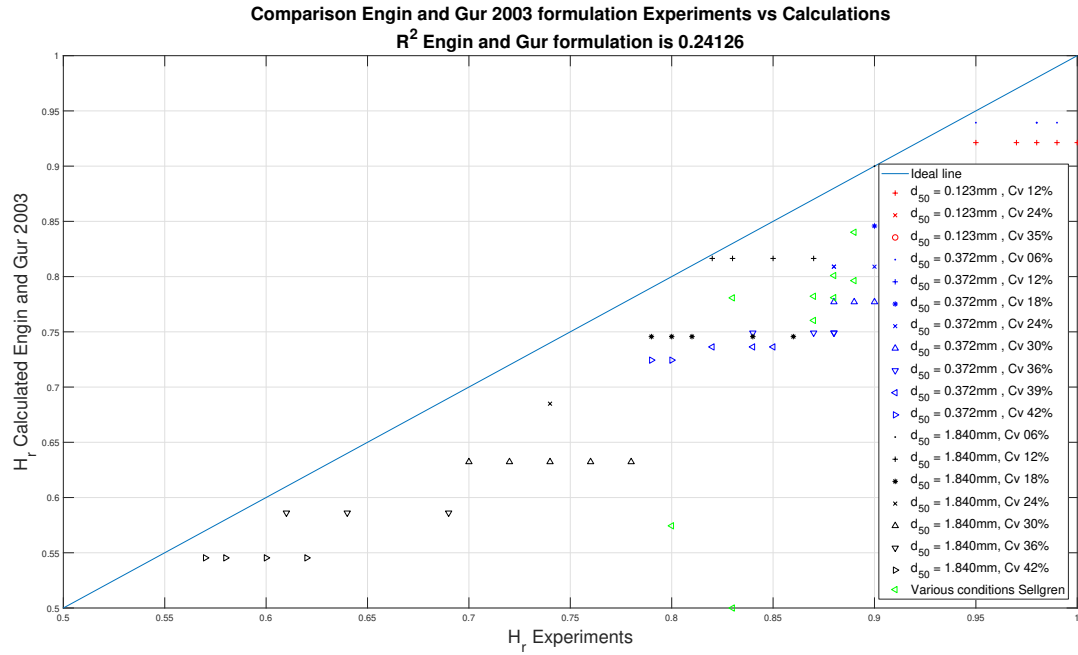


Figure 3.14: Scatter plot of Engin and Gur 2003 formulation compared with experimental data from [Vlasblom *et al.*, 1999], [Wilson *et al.*, 2006] and [Sellgren *et al.*, 2016]

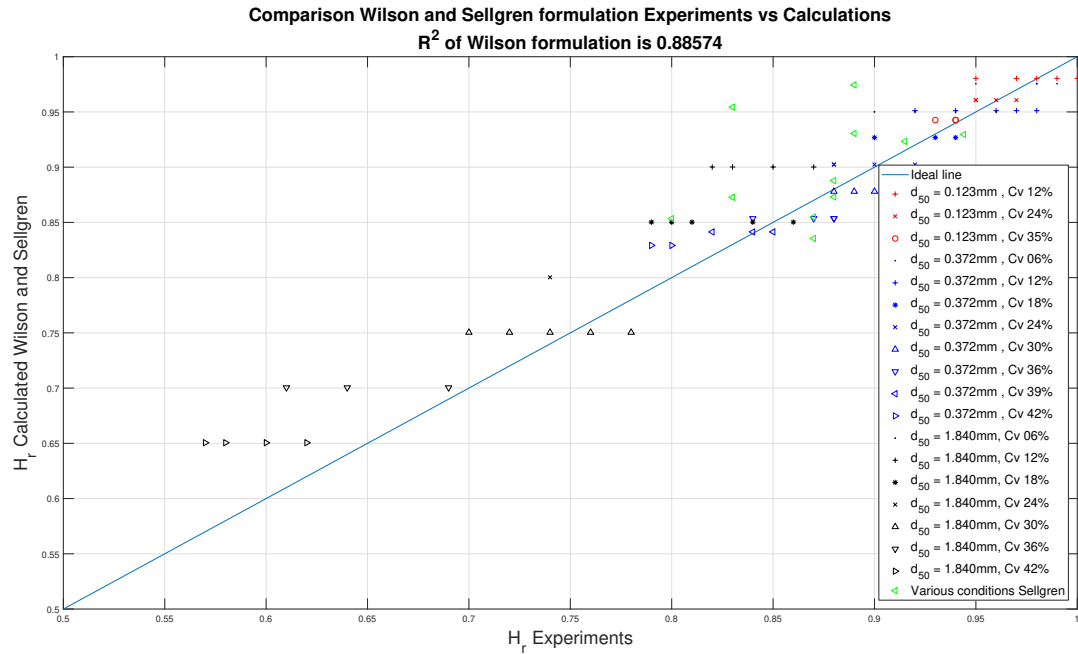


Figure 3.15: Scatter plot of Wilson and Sellgren 2017 formulation compared with experimental data from [Vlasblom *et al.*, 1999], [Wilson *et al.*, 2006] and [Sellgren *et al.*, 2016]

3.7. DISCUSSION

In this section, a discussion is formed on the previous mentioned literature. The discussion is a mix of comparisons of the different models and noticing the similarities and differences. Also, important statements and observations from papers on variables and procedures are included. To fully understand this discussion it is recommended to read Appendix B.

3.7.1. INFLUENCE OF CONCENTRATION

The first topic is the influence of concentration on the performances of centrifugal pumps. All researchers are convinced that the concentration is of great influence on the head ratio. But some researchers prefer the concentration by weight rather than the concentration by volume. This is because a linear relationship is observed between the C_w and H_r . Other than [Sellgren, 1979] and [Wilson, 1987], which have the C_w to the power 0.7, all the other researchers with a C_w in the formulation are observing a linear relation with H_r . Others use the concentration by volume explicitly in their formulation because the C_v is measurable during the experiments and has a more physical meaning as a fraction of volume occupied by solids in the transported mixture. [Kumar *et al.*, 2014] observed in complex slurries a non-linear relationship between C_w and H_r . This due to the addition of fine particles where the fluid turned into a non-Newtonian fluid.

Half the researchers chose for the C_v term and the other half for the C_w term in the formulations.

3.7.2. SPECIFIC GRAVITY

The second topic is the influence of the density of the solid, or rather the specific gravity of the solid, on the performance of the centrifugal pumps. All formulations, except Stepanoff, discussed in section 3 are using the term for the specific gravity. The researchers found a relation between S_s and H_r , where an increase of S_s resulted in a decrease in H_r . The specific gravity is mostly inserted in a $(S_s - 1)^\alpha$ term, where α ranges from 0.45 to 1. [Vocadlo *et al.*, 1974] has 2 terms with $(S_s - 1)$ in his formulation, [Cave, 1976] has a linear relation, [Sellgren, 1979] and [Wilson, 1987] have $\alpha = 0.7$ and 0.45 respectively, where [Gahlot *et al.*, 1992] uses $\alpha = 0.72$. [Engin & Gur, 2001] and [Engin & Gur, 2003] are using $\alpha = 0.64$. The mono-sized formulation of Wilson and Sellgren has $\alpha = 0.65$.

A majority of the researchers is in agreement that $H_r \propto (S_s - 1)^\alpha$. Where α is approximately 0.65

3.7.3. PARTICLE SIZE AND PARTICLE SIZE DISTRIBUTION

The most important influence on the performance of centrifugal pumps is the particle size. From the literature review it is observed that there is a transition between definitions. In the earlier models the d_{50} is used as the representative particle size. Later research from [Sellgren, 1979] and beyond started to use the d_w as the more suitable particle size to describe the solids effect. [Kazim *et al.*, 1997] shows that the d_{50} is the only representative for narrow size distributions, but for the broader sized distributions the d_w is preferred. The methods to insert the particle size are similar for all researchers. The d_{50} or d_w are used with the logarithmic function $\log_{10}$ [Stepanoff, 1965] or fitted with the natural logarithmic function $\ln$. [Cave, 1976], [Gahlot *et al.*, 1992], [Kazim *et al.*, 1997] and [Engin & Gur, 2001]. The Wilson and Sellgren 2017 formulation use a double power-law function based on the d_{50} parameter.

When the formulation only considers the particle size it is observed that the natural logarithmic function is the best suitable method to fit the influence of the particle size on the experimental data. So $H_r \propto \ln d_w$.

3.7.4. IMPELLER DIAMETER

An effect most researchers neglect to take into account is the impeller diameter. Almost all research is conducted on small scale pumps with impeller diameters ranging from 75 to 300 mm (3 to 12 inch). Most formulations are based on 1 pump size, so the effect of the impeller is not incorporated in the formulation. When comparing different sizes of impellers the effect becomes clear, see [Sellgren & Addie, 1989]. Here the comparison is made between a small and a large impeller. The head reduction term, R_H , for the larger impeller is only one-third of the R_H of the smaller impeller. This is a significant effect on the performance of a dredge pump. The researchers who did include the impeller size in the formulation often use the ratio between particle size and impeller diameter as a dimensionless number. Back in 1987 [Wilson, 1987] stated that the solids effect is independent of pump size, in this time not much was known concerning the impeller effect. However later on, in Wilson and Sellgren 2017, the effect of the impeller diameter is incorporated in the formulation.

The implementation of the impeller size in mathematical formulations is for all researchers different. Some use the ratio particle size to the impeller diameter in a square root, [Vocadlo *et al.*, 1974]. Others use the ratio to an exponent 0.313, [Engin & Gur, 2003]. [Miedema, 2015] divided the logarithmic function $\log_{10} d_{50}$ by the impeller size. According to Xijie, the H_r relation is linear proportional to the ratio between particle and impeller size. Wilson and Sellgren 2017 implemented the ratio of the particle size and impeller size more uniquely, as shown in Eq. 3.4.

There is a consensus to incorporate the impeller diameter, in formulations of the head ratio, see table 3.5. The mathematical method of implementing the impeller diameter is yet to be determined.

3.7.5. EFFICIENCY RATIO

As stated in section 2.5 all researchers provide one equation for both the head and efficiency ratio. Nevertheless, it is occasionally mentioned in papers that the efficiency deviates slightly from the head reduction. This deviation is neglected because it is still near the head ratio. From C_v larger than 25 % it is observed that the efficiency reduces significantly more than the head [Sellgren & Addie, 1989], [Gandhi *et al.*, 2001] and the formulation for the head is no longer sufficient for the efficiency ratio.

There are no separate formulations for the solids effect on the efficiency when the C_v is larger than 25 %.

3.7.6. THE INFLUENCE OF VANE DESIGNS

An important quote from [Sellgren & Addie, 1993] is, "A factor to consider is that slurry pumps design has changed over the years. Before 1980, most slurry pump impellers only employed inefficient radial vane impellers. Whereas new types of slurry pumps employ twisted vanes so that the inlet angles are correct for the design duty." "It should be noted that the McElvain curve, shown in Figure B.3, was based on older designs produced before 1974 of mostly radial vane type." This could mean that all research from before 1980 is questionable and perhaps need to be neglected for modern studies. This is an important statement to take into consideration because a formulation such as [Vocadlo *et al.*, 1974] is including the impeller diameter, but with perhaps an inefficient vane design.

The experimental data from before 1980 could be an inadequate reference for modern-day vane designs because of a fundamentally different flow pattern in the pump. But this will be checked for the Stepanoff formulation against the conducted experiments

3.7.7. FLOW RATE

Furthermore, numerous researchers agree with each other that the solids effect appears to be independent of flow rate. This is confirmed with lots of experiments in papers, [Cave, 1976] did observe a dependence for very low flow rates, but not at operational flow rates. The independence of flow rate doesn't mean that the influence of the rotational speed of the impeller, RPM, is not of influence to the solids effect. The RPMs of the impeller is not fixed to a certain flow rate.

Also, the statement from [Burgess & Reizes, 1976] where the head ratio is observed to be independent of specific speed, N_s , is important. This contradicts the foundation of the formulation of [Widenroth, 1970]. In this formulation, the specific speed is included in the solids effect equation. Combining the observations from [Sellgren & Addie, 1993], [Vocadlo *et al.*, 1974] and [Burgess & Reizes, 1976] it could be assumed that the formulation of Widenroth is not based on variables assumed to be of importance to the solids effect and therefore this formulation is not included in further research. Another reason why this formulation is not included is because it didn't provide logical values when tried for the cases in Section 3.5.

[Vlasblom *et al.*, 1999] did a study at the University of Technology in Delft on high density hydraulic transport. He also measured the pressure before and after the pump and presented data of these measurements on the solids effect. He found evidence that, for the coarsest material tested ($d_{50} = 1.84\text{ mm}$), the solids effect, H_r , is influenced by the flow rate. This is shown in Figure 3.6 for the coarse sand particles only. This is an interesting finding for further study, because what effect has the flow rate on the smaller sized particles?

The head ratio, H_r , is presumed independent of flow rate, Q , for operational ranges of Q , but further research is needed to confirm.

3.7.8. ACCURACY OF FORMULATIONS

After reviewing the three proposed formulations in section 3.4 and 3.6, it is observed that the Stepanoff and Wilson and Sellgren 2017 formulas were a decent fit to begin with. The formulation of Engin and Gur was less accurate. This could be because the data set where the formulation is fitted on was too broad and reduces the accuracy for a specific case of density and particle size. After applying an extra coefficient, β all formulations are better fitted and this results in higher goodness of fit results (R^2 values). A larger data set would provide more information about the accuracy of the formulations.

Verify with experiments which formulation is the best for small scale and full-scale dredging situations.

4

Experiment Plan

The main goal of this thesis is, stated in Chapter 1, to verify & improve an existing formulation for the solids effect. After the discussion in Section 3.7, there are some points where further research is suggested. After consulting with SSB it is determined that the following questions require further research.

- What is the relation of the concentration on the solids effect?
- What is the relation of the particle size on the solids effect?
- What is the relation of the flow rate on the solids effect?
- Which model for the solids effect is the most accurate in this test set up?

The concentration term is used for both the volumetric concentration and weight concentration. In this research is it investigated to check which concentration term is more accurate compared to the test data. The relation of particle size to the solids effect is defined with multiple functions. In this investigation, the effect of the solid size is examined to determine which functions are more accurate compared to the test data.

As discussed in Chapter 3.7 several researchers found that the solids effect is independent of flow rate. This is interesting to investigate because the general assumption is that the best efficiency point (100% QBEP) has an optimal flow field. All working points other than this QBEP point are less optimal. This would suggest that the flow rate has also some influence on the solids effect. This will be determined from the test data.

The research is done by conducting experiments at the slurry lab located in the Delft University of Technology. [Vlasblom *et al.*, 1999] has conducted his research at this test set up 20 years ago. In the following sections, the experiments are explained and important parameters are mentioned. First, the experimental set up in the slurry lab will be discussed. Then, it is determined what will be tested during the experiments and how. After this, an experimental plan is formed to illustrate all the different configurations and steps. Finally, the data processing is explained from signal to outcome.

4.1. TEST FACILITY, SLURRY LOOP SET-UP

The tests are conducted in the slurry loop at the Delft University of Technology. The slurry loop design is used for [Vlasblom *et al.*, 1999]. During the years some adjustments to the system have been made. For example, the diesel engine is replaced with an electro drive and the pump is replaced. Also, the slurry loop is relocated to another building, hence the slightly different routing of the pipes. But the principle of the slurry loop is still the same.

Experimental set up

The slurry loop is illustrated in Figure 4.1. Here the basic layout of the experimental set up is visualised with all used equipment. The centrifugal pump (1) has a $D_{imp} = 0.4\text{m}$ and is driven by a 132 kW electro drive. The material storage tank (2) has a funnel to control the sediment input. The pressures measured in the U Loop and over the pump are measured with differential pressure sensors (3). The pressure points connecting the sensors are equipped with sand collector pots. These collector pots prevent large amounts of solids from entering the pressure tubes to be sure the measured pressures are correct. The temperature of the fluid is controlled with a cooling unit located on the ascending U loop leg (5). Multiple gate valves and butterfly valves are used to control the flow (6)&(7). For future reference, the valves 1, 2, 4 and 5 are indicated in red digits. Those valves are frequently used to operate the slurry loop. The temperature is measured with a temperature sensor (10). The flow rate is determined by measurements with the magnetic flow meter (11). In Appendix C all signals and equipment are listed.

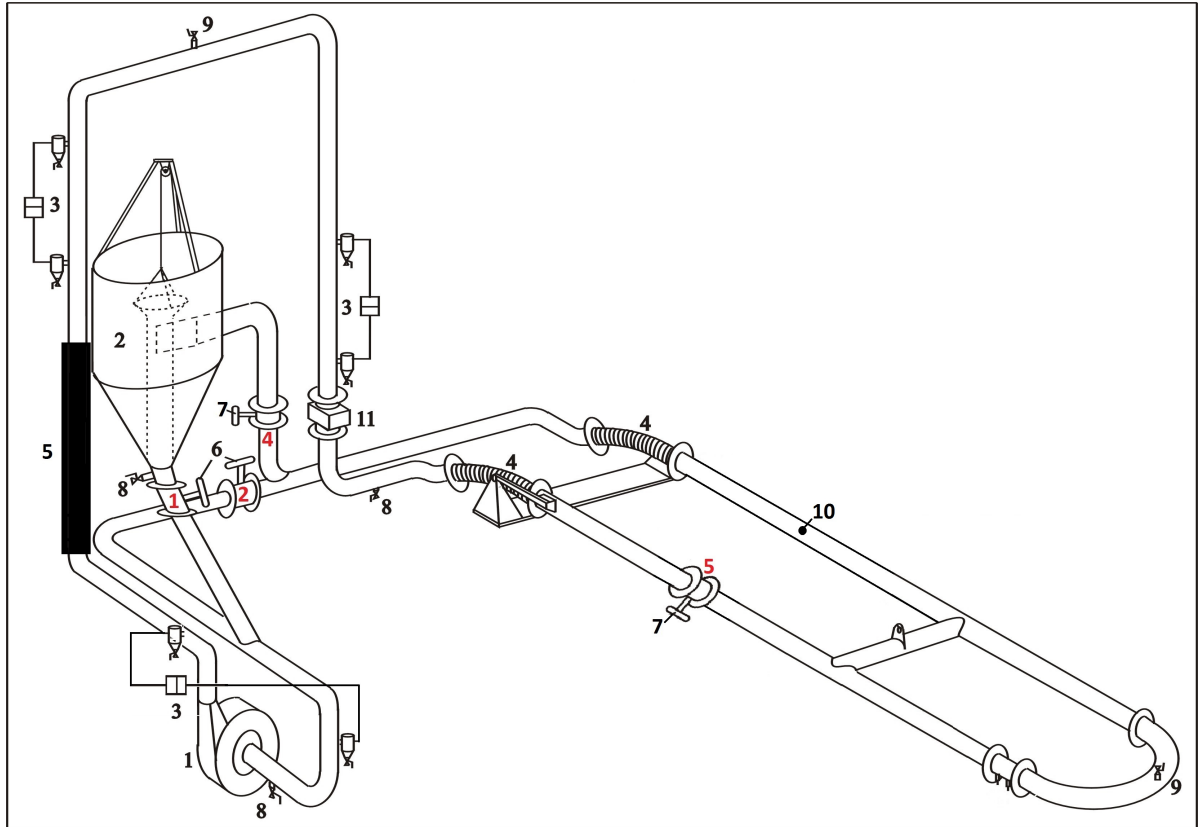


Figure 4.1: Basic lay out slurry loop set-up with used equipment

Next to the slurry loop is a computer. Here all the signals are gathered in volts and converted into the appropriate units using Labview. This is done with the help of calibration formulas to convert the volts to the corresponding units of pressure, temperature or velocity. The calibration graphs for the pressure sensors are provided in Appendix D Figures D.2, D.3 and D.4. The Labview script used for the experiments is shown in Figure 4.2.

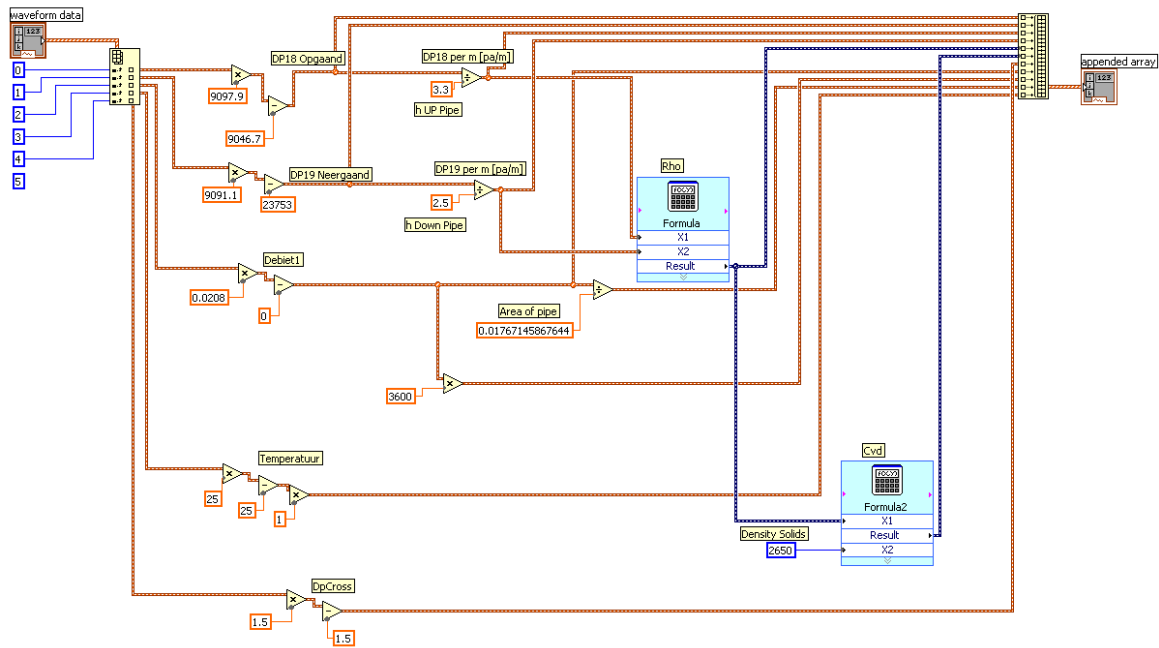


Figure 4.2: Labview script with input and output signals

All the incoming signals are gathered in the left upper corner of the script. The part in the middle of the figure shows where all the signals are converted and used to obtain the right output values. One of the signals obtained with the use of pressure measurements is the density of the mixture. This is done with the pressure measurements of the U loop sections in combination with Equation 4.2. The volumetric concentration is determined with equation 4.3 using this mixture density and the density of the solids. The output section is shown in the right upper corner. Here, all the original voltages and processed data, in physical units, are saved in the data file linked to the specific test.

Determine the density of the mixture

The pressure difference is measured between 2 points on the upward and downward leg of the U loop over distance h . Assuming that the friction, $\Delta_{friction}$, is equal in the upward and downward leg the summation shown in Equation 4.1 is used to determine the average density.

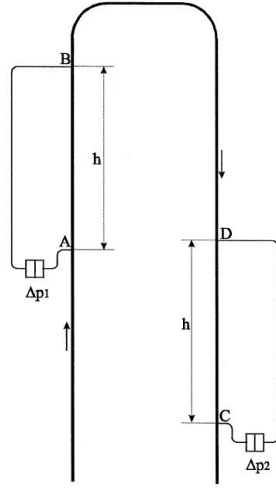


Figure 4.3

$$\begin{aligned} \Delta p_1 &= (\rho_m - \rho_w)gh + \Delta_{friction} \\ \Delta p_2 &= (\rho_m - \rho_w)gh - \Delta_{friction} + \\ (\Delta p_1 + \Delta p_2) &= 2(\rho_m - \rho_w)gh \end{aligned} \quad (4.1)$$

Equation 4.1 is then rewritten to produce the density of the mixture as output. With the distance h known, the differential pressures are converted to pressure per meter pipe length, Pa/m. After this, Equation 4.2 provides the correct formulation for the density of the transported mixture.

$$\rho_m = \frac{\Delta p_1 + \Delta p_2}{2 * 9.81} + \rho_w \quad (4.2)$$

In Equation 4.3 the concentration corresponding to the mixture density from Equation 4.2 is calculated.

$$C_v = \frac{\rho_m}{\rho_s - \rho_w} - \frac{\rho_w}{\rho_s - \rho_w} \quad (4.3)$$

Before the tests are performed, the slurry loop is inspected and every sensor is calibrated and checked. The first round of calibration was done by the lab staff. After checking and several test runs, it appeared something was wrong concerning the slurry loop. This is explained in Appendix D.

Summarizing this error, the voltage signals were correct. There was something wrong within the processing step regarding the density of the mixture. After renovating the slurry loop, new parts had different dimensions which weren't updated in the software. After adjusting the length h for both pressure measurement sections the correct density was calculated. A critical note was made by myself to check the measurement of previous students who didn't catch this mistake as their measurements are wrong. In the following sections the experimental plan is provided and the important choices are explained.

4.2. WHAT WILL BE TESTED?

The goal of the experiments is to determine the influence of solids concentration, particle size and flow rate on the solids effect. These 3 parameters are individually examined in the experiments with the help of the following research plan. This plan is formed with input from the dredging industry (Van Oord and Boskalis) to be sure the parameters are correctly matched with the practice in practical situations.

A research plan is used to clarify the objectives of the testing period at the Delft University of Technology. It also provides insight into the choices made and an overview for the test configurations which will be tested. The tests are conducted with various particle sizes, to test the solids effect for frequently encountered particle sizes. With only one pump available, this data will be used to determine the accuracy of the formulations against the small pump, which corresponds in size to the pumps used in research from the past.

The materials used are selected to simulate a range of frequently encountered grain sizes. Ranging from desert sands (fines) to North Sea particles (0.3 mm) and coarse sands (0.8 mm), additional a material similar to gravel is selected to check the influence on the solids effect for this very coarse material. This resulted in the use of the following materials;

- Geba sand, with a d_{50} of 0.1 mm
- Dorsilit 9, with a d_{50} of 0.3 mm
- Dorsilit 7, with a d_{50} of 0.8 mm
- Dorsilit 5, with a d_{50} of 2.1 mm

To examine the influence of the solids concentration for all these materials the concentration, C_v , will be varied. To verify the influence of the flow rate on the solids effect each configuration of material and concentration is tested for multiple flow rates. This results in a dataset containing multiple materials, with different concentration and multiple flow rates. Such a dataset is important to check the existing solid effect theories and to verify claims made in the past.

4.3. HOW WILL THERE BE TESTED?

The test program is constructed to test all materials in a broad range of practical situations. This is done by varying the concentration and the flow rate for all materials. To monitor eventual inaccuracies due to wear of the impeller, the clear water pressure, which is used as a reference, is determined frequently during the testing period.

Flow rate

In Table 4.1 the test plan for each material is presented. It is chosen to vary the flow rate between 60% of QBEP and 140 % QBEP. These are practical flow rate ranges during dredging operations. This variance in flow rate is achieved by applying and removing resistance in the flow. This is done by adjusting valve number 5 in the system. The flow rate is varied to check the observations made by most of the previous researchers that the solids effect is independent of flow rate for operational ranges of Q at one fixed RPM value.

The Q_{BEP} of the pump is located at 1450 RPM with 550 m³/h resulting in a η_w of 83% (according to the pump supplier). This working point of the system is impossible to reach for higher concentration mixtures due to insufficient power. Therefore it is chosen to operate the centrifugal pump at 1100 RPM. On this constant RPM line, the pump should be capable of pumping all mixtures at the corresponding flow rate range. This is shown in detail in section 4.6. When the centrifugal pump operates on this line the solids in the mixture don't settle at the specified flow rates. In Figures 4.7 till 4.12 are the working points illustrated for Dorsilit 7, the coarsest material. In Appendix G all the working points are shown. In Figures 5.2, 5.3 and 5.4 the clear water pump curves, both tested and according to Damen, are added and the observed efficiency, η , for all clear water tests is included. Q_{BEP} at 1100 rpm is 417 m³/h.

Concentration

For each flow rate the concentration, C_v , is varied between 0% and 40%. This range in concentration covers all practical dredging operations. At first the C_v of 10%, 20%, 30% and 40% are tested. If needed additional concentrations could be added, this will be determined during the experiments.

Test plan

Each mixture configuration is tested 5 times, this to check if the tests are executed correctly and consistently. Before and after each concentration adjustment, a clear water curve is checked. After all tests are done, a minimum of 240¹ mixture tests have been performed. This results in 240 data points on various concentrations, flow rates and different grain sizes. Assuming each test takes 0.5 hour to perform and 2 days to change the materials, approximately 4 weeks are required to perform all tests.

Table 4.1: Experimental plan per material

Test plan for each material			
	$Q/Q_{BEP} = 60\%$	$Q/Q_{BEP} = 100\%$	$Q/Q_{BEP} = 140\%$
Minimum of tests	C_v	C_v	C_v
5	0%	0%	0%
5	10%	10%	10%
5	20%	20%	20%
5	30%	30%	30%
5	40%	40%	40%

4.4. DATA PROCESSING

During the tests, the parameters mentioned below are monitored. These parameters are logged in Labview at a frequency of 10 Hz for a duration of 60 seconds per test. Each test begins after the system has reached an equilibrium state. This equilibrium is achieved when there are no deviations in flow rate, the pump pressure and the density.

To measure accurately it is important to check if the log frequency is high enough for examining the experiments. Due to turbulence in the flow, it is important to average the logged data points over a period of time. This averaging period is determined such that, for the lowest flow rate, the turbulence is averaged out, the produced signals are determined accurately and to check if the main motion is stationary. This averaging time is approximately 40 times the turbulent macro time scale, Eq. 4.4. For 250 m³/h, the $T_{turb,macro} = 0.038$ sec, this results in a minimum duration of 1.53 seconds. With 10 Hz there is chosen to average every 20 data points, so $T_{mean,avg} = 2$ seconds.

$$T_{turb,macro} \propto \frac{D_{pipe}}{u_{mixture}} \quad (4.4)$$

Additional is the time calculated, for a water particle, to complete one round within the slurry loop. With the minimum flow rate of 250 m³/h this would take approximately 15 seconds. So for each test all water particles are circulated at least 4 times for the lowest flow rate. The sand particles move slower than the water particles but will also complete multiple rounds during each test.

Testing for 60 seconds with a log frequency of 10 hz results in 600 logged data points per parameter. After averaging for the turbulence in the flow each test results in 30 data points for analyses. These 30 points are used to examine each test and determine the solids effect values for each individual configuration. First, it is checked if the test was indeed performed in an equilibrium state. Then, by averaging the 30 data points an average of the whole test is taken, with an averaging time of 60 seconds.

This is a relatively long period of averaging and therefore the data is very interesting to evaluate. During these tests the turbulent part, u' , of Equation 4.5 will be averaged out and the main motion $\bar{u}$ is determined. With these tests the solids effect will be very accurately measured and will provide valuable insights into the subject.

$$u = \bar{u} + u' \quad (4.5)$$

¹ 5 times each test, 4 concentrations for each flow rate, 3 flow rates for each material, 4 materials

Verify that the duration is correct

During the experiments, all tests are checked for large deviation, which could indicate the system wasn't in equilibrium while performing the test. Furthermore, the results are analysed for strange behaviour during the test. During these analyses, the variation within each test is observed to determine if there is a difference between averaging the whole test of 60 seconds, or shorter averages of ± 10 seconds. There was a deviation over all samples of $\pm 0.5\%$ difference in values. This is negligible and confirms that the tests are conducted correctly and are useful for further analysis.

In Figure 4.4, 4.5 and 4.6 examples of oscillations, u' around the mean, $\bar{u}$, are shown. These figures are from tests conducted and show the trend with variations. This u' is averaged out due to the long averaging time used in this test plan. Figure 4.4 is the flow rate, Figure 4.5 is the density of the mixture and Figure 4.6 is the head of an experiment conducted during this research.

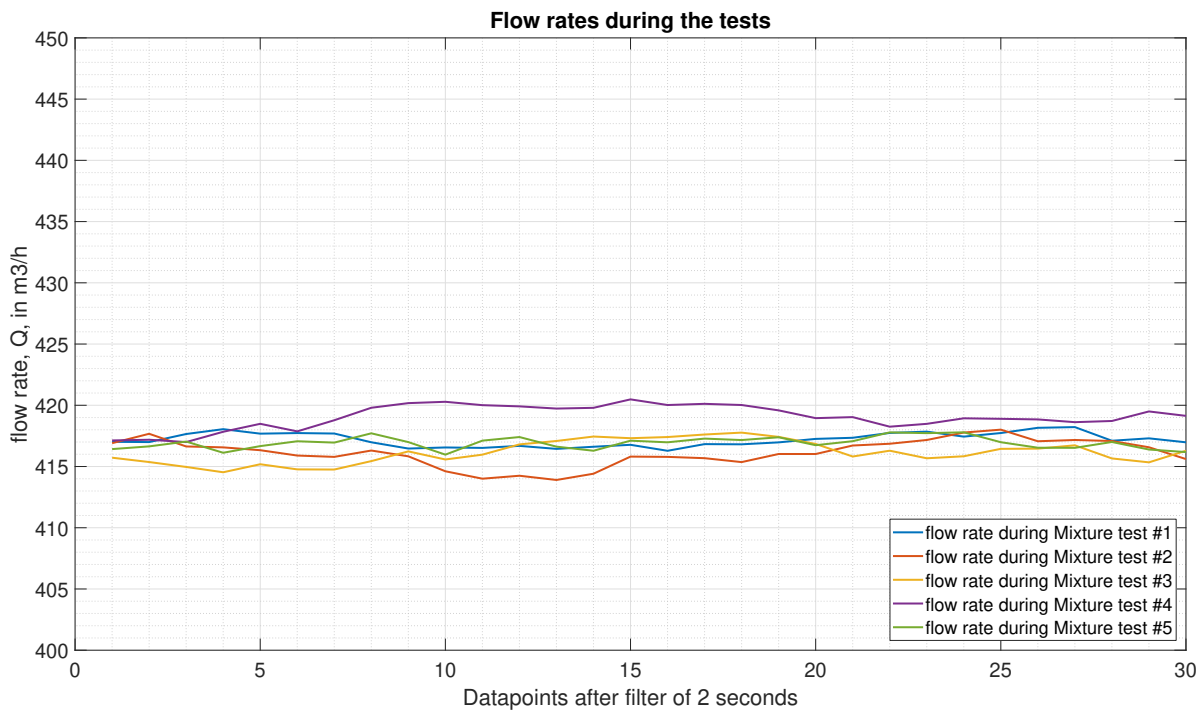


Figure 4.4: Evaluation of test data during an experiment, the fluctuation of u' around $\bar{u}$, for the flow rate.

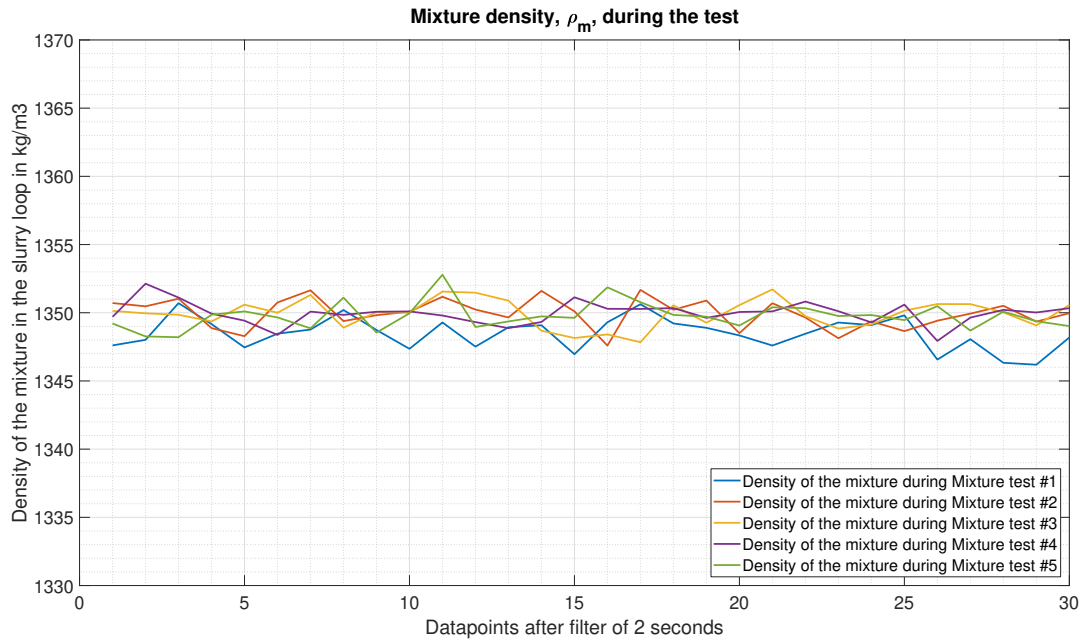


Figure 4.5: Evaluation of test data during an experiment, the fluctuation of u' around $\bar{u}$, for the density.

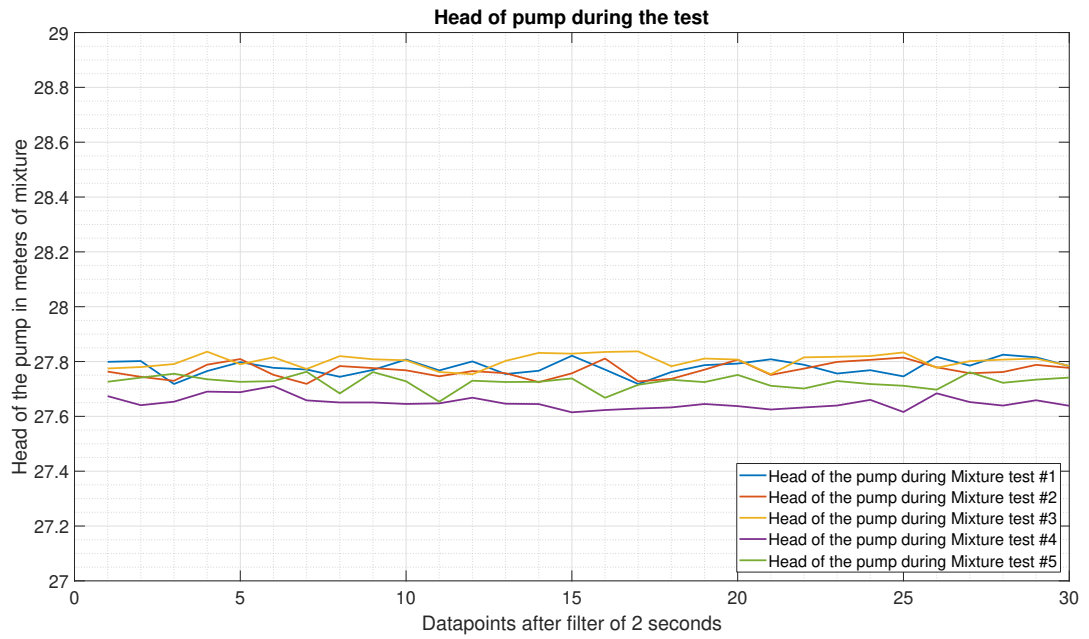


Figure 4.6: Evaluation of test data during an experiment, the fluctuation of u' around $\bar{u}$, for the head.

Logging the following signals

The data from each experiment is logged in Labview, converted and averaged in Matlab. The average values of each test are gathered and stored in Excel. Here a dataset is created for each material, which is used by Matlab to plot and analyse the data. Each configuration contains the following parameters.

- Flow rate
- Pressure difference over the pump
- Pressure differences over Ascending & Descending U loop sections
- Density of mixture (determined from pressure differences U loop)
- Concentration of solids in the mixture (determined from pressure differences U loop)
- Temperature of the mixture
- Power of the electro drive

4.5. EXPECTATIONS FOR THE EXPERIMENTS BASED ON PREVIOUS RESEARCH

Based on both the literature and talks with people from the industry the expectation is that the Stepanoff equation is still valid for the small scale experiments with quartz material. Commercial dredging companies still use this equation, sometimes with a correction for a different size dredge pump.

Another formulation expected to be accurate is the equation from Wilson and Sellgren 2017. This formulation is used in recent research as the method of calculating the solids effect. There are even researchers further improving this formulation see Chapter 3.1.3. For quartz materials with varying impeller sizes, this formulation should be accurate. This formulation is also recommended in the ANSI/HI centrifugal slurry pump standard.

The last formulation expected to be interesting is the Engin and Gur from 2003. This equation is based on a large amount of experimental data and has a reasonable accuracy according to [Engin & Gur, 2003]. A potential downfall for this formulation is the large number of different experiments with different materials and sizes gathered through four decades. This could affect the formulation which could result in a less accurate prediction of the solids effect.

After all data points are collected and processed, the accuracy of these theories is checked by plotting the data points against the calculated values of the corresponding formulas. The experimental data will be analysed and a conclusion will be drawn after this.

4.6. THEORETICAL CALCULATIONS FOR THE EXPERIMENTS

Before the experiments are conducted a prediction is made with Stepanoff's formulation, Equation 3.1. The working points of the centrifugal slurry pump are determined and a first estimation is given of what to expect during the experiments. This is done to be sure that the pump has enough power to conduct all experiments. It is also important to check if the settling limit of the mixture will be reached. If this happens the system will clog and the system will be down for a large period of time.

First, the slurry loop is measured and the hydraulic losses are inventoried. The water resistance in the pipe is determined with the Darcy Weisbach Equations 4.6 and 4.7. With the Furboter assumption, Equation 4.8, is the pipe resistance for the mixture determined for each flow rate from 0 to 900 m³/h. The critical velocity for settling is determined with the equation Jufin and Lopatin 1966, Eq. 4.9. This theory was the most conservative and therefore a good criterion to prevent clogged lines.

$$\Delta p_{totalloss,f} = \left(\lambda_f \frac{L}{D_{pipe}} + \zeta \right) \frac{1}{2} \rho_f V_f^2 \quad (4.6)$$

$$\Delta p_{totalloss,m} = I_m \rho_f g L + \zeta \frac{1}{2} \rho_m V_m^2 \quad (4.7)$$

$$I_m = I_f + S_{kt} \frac{C_v}{V_f} \quad (4.8)$$

$$V_{dl} = 8.3 D_{pipe}^{1/3} (C_v \psi^*)^{1/6} \quad (4.9)$$

Combining the equations above result in the pressure losses for clear water and the pressure losses for the transported mixtures. The next step to obtain the pump curves is to determine the pressure head for each flow rate. The clear water curves are provided by Damen Dredging, the supplier of the pump, and are shown in Appendix F. These are the curves of 900, 1100, 1300, 1500 rpm. The curves are plotted against the pipe resistance of water to verify the working points when pumping water. Data from the slurry lab is available to check the calculations. There is a reasonable match and this verifies that the calculations for water are correct.

After confirming the Matlab script, the various RPM settings with corresponding pressures are evaluated against the materials and concentrations from the test plan. The first check was with the 900 rpm line. The 900 rpm produces not enough pressure to maintain suitable working points above the critical settling velocity. This means the possibility of blockage due to clogging is high.

Second is the 1100 rpm line examined. Here all the working points are above the critical settling velocity for the first 3 materials. The optional fourth material is also above the critical velocity, but the 140% QBEP isn't reached for higher concentrations.

The 1300 rpm line provides all the working points above the critical settling velocity for all materials. But the velocities for this rpm setting are considerably higher. This produces more wear on the system and reduces the lifetime of the setup. After discussing with the SSB there is chosen to conduct the experiments at the 1100 rpm line, this to prevent excessive wear due to higher velocities in the system.

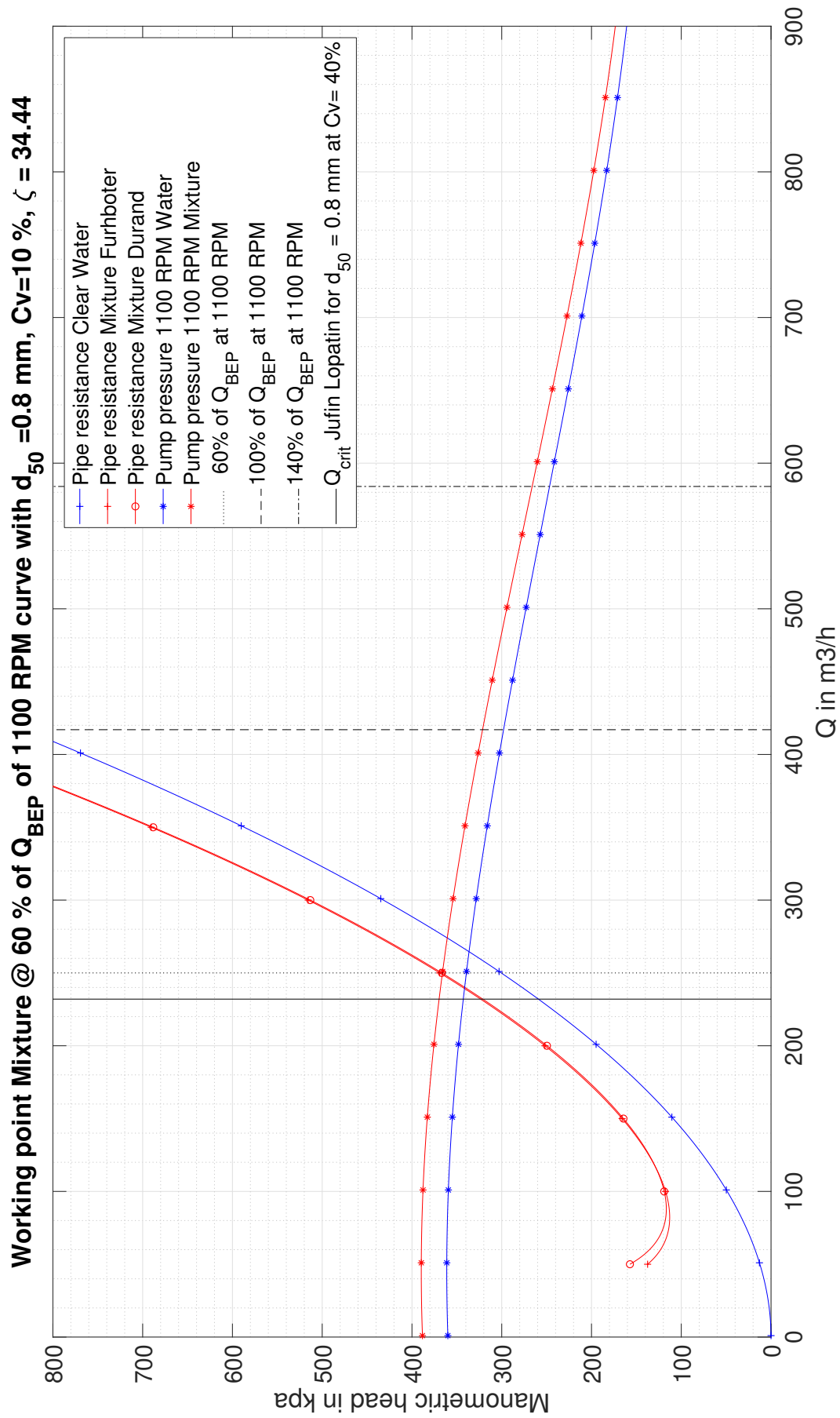
The pump curves for pumping a mixture is calculated by Equation 2.3.

$$p_{man;m}(Q) = p_{man;w}(Q) \cdot \left(\frac{\rho_m}{\rho_w} \right) \cdot H_r(Q)$$

Where the $p_{man,w}$ is a fitted formula based on data from Damen. The H_r is the Stepanoff formulation in this case, determined for each material and concentration. The required pump power is determined by using the hydraulic power of the pump divided by an approximated efficiency, η_w , of the pump in the operational range of the flow rate.

$$P_{man,m} = \frac{P_{hydraulic,m}}{\eta_m} = \frac{\rho_m}{\rho_w} \cdot \frac{Q_w \cdot p_{man,w} \cdot H_r}{\eta_w \cdot H_r} = \frac{\rho_m}{\rho_w} \cdot \frac{Q_w \cdot p_{man,w}}{\eta_w} \quad (4.10)$$

With all equations combined the pipeline resistance and pump curves are plotted. The working points are the points where a pump curve crosses the pipe resistance lines. This is the point where the system finds an equilibrium in available pressure, flow rate and pipeline resistance. In Figures 4.7 till 4.12 are the working points illustrated for Dorsilit 7 with 10 % and 30 % concentration for 60%, 100% and 140 % QBEP. This procedure is the same for all materials and all concentrations. An overview of all working points is included in Appendix G.

Figure 4.7: Working point $d_{50} = 0.8$ mm, $C_v = 10\%$, $60\%Q_{BEP}$, additional hydraulic losses ζ

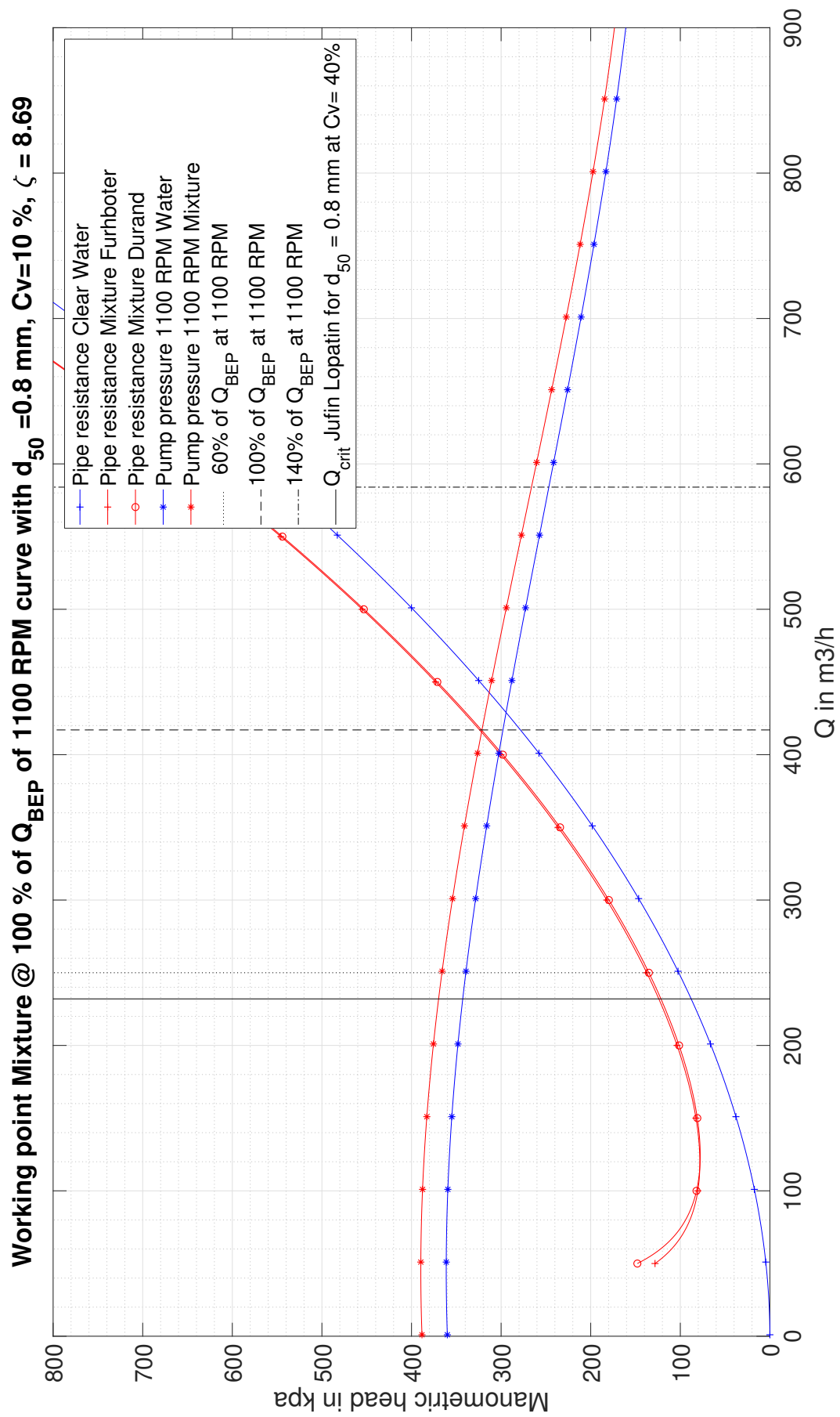
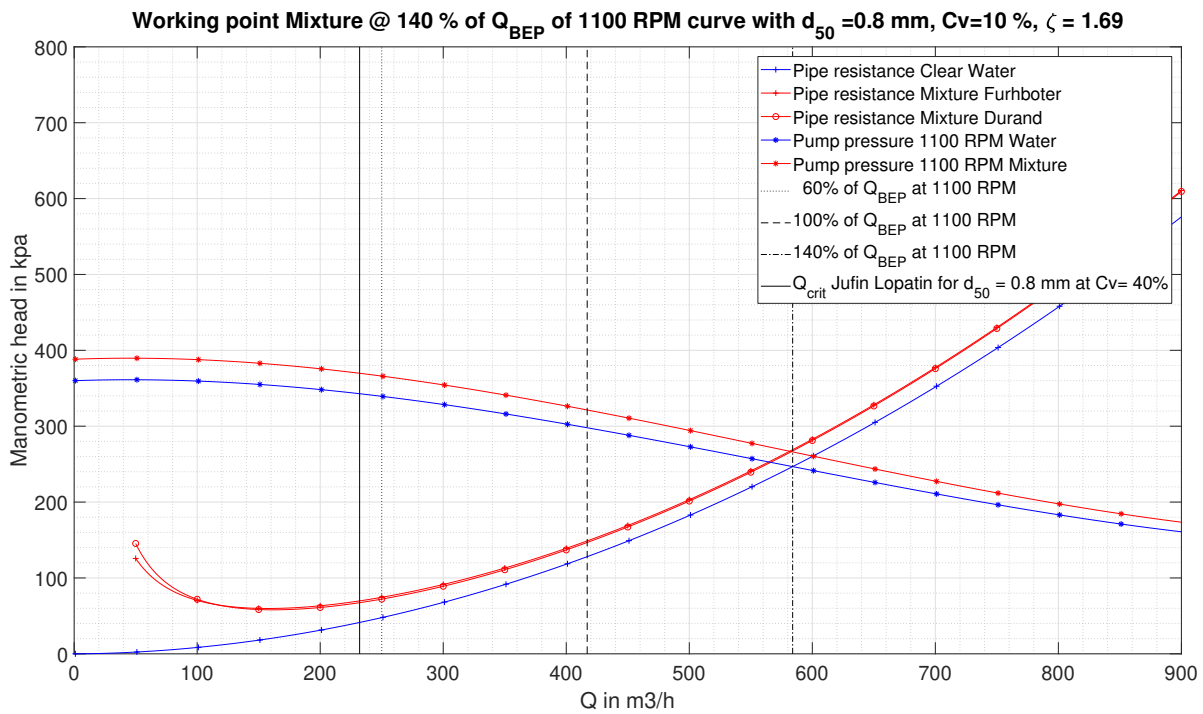
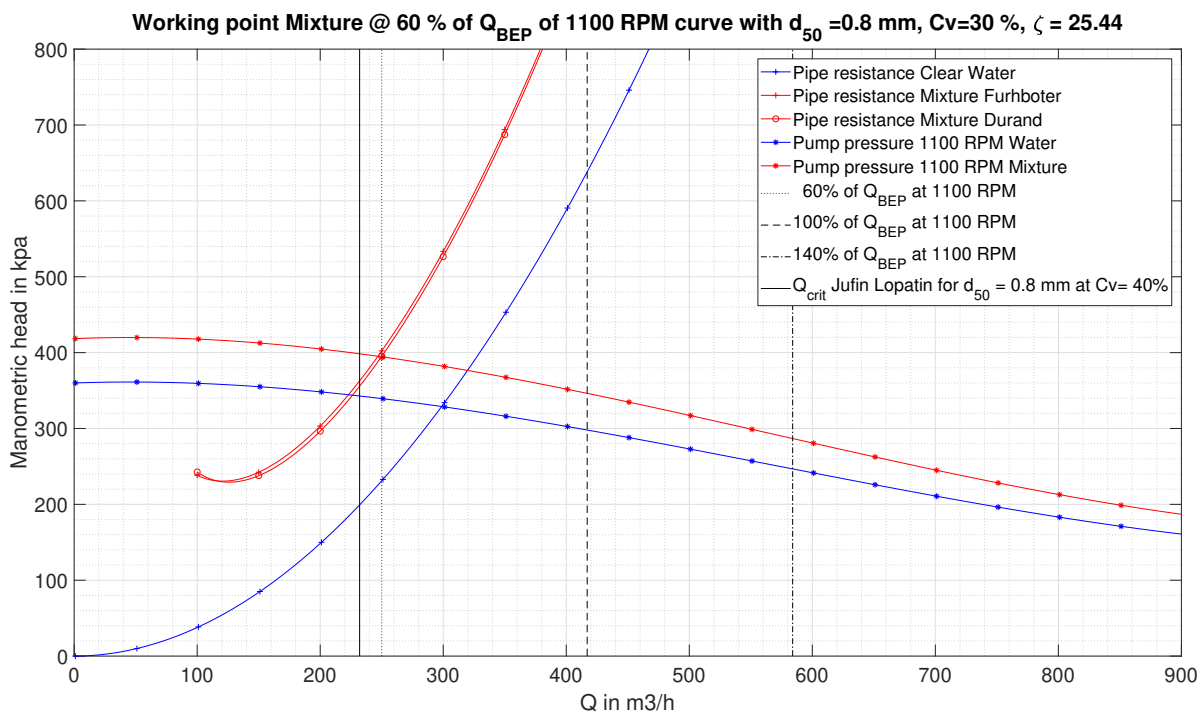


Figure 4.8: Working point $d_{50} = 0.8$ mm, $C_v = 10\%$, $100\%Q_{BEP}$, additional hydraulic losses ζ

Figure 4.9: Working point $d_{50} = 0.8$ mm, $C_v = 10\%$, $140\%Q_{BEP}$, additional hydraulic losses ζ Figure 4.10: Working point $d_{50} = 0.8$ mm, $C_v = 30\%$, $60\%Q_{BEP}$, additional hydraulic losses ζ

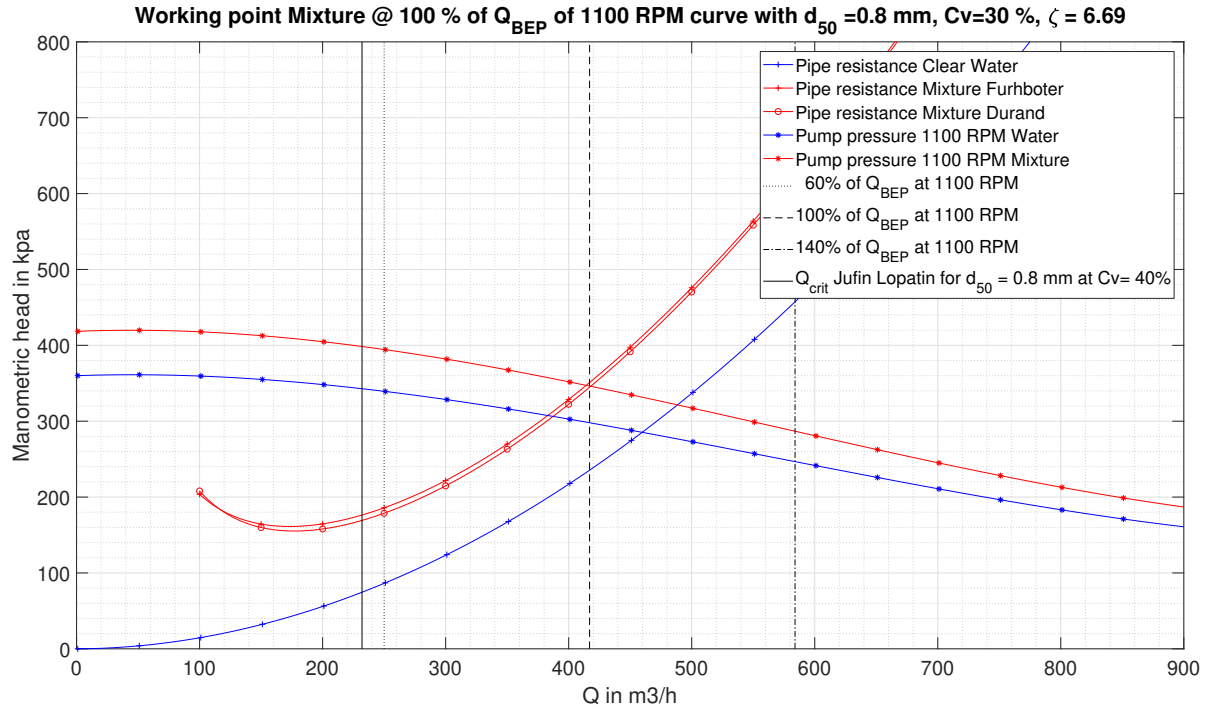


Figure 4.11: Working point $d_{50} = 0.8$ mm, $C_v = 30\%$, $100\%Q_{BEP}$, additional hydraulic losses ζ

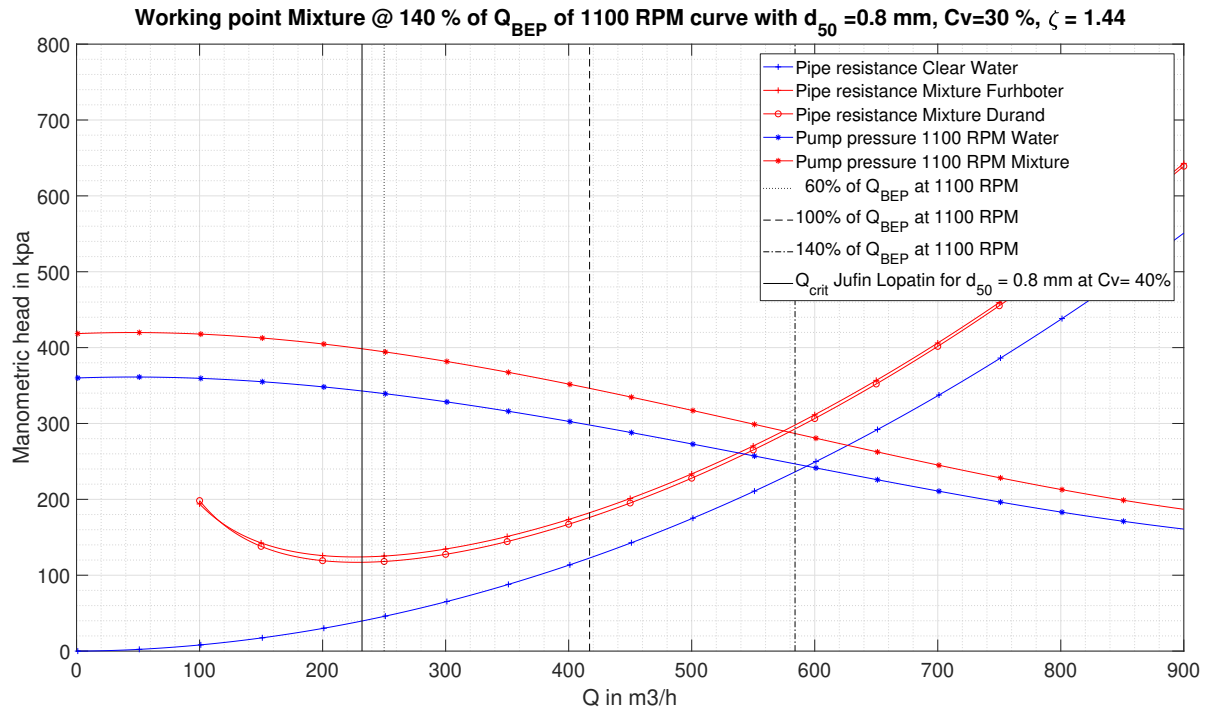


Figure 4.12: Working point $d_{50} = 0.8$ mm, $C_v = 30\%$, $140\%Q_{BEP}$, additional hydraulic losses ζ

5

Experiments and Results

In the previous chapter the experimental plan was explained, in this chapter the experiment results are presented and the data is analysed. First, the particle size distributions are determined for the materials. This is to determine the d_{50} used in the formulations. Then, the clear water results are shown, which form the reference for the mixture tests. Furthermore, the experiments are summarised, important information is provided regarding the specific tests and the obtained results are shown with preliminary conclusions. Also, the required power and the efficiency of the pump during the experiments are presented.

In the following figures the data points are spread slightly. After analysing this spread it appears that all data points are within 3 times the standard deviation. This is an acceptable spread of data points and consequently, all data points are used for the analyses in Chapters 5 and 6.

5.1. DETERMINE THE PARTICLE SIZE DISTRIBUTION

To determine the PSD for the materials is a sieve shaker used. This machine separates the particles in the different sieve sizes. In Figure 5.1 is a sieve shaker shown. To determine the PSD a representative sample is necessary. Due to the limited quantity of solids per sieve test of approximately 300 grams, there is chosen to test at least 5 samples. From these 5 samples, a PSD curve is determined. This is done before and after the experiments.

In Appendix E all sieve graphs and quantitative results are provided regarding the PSD. In the following sections only the d_{50} value is mentioned including the PSD curve. These are determined with the use of the SANDY Matlab model [Ruiz-Martínez *et al.*, 2016]. This model is capable of estimating the size distribution from a sieve analysis accurately and provides the d_{50} value as a number. This prevents errors when determining from graphs.



Figure 5.1: Haver EML 200 Premium Sieve shaker with TwinNuts

5.2. CLEAR WATER TESTING

In Figure 5.2 all clear water data points are presented. All mixture tests are compared to the results shown in this figure. It also shows the wear of the impeller, which is insignificant, based on the observation that the values obtained in the first tests are similar compared to the last tests conducted.

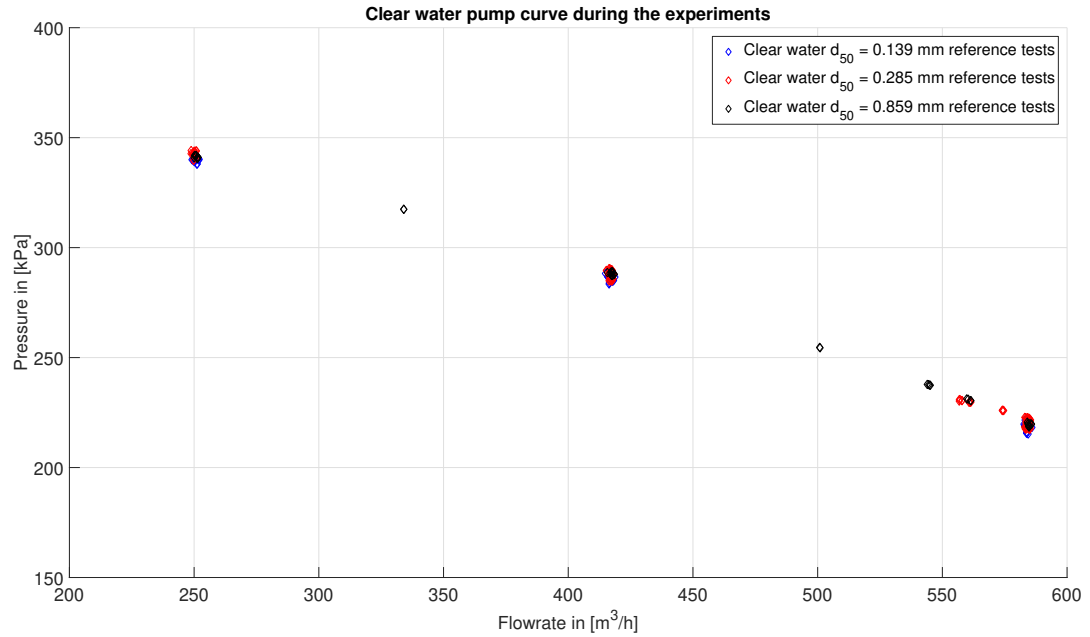


Figure 5.2: Clear water pump curve during all Q/Q_{BEP} ratios and materials.

In Figure 5.3 the pump curve is shown according to the official Damen Specification sheet. When the data points are compared for the blue line, the measured pressures are within reasonable range of the specified pressures. The Q/Q_{BEP} ratios are also shown with the vertical dotted lines. The Q_{BEP} flow rate at 1100 rpm is at 417 m³/h.

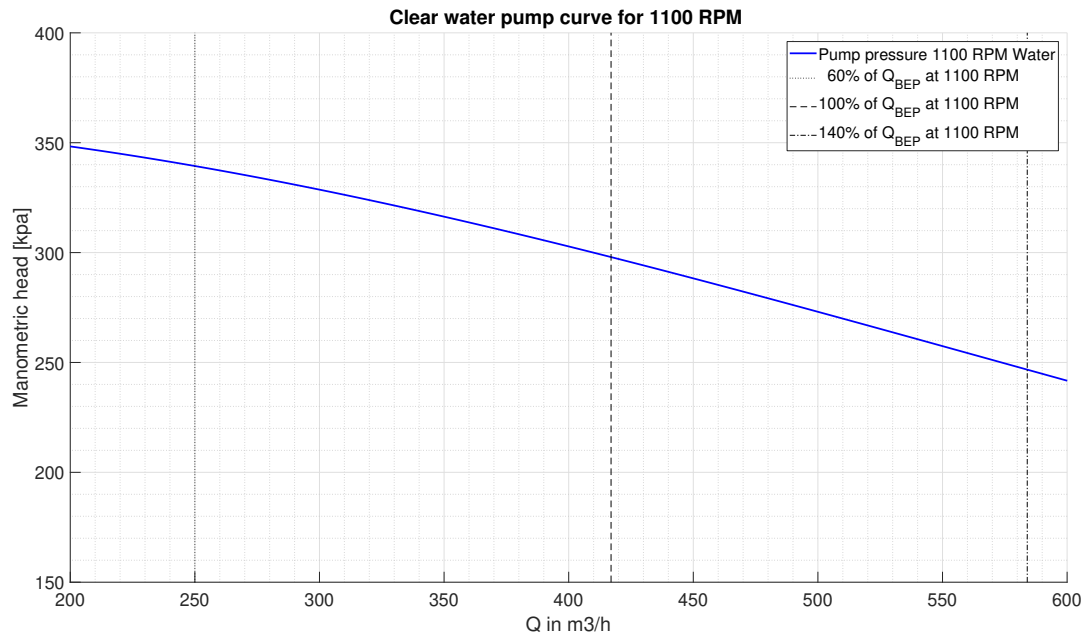


Figure 5.3: Pump curve for 1100 RPM according to the official Damen Specifications

In Figure 5.4 the efficiency of the pump is shown for the clear water tests during the experiments. Here it is confirmed that the best efficiency flow rate for the 1100 RPM setting is at 417 m³/h.

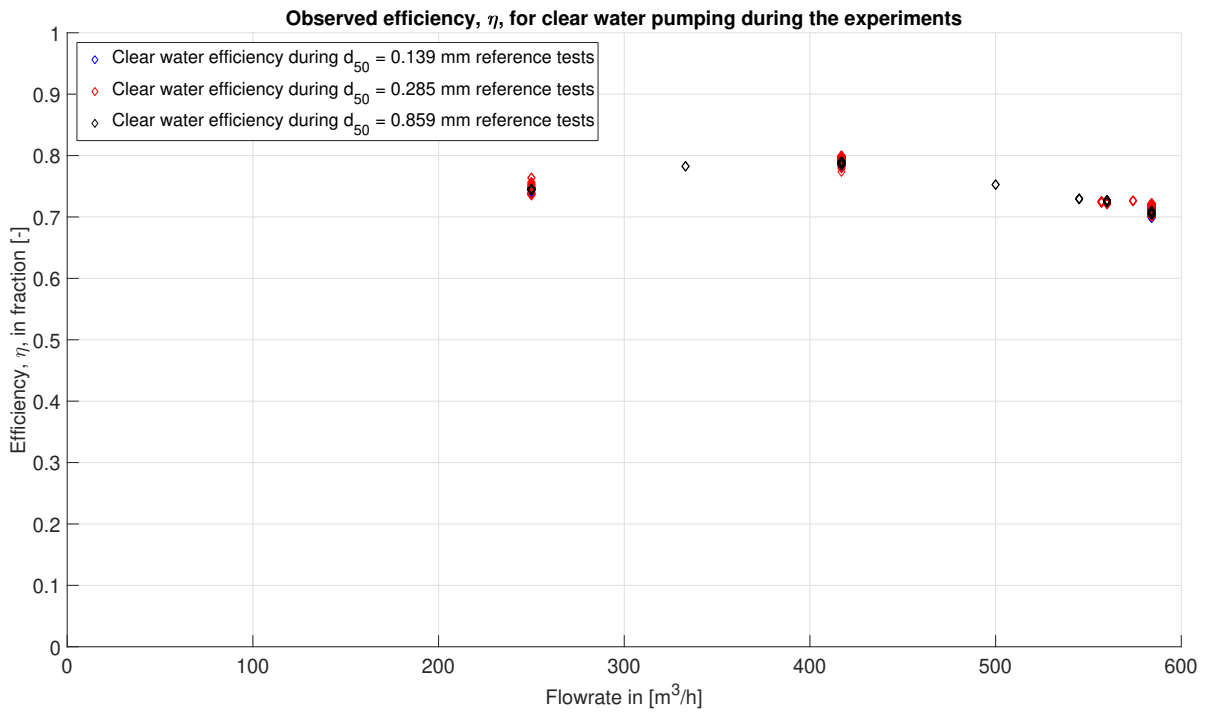


Figure 5.4: All clear water data shown for all Q/Q_{BEP} ratios and materials.

5.3. GEBA SAND

The first material tested is Geba Sand, this is the finest material in the test plan. In the following sections, the PSD is given, the execution of the experiments is discussed and the results of this material are presented.

5.3.1. PSD GEBA

As mentioned previously before and after the experiments with Geba samples are taken. These are analysed with the help of the sieve shaker and the following results are obtained. In Figure 5.5 the curves before (green) and after (blue) are plotted. Here it is shown that the grain size of the samples taken after the experiments are slightly smaller compared with the samples taken before the tests.

Before the test, a d_{50} value of 0.157 mm is determined after 1800 grams taken from at least 2 different bags. After the tests, a d_{50} value of 0.139 mm is determined after 2100 grams taken during different phases of emptying the storage tank. There is a large difference between the values of the supplier and obtained from the sieve analysis at the TU Delft. Both values exceed the d_{50} value provided by the supplier of 0.103 mm. It is chosen to specify the d_{50} for the Geba sand experiments as 0.139 mm for further calculations.

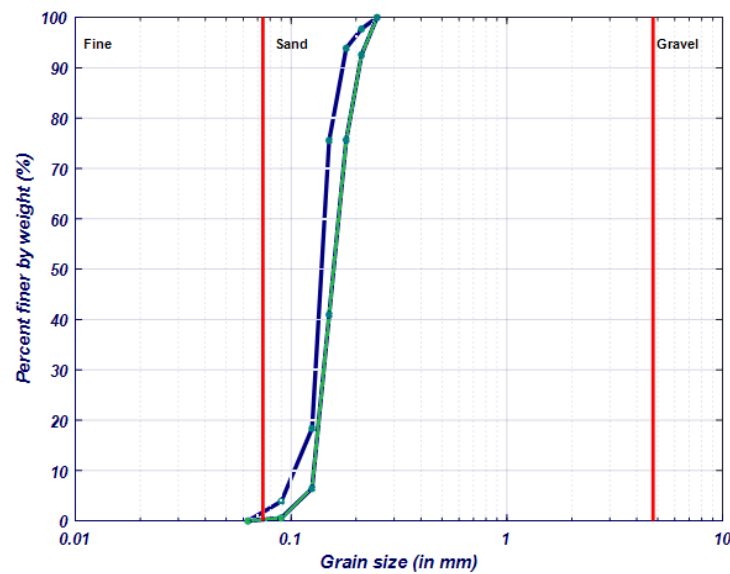


Figure 5.5: Particle size distribution of Geba - before (green) and after (blue) the experiments

In Tables E.1 and E.2 the measurement results of the sieve process are listed. All the small sieve batches are combined and together they form the PSD as illustrated in Figure 5.5.

5.3.2. SPECIFICS IN THE GEBA SAND EXPERIMENTS

During these tests with the Geba material problems occurred with the pressure sensors. The pressure tubes are very likely to clog due to the very fine particles. This prevents the sensors from measuring the correct pressure. This results in incorrect density, concentration or pump pressure measurements. Also, the differential pressure sensors could clog with these very fine particles which result in serious problems.

Another problem experienced during the Geba sand tests was excessive wear on the gate valve which controls the flow rate of the mixture. This gate valve was located at the red number 5 of Figure 4.1. The gate valve was completely worn out. Pictures of these damages are found in Appendix I shown in Figures I.5 and I.6. After consulting with the lab staff, Ed Stok stated that gate valves are not designed for this purpose so it is better to replace the gate valve by a butterfly valve. Butterfly valves are designed for controlling flow rates and can handle the excessive wear better.

5.3.3. RESULTS OF TESTING WITH GEBA SAND - ($d_{50} = 0.139\text{mm}$)

In this section, the results of the experiments with Geba sand are presented. First, the different flow rates are evaluated against the selected theories. The models are indicated in; Red for Stepanoff 1965, Dark blue for the Wilson and Sellgren 2017 and Green for the Engin and Gur 2003 models. Additionally an adapted Stepanoff formulation is included in light Blue. This formula is adjusted according to the Wilson and Sellgren 2017 method for the impeller influence and adjusts the 0.2667m impeller (10,5 inch) to the 0.4m test set up. After this, the accuracy of each formulation is determined with the goodness of fit, R^2 , values. Also, a comparison of the solids effect is made against the different flow rates.

Results of testing at multiple flow rates with Geba sand - ($d_{50} = 0.139\text{mm}$)

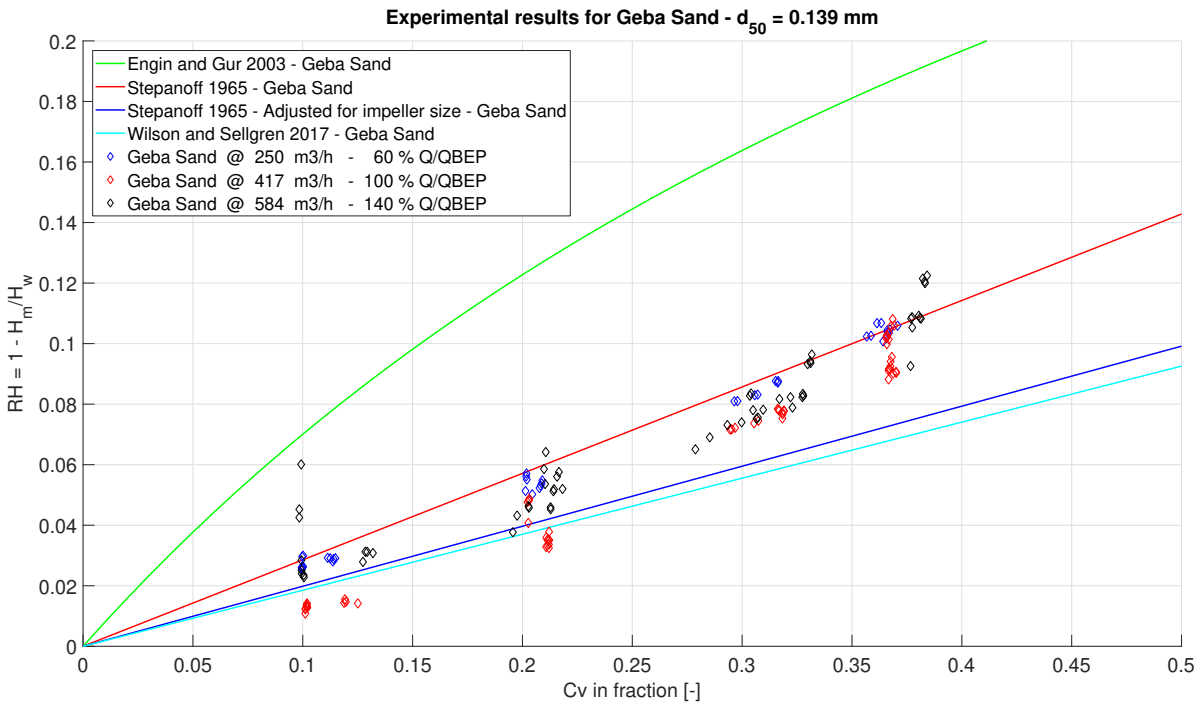


Figure 5.6: Experimental results of R_H for Geba sand for all Q/Q_{BEP} ratios with various concentrations

As shown in Figure 5.6 the blue data points obtained from the Geba experiments for 60 % Q/Q_{BEP} , 250 m³/h, are nicely grouped along the red line. According to this plot the Stepanoff formulation would be the best theory for this specific configuration. The red data points obtained from the Geba experiments for 100 % Q/Q_{BEP} , 417 m³/h, are shifting between the blue and red lines. Volumetric concentrations of 10% and 20% are close to the Wilson and Sellgren 2017 theory, while the 30% and 40% are shifting toward the Stepanoff theory. Here it is not clear which formula is the better choice. The black data points obtained from the Geba experiments for 140 % Q/Q_{BEP} , 584 m³/h, are nicely grouped along the red line.

Based on this plot the formulation of Stepanoff 1965 is the most accurate theory over the different concentrations while pumping Geba sand. In this plot, it is observed that the overall concentration trend is linear with the volumetric concentration, C_v . Both the Stepanoff 1965 and Wilson and Sellgren 2017 theory are linear dependent of the C_v . While the formulation of Stepanoff overall is the better fit for this data, the red 100% Q/Q_{BEP} data points for the lower concentration are better estimated by Wilson and Sellgren 2017. The adjusted Stepanoff formulation is slightly below the Wilson and Sellgren 2017 line and is less accurate than the original Stepanoff formulation

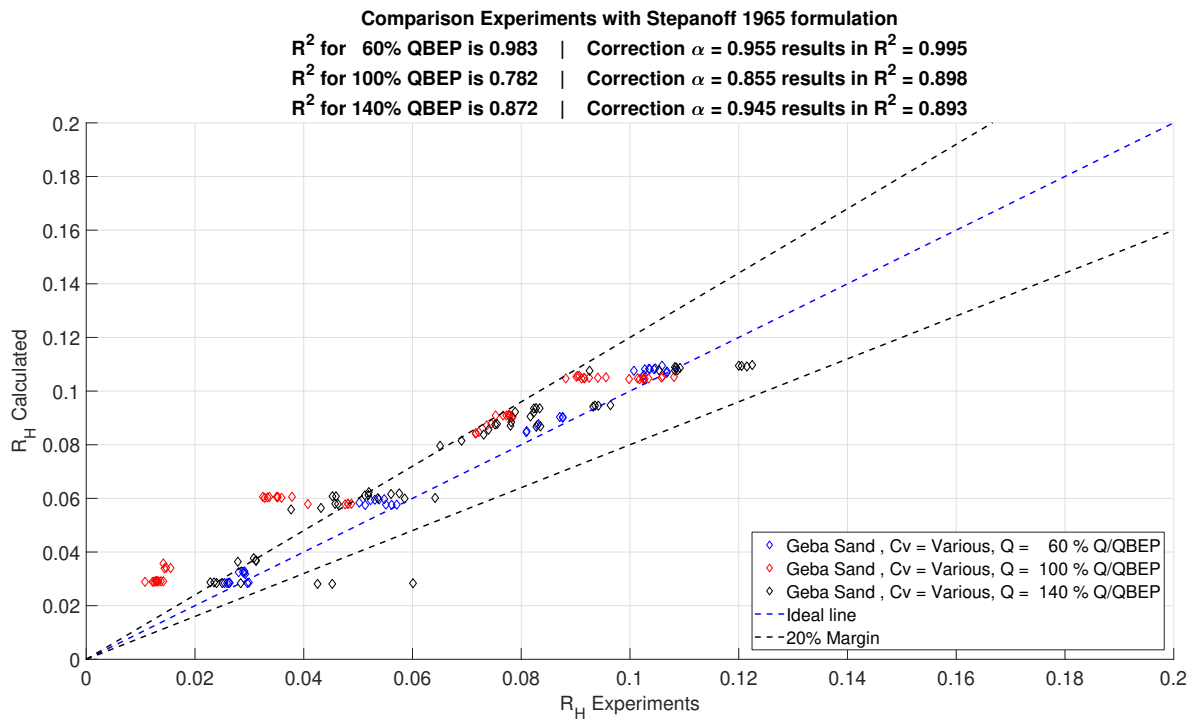
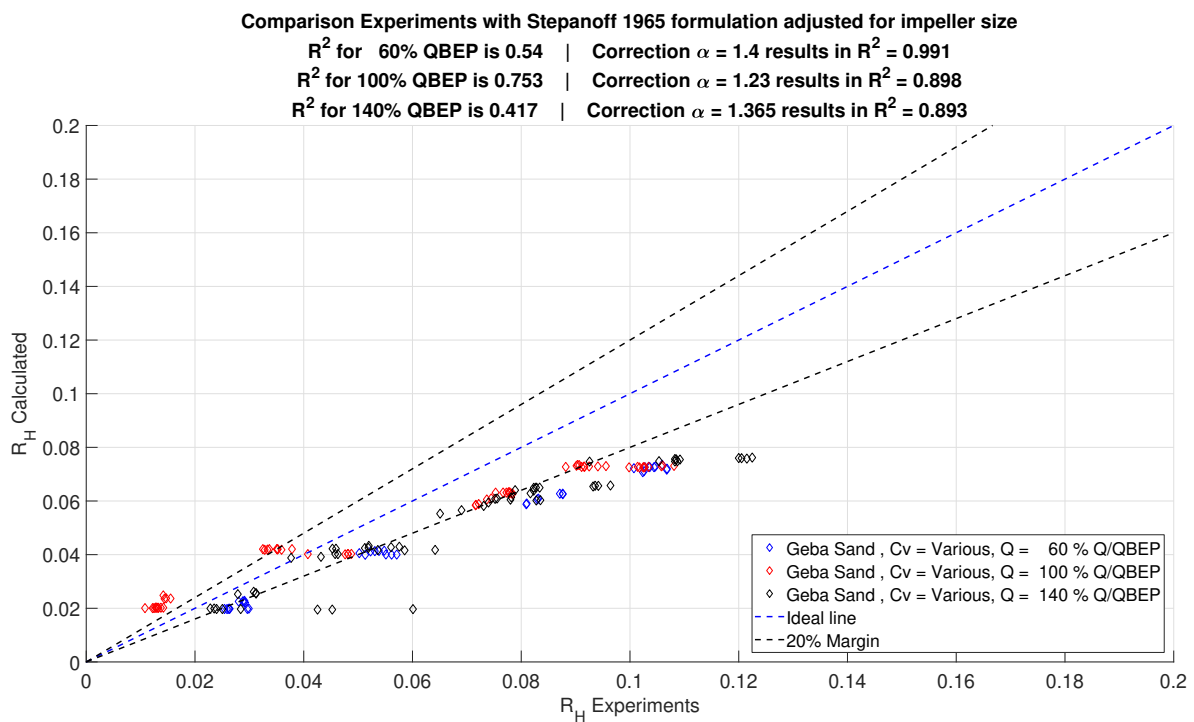
R^2 values with different flow rates with Geba sand - ($d_{50} = 0.139mm$)

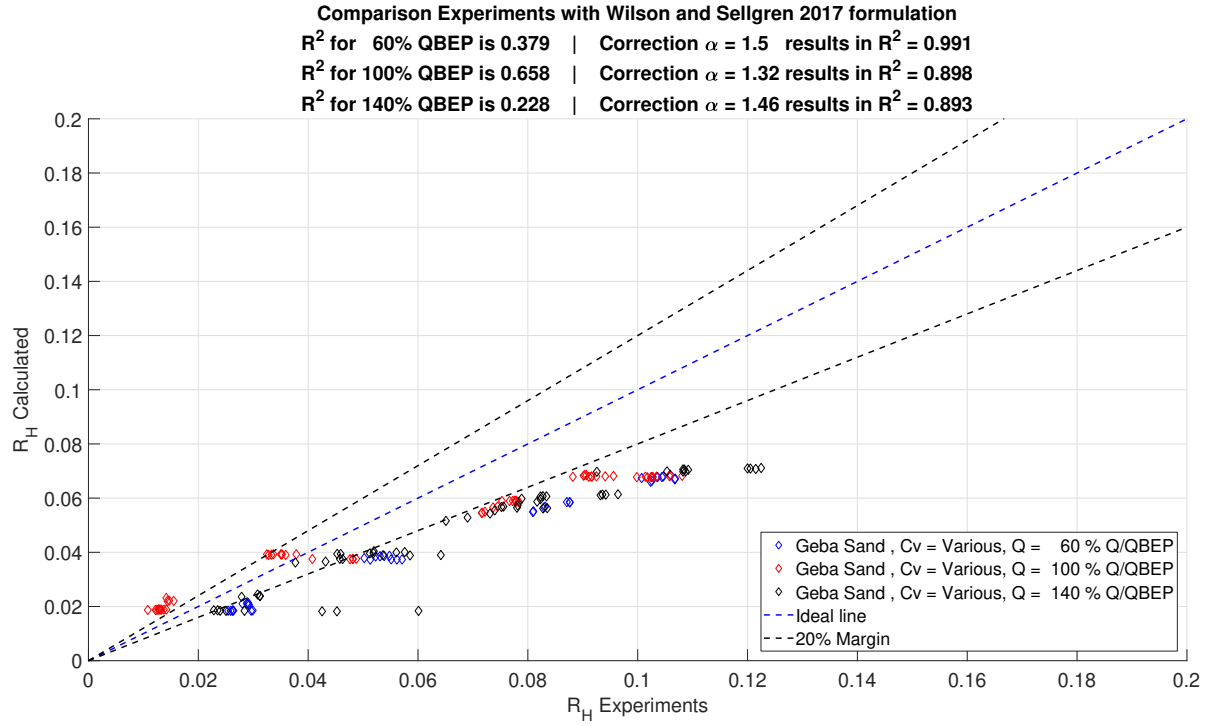
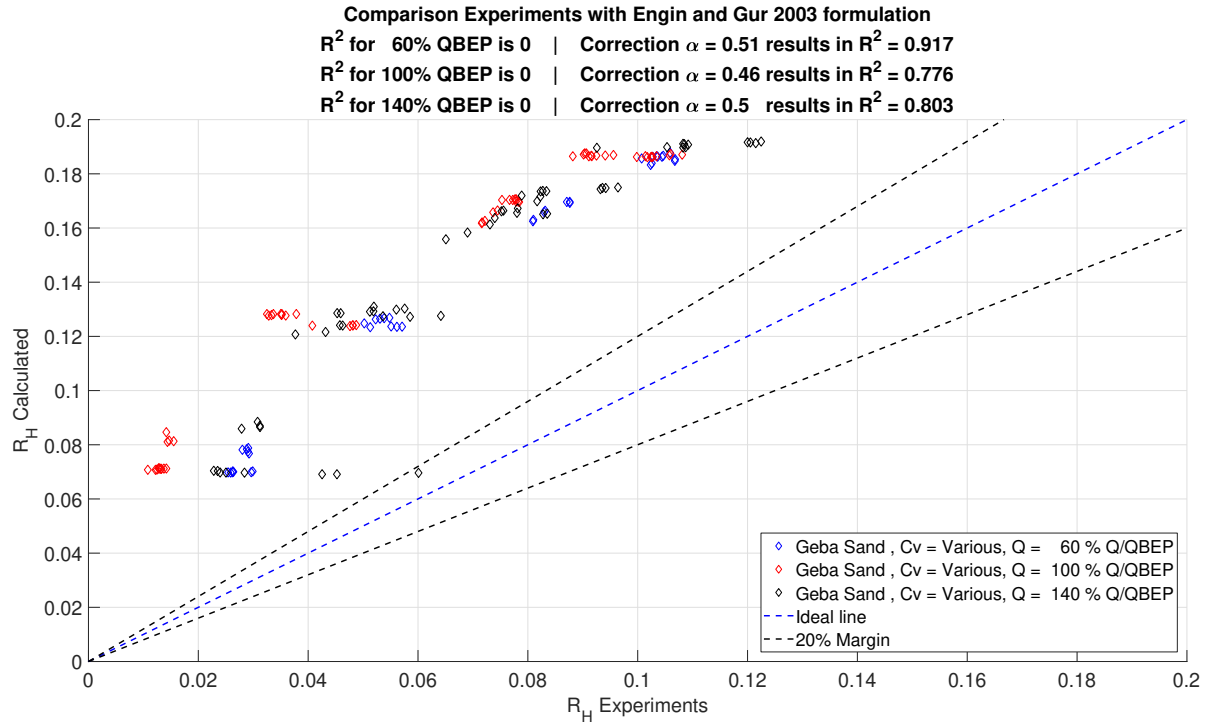
The R^2 values with corresponding plots are provided in Figures 5.7, 5.8, 5.9 and 5.10. In the R^2 figures the R^2 values are given for each flow rate tested, this to determine the accuracy of the original theories for each flow rate. Here it is clearly visible that the Stepanoff formulation is the best fit for this material and configurations.

For optimisation, there are correction factors, α , introduced which are multiplied with the R_H terms of the theories. With the help of the α factors, the R^2 values are optimised to the values shown on the right side of the figures. This is done similarly as in Section 3.6. In the next chapter the different α factors will be analysed and used for a better formulation of the solids effect. In the following figures Equation 5.1 is used for an optimal result.

$$Hr = 1 - R_H \times \alpha \quad (5.1)$$

When evaluating the optimised R^2 values shown in Figures 5.7, 5.8, 5.9 and 5.10 it is observed that the original Stepanoff, the adjusted Stepanoff and the Wilson and Sellgren theory are equal in goodness of fit, R^2 . The Engin and Gur theory is slightly less accurate after optimisation compared to the others.

Figure 5.7: R^2 for Geba experiments of all C_v and Q/Q_{BEP} ratios compared with Stepanoff 1965Figure 5.8: R^2 for Geba experiments of all C_v and Q/Q_{BEP} ratios compared with Stepanoff 1965 adjusted for impeller size

Figure 5.9: R^2 for Geba experiments of all C_v and Q/Q_{BEP} ratios compared with Wilson and Sellgren 2017Figure 5.10: R^2 for Geba experiments of all C_v and Q/Q_{BEP} ratios compared with Engin and Gur 2003

Required power during experiments

During the experiments, all data from the different sensors are monitored in Labview. The power required by the electro drive to drive the centrifugal pump is not measured by the sensors. The required power at the shaft of the electro drive is read from a display located at the other side of the lab. This is done with the help of the parameter R0032 of the Micromaster display unit, see Figure C.1. In Figure 5.11 the required power for each concentration and flow rate is presented.

The mathematical formulation for the required mechanical power while pumping mixture is given in Equation 2.2. Here it is shown that the increase in required mechanical power is linear related to the increase in density of the pumped mixture. After analysing Figure 5.11 it is observed that the required power is as expected. The data points are following the same trends as the calculated curve, based on the clear water tests, but with a slight margin.

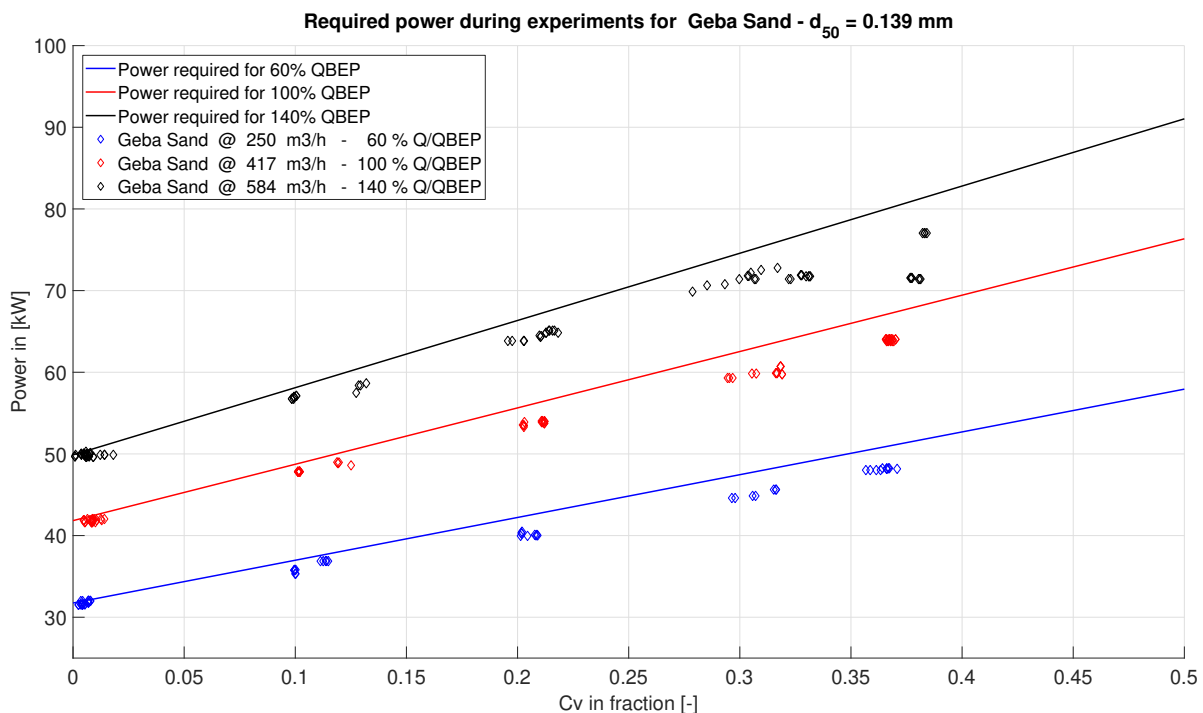


Figure 5.11: Required power while pumping Geba sand, $d_{50} = 0.139 \text{ mm}$

Efficiency of the pump during mixture tests

Also, the efficiency expressed as η is provided. This η is determined by applying Equation 2.8, where the hydraulic power of the mixture is divided by the mechanical power from the pump. In Figure 5.12 the efficiency is presented for all concentrations tested with the different flow rates. Here it is clearly visible that the 100 % Q/Q_{BEP} ratio has the best efficiency overall. There is a decreasing trend observed, which corresponds with the assumption that the efficiency is reduced due to the solids effect. This confirms the statements made in Section 2.5. The clear water efficiency data points near the 0% concentration are included.

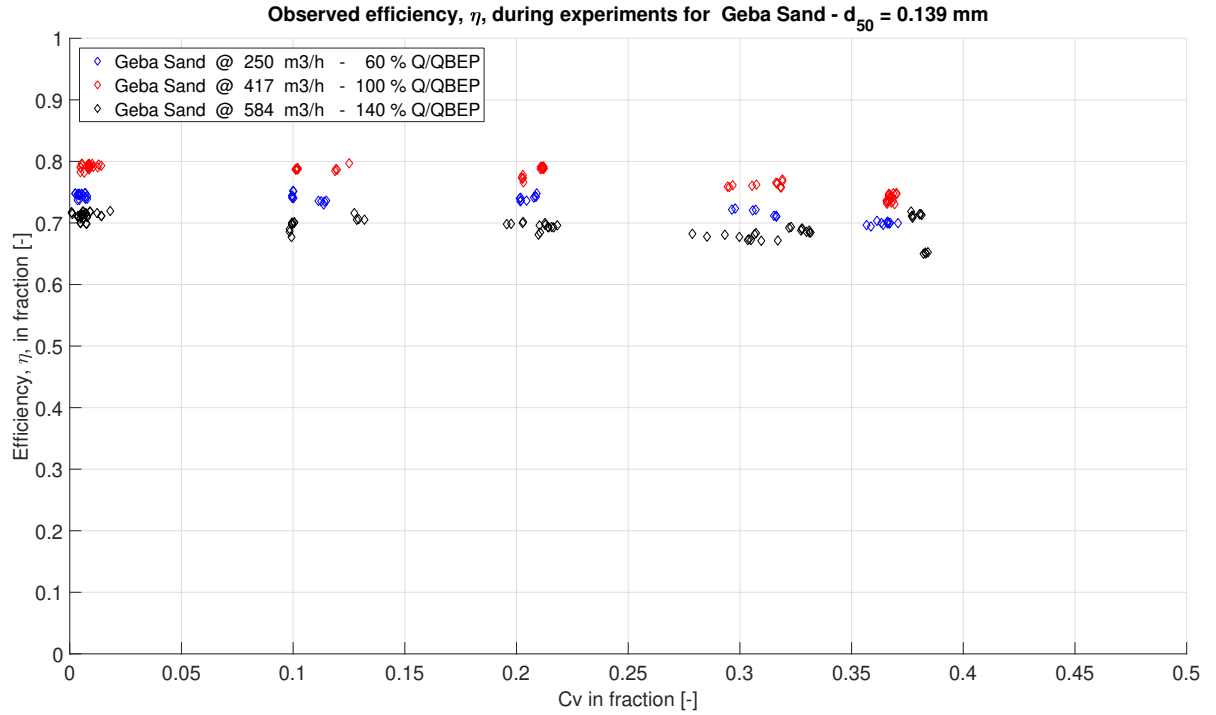


Figure 5.12: Efficiency while pumping mixtures of Geba sand, $d_{50} = 0.139$ mm

5.4. DORSILIT 9

The second material tested is Dorsilit 9, this is the finest Dorsilit material of the tests. In the following sections, the PSD is given, the execution of the experiments is discussed and the results of this material are presented.

5.4.1. PSD DORSILIT 9

As mentioned in the previous section before and after the experiments with Dorsilit 9 samples are taken. These are analysed with the help of the sieve shaker and the following results are obtained. In Figure 5.13 the curves before (green) and after (blue) are plotted. Here it is visible that the grain size of the samples taken after the experiments are almost identical compared with the samples taken before the tests.

Before the test, a d_{50} value of 0.282 mm is determined after 1800 grams taken from at least 2 different bags. After the tests, a d_{50} value of 0.285 mm is determined after 3600 grams taken during different phases of emptying the storage tank. Both values are below the d_{50} value provided by the supplier of 0.33 mm. There is a decent difference between the values of the supplier and obtained from the sieve analysis at the TU Delft. It is chosen to specify the d_{50} for the Dorsilit 9 experiments as 0.285 mm.

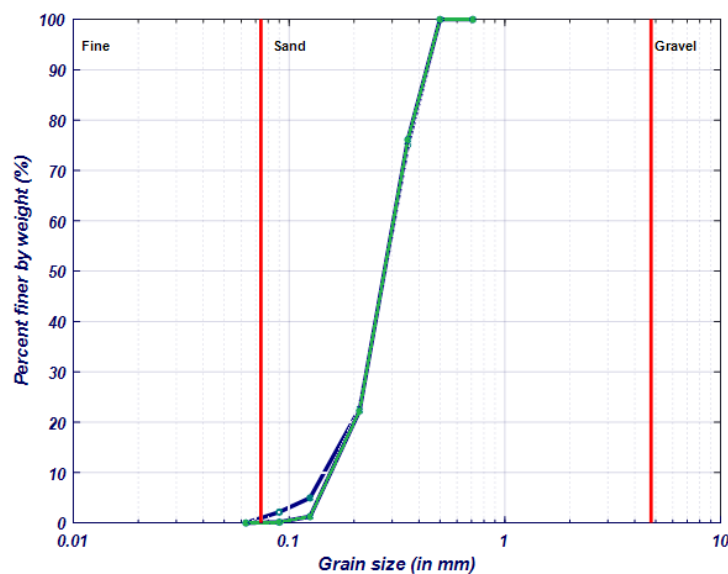


Figure 5.13: Particle size distribution of Dorsilit 9 - before and after the experiments

In Tables E.3 and E.4 the measurement results of the sieve process are listed. All the small sieve batches are combined and together they form the PSD as illustrated in Figure 5.13.

5.4.2. SPECIFICS IN THE DORSILIT 9 EXPERIMENTS

During these tests with the Dorsilit 9 material problems occurred with the slurry loop. The butterfly valve and the pressure tubes were not affected by this material. But multiple bends are worn out which results in leakages. To repair these sections the entire loop needed to be drained and a welder placed reinforcement plates around the leakages. Pictures of these damages are found in Appendix I in Figures I.7 and I.8.

5.4.3. RESULTS OF TESTING WITH DORSILIT 9 - ($d_{50} = 0.285\text{mm}$)

In this section the results of the experiments with Dorsilit 9 are presented, this follows the same procedure as with the Geba experiments. First, the different flow rates are evaluated against the selected theories. The models are indicated in; Red for Stepanoff 1965, dark Blue for the Wilson and Sellgren 2017, Green for the Engin and Gur 2003 and light Blue for the adjusted Stepanoff model. After this, the accuracy of each formulation is determined with the help of the goodness of fit, R^2 , values. Also, a comparison of the solids effect is made against the different flow rates. Compared with the Geba tests more concentrations are tested to obtain a good understanding of the effect of the concentration.

Results of testing with different flow rates with Dorsilit 9 - ($d_{50} = 0.285\text{mm}$)

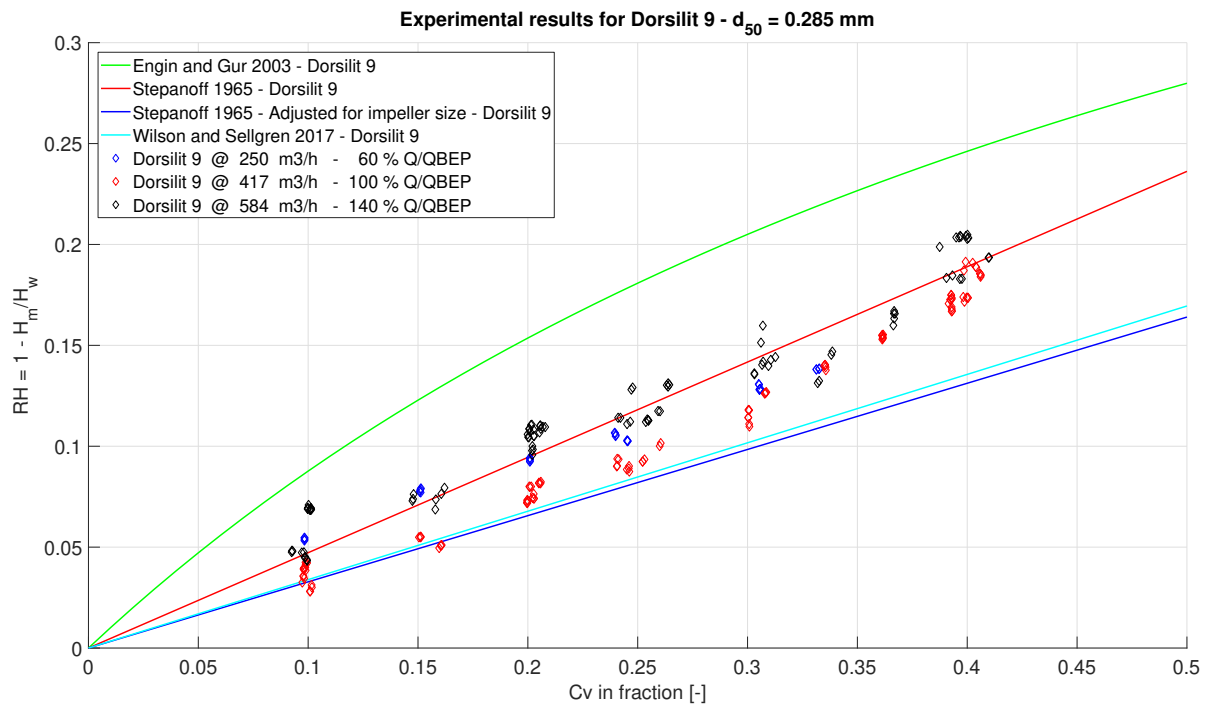


Figure 5.14: Experimental results of R_H for Dorsilit 9 for all Q/Q_{BEP} ratios with various concentrations

As shown in Figure 5.14 the blue data points obtained from the Dorsilit 9 experiments for 60 % Q/Q_{BEP} , 250 m^3/h , are nicely grouped along the red line. According to this plot the Stepanoff formulation would be the best theory for this specific configuration. The red data points obtained from the Dorsilit 9 experiments for 100 % Q/Q_{BEP} , 417 m^3/h , are shifting between the blue and red lines. Volumetric concentrations of 10%, 20% and 30% C_v are close to both the Wilson and Sellgren and the adjusted Stepanoff theory, while above 30% the data points are shifting toward the Stepanoff theory. For concentrations up to 30% C_v the Wilson and Sellgren 2017 theory would be the better fit. The black data points obtained from the Dorsilit 9 experiments for 140 % Q/Q_{BEP} , 584 m^3/h , are grouped along the red line.

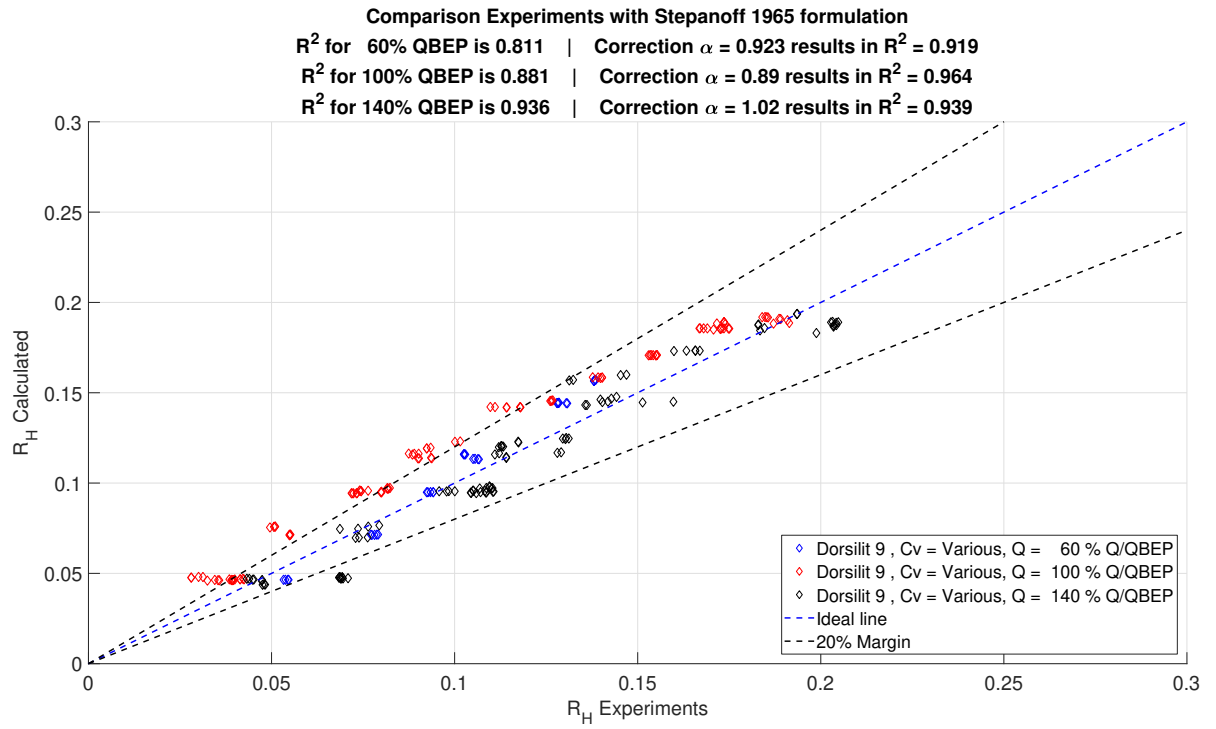
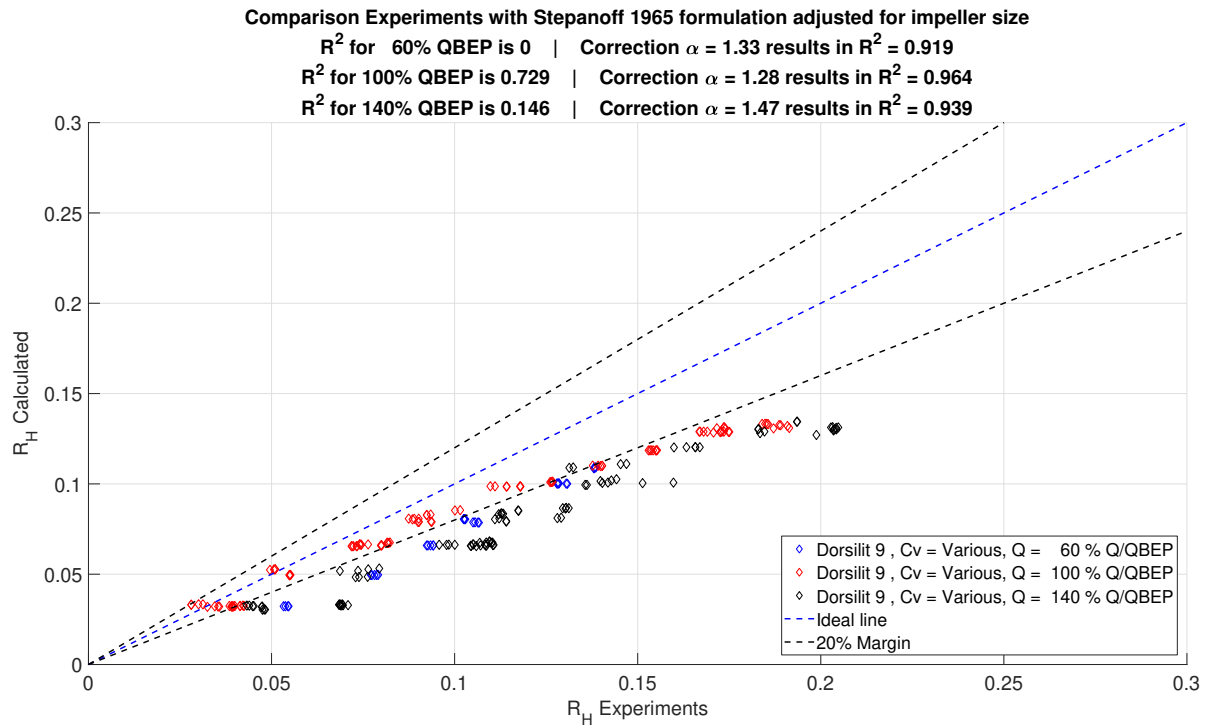
Based on this plot the Stepanoff 1965 formulation is the most accurate model over all the different concentrations and flow rates while pumping Dorsilit 9. In this plot, it is observed that the overall concentration trend is linear with the volumetric concentration, C_v , similar to the previous results from the Geba sand experiments. Interesting to see in this set of experiments is that both the Wilson and Sellgren 2017 theory and the adjusted Stepanoff are accurate for the 100 % QBEP flow rate up until 30 % C_v . When the concentration is increased above the 30%, the 100 % Q/Q_{BEP} flow rate results of R_H are similar to the 140% Q/Q_{BEP} flow rate.

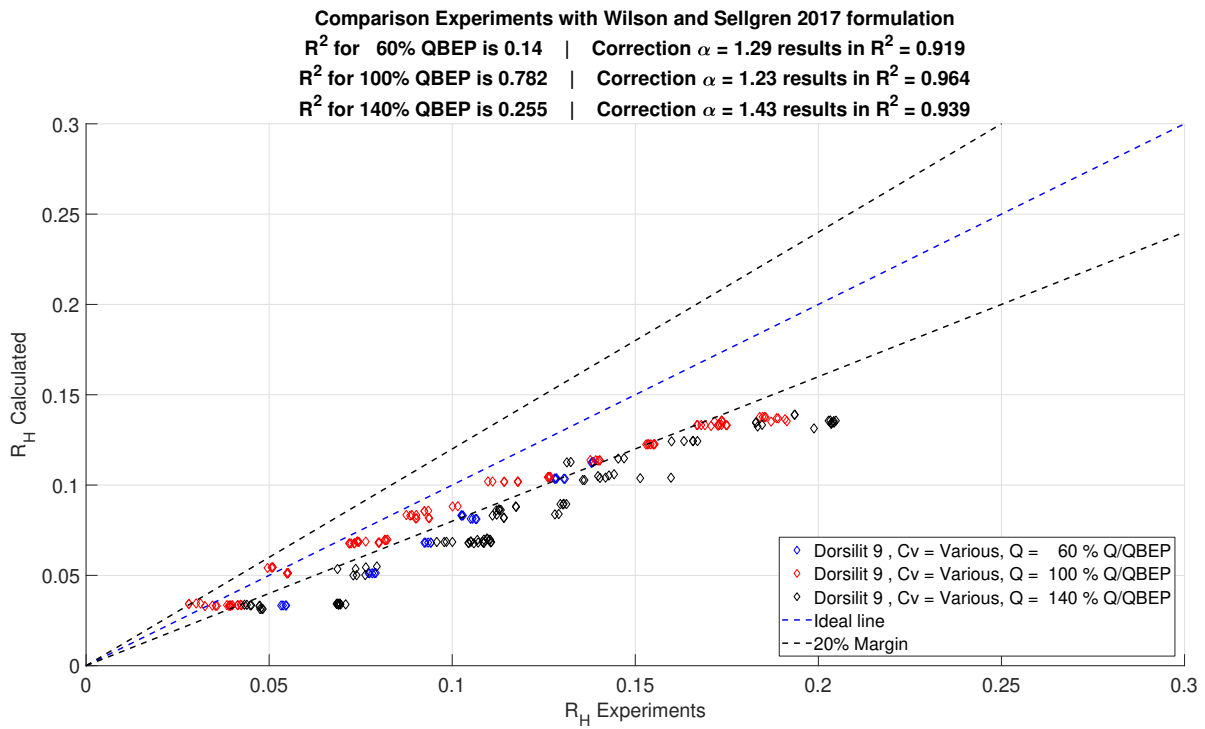
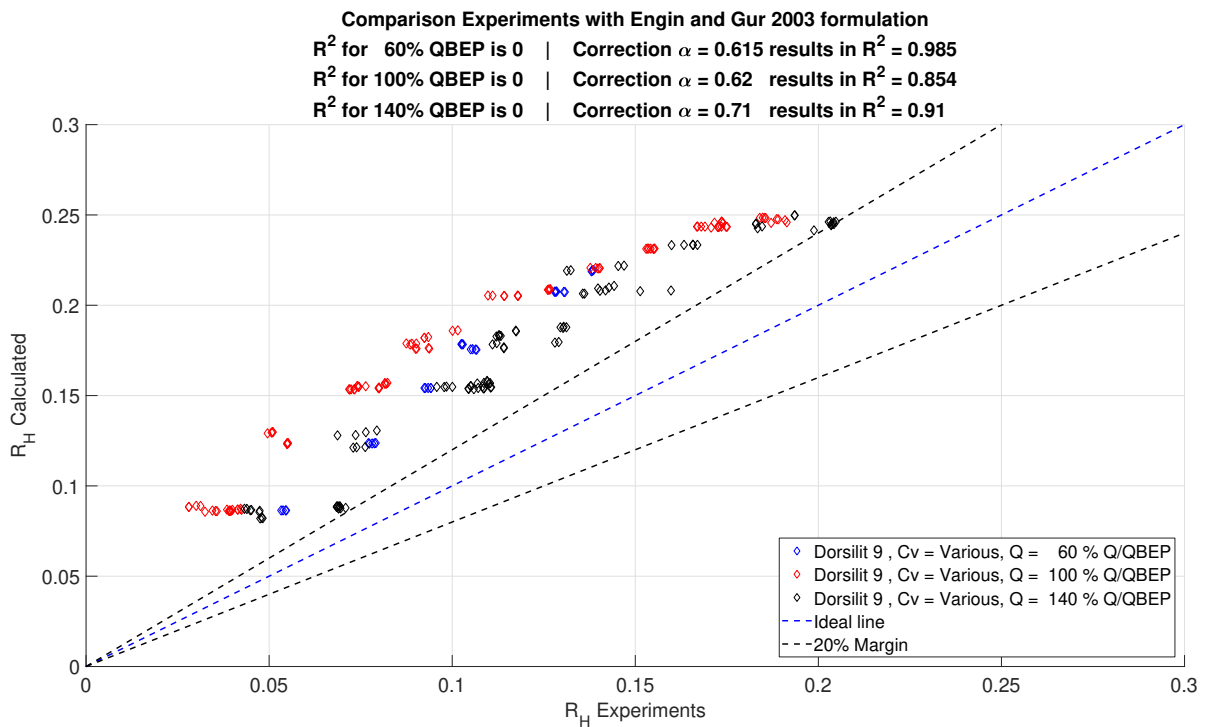
R^2 values with different flow rates with Dorsilit 9 - ($d_{50} = 0.285\text{ mm}$)

The R^2 values with corresponding plots are provided in Figures 5.15, 5.16, 5.17 and 5.18. In the R^2 figures the R^2 values are given for each flow rate tested, this to determine the accuracy of the original theories for each flow rate. Here it is clearly visible that the Stepanoff formulation is the best fit for this material and configurations.

For optimisation, there are correction factors, α , introduced which are multiplied with the R_H terms of the theories. With the help of the α factors, the R^2 values are optimised to the values shown on the right side of the figures. This is done similarly as in the previous section with the Geba material. As stated before, in the next chapter the different α factors will be analysed and used for a better formulation of the solids effect. In the following figures Equation 5.1 is used for an optimal result.

When evaluating the optimised R^2 values shown in Figures 5.15, 5.16, 5.17 and 5.18 it is observed that the original Stepanoff, the adjusted Stepanoff and the Wilson and Sellgren theory are equal in goodness of fit, R^2 . The Engin and Gur theory is slightly less accurate after optimisation compared to the others, especially for the 100 % Q/Q_{BEP} values.

Figure 5.15: R^2 for Dorsilit 9 experiments of all C_v and Q/Q_{BEP} ratios compared with Stepanoff 1965Figure 5.16: R^2 for Dorsilit 9 experiments of all C_v and Q/Q_{BEP} ratios compared with Stepanoff 1965 adjusted for impeller size

Figure 5.17: R^2 for Dorsilit 9 experiments of all C_v and Q/Q_{BEP} ratios compared with Wilson and Sellgren 2017Figure 5.18: R^2 for Dorsilit 9 experiments of all C_v and Q/Q_{BEP} ratios compared with Engin and Gur 2003

Required power during experiments

Similarly as for the previous material is in Figure 5.19 the required power for each concentration and flow rate presented while pumping Dorsilit 9 material. After analysing Figure 5.19 it is observed that the required mechanical power is as expected. The data points, taken from the Micromaster R0032 parameter, are following the calculated curve, based on the clear water tests, but with a slight margin.

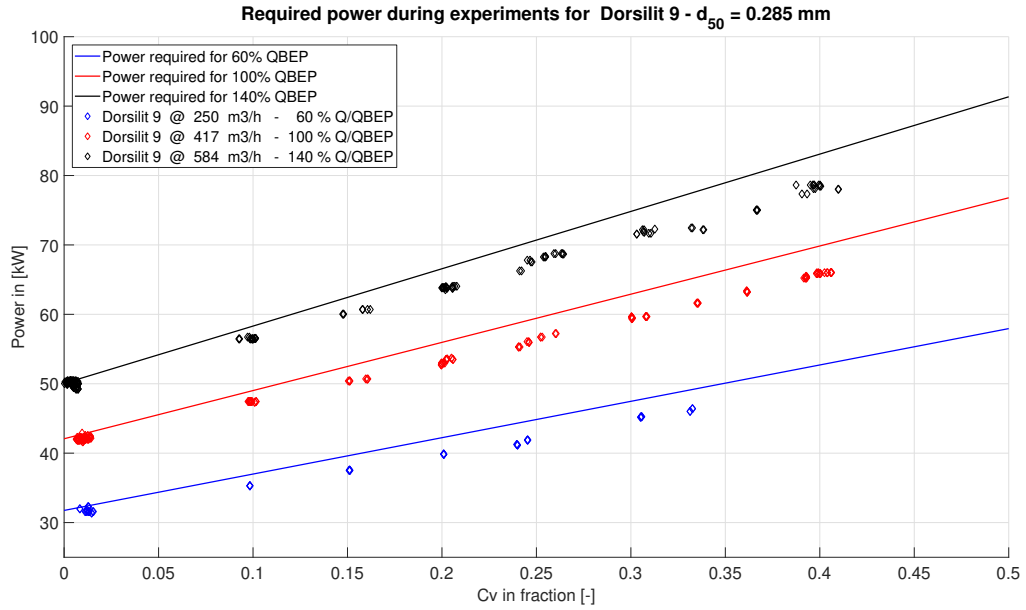


Figure 5.19: Required power while pumping Dorsilit 9, $d_{50} = 0.285 \text{ mm}$

Efficiency of the pump during mixture tests

Also, the efficiency is determined for the Dorsilit 9 material. In Figure 5.20 the efficiency is presented for all concentrations tested with the different flow rates. Here it is clearly visible that the 100 % Q/Q_{BEP} ratio has the best efficiency overall. There is a decreasing trend observed, which is more significant than in Figure 5.12. Similar to Figure 5.12, the clear water efficiency data points near the 0% concentration are included.

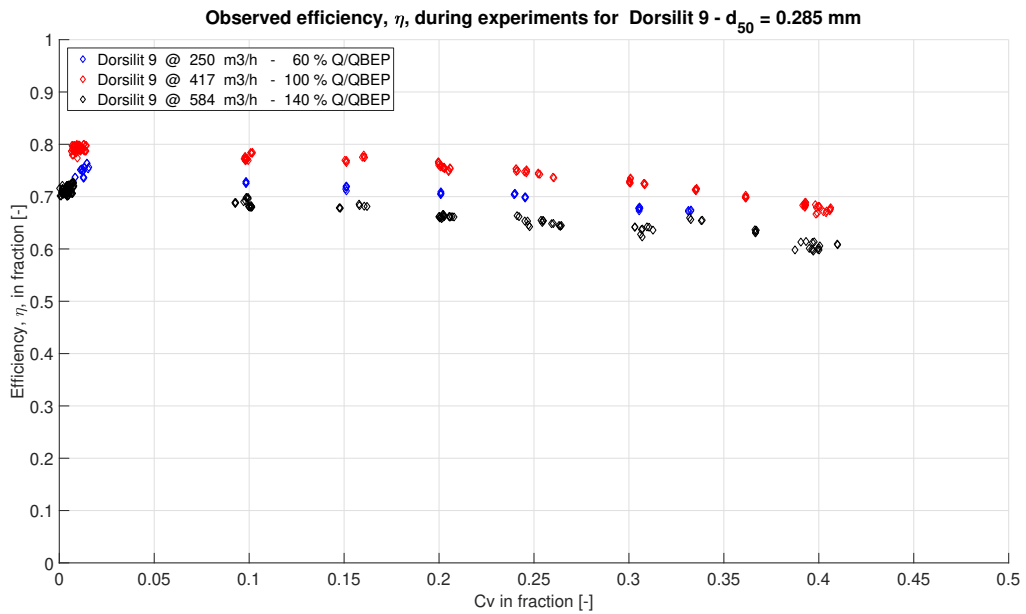


Figure 5.20: Efficiency while pumping mixtures of Dorsilit 9, $d_{50} = 0.285 \text{ mm}$

5.5. DORSILIT 7

The last material tested is Dorsilit 7. In the following sections, the PSD is given, the execution of the experiments is discussed and the results of this material are presented.

5.5.1. PSD DORSILIT 7

As mentioned in the previous sections, before and after the experiments with Dorsilit 7 samples are taken. These are analysed with the help of the sieve shaker and the following results are obtained. In Figure 5.21 the curves before (green) and after (blue) are plotted. Here it is visible that the grain size of the samples taken after the experiments are slightly smaller compared with the samples taken before the tests. This could be due to wear of the solid particles during the experiments.

Before the test, a d_{50} value of 0.911 mm is determined after 2600 grams taken from at least 2 different bags. After the tests, a d_{50} value of 0.859 mm is determined after 3600 grams taken during different phases of emptying the storage tank. Both values exceed the d_{50} value provided by the supplier of 0.78 mm. There is a large difference between the values of the supplier and obtained from the sieve analysis at the TU Delft. It is chosen to specify the d_{50} for the Dorsilit 7 experiments as 0.859 mm.

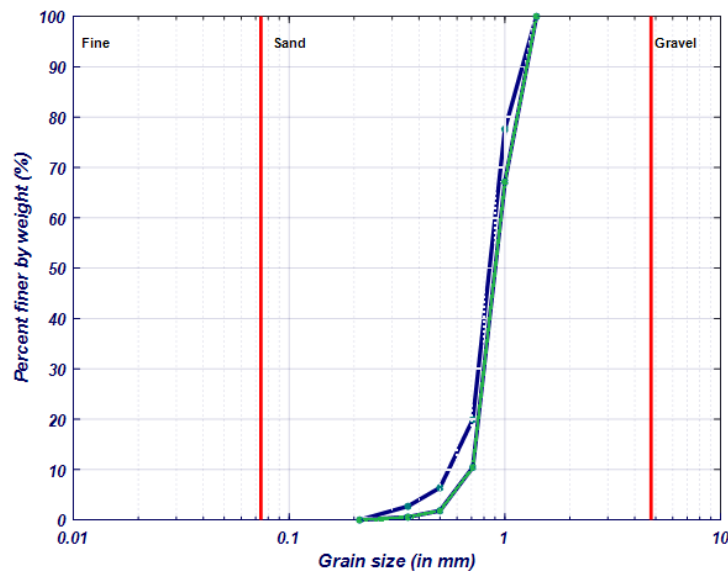


Figure 5.21: Particle size distribution of Dorsilit 7 - before and after the experiments

In Tables E.5 and E.6 the measurement results of the sieve process are listed. All the small sieve batches are combined and together they form the PSD as illustrated in Figure 5.21.

5.5.2. SPECIFICS IN THE DORSILIT 7 EXPERIMENTS

During these tests with the Dorsilit 7 material problems occurred with the slurry loop. The butterfly valve and the pressure tubes were not affected by this material. But several bends are worn out again which results in leakages. To repair these sections the entire loop needed to be drained and a welder placed reinforcement plates around the leakages.

During the tests with Dorsilit 7, it is determined by SSB to stop the experiments after obtaining a decent amount of data points which are checked with preliminary analyses. This due to the poor condition of several bends in the slurry loop. After the last experiments, the slurry loop is dismantled and procedures to repair the slurry loop are started.

5.5.3. RESULTS OF TESTING WITH DORSILIT 7- ($d_{50} = 0.859mm$)

In this section the results of the experiments with Dorsilit 7 are presented, this follows the same procedure as with the previous materials. First, the different flow rates are evaluated against the selected theories. The models are indicated in; Red for Stepanoff 1965, Blue for the Wilson and Sellgren 2017, Green for the Engin and Gur 2003 and light Blue for the adjusted Stepanoff model. After this, the accuracy of each formulation is determined with the help of the goodness of fit, R^2 , values. Also, a comparison of the solids effect is made against the different flow rates. Due to the excessive wear of the slurry loop, only a limited amount of tests are done with this material.

Due to the coarser solid particles, the pipe resistance increases significantly. As mentioned in Chapter 4 the flow rate is altered for higher ratios of Q/Q_{BEP} , due to the maximum produced pressure of the centrifugal pump. Also, due to the extensive wear of the butterfly valve problems are encountered when higher concentrations of solids are pumped. Due to this wear, the valve needed to be closed too much for a good passage of the mixture through the valve. To counter this problem, the minimum flow rate, if possible, is 60 % Q/Q_{BEP} , but if not possible it is changed to 80% Q/Q_{BEP} .

Results of testing with different flow rates with Dorsilit 7- ($d_{50} = 0.859mm$)

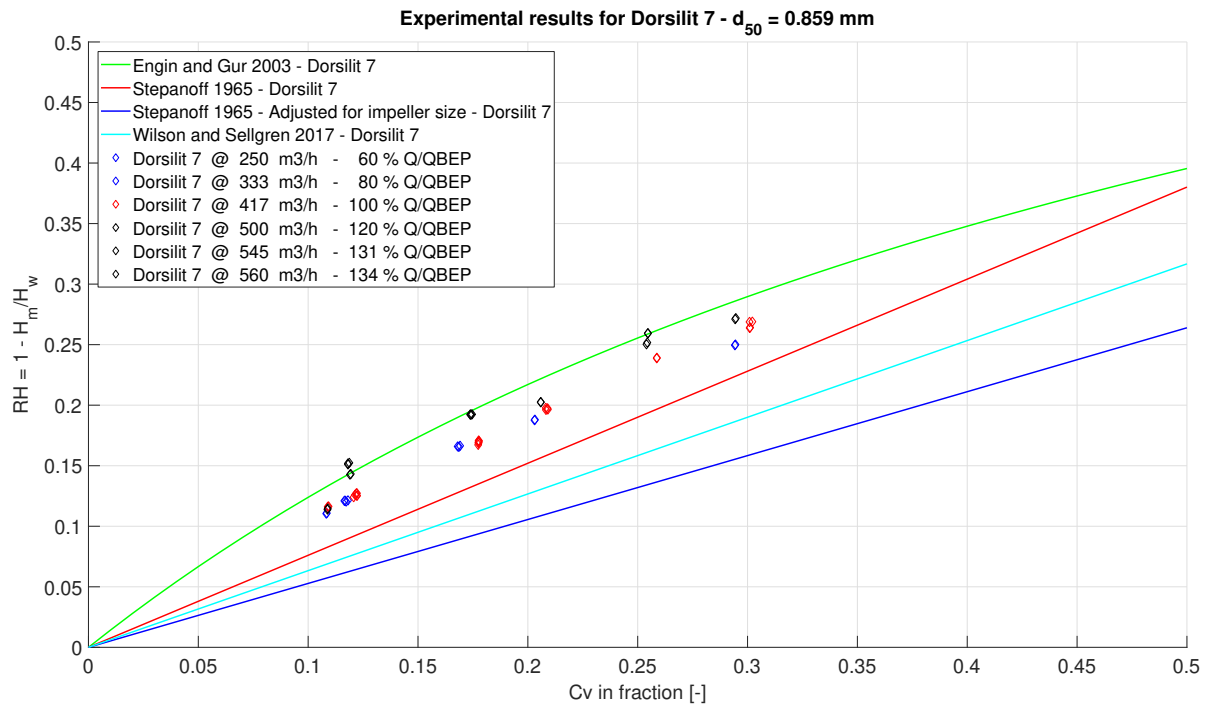


Figure 5.22: Experimental results of R_H for Dorsilit 7 for all Q/Q_{BEP} ratios with various concentrations

As shown in Figure 5.22 the blue data points obtained from the Dorsilit 7 experiments for 60% and 80% Q/Q_{BEP} , 250 and 333 m³/h, are between the red and green line. The red data points obtained from the Dorsilit 7 experiments for 100 % Q/Q_{BEP} , 417 m³/h, are also between the red and green line. For both flow rates it is not clear which formulation is the better choice. The black data points obtained from the Dorsilit 7 experiments for 120+ % Q/Q_{BEP} , 500+ m³/h, are along the green line. For this flow rate, the Engin and Gur 2003 formulation would be the better fit.

The pipe resistance for multiple concentrations were too much for the centrifugal pump and the electro drive and resulted in lower maximum flow rates than the other materials. These tests are conducted from the 120 % Q/Q_{BEP} , 500 m³/h, till 134 % Q/Q_{BEP} , 560 m³/h, with additional clear water tests as reference.

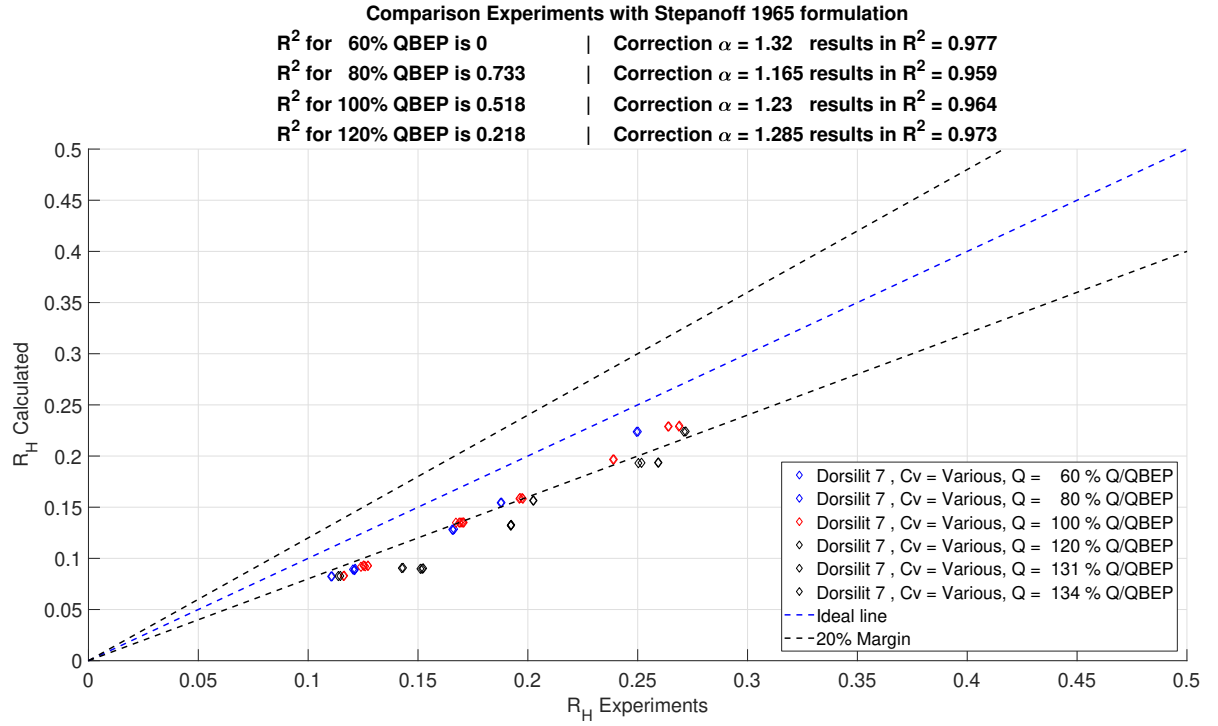
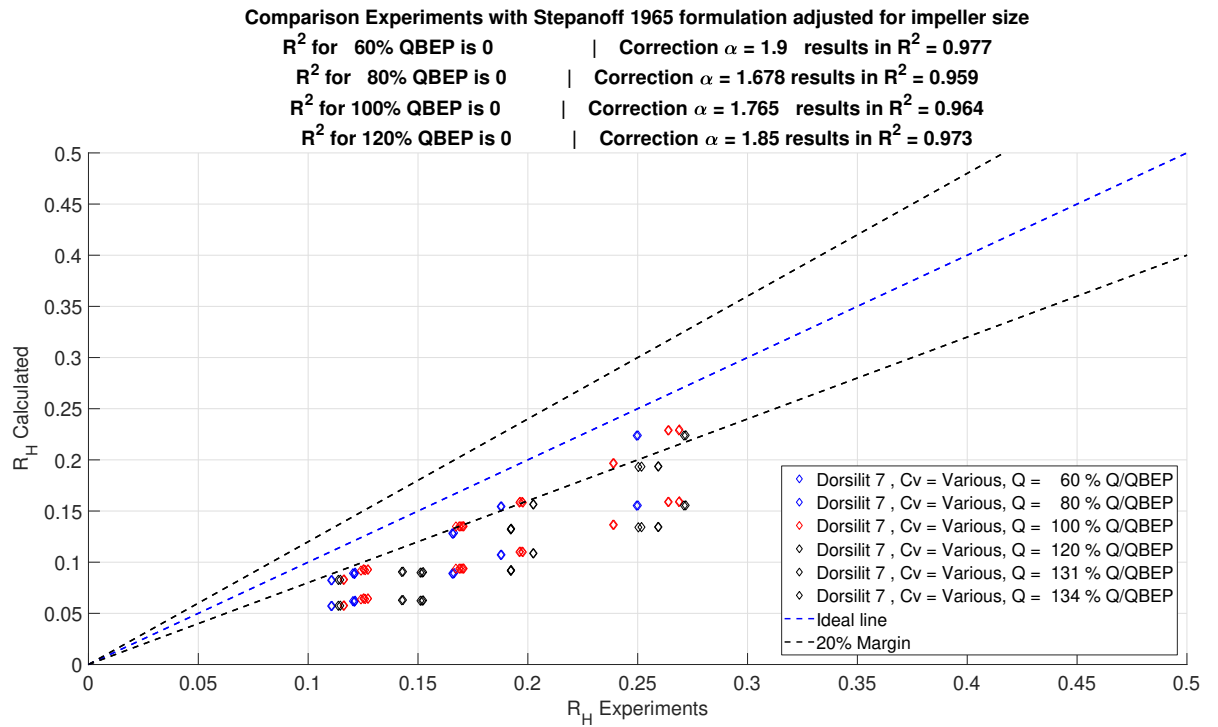
Based on this plot the Engin and Gur 2003 formulation is more accurate for the higher flow rate, while the other flow rates are between the Engin and Gur and Stepanoff formulation. As mentioned in the previous chapter the experiments are stopped due to excessive wear of the slurry loop. For this reason, there is limited data to provide information about pumping coarser materials.

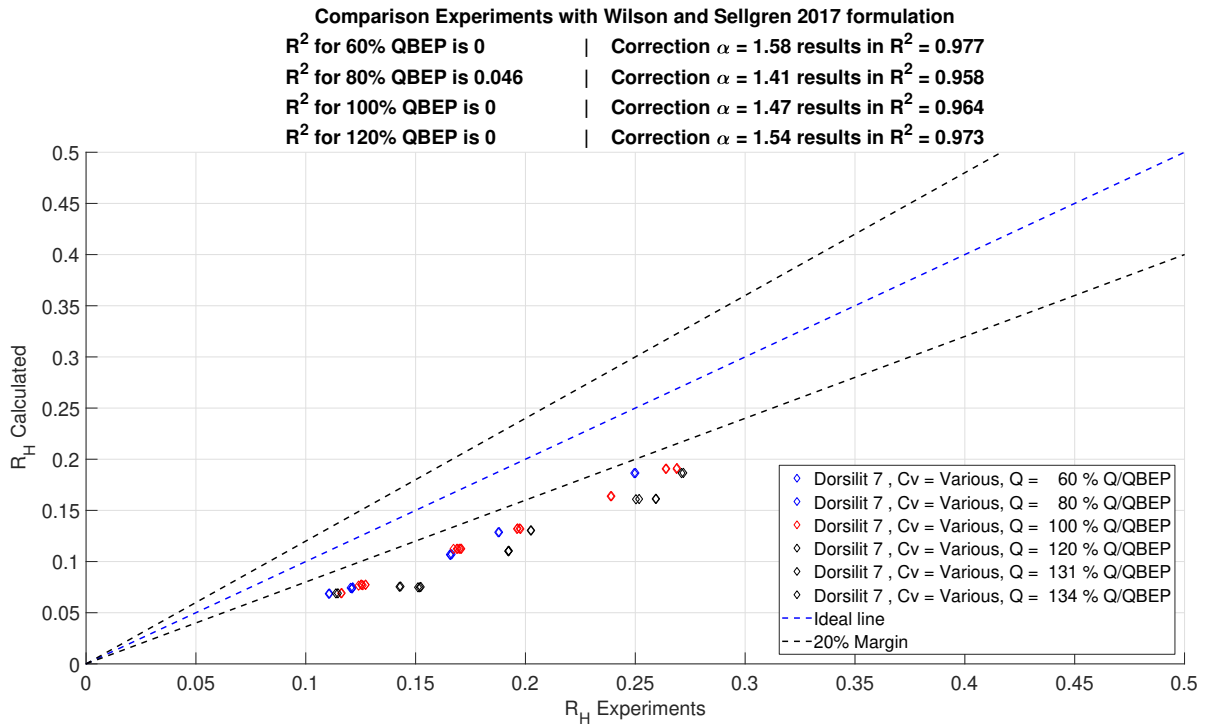
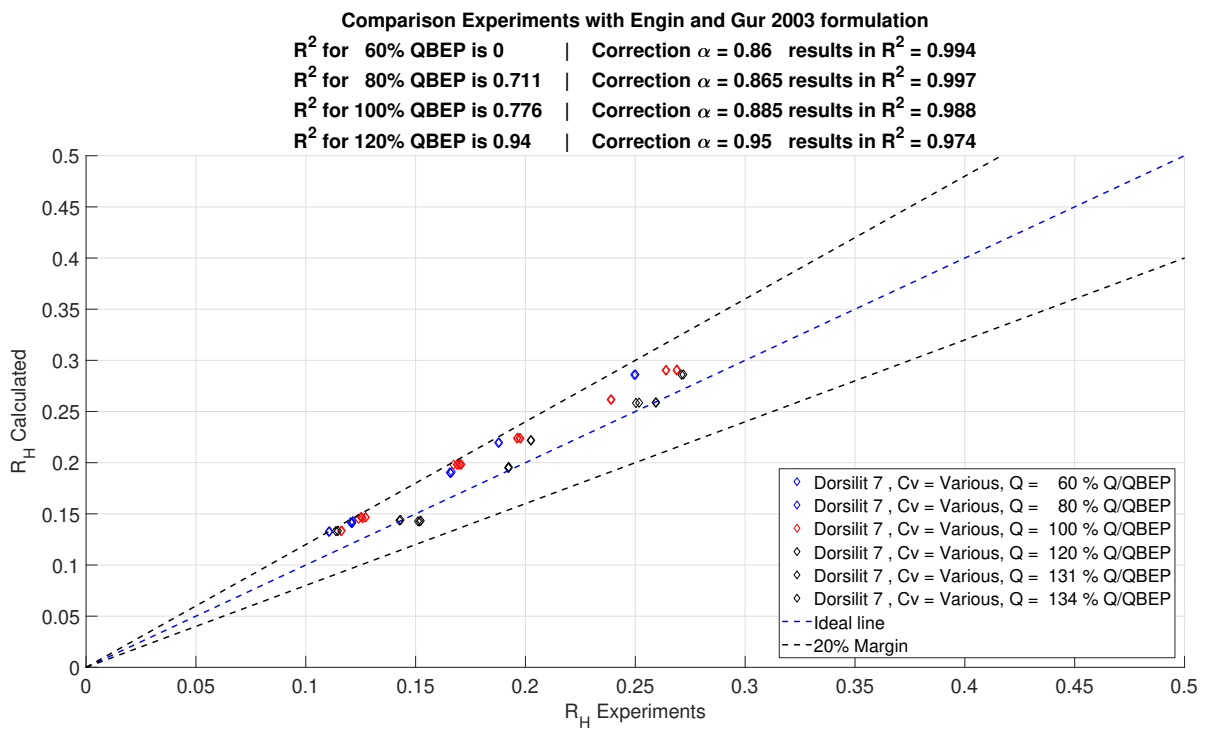
R^2 values with different flow rates with Dorsilit 7 - ($d_{50} = 0.859mm$)

The R^2 values with corresponding plots are provided in Figures 5.23, 5.24, 5.25 and 5.26. In the R^2 figures the R^2 values are given for each flow rate, this to determine the accuracy of the original theories for each flow rate. Here it is shown that the Engin and Gur 2003 formulation is the best fit for this material and configurations.

For optimisation, there are correction factors, α , introduced which are multiplied with the R_H terms of the theories. With the help of the α factors, the R^2 values are optimised to the values shown on the right side of the figures. This is done similarly as in the previous sections with the Geba and Dorsilit 9 material. As stated before, in the next chapter the different α factors will be analysed and used for a better formulation of the solids effect. In the following figures Equation 5.1 is used for an optimal result.

When evaluating the optimised R^2 values shown in Figures 5.23, 5.25 and 5.26 it is observed that all formulations are equal in goodness of fit, R^2 , after optimisation.

Figure 5.23: R^2 for Dorsilit 7 experiments of all C_v and Q/Q_{BEP} ratios compared with Stepanoff 1965Figure 5.24: R^2 for Dorsilit 7 experiments of all C_v and Q/Q_{BEP} ratios compared with Stepanoff 1965 adjusted for impeller size

Figure 5.25: R^2 for Dorsilit 7 experiments of all C_v and Q/Q_{BEP} ratios compared with Wilson and Sellgren 2017Figure 5.26: R^2 for Dorsilit 7 experiments of all C_v and Q/Q_{BEP} ratios compared with Engin and Gur 2003

Required power during experiments

Similarly as for the previous materials tested, is in Figure 5.27 the required mechanical power for each concentration and flow rate presented while pumping Dorsilit 7 material. During the experiments with this material lower flow rates needed to be used to pump the required concentrations. After analysing Figure 5.27 it is observed that the required mechanical power is not exactly as expected. The data points, from the display unit using parameter R0032, are following the calculated curve, based on the clear water tests, with a larger margin than the previous materials.

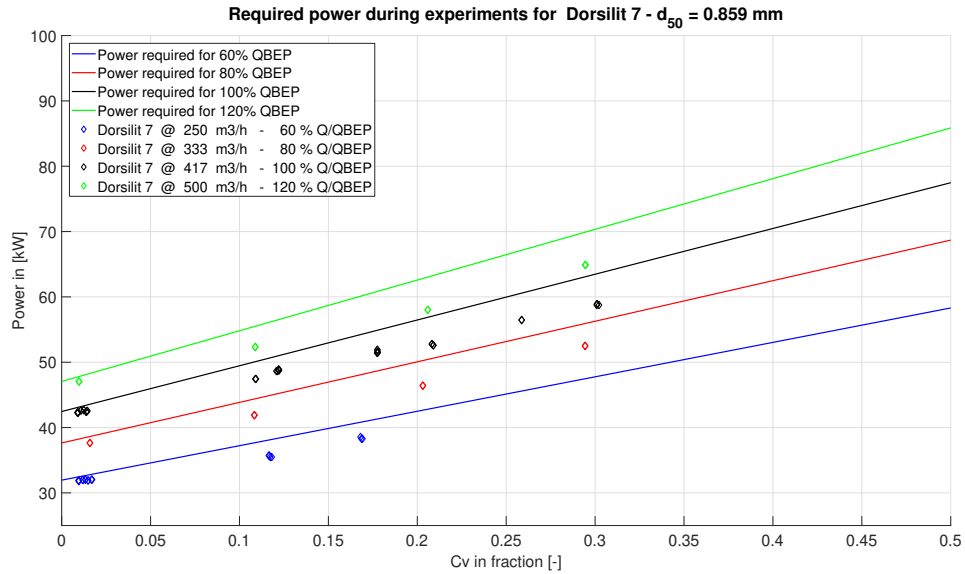


Figure 5.27: Required power while pumping Dorsilit 7, $d_{50} = 0.859$

Efficiency of the pump during mixture tests

Also, the efficiency is determined for the Dorsilit 9 material. In Figure 5.28 the efficiency is presented for all concentrations tested with the different flow rates. Here it is clearly visible that the 100 % Q/Q_{BEP} ratio has the best efficiency overall. There is a decreasing trend observed, which is significantly more than in Figures 5.12 and 5.20. Similar to Figures 5.12 and 5.28 the clear water efficiency data points near the 0% concentration are included.

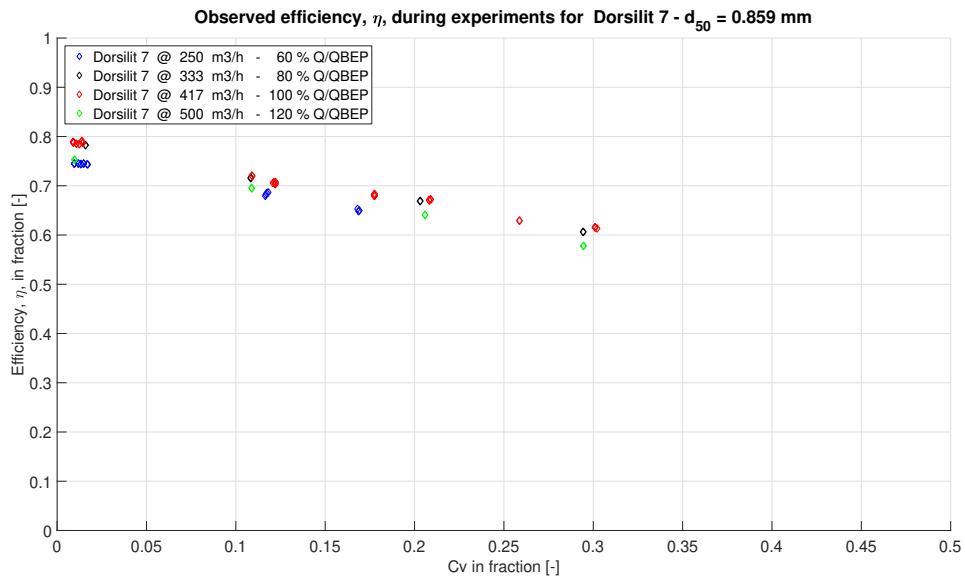


Figure 5.28: Efficiency while pumping mixtures of Dorsilit 7, $d_{50} = 0.859$

5.5.4. PRELIMINARY REVIEW OF THE EXPERIMENTS

After analysing Figures 5.6 (Geba material) and 5.14 (Dorsilit 9 material) it is observed that the solids effect for smaller particles is linearly affected by the volumetric concentration. Here the difference in flow rate is clearly visible for concentrations up to 30% C_v . When the volumetric concentration is above 30%, the influence of the Q/Q_{BEP} ratios reduces and all data points are closely gathered. A possible explanation for this observation could be that the hydraulic flow field of the centrifugal pump is less important for concentration higher than 30%.

For the coarsest material tested, Dorsilit 7, it appears that the influence of Q/Q_{BEP} ratios is minimal. All data points up to 30% volumetric concentration, for all flow rates, are following the same trend as shown in Figure 5.22.

This chapter also contains the required power and the efficiency of the pump observed while pumping the different materials, concentrations and flow rates. During the observations, it is confirmed that the 100% Q/Q_{BEP} ratio has the best overall efficiency, at each concentration and material configuration, as expected. Also the trends in Figures 5.12, 5.20 and 5.28 are as expected. These figures indicate that the efficiency of the centrifugal pump will decrease with increasing concentration and solid size. This is because the efficiency is influenced by H_r as stated in section 2.5.3.

As shown above, all clear water tests are nicely gathered. No significant differences in efficiency, which result in a reliable reference which can be used to compare all experiments with mixture against. The centrifugal pump used for testing was reliable and worked perfectly during the experiment phase of this thesis.

6

Data Analyses

In the previous chapter, the PSD's are determined, data points are compared with the chosen theories and the corresponding R^2 values are determined and optimised. In this chapter, the different test results are analysed and some preliminary conclusions are drawn. First, the influence of concentration on the solids effect is determined. Then the influence of the particle size on the solids effect is checked. After that, the influence of the impeller diameter is assumed based on literature and the influence of flow rates is checked. After this, both an existing theory from the literature study is modified and a new formulation is formed. After this the most accurate formula is determined for this experimental setup.

6.1. THE INFLUENCE OF CONCENTRATION ON THE SOLIDS EFFECT

In this section, the influence of different concentrations is analysed for all materials tested. Here the relation between the measured head reduction term, R_H , and the measured concentration will be determined and checked against the known literature listed below. At the end of the section, it will be clear which mathematical contribution the concentration has on the solids effect.

- $R_H \propto \alpha C_v$
- $R_H \propto \alpha C_v^\beta$
- $R_H \propto \alpha C_w$
- $R_H \propto \alpha C_w^{0.7}$
- $R_H \propto \alpha C_w^\beta$

There are lots of researchers who are using the C_w or $C_w^{0.7}$ concentration terms in the solids effect formulations. Additionally it is chosen to add an extra C_w term with an optimised power term. There have been some researchers who used the C_v in the solids effect theories. All of them used a linear relation for C_v , additionally it is chosen to check for a non-linear relation of C_v . All five of these different concentration contributions are evaluated and shown in the figures on the following pages. After this, all variables and the corresponding goodness of fit, R^2 , values are presented in Table 6.1. In this table, all values are gathered for all materials and flow rates.

The influence of concentration for the finest material tested - $d_{50} = 0.139\text{mm}$

In Figures 6.1, 6.2 and 6.3 the influence of concentration, in the Geba sand experiments, is analysed for each flow rate against various different concentration trends. These different trends of the concentration are from the literature study and completed with possible optimisations.

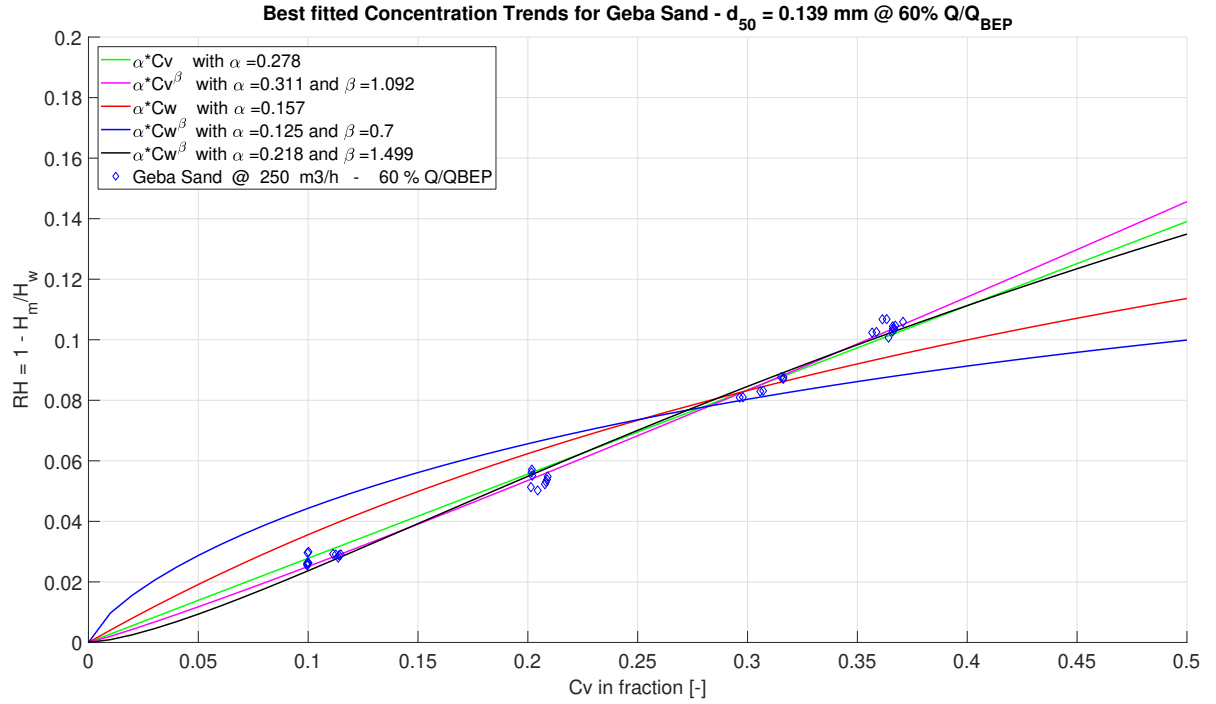
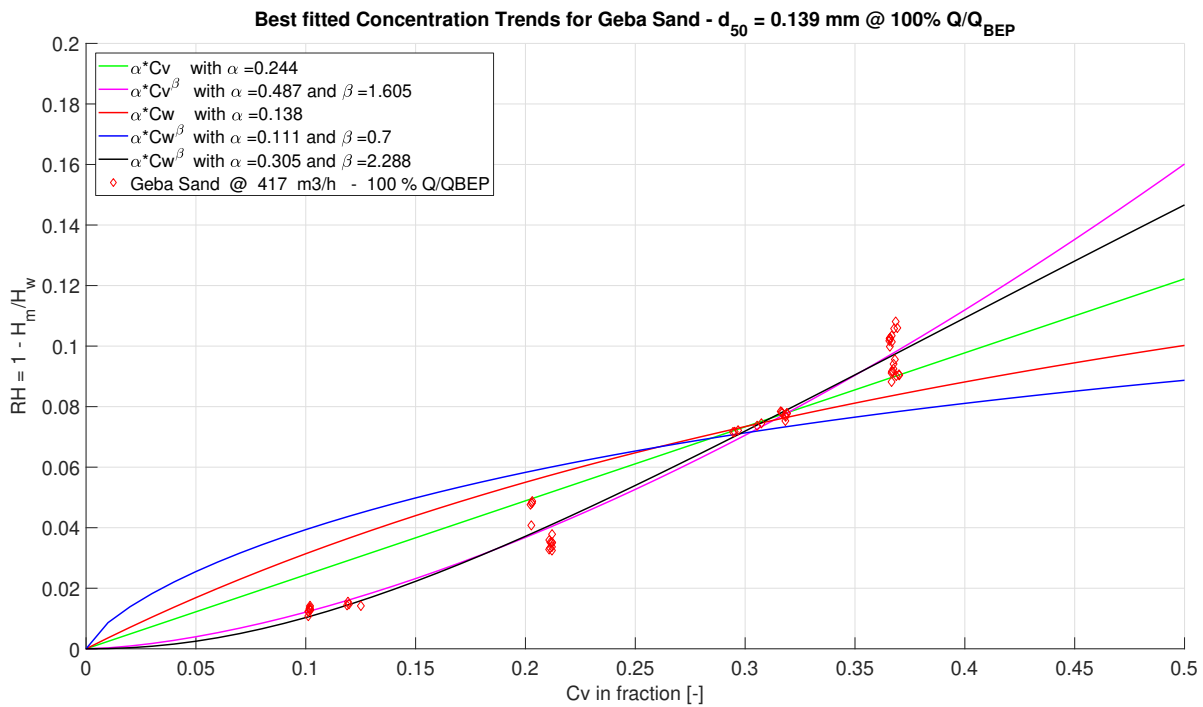
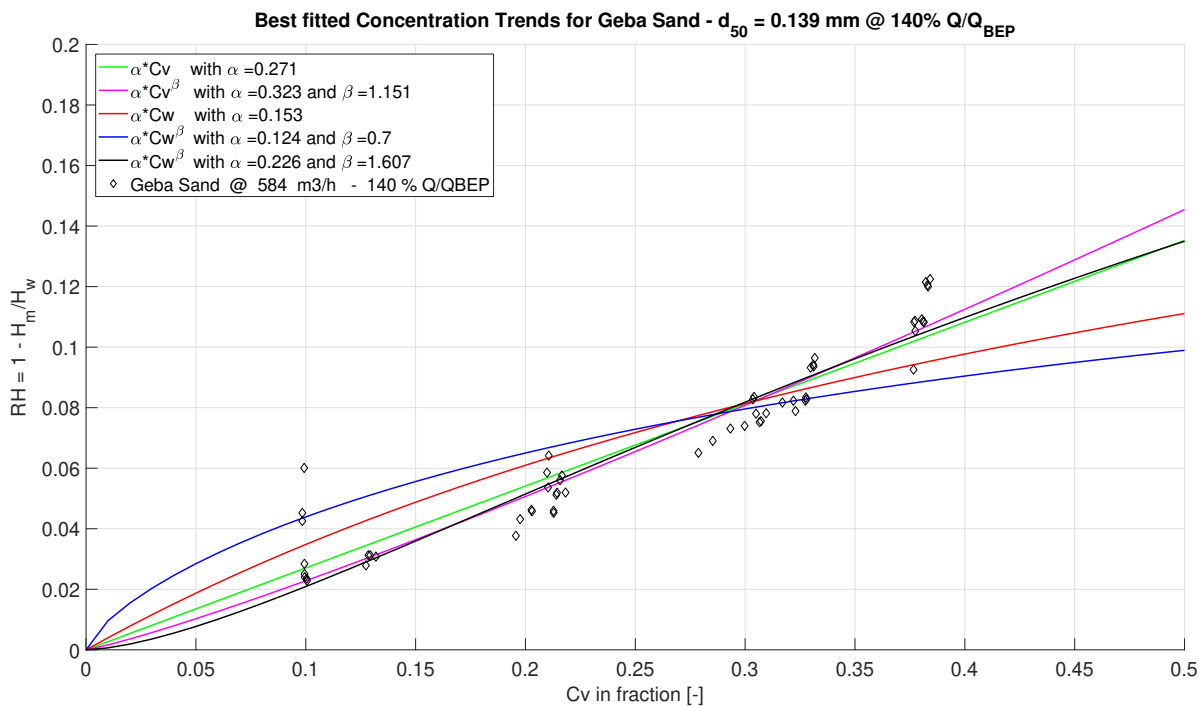


Figure 6.1: Experimental results of R_H for Geba sand for 60 % Q/Q_{BEP} with various concentrations

The blue data points in Figure 6.1 are following the green, magenta and black coloured trend lines. These lines represent the linear C_v , non-linear C_v and the optimised non-linear C_w lines respectively. In Table 6.1 the R^2 values are presented and the best scoring trend line in Figure 6.1 is the magenta coloured non linear C_v trend. But the difference between the three lines is minimal.

The red data points in Figure 6.2 are following the green, magenta and black coloured trend lines. These lines represent the linear C_v , non-linear C_v and the optimised non-linear C_w lines respectively. The best scoring trend line in Figure 6.2 is the magenta coloured non linear C_v trend. But the difference between the three lines is negligible.

The black data points in Figure 6.3 are following the magenta and black coloured trend lines. These lines represent the non-linear C_v and the optimised non-linear C_w lines respectively. The best scoring trend line in Figure 6.3 is the magenta coloured non linear C_v trend. Here the difference between the three lines is more noticeable and the non-linear C_v sticks out.

Figure 6.2: Experimental results of R_H for Geba sand for 100 % Q/Q_{BEP} with various concentrationsFigure 6.3: Experimental results of R_H for Geba sand for 140 % Q/Q_{BEP} with various concentrations

The influence of concentration for the second material tested - $d_{50} = 0.285\text{ mm}$

In Figures 6.4, 6.5 and 6.6 the influence of concentration, in the Dorsilit 9 experiments, is analysed for each flow rate against the same concentration trends as before.

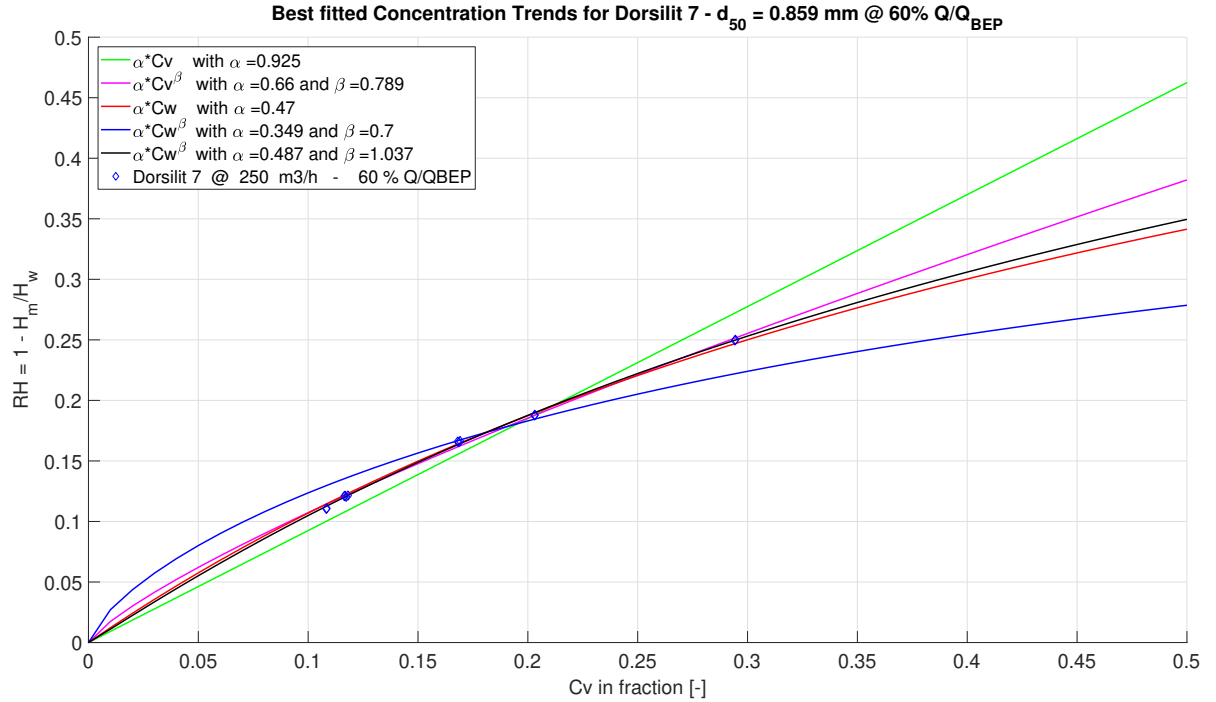
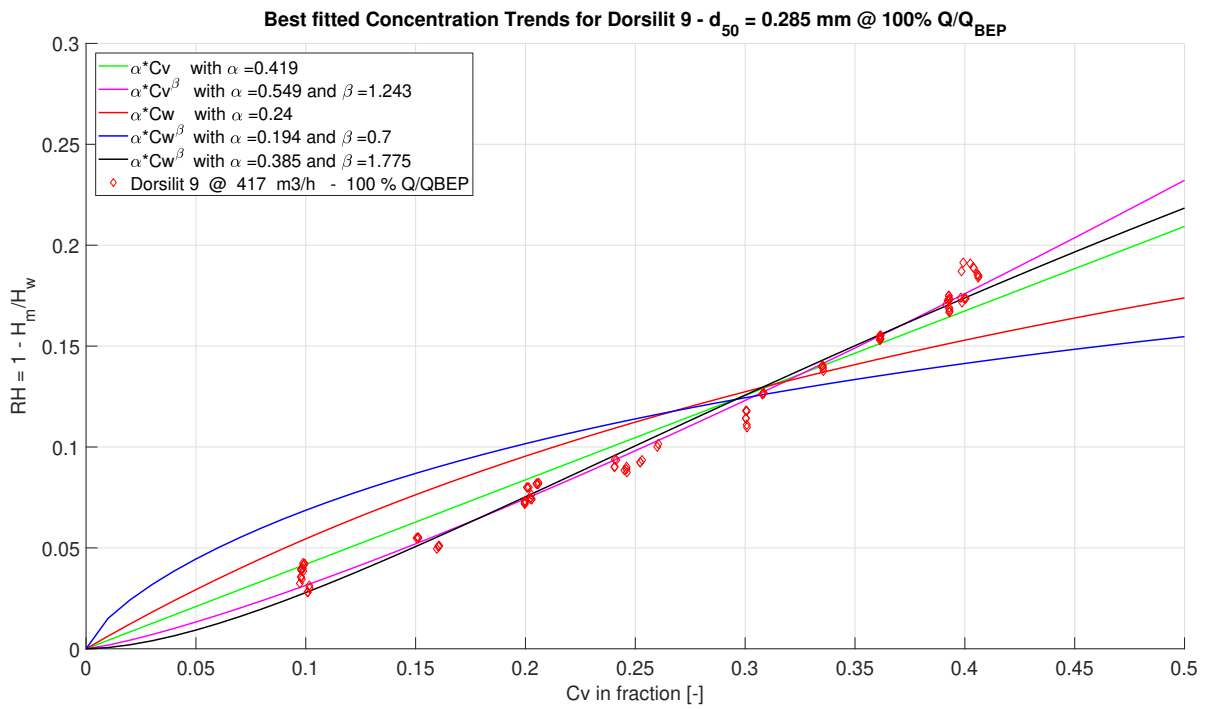
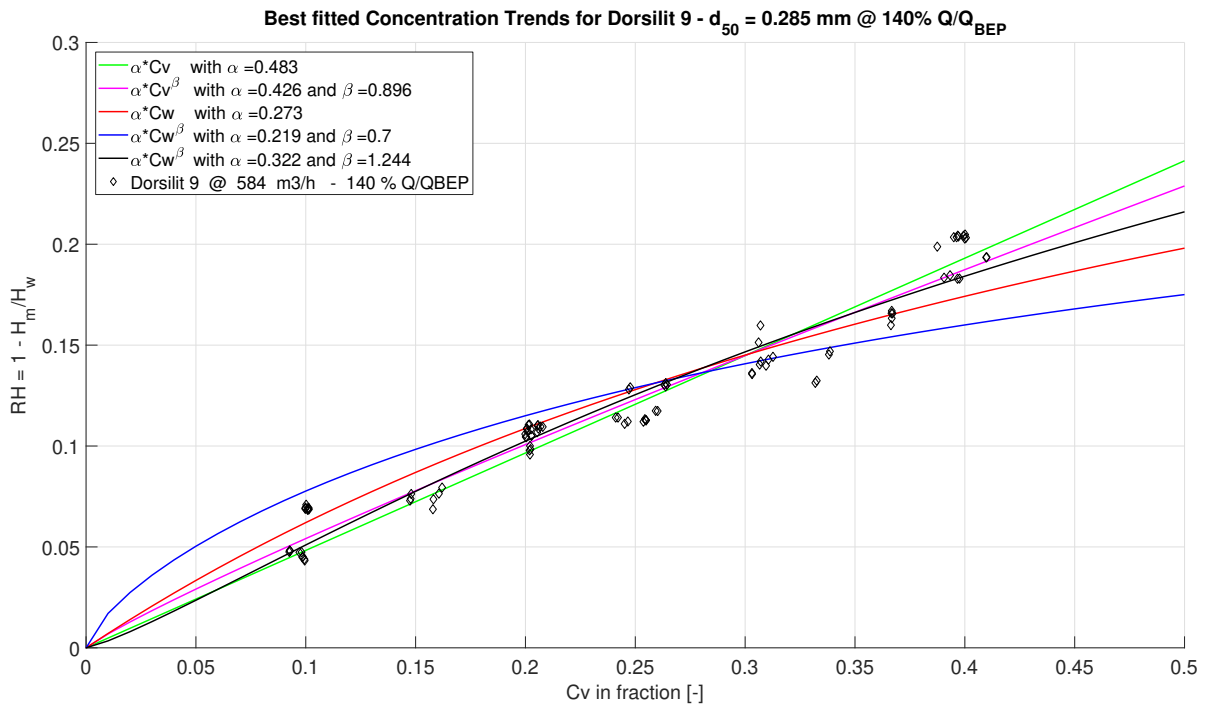


Figure 6.4: Experimental results of R_H for Dorsilit 9 for 60 % Q/Q_{BEP} with various concentrations

The blue data points in Figure 6.4 are following the magenta, red and black coloured trend lines. These lines represent the non-linear C_v , the linear C_w and the optimised non-linear C_w lines respectively. In Table 6.1 the R^2 values are presented and the best scoring trend line in Figure 6.4 is the magenta coloured non linear C_v trend. But the difference between the three lines is minimal.

The red data points in Figure 6.5 are following the green, magenta and black coloured trend lines. These lines represent the linear C_v , non-linear C_v and the optimised non-linear C_w lines respectively. The best scoring trend line in Figure 6.5 is the magenta coloured non linear C_v trend. The difference between the three lines is minimal.

The black data points in Figure 6.6 are following the green, magenta and black coloured trend lines. These lines represent the linear C_v , non linear C_v and the optimised non linear C_w lines respectively. The best scoring trend line in Figure 6.6 is the magenta coloured non linear C_v trend. Similar as Figures 6.4 and 6.4 is the difference minimal.

Figure 6.5: Experimental results of R_H for Dorsilit 9 for 100 % Q/Q_{BEP} with various concentrationsFigure 6.6: Experimental results of R_H for Dorsilit 9 for 140 % Q/Q_{BEP} with various concentrations

The influence of concentration for the coarsest material tested- $d_{50} = 0.859\text{ mm}$

In Figures 6.7, 6.8 and 6.9 the influence of concentration, in the Dorsilit 7 experiments, is analysed for each flow rate in the same manner as in the previous sections.

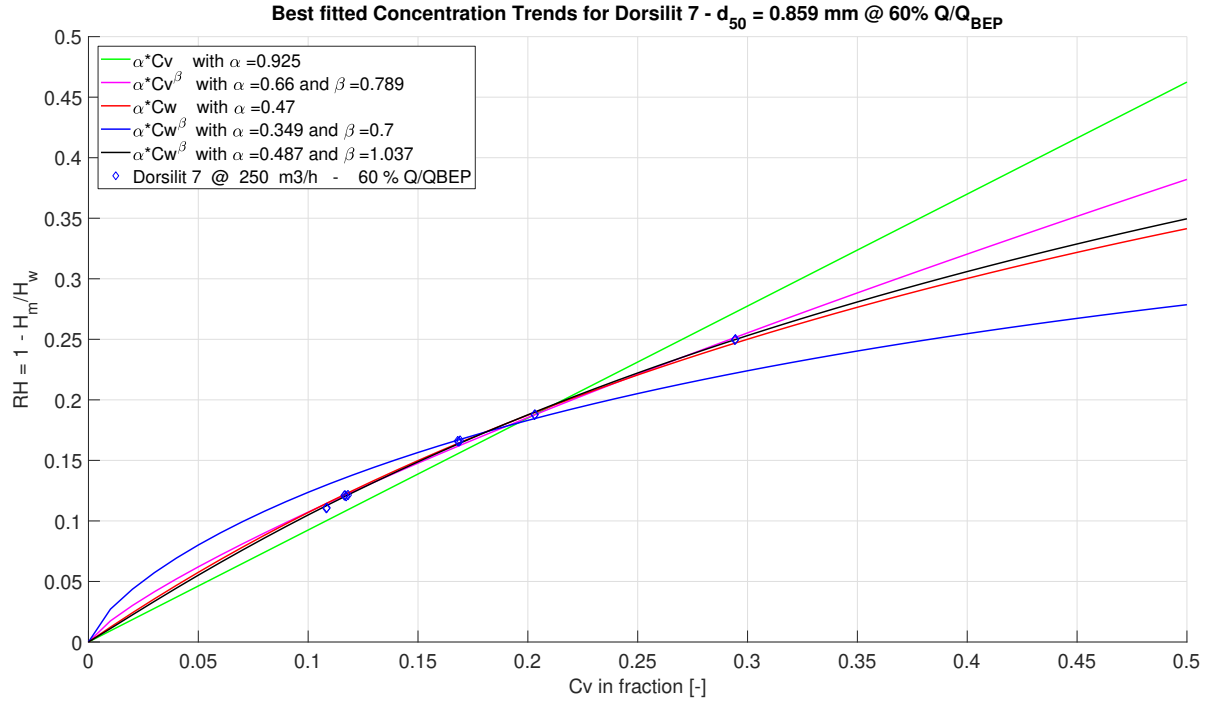
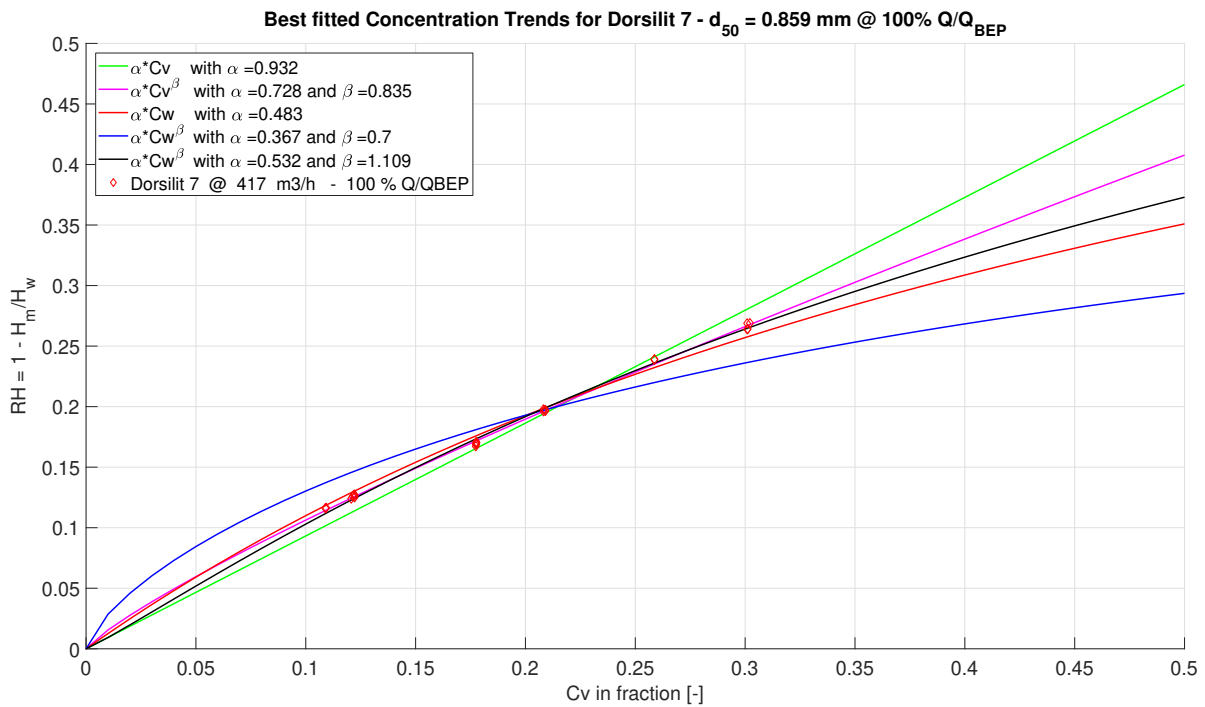
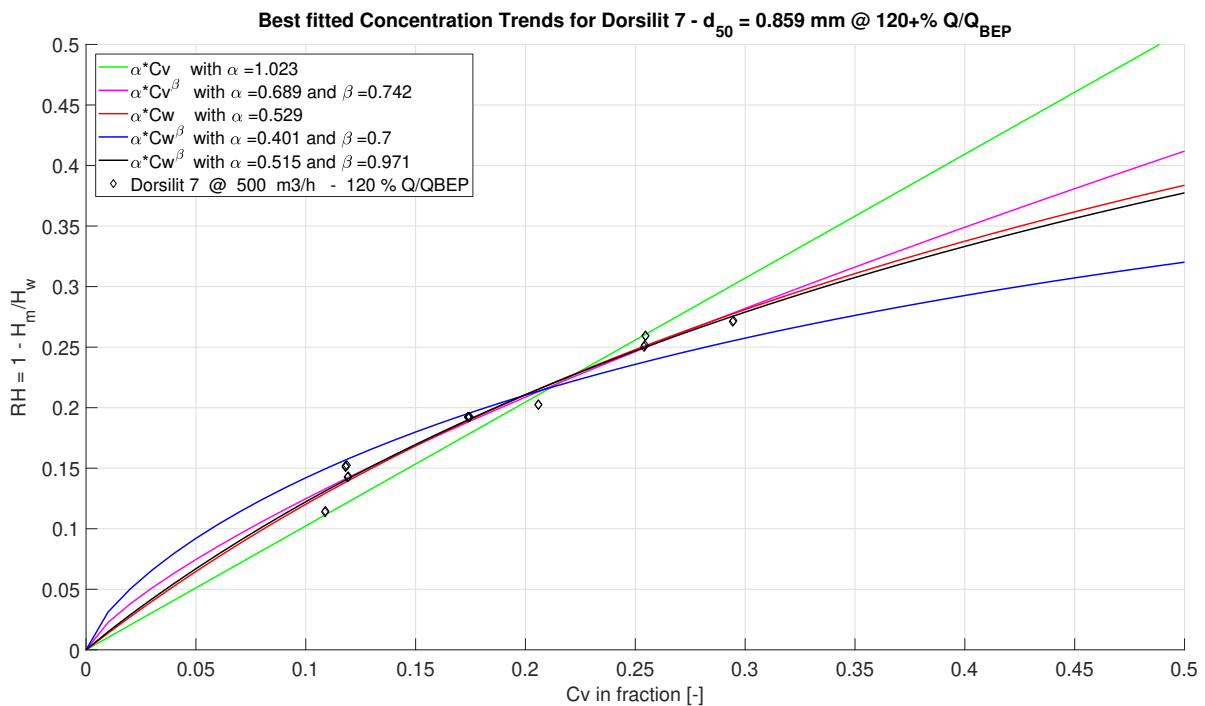


Figure 6.7: Experimental results of R_H for Dorsilit 7 for 60 % Q/Q_{BEP} with various concentrations

The blue data points in Figure 6.7 are following the green, magenta, red and black coloured trend lines. These lines represent the linear C_v , non-linear C_v , the linear C_w and the optimised non-linear C_w lines respectively. In Table 6.1 the R^2 values are presented and the best scoring trend line in Figure 6.7 is the black coloured optimised non linear C_w trend. But the difference between the lines is negligible.

The red data points in Figure 6.8 are following the green, magenta, red and black coloured trend lines. These lines represent the linear C_v , non-linear C_v , the linear C_w and the optimised non-linear C_w lines respectively. The best scoring trend line in Figure 6.8 is the magenta coloured non linear C_v trend. The difference between the lines is minimal with negligible differences between the non-linear C_v and non-linear C_w trend lines.

The black data points in Figure 6.9 are following the magenta, red and black coloured trend lines. These lines represent the non-linear C_v , the linear C_w and the optimised non-linear C_w lines respectively. The best scoring trend line in Figure 6.9 is the black coloured optimised non linear C_w trend. But the difference between the three lines is negligible.

Figure 6.8: Experimental results of R_H for Dorsilit 7 for 100 % Q/Q_{BEP} with various concentrationsFigure 6.9: Experimental results of R_H for Dorsilit 7 for 120 + % Q/Q_{BEP} with various concentrations

Material	Trend	60 % Q/Q_{BEP}			100 % Q/Q_{BEP}			140 % Q/Q_{BEP}		
		α	β	R^2	α	β	R^2	α	β	R^2
Geba sand - $d_{50} = 0.139 \text{ mm}$	αC_v	0.278		0.99	0.2444		0.90	0.271		0.89
	αC_v^β	0.311	1.092	1	0.487	1.605	0.98	0.323	1.151	0.90
	αC_w	0.157		0.92	0.138		0.78	0.153		0.80
	$\alpha C_w^{0.7}$	0.125	0.7	0.77	0.111	0.7	0.63	0.124	0.7	0.68
	αC_w^β	0.218	1.499	0.99	0.305	2.288	0.98	0.226	1.607	0.88
Dorsilit 9 - $d_{50} = 0.285 \text{ mm}$	αC_v	0.436		0.92	0.419		0.97	0.483		0.94
	αC_v^β	0.314	0.756	0.99	0.549	1.243	0.99	0.426	0.896	0.95
	αC_w	0.237		0.99	0.24		0.85	0.273		0.91
	$\alpha C_w^{0.7}$	0.187	0.7	0.91	0.194	0.7	0.70	0.219	0.7	0.79
	αC_w^β	0.239	1.015	0.99	0.386	1.775	0.98	0.322	1.245	0.94
Dorsilit 7 - $d_{50} = 0.859 \text{ mm}$	αC_v	0.925		0.93	0.932		0.96	1.024		0.87
	αC_v^β	0.66	0.789	1	0.728	0.835	1	0.689	0.742	0.97
	αC_w	0.47		1	0.483		0.99	0.529		0.97
	$\alpha C_w^{0.7}$	0.349	0.7	0.89	0.367	0.7	0.87	0.4	0.7	0.90
	αC_w^β	0.487	1.037	1	0.532	1.109	1	0.515	0.971	0.97

Table 6.1: Overview of all parameters used in this section with the resulting R^2 values.**Preliminary conclusion for the influence of concentrations on the solids effect**

In Table 6.1 the Figures 6.1, 6.2, 6.3, 6.4, 6.5, 6.6, 6.7, 6.8 and 6.9 are summarised. In this table it is visible that the optimised trendlines for the C_v and C_w are the best performing of the five trends.

But when we look at the concentration contributions found in the literature study it appears that the linear C_v is the best fitted trend for the finest material ($d_{50} = 0.139 \text{ mm}$) and for the 100 % and 140 % Q/Q_{BEP} tests with Dorsilit 9, ($d_{50} = 0.285 \text{ mm}$). While the linear C_w trend is the better fit for the 60 % Q/Q_{BEP} of the Dorsilit 9 material and the coarsest material, Dorsilit 7 ($d_{50} = 0.859 \text{ mm}$).

6.2. THE INFLUENCE OF SOLID PARTICLE SIZES ON THE SOLIDS EFFECT

In this section, the influence of the solid particle size is analysed. As seen in previous figures the head reduction term, R_H , is larger for larger values of d_{50} . In the following figures is the head reduction term, R_H , averaged for each concentration and flow rate. The averaged values are plotted for 10 %, 20% and 30 % volumetric concentration for all materials used. The volumetric concentrations 15 %, 25%, 35% and 40% are not tested for all materials and all flow rates, so they are excluded for this comparison.

In Figure 6.10 are the averaged data points observed for the lowest ratios of Q/Q_{BEP} . In Figure 6.11 the data points are observed for the best efficiency working point of the centrifugal pump. The highest ratios of Q/Q_{BEP} are shown in Figure 6.12.

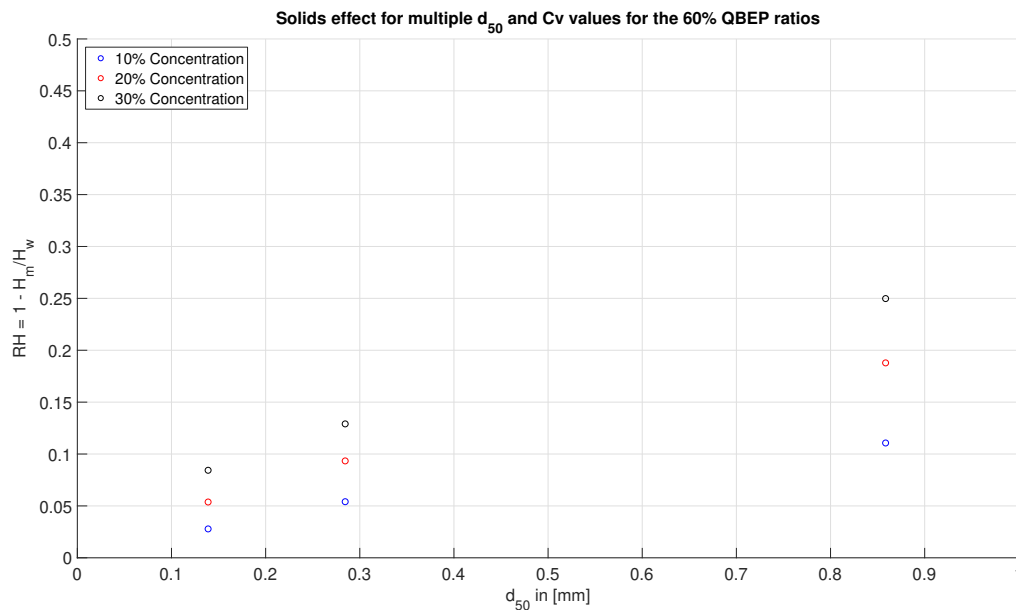


Figure 6.10: Comparison of solid effect for different particle sizes for the lower QBEP ratios

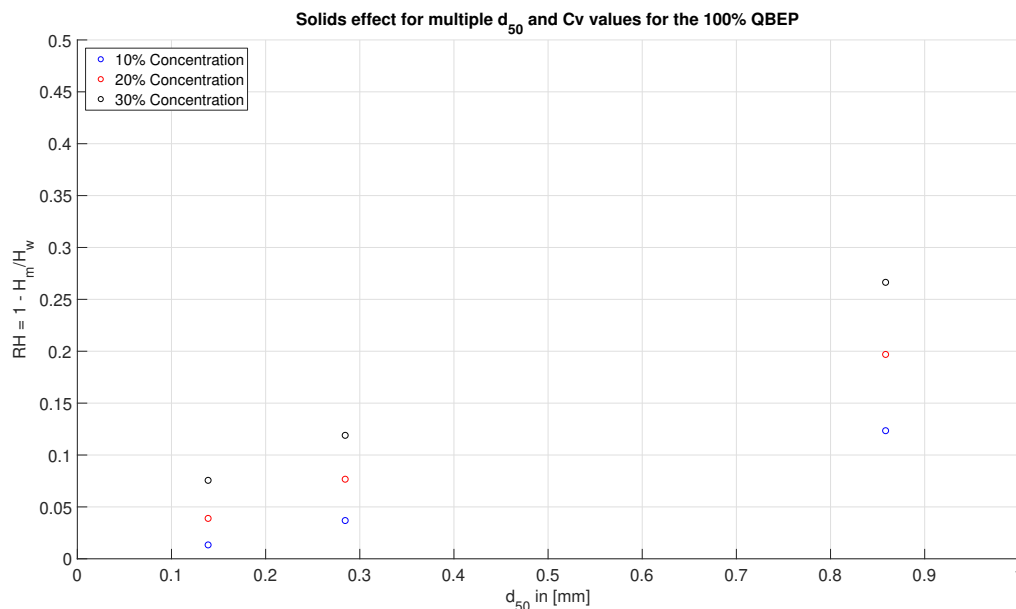


Figure 6.11: Comparison of solid effect for different particle sizes for the 100 % QBEP ratio

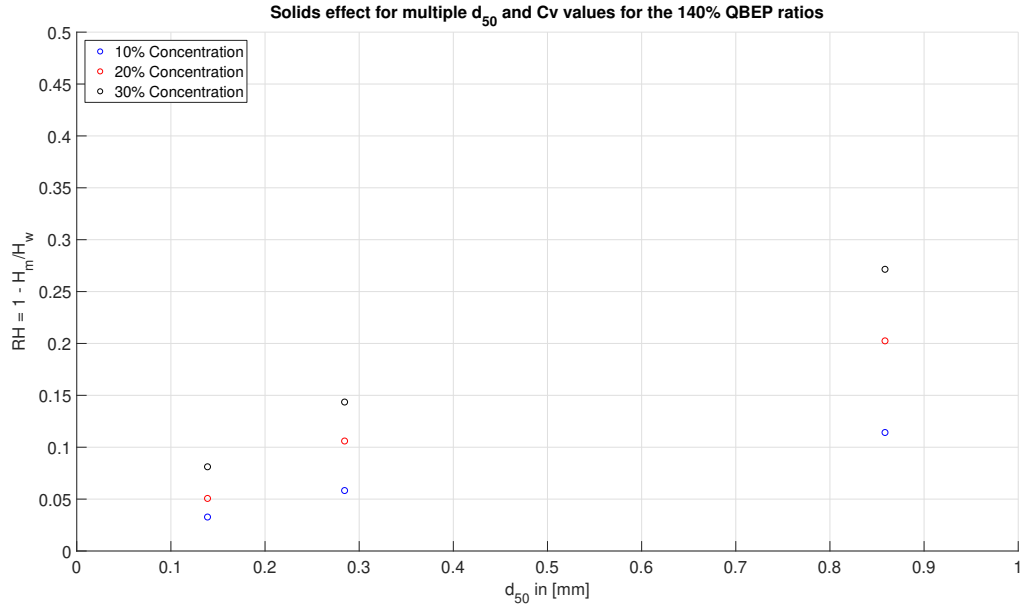


Figure 6.12: Comparison of solid effect for different particle sizes for the high QBEP ratios

In the following section Figures 6.10, 6.11 and 6.12 are analysed and several different functions are fitted against the R_H values for the d_{50} particle sizes tested.

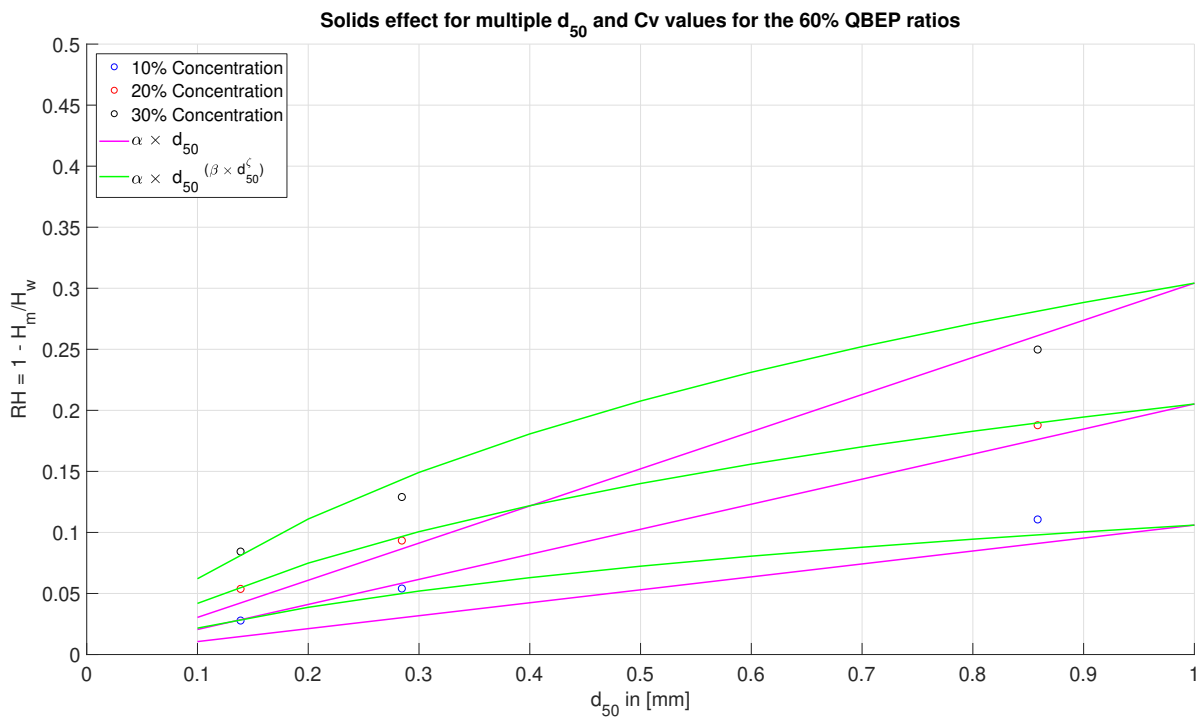
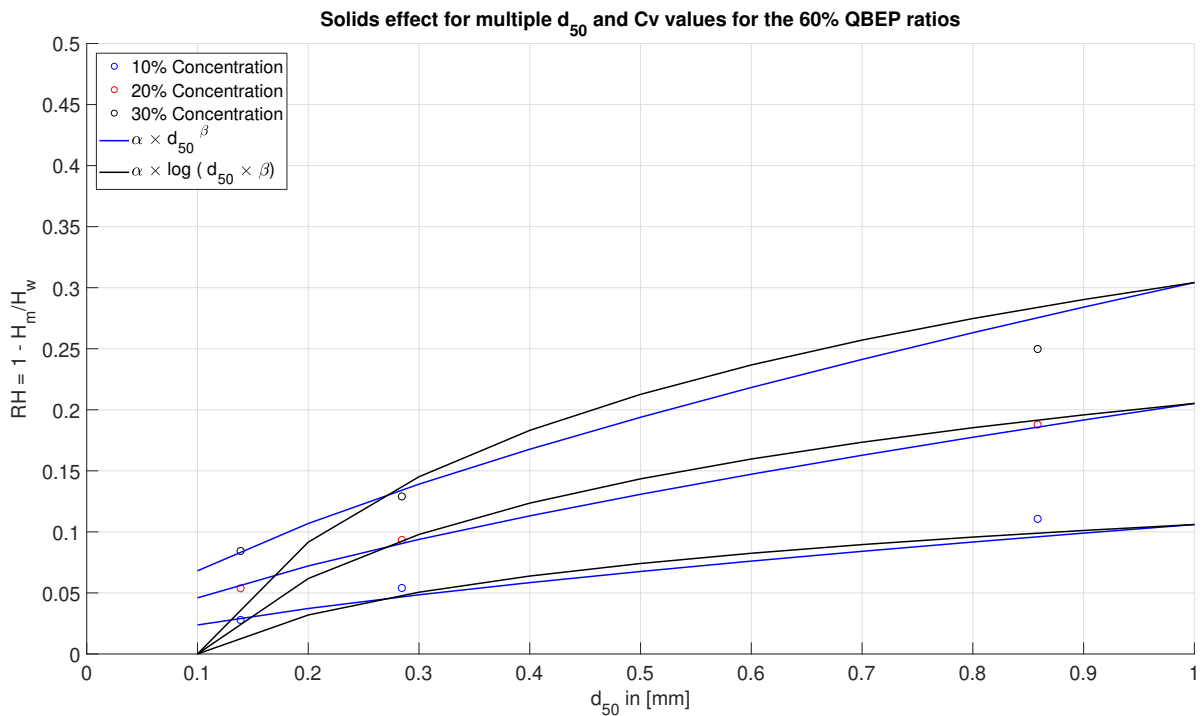
6.2.1. FITTED TRENDS FOR THE SOLID SIZE INFLUENCE ON THE SOLIDS EFFECT

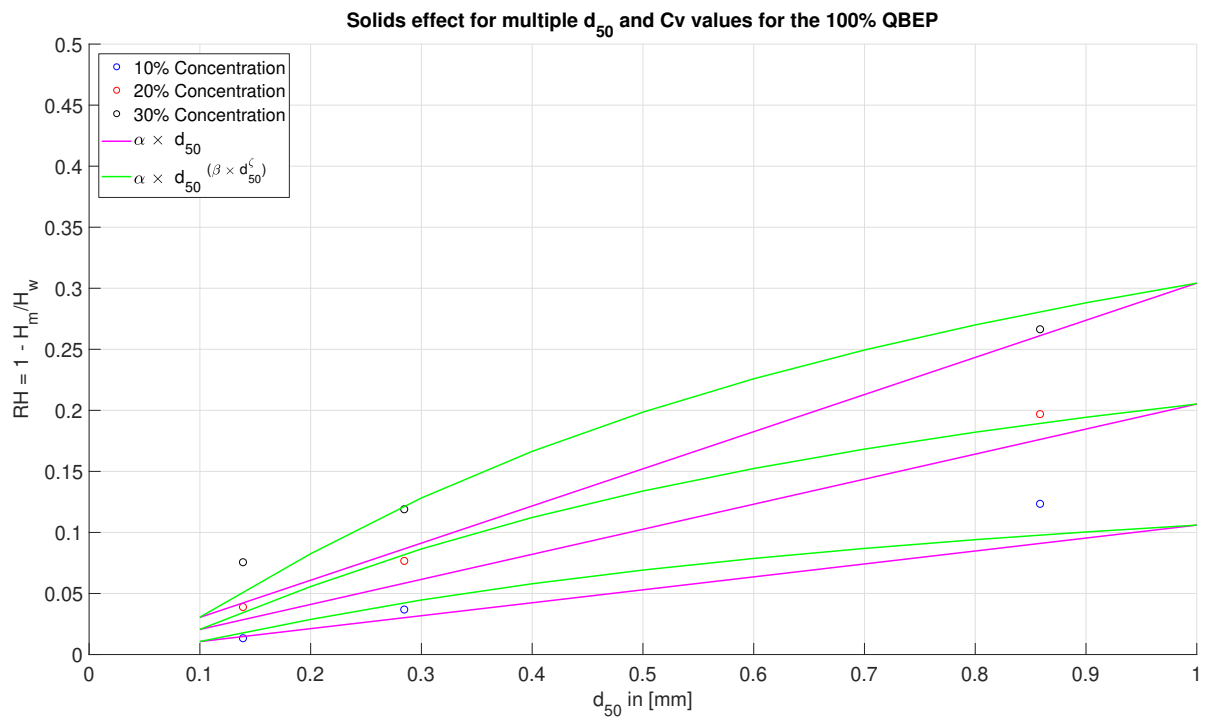
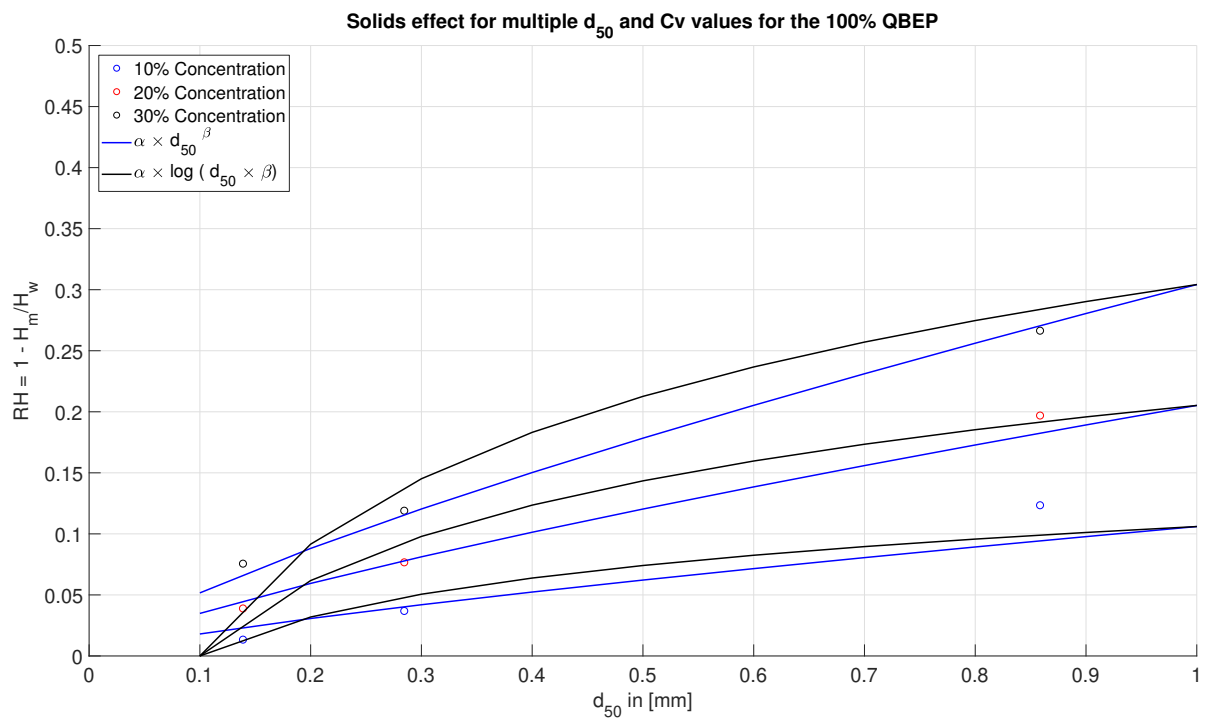
In this section are the data points analysed and several functions are fitted against the R_H and d_{50} values. This is done to check which function is better suited to be used in the solids effect formulations. In Chapter 3.4 multiple models are against particle sizes plotted. Here it was clear there were two different philosophies. A linear decreasing H_r trend with increasing particle size, and a logarithmic trend which reached a constant H_r value after a certain particle size.

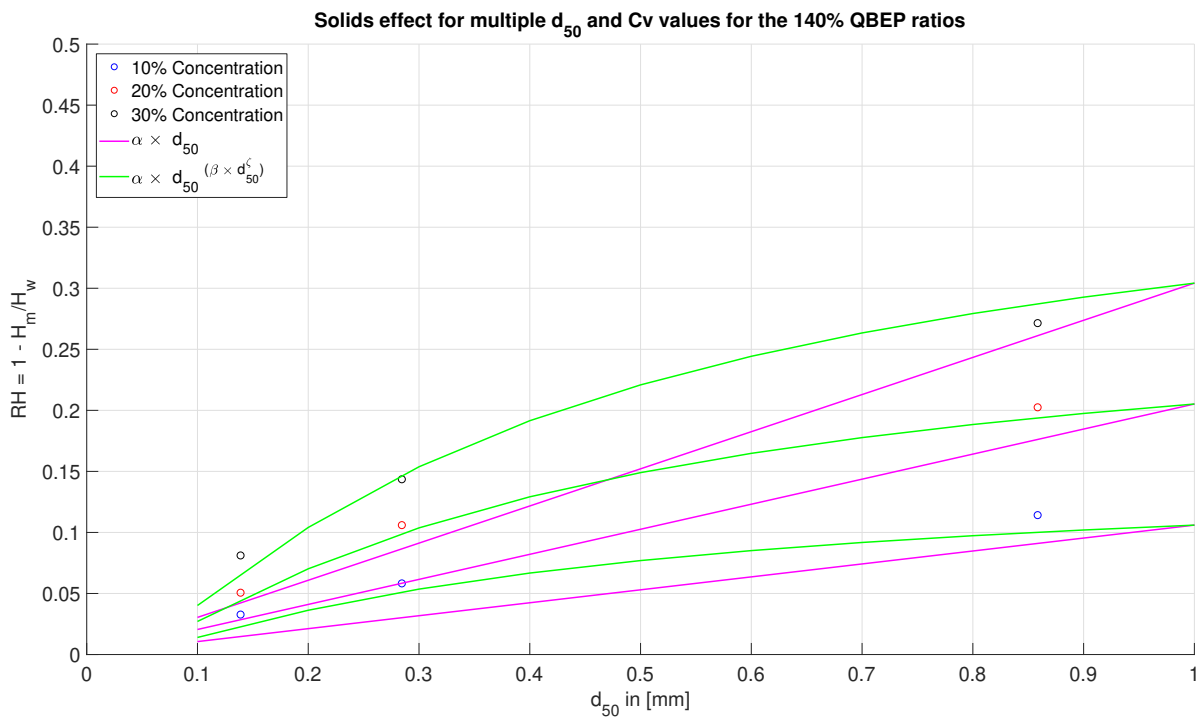
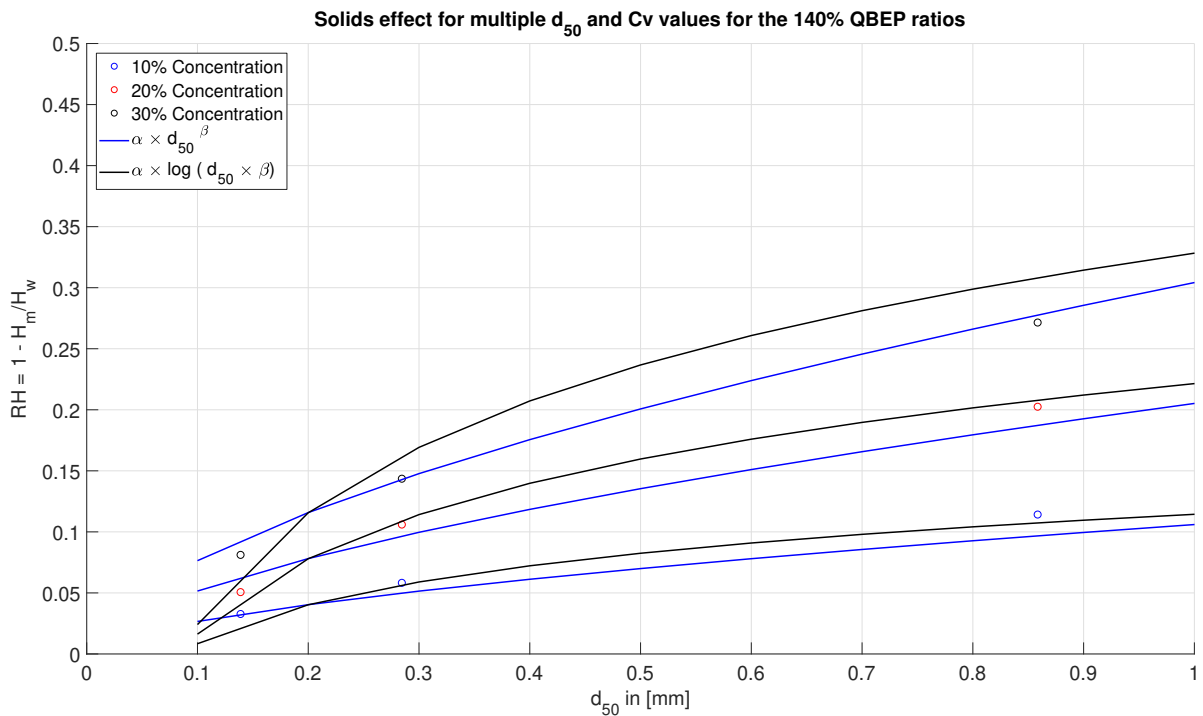
Not all, but a vast majority of researchers have shown in their studies and figures some form of maximum influence of the particle size. These include [McElvain, 1974], [Wilson, 1987], [Sellgren & Addie, 1989], [Wightley, 2002] and [Visintainer *et al.*, 2017]. This doesn't mean a linear relation can't be used in a specific range of sizes. But in general the assumption is a logarithmic function with respect to the particle size. Besides the logarithmic and linear relations is the option of Wilson and Sellgren 2017 given in Chapter 3.1.3. Here the relation of the particle size is a power law provided here; $d_{50}^{0.4d_{50}^{-0.25}}$. As an extra trend line is a normal power law trend added to provide a more complete picture.

In the following figures are the different trend lines with d_{50} shown. For better visibility of the different trends are the four functions separated into 2 figures for each flow rate. In Figures 6.13 and 6.14 are the four different trend for the 60 % Q/Q_{BEP} presented. Here is clearly shown that a linear trend is not accurate, the power laws are much more accurate as shown in Table 6.2, where all parameters and goodness of fit values are gathered.

In Figures 6.15 and 6.16 are the trends shown for the 100 % Q/Q_{BEP} flow rates and in Figures 6.17 and 6.18 are the fitted trends shown for the 140 % Q/Q_{BEP} flow rates.

Figure 6.13: Fitted trend lines linear and power law 2 for 60 % Q/Q_{BEP} Figure 6.14: Fitted trend lines power law 1 and log for 60 % Q/Q_{BEP}

Figure 6.15: Fitted trend lines linear and power law 2 for 100 % Q/Q_{BEP} Figure 6.16: Fitted trend lines power law 1 and log for 100 % Q/Q_{BEP}

Figure 6.17: Fitted trend lines linear and power law 2 for 140 % Q/Q_{BEP} Figure 6.18: Fitted trend lines power law 1 and log for 140 % Q/Q_{BEP}

trend	C_v	60 % Q/Q_{BEP}				100 % Q/Q_{BEP}				140 % Q/Q_{BEP}			
		α	β	ζ	R^2	α	β	ζ	R^2	α	β	ζ	R^2
αd_{50}	10%	0.1060			0.69	0.1060			0.84	0.1060			0.52
	20%	0.2052			0.79	0.2052			0.94	0.2052			0.71
	30%	0.3042			0.75	0.3042			0.89	0.3042			0.74
αd_{50}^β	10%	0.1060	0.65		0.92	0.1060	0.77		0.86	0.1060	0.6		0.89
	20%	0.2052	0.65		1	0.2052	0.77		0.98	0.2052	0.6		0.96
	30%	0.3042	0.65		0.95	0.3042	0.77		0.99	0.3042	0.6		0.99
$\alpha d_{50}^{\beta d_{50}^\zeta}$	10%	0.1060	0.5	-0.14	0.95	0.1060	0.5	-0.3	0.90	0.1060	0.35	-0.4	0.94
	20%	0.2052	0.5	-0.14	1	0.2052	0.5	-0.3	0.99	0.2052	0.35	-0.4	0.99
	30%	0.3042	0.5	-0.14	0.92	0.3042	0.5	-0.3	0.96	0.3042	0.35	-0.4	0.96
$\alpha \log(d_{50}\beta)$	10%	0.1060	10		0.91	0.1060	10		0.89	0.1060	12		0.96
	20%	0.2052	10		0.94	0.2052	10		0.97	0.2052	12		0.99
	30%	0.3042	10		0.80	0.3042	10		0.91	0.3042	12		0.90

Table 6.2: Overview of different fits for the R_H and d_{50} values.

For all trendlines fitted are the α values equal to the averaged concentrations for the tests. This to reduce the number of different variables. The accuracy of the linear fitted trend lines is low compared to the other trends. Where the linear trend reaches goodness of fit, R^2 , values between 0.5 till 0.94 are the other trends ranging from 0.8 till 1. Also the mathematical properties of linear trends needs to be considered. There is no limit or asymptotic behaviour for this trend. This is observed by many researchers. Due to this is the linear trend not the best fit to describe the contribution of the particle size for the solids effect.

The accuracy of the two power law trend lines is impressive. The simple αd_{50}^β trend line has a R^2 range for this data set of 0.86 till 1. The power law similar to the Wilson and Sellgren 2017 model has a goodness of fit of 0.9 till 1. This is obviously due to the limited data points and multiple fitting variables. Both trends are useful to describe the particle size contribution of the solids effect.

The accuracy of the logarithmic fitted trend lines is slightly less than the power laws. But with R^2 values between 0.8 and 0.99 it appears to fit also very accurate. This means that for this specific data set a logarithmic relation between the different particle sizes is also an acceptable assumption.

Based on the findings in Figures 6.13, 6.14, 6.15, 6.16, 6.17, 6.18 and Table 6.2 the best fitted trend lines are the power-law trendlines.

6.3. THE INFLUENCE OF IMPELLER DIAMETER ON THE SOLIDS EFFECT

The influence of the impeller size is not investigated in this study. But during the evaluation of the experimental data in Sections 5.3.3, 5.4.3 and 5.5.3 it was observed that all the theories overestimated or underestimated the solids effect losses for multiple flow rates.

For the Wilson and Sellgren 2017 formulation, a possible explanation is the size of the centrifugal pump used for testing. This 0.4 m diameter impeller is much smaller than the 1.11 m diameter used as a reference value in the formulation. The Engin and Gur 2003 formulation used a large number of different studies, with various impeller sizes, to determine the impeller size contribution. But here the formulation was overestimating all the tests.

The Stepanoff 1965 formulation does not contain an impeller size contribution. In this study, an extra Stepanoff formulation is added which is adjusted for the impeller size used during the experiments. This is done with the help of the impeller effect contributions of the Wilson and Sellgren 2017 formulations. Stepanoff used data from a 10.5 inch (0.2667 m) impeller diameter for his formulation, mentioned below as D_{ref} . The contribution of the impeller effect for the use of an impeller of 0.4 m (mentioned below as D_{test}) is 0.69 times the contribution of a 0.2667 m impeller according to the Wilson and Sellgren 2017 formulation.

$$\gamma_{Impeller} = \frac{\left(\frac{1.11}{D_{test}}\right)^{0.9}}{\left(\frac{1.11}{D_{ref}}\right)^{0.9}} = 0.6943 \quad (6.1)$$

6.4. THE INFLUENCE OF FLOW RATE ON THE SOLIDS EFFECT

During the experiments, an interesting result is found when investigating the influence of the flow rate on the solids effect. As discussed in Chapter 3.7 was in previous studies the flow rate deemed not of influence to the solids effect. Vlasblom et al (1999) showed in Figure 3.6 that, for higher ratios of Q/Q_{BEP} while pumping the coarsest material tested, the head ratio, H_r , becomes smaller [Vlasblom *et al.*, 1999].

In Figure 6.19 the R_H term is shown against the different Q/Q_{BEP} ratios for multiple concentration of the Geba sand. For all concentrations a minimum value for the term R_H is found over the range 60% - 140% Q/Q_{BEP} at 100% Q/Q_{BEP} . This trend is consistent for concentrations ranging from 10% - 40% C_v .

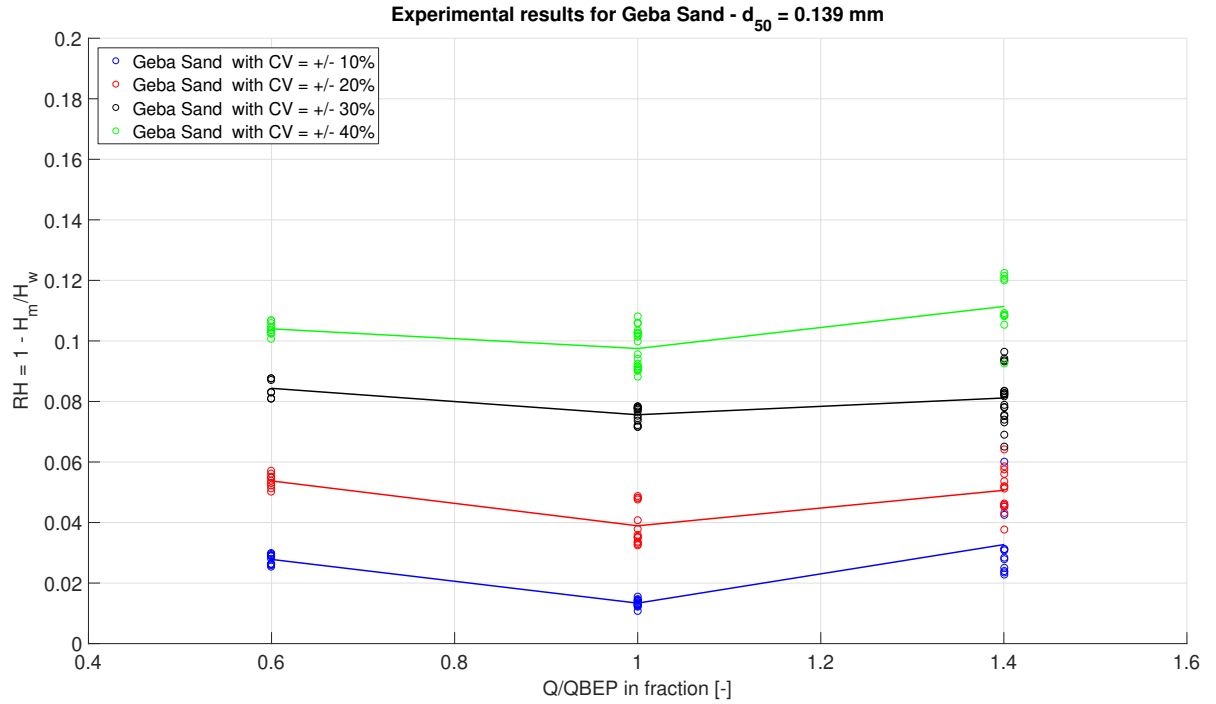


Figure 6.19: Experimental results for Geba sand $d_{50} = 0.139mm$ - R_H vs Q/Q_{BEP}

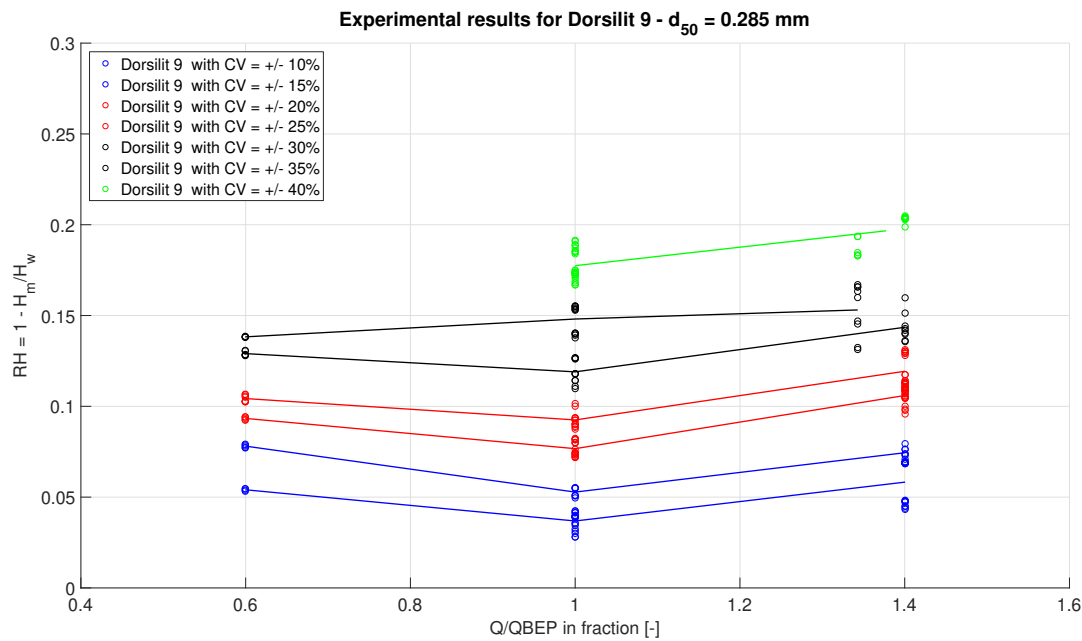
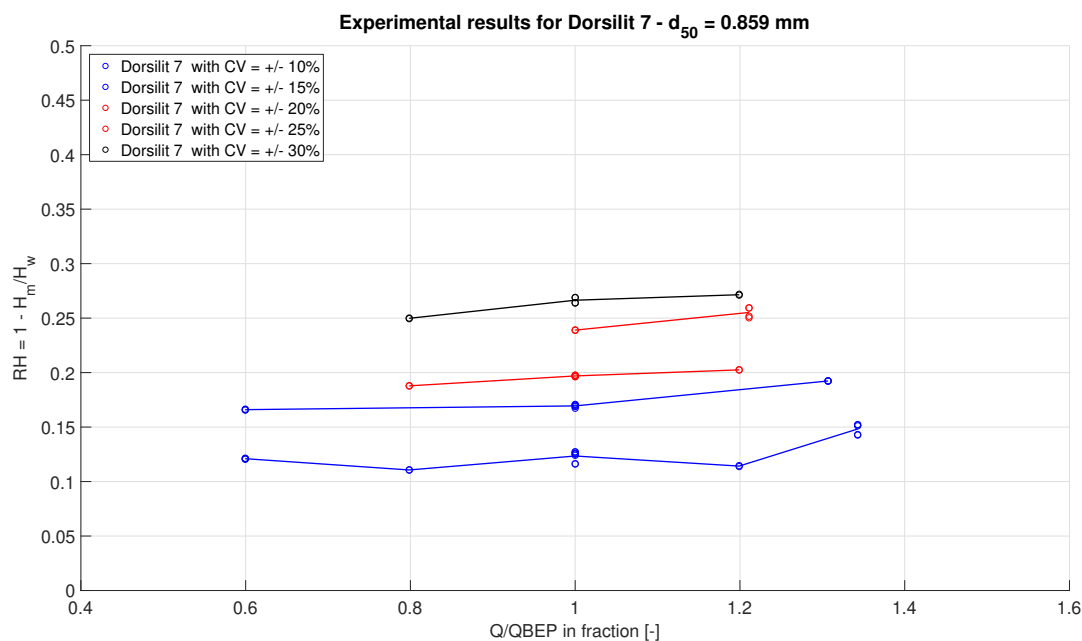
In figure 6.20 the same trends are observed as in Figure 6.19. The only experiments not consistent with these trends are the experiments at 35% concentration. This is peculiar as the 30% and 40% concentration appear to contain distinct minima.

In Figure 6.21 different trends are observed than in Figures 6.19 and 6.20. With minimal variations in the measured data, the R_H values are about level over the range 60%-140% Q/Q_{BEP} , it appears that the Q/Q_{BEP} contribution has less influence on material of this size. Here no difference between on and off BEP pumping is shown.

Preliminary conclusion for the influence of flow rate on the solids effect

After analysing Figures 6.19, 6.20 and 6.21 it is observed that for finer materials there is an influence on the solids effect due to the flow rate. When all data and observations are combined it appears that the head ratio, H_r , has an optimum when pumping at 100% Q/Q_{BEP} with fine materials, particle size ranging $d_{50} = 0.1 - 0.3mm$. When Dorsilit 7, $d_{50} = 0.859mm$, is pumped through the slurry loop minimal to no influence of flow rate is noticed. It appears that the flow rate effect is less noticeable when pumping this size of solids.

During previous tests conducted by Vlasblom et al (1999) the coarsest material tested was $d_{50} = 1.84mm$. With this particle size a clear decrease in head ratio, H_r , is shown in Figure 3.6 along the Q/Q_{BEP} range for increasing ratios of Q/Q_{BEP} .

Figure 6.20: Experimental results for Dorsilit 9 $d_{50} = 0.285 \text{ mm}$ - R_H vs Q/Q_{BEP} Figure 6.21: Experimental results for Dorsilit 7 $d_{50} = 0.859$ - R_H vs Q/Q_{BEP}

The difference between on and off BEP pumping is shown in the previous figures and the influence on the R_H values is clear. The impact on the overall solids effect is less than a change in concentration or particle size. Yet when the analyses in Chapter 5 are made, the accuracy of the formulations is seriously affected by the Q/Q_{BEP} ratios. This effect is incorporated in a correction term for the adjusted Stepanoff formulation to accurately describe the conducted experiments in section 6.5.1.

6.5. Q/Q_{BEP} ANALYSIS

In section 6.5.1 a modified Stepanoff formulation is formed. This formulation, based on the original Stepanoff 1965, includes an additional impeller contribution and a Q/Q_{BEP} adaptation. In Section 6.5.2 a new formulation is formed based on the preliminary conclusions of sections 6.1, 6.2 and 6.3.

6.5.1. STEPANOFF MODIFIED WITH Q/Q_{BEP}

With the information from the previous section, a deeper analysis is conducted on the influence of the flow rate. The α coefficients from R^2 analyses of Sections 5.3.3, 5.4.3 and 5.5.3 are used to form a formulation of this Q/Q_{BEP} contribution, γ_{QBEP} , in combination with the Stepanoff 1965 theory adjusted for the impeller influence. In Table 6.3 are the different α coefficients gathered for the modified Stepanoff 1965 formulation. With these coefficients, the modified Stepanoff formulation provides the most accurate predictions against the experimental data according to the R^2 analyses.

Q/Q_{BEP}	Geba	Dorsilit 9	Dorsilit 7
60%	1.4	1.33	1.9
100%	1.23	1.28	1.765
120%			1.85
140%	1.365	1.47	

Table 6.3: α values from R^2 analyses of the Stepanoff 1965 formulation

First, the values in Table 6.3 are described with a fit depending on the Q/Q_{BEP} ratio. This fit is given in Equation 6.2. Here the α_{QBEP} and β_{QBEP} values are determined with a best fit R^2 analysis and shown in Table 6.4. In Figure 6.22 the fitted trendlines with the data points are presented.

$$\alpha_{QBEP} (1 + (1 - Q/Q_{BEP})^2)^{\beta_{QBEP}} \quad (6.2)$$

d_{50}	α_{QBEP}	β_{QBEP}
0.139	1.23	0.79
0.2485	1.28	0.60
0.859	1.76	0.41

Table 6.4: α_{QBEP} and β_{QBEP} values for the Q/Q_{BEP} formulation

Then, the α_{QBEP} and β_{QBEP} terms are used to fit trendlines depending on functions of the d_{50} parameter. These trendlines are shown in Figures 6.23a and 6.23b. There is determined to use a linear fit for both the Alpha and Beta value. The blue line in Figure 6.23a, which is a linear function with d_{50} . And in Figure 6.23b the orange line, which is a linear function with d_{50}^{-1} .

The formulation for α_{QBEP} is shown in Equation 6.3.

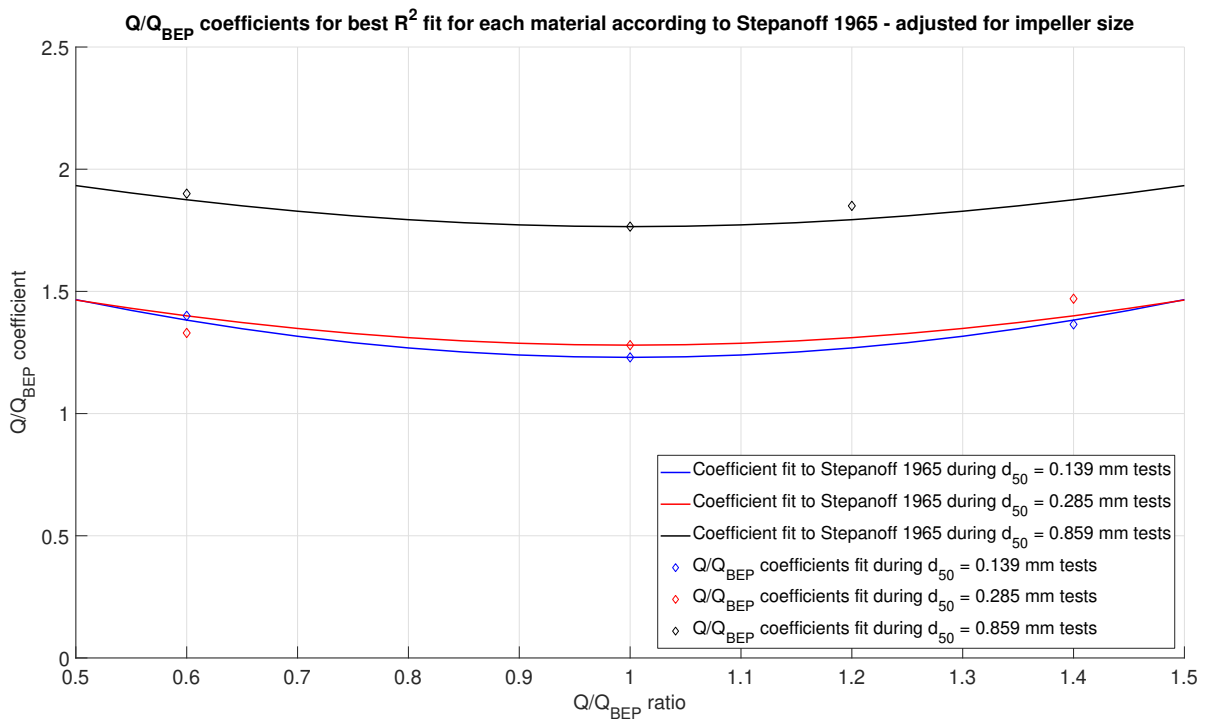
$$(0.7609 \cdot d_{50} + 1.109) \quad (6.3)$$

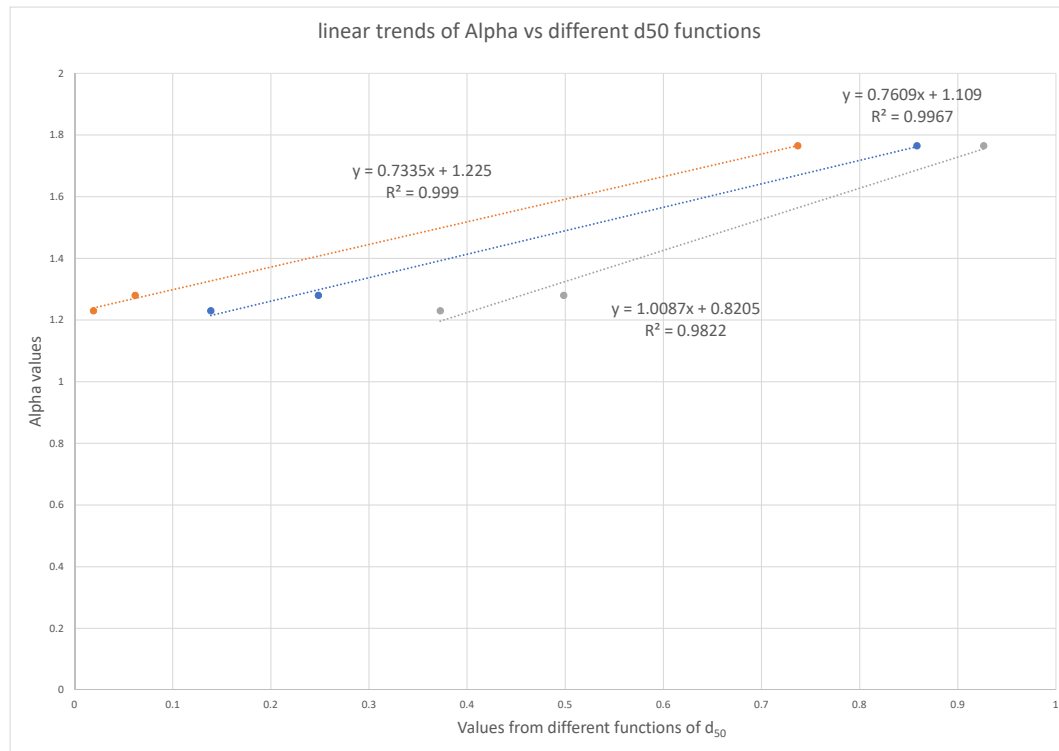
The formulation for β_{QBEP} is shown in Equation 6.4.

$$\left(\frac{0.0629}{d_{50}} + 0.3398 \right) \quad (6.4)$$

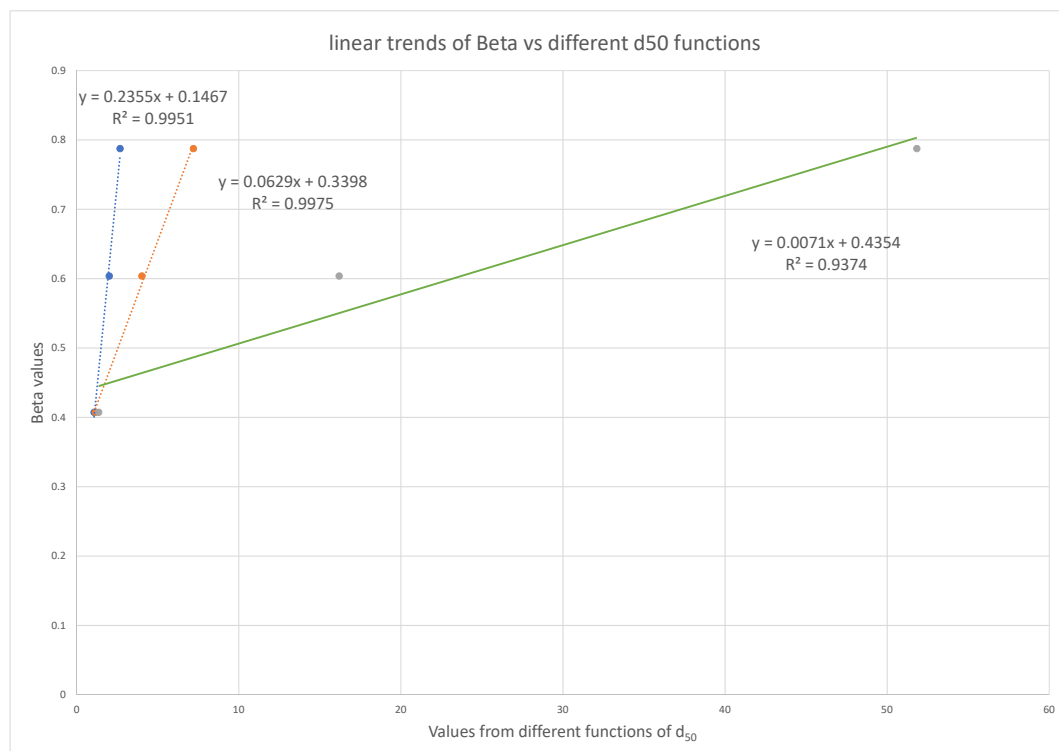
After combining all information, the Q/Q_{BEP} addition for the modified Stepanoff 1965 formula, γ_{QBEP} , is shown in Equation 6.5.

$$\gamma_{QBEP} = (0.7609 \cdot d_{50} + 1.109) \left(1 + \left(1 - \frac{Q}{Q_{BEP}} \right)^2 \right)^{\left(\frac{0.0629}{d_{50}} + 0.3398 \right)} \quad (6.5)$$

Figure 6.22: Q/Q_{BEP} coefficient fit for Stepanoff 1965 formulation



(a) α_{QBEP} trendlines, linear with d_{50} , d_{50}^2 , $\sqrt{d_{50}}$



(b) β_{QBEP} trendlines, linear with $\frac{1}{d_{50}}$, $\frac{1}{d_{50}^2}$, $\frac{1}{\sqrt{d_{50}}}$

Results of the new formulation

In this subsection the results of γ_{QBEP} are evaluated. This is done with a new R^2 analyses for the tested materials. Here the experimental data is checked against the modified Stepanoff 1965 formulation with the γ_{QBEP} term for the Q/Q_{BEP} effect, the full equation shown in Equation 6.6.

$$H_r = 1 - C_v (0.8 + 0.6 \log d_{50}) \gamma_{Impeller} \gamma_{QBEP} \quad (6.6)$$

In Figure 5.7 the R^2 values for the original Stepanoff formulation are shown with R^2 values of 0.983, 0.782 and 0.872 for the 60 %, 100 % and 140% Q/Q_{BEP} ratios respectively. In Figure 6.24 the experimental data points are shown for the Geba tests against the modified Stepanoff formulation. Here, the values R^2 of 0.983, 0.897 and 0.893 are found. The γ_{QBEP} improved the general accuracy of the adjusted Stepanoff 1965 formulation.

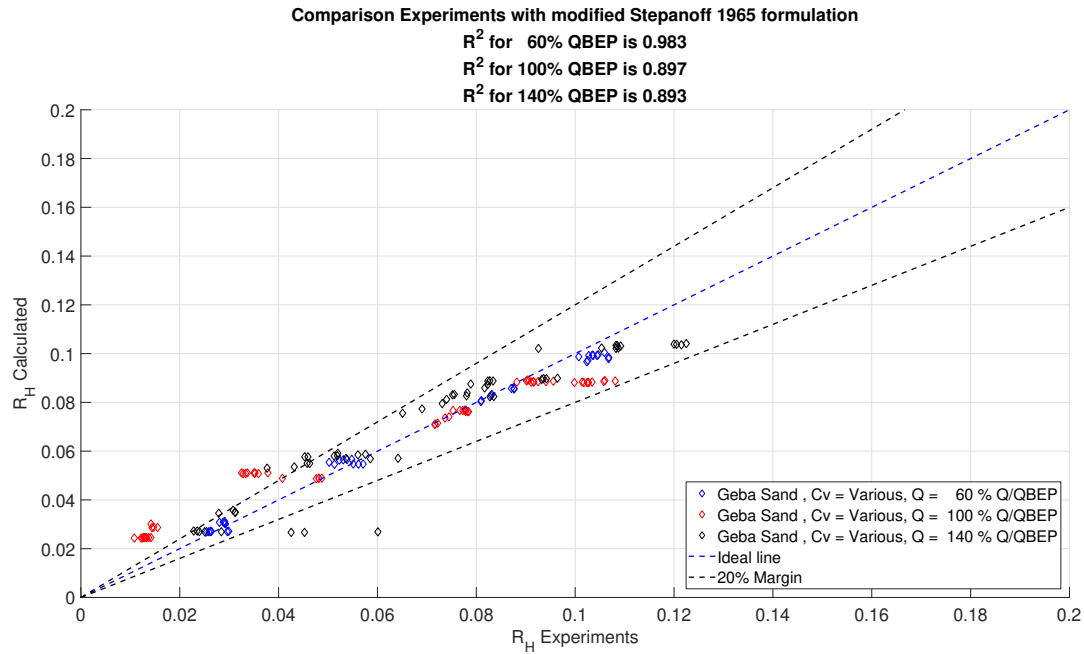


Figure 6.24: R^2 for Geba experiments compared with the modified Stepanoff 1965 formulation

In Figure 5.15 the R^2 values for the original Stepanoff formulation are shown with R^2 values of 0.811, 0.881 and 0.936 for the 60 %, 100 % and 140% Q/Q_{BEP} ratios respectively. In Figure 6.25 the experimental data points are shown for the Dorsilit 9 tests against the modified Stepanoff formulation. Here, the values R^2 of 0.809, 0.957 and 0.939 are found. The γ_{QBEP} improved the accuracy of the Stepanoff 1965 formulation for the 60% 100 % and 140% Q/Q_{BEP} ratios.

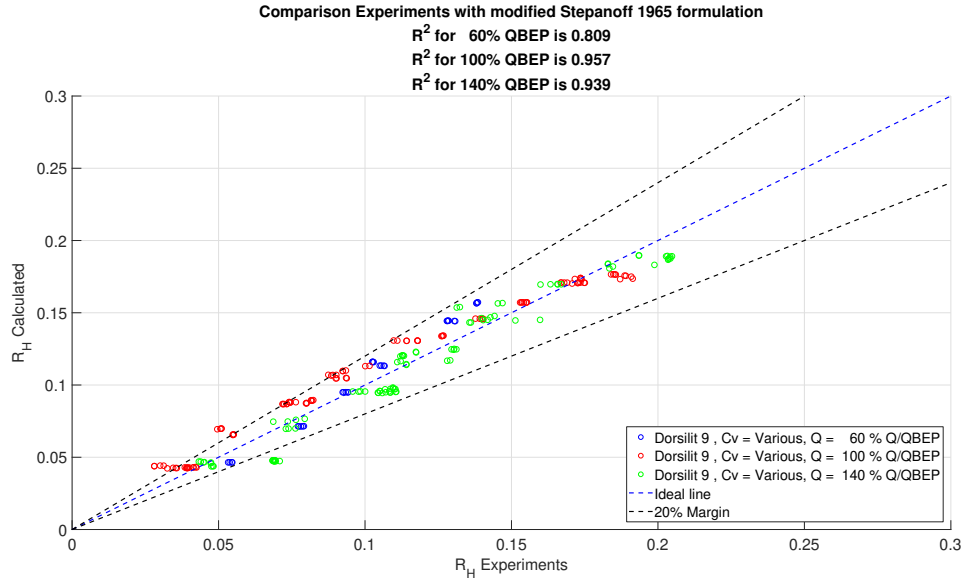


Figure 6.25: R^2 for Dorsilit 9 experiments compared with the modified Stepanoff 1965 formulation

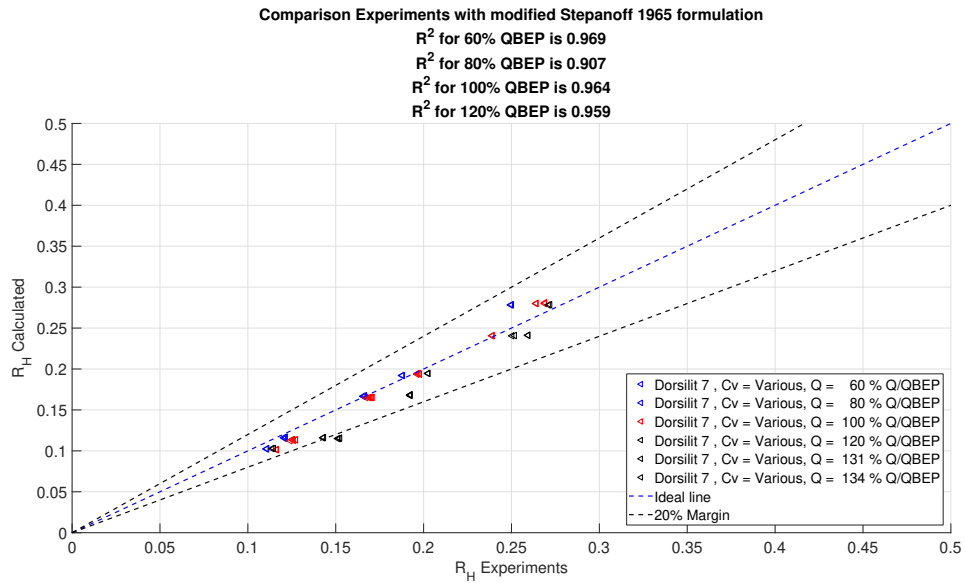


Figure 6.26: R^2 for Dorsilit 7 experiments compared with the modified Stepanoff 1965 formulation

In Figure 5.23 the R^2 values for the original Stepanoff formulation are shown with R^2 values of 0, 0.733, 0.518 and 0.218 for the 60%, 80% 100% and 120% Q/Q_{BEP} ratios respectively. In Figure 6.26 the experimental data points are shown for the Dorsilit 7 tests against the modified Stepanoff formulation. Here, the values R^2 of 0.969, 0.907, 0.964 and 0.959 are found. The γ_{QBEP} improved the accuracy of the Stepanoff 1965 formulation significantly over the whole range of Q/Q_{BEP} ratios.

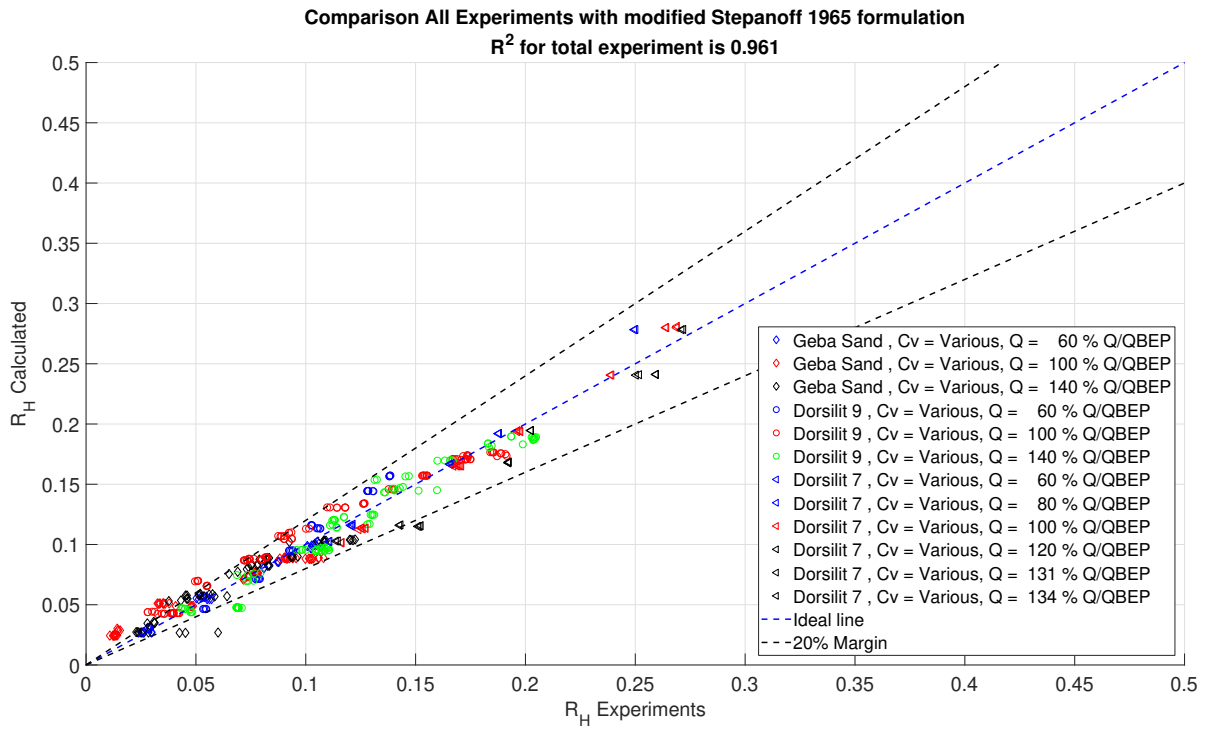


Figure 6.27: R^2 for all experiments combined compared with the modified Stepanoff 1965 formulation

The γ_{QBEP} addition improves the overall accuracy of the modified Stepanoff 1965 formulation for all materials and flow rates. This formulation provides a new parameter which contributes to the solids effect, the Q/Q_{BEP} ratio.

6.5.2. NEW FORMULATION BASED ON PRELIMINARY CONCLUSIONS

With the information gathered from Chapter 6 a new formulation is formed. From Section 6.1 is observed that a linear relation with C_v provides accurate results for the experimental data set. In Section 6.2 the power laws are the best fitted relations for the provided experimental data set. The first power law, αd_{50}^β , is used due to the simplicity and to reduce the number of variables. The Q/Q_{BEP} adaptation in this new formulation is integrated in the form of the power law, based on the variations shown in Table 6.2. Section 6.3 provides insight into the impeller effect based on the literature study.

This results in the following equation:

$$H_{r_{new}} = 1 - \alpha_{new} C_v d_{50}^{\beta_{new} \gamma_{QBEP_{new}}} \gamma_{Impeller} \quad (6.7)$$

This formulation is fitted using α_{new} and β_{new} . The $\gamma_{QBEP_{new}}$ is an adjusted version of the γ_{QBEP} .

$$\gamma_{QBEP_{new}} = (1 - (1 - \frac{Q}{Q_{BEP}})^2) \quad (6.8)$$

With the form of the formulation determined, the variables α_{new} and β_{new} are used to optimize the accuracy of the formulation for the experimental data set. The best accuracy is acquired with $\alpha_{new} \approx 1.525$ and $\beta_{new} \approx 0.752$.

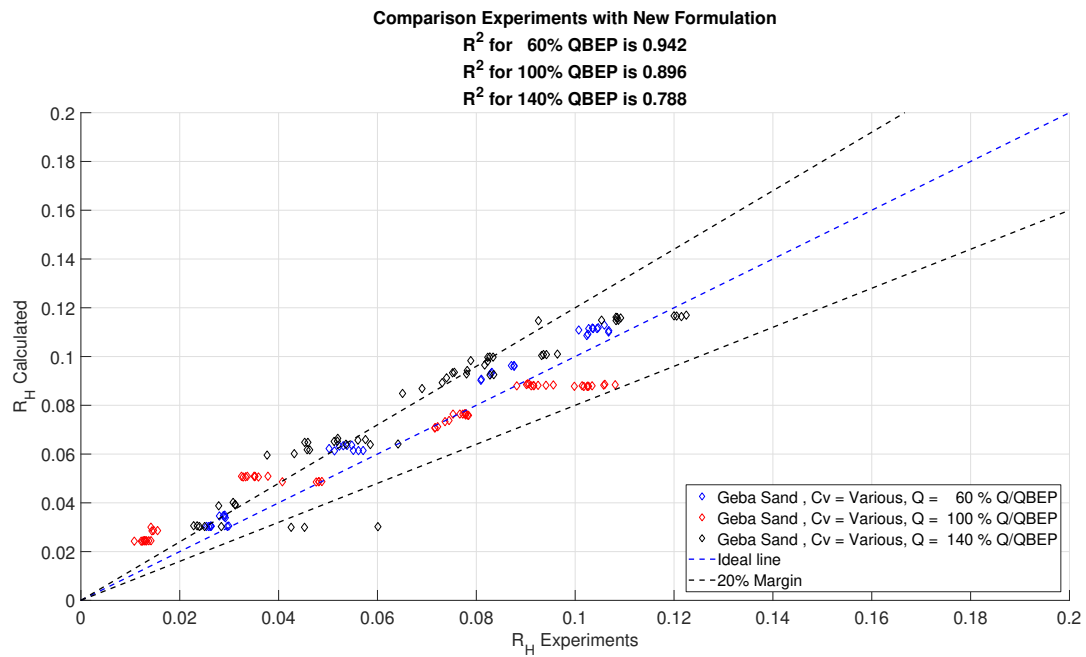
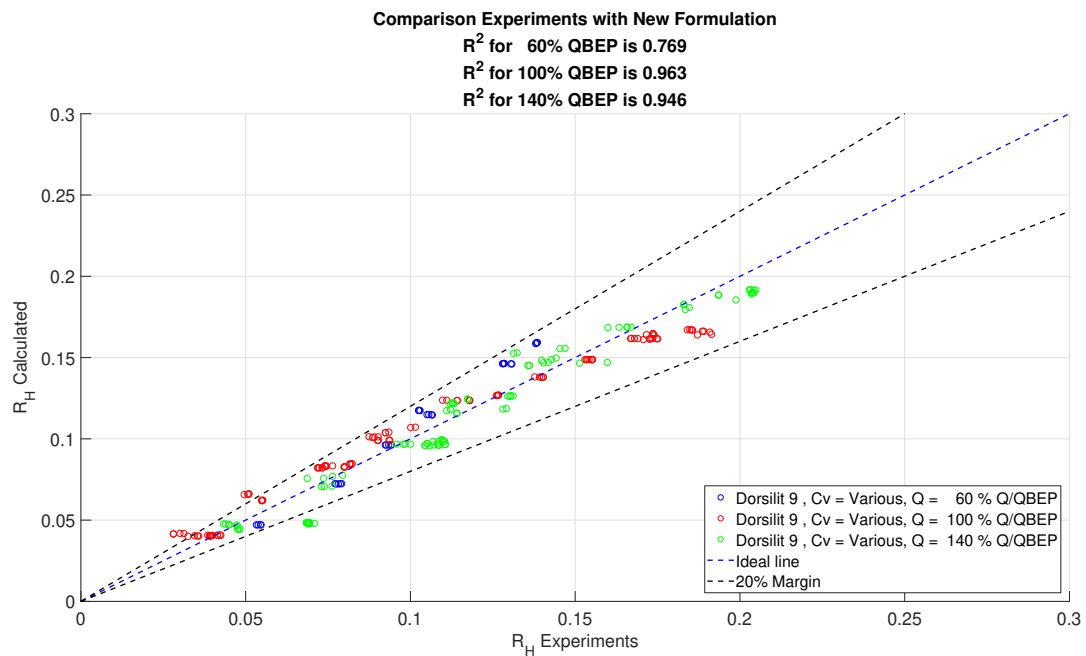
Results of the new formulation

In this subsection the results of the new formulation are evaluated. This is done with a new R^2 analyses for the tested materials. Here the experimental data is checked against the new formulation, the full equation is shown in Equation 6.9.

$$R_{H_{new}} = 1.525 C_v d_{50}^{0.752 \gamma_{QBEP_{new}}} \gamma_{Impeller} \quad (6.9)$$

In Figure 6.24 the R^2 values for the modified Stepanoff formulation are shown with R^2 values of 0.983, 0.897 and 0.893 for the 60 %, 100 % and 140% Q/Q_{BEP} ratios respectively. In Figure 6.28 the experimental data points are shown for the Geba tests against the new formulation. Here, the values R^2 of 0.942, 0.896 and 0.788 are found. The new formulation has a slightly lower accuracy as the modified Stepanoff for the first material.

In Figure 6.25 the R^2 values for the modified Stepanoff formulation are shown with R^2 values of 0.809, 0.957 and 0.939 for the 60 %, 100 % and 140% Q/Q_{BEP} ratios respectively. In Figure 6.29 the experimental data points are shown for the Dorsilit 9 tests against the new formulation. Here, the values R^2 of 0.769, 0.963 and 0.946 are found. The new formulation has the same accuracy as the modified Stepanoff for the second material.

Figure 6.28: R^2 for Geba experiments compared with the new formulationFigure 6.29: R^2 for Dorsilit 9 experiments compared with the new formulation

In Figure 6.26 the R^2 values for the modified Stepanoff formulation are shown with R^2 values of 0.969, 0.907, 0.964 and 0.959 for the 60%, 80% 100% and 120% Q/Q_{BEP} ratios respectively. In Figure 6.30 the experimental data points are shown for the Dorsilit 7 tests against the new formulation. Here, the values R^2 of 0.907, 0.902, 0.962 and 0.961 are found. The new formulation has a slightly lower accuracy as the modified Stepanoff for the last material.

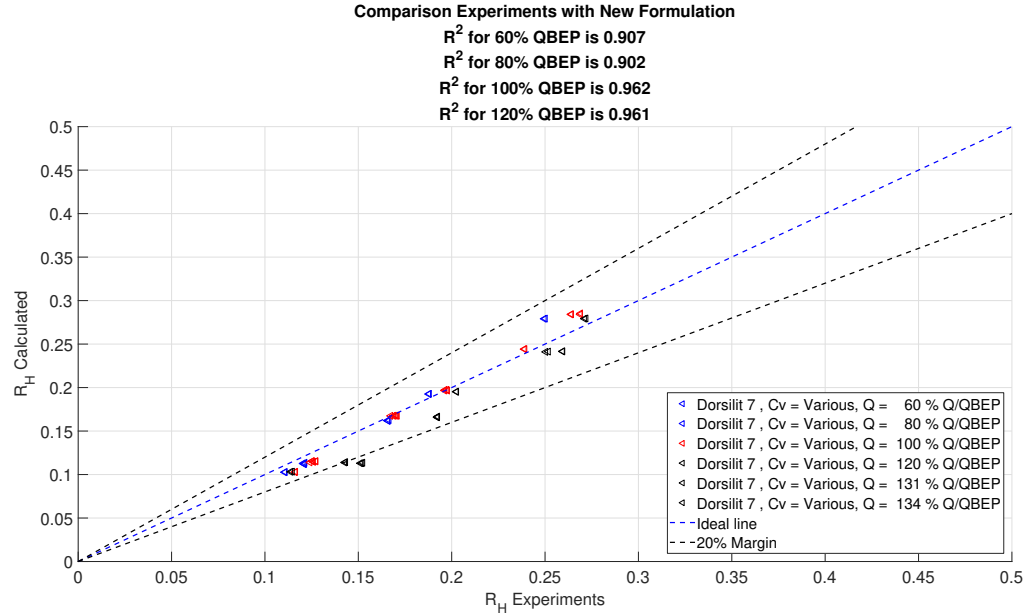


Figure 6.30: R^2 for Dorsilit 7 experiments compared with the new formulation

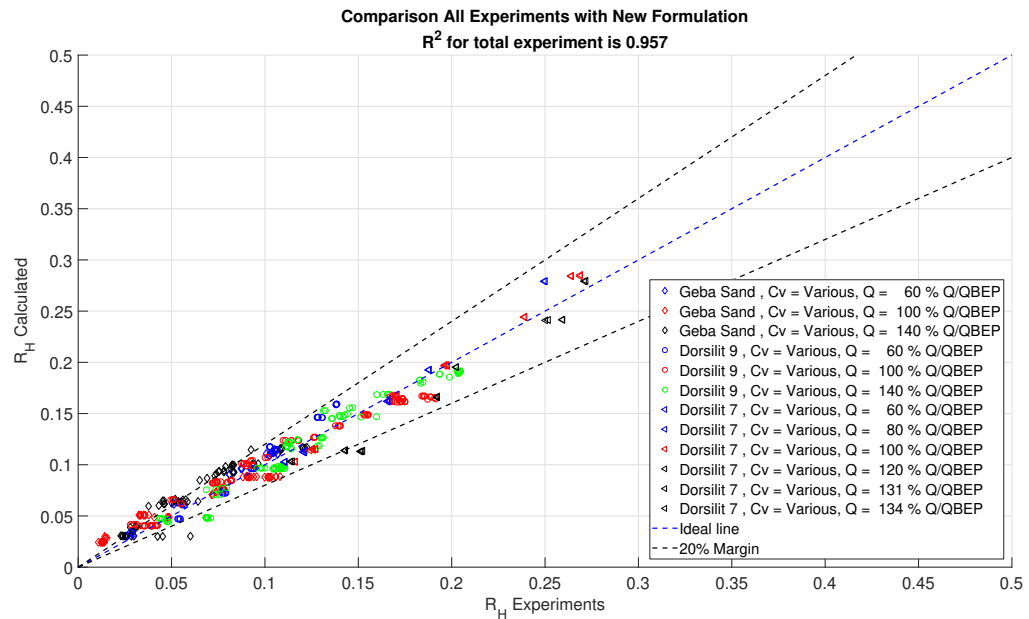


Figure 6.31: R^2 for all experiments combined compared with the new formulation

The new formulation performs with a similar accuracy as the modified Stepanoff for this particular data set, while the new formulation is purely based on observations made in Chapter 6. When comparing the accuracy over all the data points combined, the difference in accuracy is negligible, 0.961 against 0.957 for the modified Stepanoff and the new formulation respectively. Both are a significant improvement with respect to the existing theories for this particular data set of self conducted experiments.

7

Conclusions & Recommendations

In this chapter, the general outcome of the research is evaluated according to the objectives set before the start of the experiments. The main research question is answered and recommendations are made for further research on the subject of the solids effect while using centrifugal pumps.

The main objective of this thesis is:

Verify & Improve an existing, or develop a new, formulation to estimate the solids effect on the centrifugal pump for the transported slurries. Furthermore, find knowledge or data gaps and perform experiments to fill these gaps.

During the literature study, important statements are made regarding the different parameters of the formulations. Statements concerning the concentration, density, particle size, impeller diameter and flow rate provided a better understanding of the individual effect on the solids effect. Those statements are used to determine where the knowledge gaps are located and some of those are filled with new data and insights. This is done by conducting experiments in the slurry lab at the Delft University of Technology. The experiments are done to obtain more knowledge over the following topics:

- What is the influence of the solids concentration on the solids effect?
- What is the influence of the particle size on the solids effect?
- What is the influence of the flow rate on the solids effect?
- Which formulation of the solids effect is the most accurate in this test set up?

7.1. WHAT KNOWLEDGE IS OBTAINED FROM THE LITERATURE STUDY?

In this section, the most important results of the literature study are summarized. The statements are from Section 3.7 and are the inspiration of the conducted experiments.

Literature study on the different concentrations

While examining the different formulations lots of similarities are observed. Half of the researchers use the C_w notation while the other half use the C_v . This was the reason to conduct a study on the influence of the different concentration terms on the solids effect in this thesis report.

Literature study on the solid density influence

An important parameter, according to all researchers, is the density of the solids in the mixture. When formulations lack the variable of the density it is assumed the formulation is based on one specific material. To make the density parameter dimensionless the specific gravity term, S_s , is used. This variable is incorporated in almost all formulations in the form of $H_r \propto (S_s - 1)^\alpha$, where α is approximately 0.65. Due to the interest in only quartz-like materials, the density effect is not evaluated during this thesis.

Literature study on the particle size contribution

All formulations in the literature study are using the solid particle size. This is for narrow graded materials the d_{50} parameter, where broader graded materials are more accurately described with the d_w parameter. The general assumption is the use of a $\log_{10}$ or natural logarithmic function with the particle size. In this thesis, the effect of the different solid sizes on the solids effect is observed and analysed.

Literature study on the impeller size contribution

A few researchers have investigated the influence of different impeller sizes on the solids effect. The overall consensus is that a smaller R_H value is observed for larger impeller diameters compared to small scale impellers while pumping the same mixture. There are lots of different mathematical methods to incorporate this effect in the head reduction formulas. Since there was one single pump in the slurry loop, this effect is not determined during this thesis. But very promising results are obtained according to [Visintainer *et al.*, 2017] with the Wilson and Sellgren formulation of 2017 with the proportionality of the function $D_{impeller}^{0.9}$. This is also found in [Sellgren & Addie, 1989] which also appears to be independent of particle sizes.

Difference between off BEP and on BEP pumping

The solids effect is independent of flow rate according to all researcher who produced a formulation. Yet when [Vlasblom *et al.*, 1999] conducted research the effect of high delivered volumetric concentration on the characteristics of a slurry pump, he found indications of a relationship between the solids effect and the flow rate. In Figure 3.6 it is clearly shown that for different flow rates and different ratios of Q/Q_{BEP} other values for H_r are found while pumping the same mixture with coarse material, $d_{50} = 1.84$ mm.

[Vlasblom *et al.*, 1999] tested, for his research, multiple RPM settings over a broad range of Q/Q_{BEP} ratios. In this thesis, only one RPM setting is used. By adding and removing resistance in the flow, the pump is forced into different flow rates with corresponding pressures. These flow rates are representing Q/Q_{BEP} ratios for this specific rpm curve and are shown in Appendix G.

7.2. WHAT IS THE INFLUENCE OF THE CONCENTRATION ON THE SOLIDS EFFECT?

After conducting the experiments it is observed in Chapters 5 and 6.1 that there isn't one conclusive answer for this research question. For the two finer materials, Geba Sand and Dorsilit 9, the best-fitted trend through the data points is with the αC_v^β function. This function is new for formulations of the solids effect. Of all existing functions, the linear relation of αC_v has the best fit and is with fewer variables.

While testing with the coarser material, Dorsilit 7, a non-linear relationship is observed for the volumetric concentration C_v . Here the function αC_w^β appears to be the best fit, based on the observations made in Chapter 6.1. This function is an optimised version of the $C_w^{0.7}$ trend line used by several researchers.

In Chapter 6.1 independence of Q/Q_{BEP} is observed for volumetric concentrations higher than 30%. For these high-density mixtures, the effect of different flow rates vanishes and all data points are closely gathered. This is presumably due to changes in the hydraulic flow field inside the pump when pumping high-density mixtures and it appears for the finer materials tested.

Based on the knowledge obtained it is concluded that the solids effect is best fitted by the optimised αC_v^β , which is a new relationship for the concentration. Of all existing relations with the concentration, the linear αC_v relation is the best overall fit. Also when pumping mixtures with more than 30 % C_v , the hydraulic flow field changes inside the pump and this influences the effect of flow rate on the solids effect.

7.3. WHAT IS THE INFLUENCE OF THE PARTICLE SIZE ON THE SOLIDS EFFECT?

The influence of the solid particle size is very dominant. As shown in Figures 6.13, 6.14, 6.15, 6.16, 6.17, 6.18 and Table 6.2 will an increase in particle size result in a drastic increase in solids effect losses.

In chapter 6.2.1 four different trends are used to check the best fitted function for the d_{50} shown in Figures 6.10, 6.11 and 6.12. It appears for this specific data set, with unfortunately only three materials, that the two power-law functions (αd_{50}^β and $\alpha d_{50}^{\beta d_{50}^\beta}$) are the best-fitted solutions. With the logarithmic function close behind. The difference between the two power laws is negligible and the simpler power law is with only 2 parameters.

7.4. WHAT IS THE INFLUENCE OF THE IMPELLER SIZE ON THE SOLIDS EFFECT

The effect of the impeller size on the solids effect is decreasing with increasing impeller diameter. Large centrifugal pumps experience significantly less solids effect than smaller pumps, as used in this experiment. An impeller effect is found in the test data, which is consistent with the Wilson and Sellgren 2017 and Engin and Gur 2003 formulations mentioned in Section 6.3. The size of the impeller contributes significantly to the solids effect. The experimental data shows that the 0.4 m pump used in the test set-up results in less solids effect than according to Stepanoff 1965, which used data from a smaller 0.2667 m pump. Due to this, Stepanoff 1965 appears to be conservative. For this, the Stepanoff 1965 formulation is adjusted for the impeller size. After adjusting according to the Wilson and Sellgren 2017 method, the adjusted formulation was underestimating the solids effect. This is optimised with help of the α correction coefficients.

7.5. WHAT IS THE INFLUENCE OF THE FLOW RATE @ CONSTANT RPM ON THE SOLIDS EFFECT?

The objective was to identify differences in solids effect with different flow rates due to the flow field inside of the pump. The assumption was that the 100 % Q/Q_{BEP} working point would be minimally affected by the solids effect. After the experiments were conducted with multiple flow rates, concentrations and particle sizes there is a slight difference along the different flow rates. As shown in Chapter 5 and Section 6.4 the figures show a minimal solids effect for finer materials, Geba sand and Dorsilit 9, while pumping at 100% Q/Q_{BEP} . However, when the solids concentration is above 30 % the difference in flow rate is reduced. During the Dorsilit 7 experiments the head reduction term, R_H , remains level during different flow rates, at constant RPM. For this material, least influence of the flow rate is observed.

Based on the knowledge obtained it is concluded that the solids effect is dependent on Q/Q_{BEP} ratios for the finer materials, ranging from $d_{50} = 0.1 - 0.3mm$, resulting in an optimum at 100% Q/Q_{BEP} . For materials with medium size particles, $d_{50} = 0.8mm$, a reduced flow rate effect is found. The observed R_H values remain level over the Q/Q_{BEP} range. And, the result of [Vlasblom *et al.*, 1999] indicate that the solids effect is continuously decreasing for increasing Q/Q_{BEP} ratios for very coarse sand to gravel-sized particles. Yet this is not tested in this thesis, assumption purely based on observations made in Section 3.2.

After analysing all experimental data, a Q/Q_{BEP} formulation is formed to improve the Stepanoff 1965 formulation. The Stepanoff 1965 formulation is first corrected by means of the Wilson and Sellgren 2017 impeller correction. After this, a new γ_{QBEP} term, which is based on the particle size and the Q/Q_{BEP} ratio, improves the overall accuracy of the formulation significantly.

7.6. WHICH MODEL FOR THE SOLIDS EFFECT IS THE MOST ACCURATE IN THIS TEST SET UP?

Before the experiments, the Stepanoff 1965 and Wilson and Sellgren 2017 theories were presumed to be the most accurate. This was based on R^2 analyses with available data from papers. After the experiments, it is confirmed that the Stepanoff formulation is the most accurate for finer materials, and the Engin and Gur 2003 formulation appears to be the most accurate model for the coarser sand material. The Wilson and Sellgren 2017 formulation was first thought to be the best formulation but is not accurate for this specific test set up and material configurations. This is perhaps due to the fairly small centrifugal pump because their formulation is based on a 1.11 m impeller.

Based on the knowledge obtained it is concluded that the solids effect is best described by the Stepanoff 1965 theory. With or without the γ_{QBEP} addition the Stepanoff 1965 is the best formulation for small scale experiments.

The new formulation, Equation 6.7, is similarly accurate compared to the modified Stepanoff and purely constructed based on the observation made in Chapter 6. This new formulation forms a good alternative to determine the solids effect for the experimental data used in this thesis.

7.7. IS THE MAIN OBJECTIVE OF THIS THESIS REPORT ACCOMPLISHED?

Before this graduate project, various questions were unanswered. Questions regarding the correct use of concentration terms, effects of different flow rates and the relation between the d_{50} and the solids effect. With this thesis report, new insights are found and questions are answered.

For this experiment, the best-fitted form for the concentration dependency term is the αC_v^β , which is accurate over the whole range of concentration and Q/Q_{BEP} ratios. Additionally, meaningful information is found concerning concentrations above 30% C_v where the solids effect, H_r , is minimally influenced by the flow rate which is probably due to a change in flow field within the centrifugal pump.

There is also an optimal flow rate observed for the finer materials, while there is no optimal flow observed for the medium material. Based on the observations made by [Vlasblom *et al.*, 1999], a continuously decreasing trend of the H_r values for increasing Q/Q_{BEP} ratios could happen but this is not tested in this thesis.

For this specific test set up is also a trend observed for the particle size contribution as mentioned in Section 6.2.1. The power-law functions are the best fitted trends, but also the logarithmic trend is very accurate. The Stepanoff 1965 formulation is chosen as most accurate for the small scale experiments as existing theory, while the modified Stepanoff and the new formulation are both the most accurate for the small scale experiment data from this thesis.

7.8. RECOMMENDATIONS

In this section, a few recommendations are given for further research on this subject. Some are for the experimental setup and testing, while others are for the general process.

- Use more wear-resistant materials and improve the design.
During the experiments, it became very obvious, that this set up isn't designed to pump medium and high-density mixtures with moderate and high velocities. The bends and welds were worn out in no time. I suggest if this set up is used in further research, to use more wear-resistant material as wear-resistant steel or ceramic. Also, place butterfly valves in series instead of one single valve. This to reduce the wear on the valves.
- Use experimental and available practical data from the industry.
When this thesis started, the intention was to check the difference between small scale experiments and real dredging data from the industries. Unfortunately, this did not happen, so there is no data available to check the formulations against larger dredging pumps.
- For a follow-up study, check all selected formulations against larger impeller sizes.
Especially the Wilson and Sellgren 2017 formulation could surprise based on the literature study. Also, add coarser material to the existing data set for more information on the relation of d_{50} and R_H .
- Investigate the behaviour of coarser solids like Vlasblom *et al* 1999, but with the measuring strategy as applied in the current study.

A

Background important variables

The important variables, necessary for calculations, are explained in this chapter. Without knowledge of the different variables, understanding the calculations is difficult and errors can easily be made with the model's reviewed in Chapter 3 and the calculations made for the experimental plan in chapter 4.

A.1. DENSITY AND SPECIFIC GRAVITY

With hydraulic calculations, there is not one single density, ρ , but several different densities which need to be distinguished. These include the density of the fluid, ρ_f , the density of the solid particles, ρ_s , and the density of the transported mixture ρ_m .

A typical value for the ρ_f is that of clear water. Water is the most used carrying liquid in the slurry transport with a density of 1000 kg/m^3 . In marine dredging operations, the encountered fluid density is from salty water, which varies but generally has a value around 1025 kg/m^3 . Then there is the solid density, ρ_s , which has a typical value around 2650 kg/m^3 for quarts such as sand and gravel. The density of the mixture, ρ_m , is determined with the equation from table A.2.

From studying the models it is noticed that not only the density but also the relative density, or 'specific gravity', is used to calculate the solids effect. The specific gravity, S , is the ratio of the density of a substance to the density of a reference substance. The reference substance for hydraulic calculations is almost always water at its densest (4°C). For example the specific gravity of the solids like quartz is, $S_s = \frac{\rho_s}{\rho_f}$, resulting in the value 2.65.

An important note here is that the specific gravity uses the clear water density. If the models are applied for marine operations instead of laboratory testing, a correction for the saltwater is needed because the specific gravity of saltwater, $S_{saltwater}$, is 1.025.

Another commonly used parameter is the submerged specific density, Δ , which is the specific density of a material underwater. This is calculated by $\Delta_i = \frac{\rho_i - \rho_f}{\rho_f}$. For example, the submerged specific density of a solid particle, Δ_s , has the value 1.65.

Summarizing the information given above:

Table A.1: Commonly used densities and specific gravities

	ρ [kg/m ³]	S [-]	Δ [-]
Water	1000	1	-
Salt water	1025	1.025	-
Solids (Quartz)	2650	2.65	1.65

A.2. CONCENTRATIONS

The definition of concentration is interpreted in different ways, some researchers use the concentration by volume of the mixture while others use the concentration by weight. In this section, both will be explained in terms of physical representation and the mathematical formula to calculate the concentrations according to the slurry handbook [Wilson *et al.*, 2006]. Also, conversion equations will be presented.

A.2.1. CONCENTRATION BY VOLUME

The volumetric concentration is defined as the volume fraction of the solids within the mixture divided by the total volume of the mixture. This is visualised in Equation A.1. When only the mixture density and solid density is known, the volumetric concentration is calculated with Equation A.2. This concentration is easy to measure during experiments and in practice, therefore this will be the standard concentration which will be used in all the equations.

$$C_v = \frac{\text{Volume of solids}}{\text{Total volume of mixture}} \quad (\text{A.1})$$

$$C_v = \frac{\rho_m - \rho_f}{\rho_s - \rho_f} \quad (\text{A.2})$$

A.2.2. CONCENTRATION BY WEIGHT

The concentration by weight represents the weight of the solids in the mixture compared to the weight of the total volume. If the volumetric concentration is known the C_w is calculated with Equation A.3. This concentration is hard to measure during the experiment and is therefore not applied in the models in this study. If the C_w is used, the model will be rewritten in the form with C_v .

$$C_w = C_v \times \frac{\rho_s}{\rho_m} \quad (\text{A.3})$$

In table A.2, the relations are summarized to calculate the parameters mentioned in this section. Take notice if C_v and C_w values are in percentages (%), first convert them to fractions before using the concentrations in the equations.

Table A.2: Density and concentration equations from WEIR Slurry Manual [Wightley, 2002]

Variable	Relation
C_v	$\frac{\rho_m - \rho_f}{\rho_s - \rho_f}$
C_w	$C_v \times \frac{\rho_s}{\rho_m}$
ρ_m	$\rho_f + C_v(\rho_s - \rho_f)$

In research and practice, the concentration is always the in-situ concentration. The in-situ concentration is the concentration measured during transport processes and is measured with the help of ultrasound or x-ray devices in real-time. In the slurry loop is the concentration measured in the U loop, here the mixture is completely mixed and no settling occurs.

During a stationary process, it is assumed that the transported concentration (the concentration of the mixture entering passing the U loop measuring points) is the same as the concentration entering and leaving the pump. As no deposition is expected in the pump the concentration around the impeller is also the same.

A.3. PARTICLE PROPERTIES

Every researcher has concluded that the solids effect relates to the particle properties. These properties are; shape, size, density or settling velocity of the transported particles. In the following subsections are these properties explained.

A.3.1. PARTICLE SIZE

One of the most important parameters of the particles is the grain size. There are several notations of the size of a particle through the years, and in this section the most common definitions will be explained. The d_{50} is known as the 50% passing diameter in the sieve analysis. This value represents the median diameter of the particle size distribution of a given soil sample. This d_{50} holds that 50% of the particles are smaller and therefore 50% of the particles are larger than this diameter. For a narrow range particle size distribution, the d_{50} is the representative particle diameter to use in the calculations for the solids effect according to Gahlot [Gahlot *et al.*, 1992].

If the particle size distribution is of a broad range, the weighted particle size notation is preferred according to Sellgren [Sellgren, 1979], Gahlot [Gahlot *et al.*, 1992] and Khalil [Khalil *et al.*, 2013]. The d_w is the weighted particle size, this diameter is calculated in the following manner:

Weighted mean diameter:

$$d_w = \sum_{i=1}^k X_i d_i \quad (\text{A.4})$$

Where,

k = number of fractions in which the total sample was divided

X_i = Weight fraction of solid retained in the i^{th} size fraction

d_i = particle size diameter in the i^{th} size fraction

or illustrated in an different from:

$$d_w = \frac{d_{10} + d_{20} + \dots + d_{80} + d_{90}}{9} \quad (\text{A.5})$$

A.3.2. SETTLING VELOCITY

The terminal settling velocity, w_t , is the maximum velocity a particle can reach in submerged conditions. The velocity is the result of a balance of the gravitational force acting on the particle and the drag forces.

There are 3 distinct regimes with the terminal settling velocity. The first is the viscous shear dominated regime, or laminar regime, for very low Reynolds numbers ($Re < 1$) given by Stokes. The second is the drag force dominated regime, or turbulent regime, for high Reynold numbers $Re > 2000$ given by the Newton impact law. And as third the intermediate regime where the contribution of viscous shear and drag force both influence the terminal settling velocity of a particle $1 < Re < 2000$ given by Ferguson and Church.

Stokes

The first formulation dates back to 1851, the year that Stokes stated that the force holding the particle back was due to the viscous resistance of the fluid on the surface of the sphere [Moore, 2006]. This equation is applicable for very low Reynold particle numbers, so very small particles.

$$w_t = \frac{\rho_s - \rho_f}{18\mu} g d^2 \quad (\text{A.6})$$

Newtons impact law

This is however just the first component of the total balance, besides viscous forces, there is one more component to consider. The impact of water colliding with the particle [Moore, 2006].

$$w_t = \sqrt{\frac{2}{3} \frac{\rho_s - \rho_f}{\rho_f} g d} \quad (\text{A.7})$$

This results in an equation which assumes all water particles have an equal contribution, which is not true. So this is covered by introducing the drag coefficient, C_D , this coefficient generalizes the contribution of the water interaction with the particle and will account for viscous and impact forces. The formulation for this drag force is:

$$F_{drag} = \frac{1}{2} C_D A \rho_f w_t^2 \quad (A.8)$$

From this moment the only problem left is to categorise the drag coefficient for different shapes of particles and different flow situations. The drag coefficient is a function of the Reynolds particle number and the viscosity of the fluid. In figure A.1 is a picture of a sphere in a flow with different Reynolds numbers, note the difference in flow behaviour. The distinction between drag dominated (low Reynolds numbers so laminar flow) and impact dominated (high Reynolds numbers so turbulent flow) is visible.

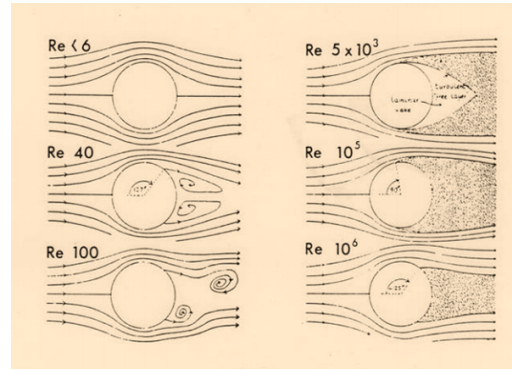


Figure A.1: Effect of Reynolds numbers on flow behaviour around spherical particles [Moore, 2006]

When considering this, the Newtons impact law is formed below:

$$w_t = \sqrt{\frac{4}{3} \frac{gd}{C_D} \left(\frac{\rho_s - \rho_f}{\rho_f} \right)} \quad (A.9)$$

This is a commonly used expression for the settling velocity, where the only unknown is the drag coefficient. This drag coefficient is determined by lots of researchers with an average value of $C_D = 0.07 - 0.5$ for spheres according to <https://www.grc.nasa.gov/WWW/k-12/airplane/shaped.html>. This range is because the drag coefficient of a sphere is highly dependent on the Reynolds number. If the settling velocity is measured the C_D factor could be calculated by rearranging equation A.9. Applying this procedure requires multiple iteration steps.

A method to calculate the drag coefficient is provided by Turton and Levenspiel. [Engin & Gur, 2003]

$$C_D = \frac{24}{Re_p} \left(1 + 0.173 Re_p^{0.657} \right) + \frac{0.413}{1 + 16300 Re_p^{-1.09}} \quad (A.10)$$

Ferguson and Church

Ferguson and Church developed a formulation in 2004 where the relation between the settling velocity, w_t , and diameter of the particle, d , would depend on the kinematic viscosity, ν , density of the fluid, ρ_f , and the immersed unit weight, $\gamma = (\rho_s - \rho_w)g$. So there needed to be an equation where the settling velocity would be described with these parameters. After comparing a lot of data and performing experiments they found the following relation with 2 coefficients for the different type of particles [Ferguson & Church, 2004].

$$w_t = \frac{\Delta_s g d^2}{C_1 \nu + \sqrt{0.75 C_2 \Delta_s g d^3}} \quad (\text{A.11})$$

Where ν is the kinematic viscosity of the fluid (fresh water) which is approximately $1.0 \times 10^{-6} \text{ m}^2/\text{s}$ for water at 20 °C. C_1 and C_2 are constants related to the shape and smoothness of the particles settling, provided in table A.3.

An important advantage of this relation is that it does not require iteration steps. This equation is applicable for laminar flow, turbulent flow and in the transition region. Another advantage is the possibility to vary between sieve diameters or nominal diameters, by adjusting the coefficient values slightly as suggested in table A.3.

Table A.3: Settling velocity coefficients Ferguson and Church

Constant	Smooth Spheres	Natural Grains: Sieve Diameters	Natural Grains: Nominal Diameters	Limit for Ultra Angular Grains
C_1	18	18	20	24
C_2	0.4	1.0	1.1	1.2

Hindered settling

After defining the settling velocity for a single particle, there is another phenomenon which is the hindered settling. This is the principle of multiple particles settling together and blocking the flow of water around the individual particles. This results in an increase in drag force which decreases the settling velocity of the cloud of particles. The hindering effects are strongly dependent on the volumetric concentration of the solids in the settling cloud, C_v , (according to Richardson & Zaki, 1954) [Matousek, 2004].

$$w_{hindered} = w_t (1 - C_v)^m \quad (\text{A.12})$$

Where m is the empirical exponent related to the particle Reynolds number Re_p .

There are different values for the exponent m which apply for different regimes of Reynolds numbers. But Wallis (1969) suggested an approximation for m which covered all ranges of the particle Reynolds number, definition provided in equation A.18.

$$m = \frac{4.7 \left(1 + 0.15 Re_p^{0.687} \right)}{1 + 0.253 Re_p^{0.687}} \quad (\text{A.13})$$

The validity of equation A.12 is limited to a maximum concentration of $C_v = 0.57$. This is the maximum concentration in an incipient fluidized bed, but the validation of the equation by experiments is based on concentrations not far above $C_v = 0.30$.

A.4. DEFINITION SETTLING & NON SETTLING SLURRIES

An important distinction between pumped slurries is the behaviour of the slurry itself. Due to the presence of very fine particles or clay the slurry mixture could result in a Non-Newtonian slurry which behaves significantly different from Newtonian slurries. In the following sections, a brief distinction is made to identify settling or non-settling slurries [Matousek, 2004].

A.4.1. NON SETTLING SLURRY

Due to the very fine particles in the slurry, rule of thumb $d < 75 \mu m$, is the hindered settling velocity neglected which means the particles do not tend to settle. Given the particles will not settle, the fluid is considered as a single-phase fluid or a homogeneous liquid-solid mixture. The concentration over the cross-section does not vary. The particles move at the same fluid speed as the surrounding fluid particles, so the in situ concentration and the delivered concentration are identical. This type of slurry doesn't normally follow Newton's law of viscosity. So this identifies as a Non-Newtonian slurry.

A.4.2. SETTLING SLURRY

For slurries with larger particles in the fluid, $d > 75 \mu m$, is the hindered settling no longer neglected. The particles are large enough to settle but will interact with turbulent mixing of the fluid. The liquid-solid mixture is heterogeneous with a varying concentration over the cross-section. For this study, the settling slurry is used to determine the solids effect. Due to the clear distinction between particles and liquid the slurry is obeying the Newton law of viscosity and therefore is a Newtonian slurry.

A.5. KNOWN DIMENSIONLESS NUMBERS

The characteristics of a centrifugal pump are important for the design of a project. In [Timar, 2005] dimensional analyses are performed and the results are dimensionless numbers which are used in several papers on the topic of solids effects on centrifugal pumps. The coefficients for C_C , C_H and Re_{pump} are derived from physical quantities according to the affinity laws and are used to evaluate an operation condition of a pump. Some information is obtained from [https://www.ksb.com/centrifugal-pump-lexicon/characteristic-coefficient/191070]

A.5.1. HEAD COEFFICIENT

The head coefficient, C_H , used by [Vocadlo *et al.*, 1974] is a characteristic coefficient following from dimensional analyses on the performances of centrifugal pumps. The C_H is formed by taking the specific energy of the pump, gH in m^2/s^2 and normalised with the rotational speed of the pump, ω in s^{-1} , and the impeller diameter, $D_{impeller}$. The result is given in Equation A.14.

$$C_H = \frac{gH}{\omega^2 D_{impeller}^2} \quad (A.14)$$

A.5.2. CAPACITY COEFFICIENT

The capacity coefficient, C_C is used by [Vocadlo *et al.*, 1974] as the second dimensionless group after the C_H . The C_C is the ratio of meridional velocity, $v_{meridional}$, or mean channel velocity, and the circumferential speed of the impeller, $u_{impeller}$.

$$C_C = \frac{v_{meridional}}{u_{peripheral}} \quad (A.15)$$

It is also known as the flow coefficient, C_F from [Timar, 2005]. This dimensionless number is used to characterise the flow rate, Q .

$$C_F = \frac{Q}{\omega D_{impeller}^3} \quad (A.16)$$

A.5.3. REYNOLDS NUMBER IMPELLER

The last group from the dimensionless analyses of [Timar, 2005] is the reciprocal of the Reynolds number. This Reynolds number describes the turbulence in the pump and is similar to the Reynolds number of a flow, but the diameter of the impeller is used.

$$Re_{pump} = \frac{\rho_m N D_{impeller}^2}{\mu} \quad (A.17)$$

A.5.4. REYNOLDS NUMBER PARTICLE

Besides the Reynolds number of the pump, is there also the Reynolds number of the particle. This is the dimensionless quantity for the flow around a particle. With this number, it is indicated if it is laminar flow or a turbulent flow around the particle.

$$Re_p = \frac{w d_{50} \rho_w}{\mu} \quad (A.18)$$

Where w is the settling velocity of the particle in [m/s], d_{50} is the median grain size in [m] and μ is the dynamic viscosity of the fluid in [kgm⁻¹s⁻¹].

A.5.5. SPECIFIC SPEED

Pump specific speed, N_s , is a measure to characterize turbo-machinery speed. In this case, the specific speed characterises the duty of the pump by the head, flow rate and rotational speed. Using the specific speed is it possible to determine a pump which is the best suitable of the given application. The specific speed formula which is the most common is not dimensionless. However, the dimensions are only important if they need to be converted to other standards for example from metric basis to US customary basis [Apsley, 2013].

The specific speed, N_s , is given by the equation:

$$N_s = \frac{N \sqrt{Q}}{(H)^{3/4}} \quad (A.19)$$

Where N_s is the dimensional specific speed, N is the rotational speed of the pump in 1/min, Q is the flow rate in m³/s at the BEP and H is the total head in meters per stage at the BEP. In the UK and Europe, N is always in 1/min, but others will use radians per second indicated as ω .

The truly dimensionless specific speed, N_{sd} , is given by the equation:

$$N_{sd} = \frac{\omega \sqrt{Q}}{(gH)^{3/4}} \quad (A.20)$$

Where N_{sd} is the dimensional specific speed and g is the gravitational constant in m/s².

It is important to specify the units when the specific speed is discussed. Often it is neglected and errors are made due to the difference in N and ω of a factor $2\pi/60$. In table A.4 are some approximated ranges given of N_s for different types of pumps according to [Apsley, 2013];

Table A.4: Specific speed ranges of different pump types

Type pump	N_s	Remarks
Radial (centrifugal)	10 - 70	Large Head
Mixed flow	70 - 170	
Axial	>110	Small Head

B

Literature Study

B.1. WIDENROTH, 1970

Widenroth was the first to publish a paper in the proceedings of Hydrotransport on the topic of pumps and the influence of sand and gravel on the characteristics of centrifugal pumps [Widenroth, 1970].

Table B.1: Widenroth's parameters for research experiments

	Fine Sand	Coarse Sand	Fine gravel	Medium Gravel	Coarse Gravel
ρ_s [kg/m ³]	2650	2650	2650	2650	2650
d_{50} [mm]	0.2	0.8	2.5	4.5	6
C_v [-]	0 - 0.3	0 - 0.3	0 - 0.3	0 - 0.3	0 - 0.3
C_w [-]	0 - 0.53	0 - 0.53	0 - 0.53	0 - 0.53	0 - 0.53
Pump Type	non-plugging pump type 150-30		model-dredge-pump		
N [RPM]	1000 & 1250		500 & 750 & 875		

Variables

For the Widenroth formulation the following variables are used;

- Volumetric concentration, C_v .
- Reynolds particle number, Re_p , see equation A.18
- Specific speed, N_s , see equation A.19
- Power applied to the mixture by the pump, ΔE_m .

Widenroth's formulation is empirically fitted against his experimental data.

Equations

Widenroth stated that the transportation in the pipelines and pump is influenced by geometrical, physical and in certain cases chemical properties of the transported solids. If chemical stability is assumed, the density, particle diameter and settling velocity are definable dimensions that can easily be used to describe the behaviour during transportation and pumping.

Two conclusions drawn from the measurements, performed by Widenroth, for the design of pumps are the pressure index, ψ , and the flow index, ϕ . Both are dimensionless numbers.

$$\psi = \frac{\Delta \dot{E}_m}{\rho_m \cdot \dot{V}_m \cdot \frac{u_s^2}{2}} \quad (\text{B.1})$$

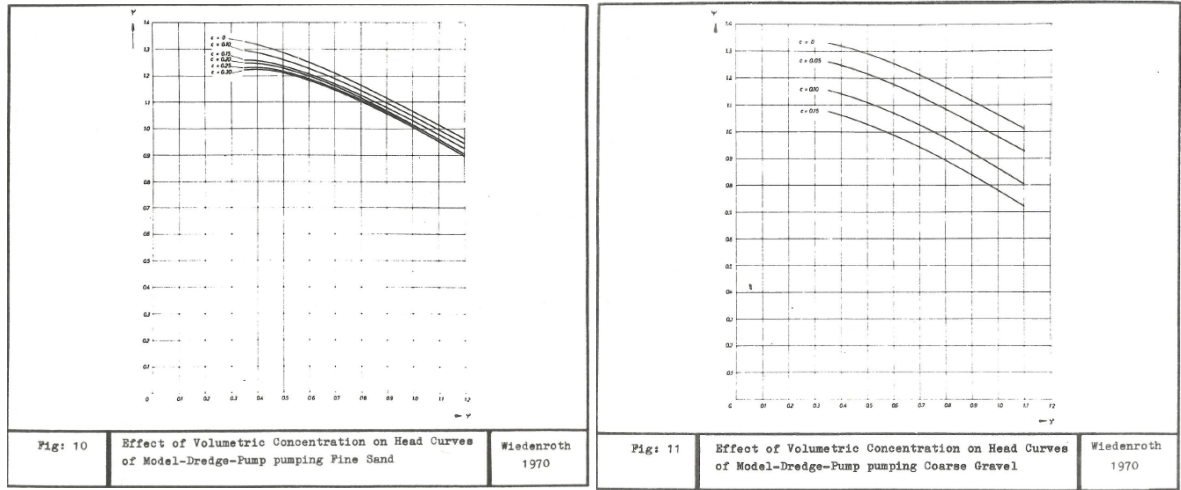
$$\phi = \frac{\dot{V}_m}{\frac{\pi}{4} \cdot D_{intake}^2 \cdot u_s} \quad (\text{B.2})$$

where

$\Delta \dot{E}_m$	= the power applied to the mixture by the pump.
u_2	= Peripheral velocity at the external diameter of the impeller
u_m	= Mixture velocity
$\dot{V}_m$	= Volume of mixture
D_{intake}	= Intake diameter impeller
u_s	= Peripheral velocity at the intake diameter of the impeller

To determine the variable $\Delta \dot{E}_m$ the equation provided by Widenroth in the paper is a comprehensive formulation of the hydraulic capacity of the pump. This could also be calculated by the hydraulic power of the fluid, $\Delta p \times Q$. After everything is measured and calculated the data will be plotted. Widenroth found an interesting relation when the pressure index is plotted against the flow index.

If the measurements are plotted in a $\psi - \phi$ diagram as in the paper of Widenroth, figure 9 - Non-dimensional head curve, a single line can be drawn for the transmission of solid matter at the speed of rotation used. If this is repeated for different concentrations, the volumetric influence on the head of the pump is visualized. This is shown in figure B.1a and B.1b, figure 10 and 11 of the paper, for fine and coarse particles respectively.



(a) Effect of volumetric concentration on head curve while pumping fine sand particles, $d_{50} = 0.2\text{ mm}$

(b) Effect of volumetric concentration on head curve while pumping coarse gravel particles, $d_{50} = 6\text{ mm}$

Figure B.1: Effect of volumetric concentration on head curves by Widenroth

From the plots it is observed that there is a linear relationship between the pressure index ψ and the concentration of the solids transported. The inclination of the linear function increases with particle size, the relationship between the pressure index for water, ψ_w , and mixture transportation, ψ_m , is given by:

$$\psi_w = \psi_m + \psi_v \quad (\text{B.3})$$

Where ψ_v is defined as the head loss index proportional to the transported concentration, which on turn is dependent on the particle size and the type of pump used. For the calculation of the headloss index as a function of the transported concentration, the particle size and the type of pump it follows that:

$$\psi_v = 3.16 \cdot 10^{-4} \cdot C_v \cdot Re_p \cdot N_s^{-2.46} \quad (\text{B.4})$$

After rearranging the equations the following equation is formed.

$$H_r = \frac{\psi_m}{\psi_w} = 1 - \frac{\psi_v}{\psi_w} \quad (\text{B.5})$$

An important note for the formulation of Widenroth is that there needs to be a large amount of information known beforehand concerning the pump, operational setup and material. This is not straightforward for a general formulation of the solids effect for multiple materials and pumps. Modelling this formulation will require more input and knowledge of the system and others.

B.2. VOCADLO ET AL, 1974

The economical use of slurry pumps depends on the optimum design and operation of the entire slurry system. However, some designs of the slurry handling systems are based on the pump performance with clear water only. This may lead to inefficient use of the system and even lead to the failure of the system itself.

In the paper of Vocadlo [Vocadlo *et al.*, 1974], a brief discussion on the effect of the solids on the system operation and design is presented. It is followed by the theoretical as well as an experimental investigation on the effect of solids on the performance of centrifugal pumps.

Table B.2: Vocadlo's parameters for research experiments

Silica		
ρ_s [kg/m ³]	2640	
d_w [mm]	0.1 - 2	
C_v [-]	0.06 - 0.30	
C_w [-]	0.1442 - 0.5308	
Pump	Rubber lined pump	Metal lined Pump
$D_{impeller}$ [m]	0.28	0.28
D_{inlet} [m]	0.102	0.102
Specific speed N_s [-]	0.392	0.472
N [RPM]	1180 & 1780	1180 & 1780

Variables

For the Vocadlo formulation the following variables are used;

- Particle size, d_{50} , in [m].
- Specific gravity of the solid, S_s .
- Impeller diameter, $D_{impeller}$, in [m].
- Head coefficient, C_H .
- Volumetric concentration, C_v .
- Capacity coefficient, C_C .

Vocadlo's formulation is an empirically fitted equation to experimental data and is based on the variables mentioned above. For this formulation the particle size and volumetric concentration are varied. The metal pump 3M-111 and the rubber lined pump 3R-111 were used to determine the constants of equation B.7. A pump characteristic, shown in the paper, is given in figure B.2.

Equations

The theoretical analysis of the losses in the pump passages is presented in this section. The total losses in the pump passage is assumed to be composed of three additive terms.

$$i = i_f + i_i + i_s \quad (B.6)$$

The pressure gradient of the carrier liquid, i_f , the pressure gradient of the mixture, i_i , and the pressure gradient for the solids in the mixture, i_s . For the full derivation see the paper of Vocadlo.

The pressure gradients are converted to hydraulic head losses and the total relative head loss is defined as the ratio of the head loss due to the presence of solid particles over the head developed by the pump with only the carrier liquid both at the best efficiency point.

$$R_H = \frac{\Delta H_m}{H_f} = C_v \cdot (S_s - 1) \left(k_1 + \frac{k_2}{C_H \cdot C_C} \sqrt{\frac{d_{50}}{D_{impeller}}} (S_s - 1) \right) \quad (B.7)$$

Where k_1, k_2 are calibration constants. C_H, C_C are the head coefficient and capacity coefficient respectively. The experimental data is used to fit equation B.7 and results in the following formula for small metal pumps. The use of C_H and C_C in combination with k_1, k_2 make this formulation applicable specifically for this type of pumps. When other pumps are used, this calibration step will need to be done again.

$$H_r = 1 - C_v \cdot (S_s - 1) \left[0.167 + 6.02 \sqrt{\frac{d_{50}}{D_{\text{impeller}}}} (S_s - 1) \right] \quad (\text{B.8})$$

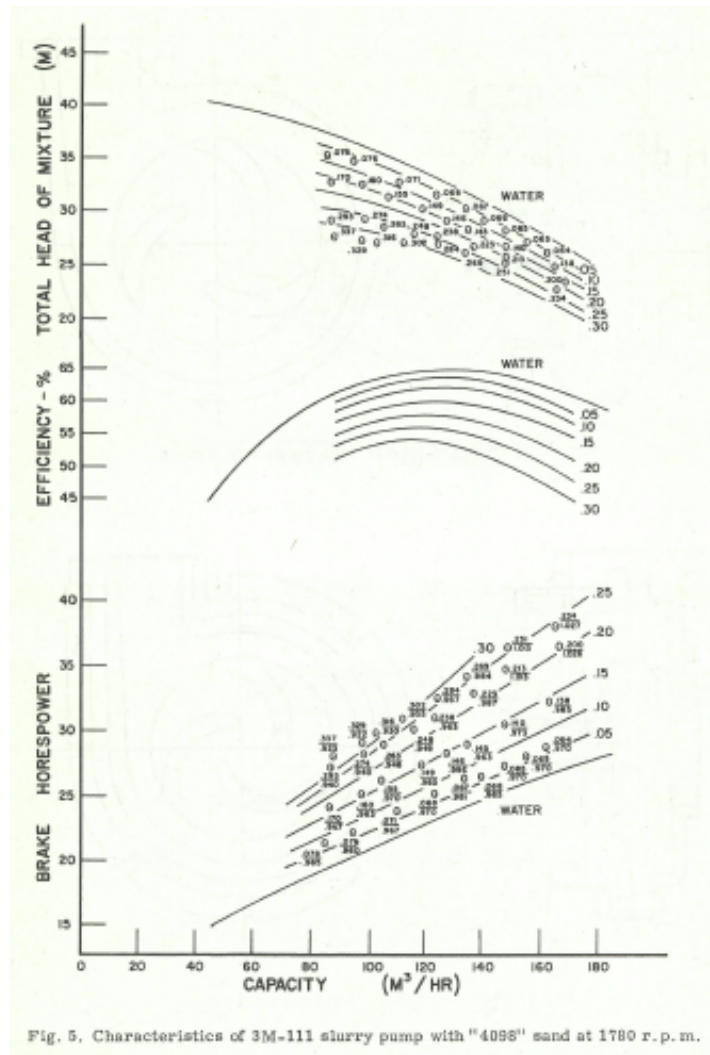


Figure B.2: Metal pump characteristics by Vocadlo

Conclusions

- The theoretical analysis presented in this paper shows a linear relationship between the head ratio and the concentration.
- The head losses of rubber-lined pumps are larger than metal lined pumps.
- The experimental data from this study show that the power increase while pumping a mixture is approximately equal to equation 2.2. This implies that the head ratio equals the efficiency ratio.

B.3. McELVAIN, 1974

The intent of this paper [McElvain, 1974] is to outline the existing developments on the part of the pump manufacturer and some of the projected requirements for high-pressure systems.

Experimental Set-up and Procedure

McElvain used the standard GAH heavy duty slurry pump, operating at 550 to 820 kpa on a single-stage tailing line. The transported slurries are not specified in this paper, but in figure B.3 are multiple specific gravities of solids used.

Table B.3: McElvain's parameters for research experiments

	Specular hematite tails
ρ_s [kg/m ³]	not specified
d_w [mm]	0.125
C_v [-]	not specified
<i>Tonnage</i> [Tonnes per hour]	800 - 875
Pump	Metal lined Pump
D_{inlet} [m]	0.23556
$D_{discharge}$ [m]	0.3048

Variables

For the McElvain formulation the following variables are used;

- K coefficient, from figure B.3.
- Concentration by volume, C_v .
- particle size, d_{50} , used for K.
- specific gravity of particle, S_s , used for K.

The formulation for the K coefficient is not mentioned but can be determined by using figure B.3. This coefficient is combined with the volumetric concentration, and calibrated with a reference concentration.

Equations

McElvain provided a graph, see figure B.3, for the pump head and efficiency ratios for operating on slurries. This graph plots the value K , for different d_{50} values per specific gravity of the pumped material.

This graph is not explained in the paper and the numerical base of the graph is not mentioned. For this study it is possible to use the graph for single points but, for further use, if the formulation is proven to be accurate, the graph should be converted in an equation to calculate the K value for a broader range of particle sizes.

McElvain formulated the equation B.9, with a reference value for the volumetric concentration of 20 %.

McElvain's formulation for the head ratio reads;

$$H_r = 1 - \frac{K \cdot C_v}{20} \quad (\text{B.9})$$

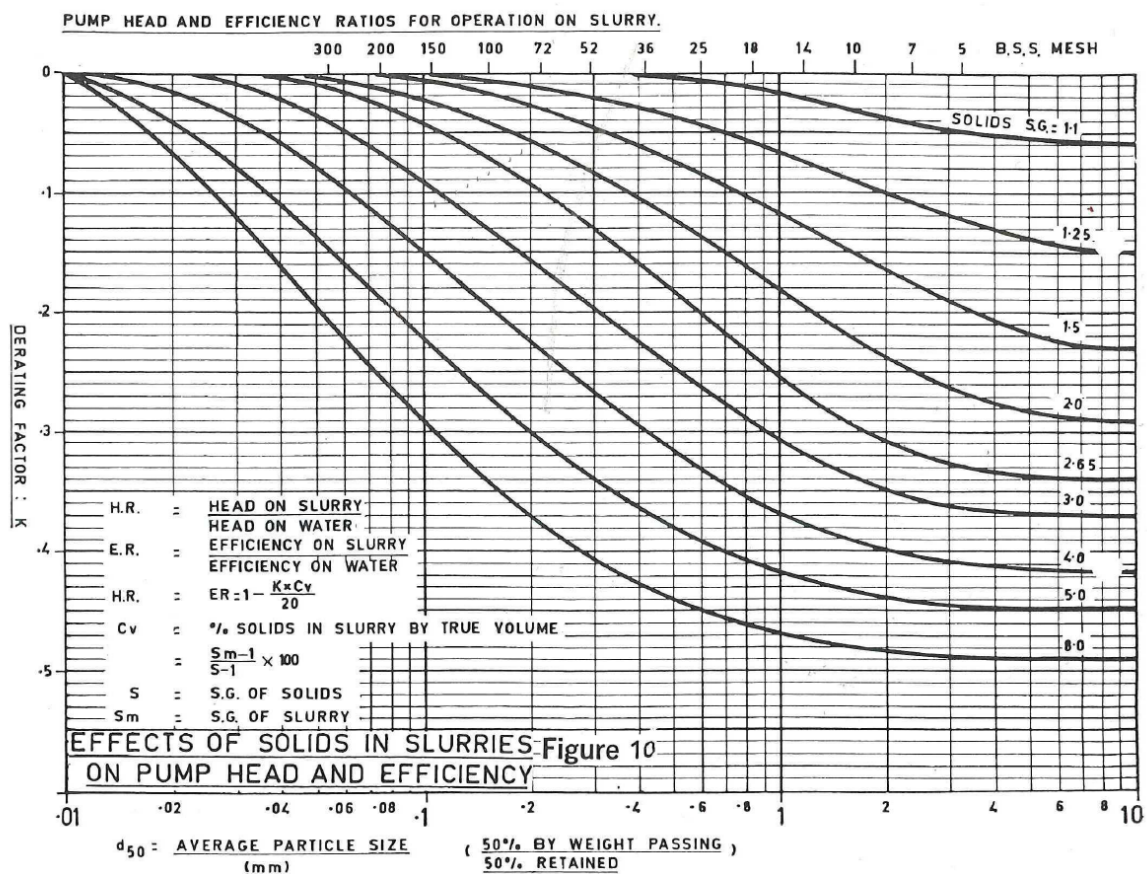


Figure B.3: K value from [McElvain, 1974]

B.4. BURGESS AND REIZES, 1976

Burgess and Reizes have carried out experiments to determine the effect of a slurry on the centrifugal pump characteristics. Their conclusion based on the experiments is that the performance of the pump depends mainly on the sizing, specific gravity and concentration of the transported solids in the slurry mixture. Burgess and Reizes have developed a method for predicting the characteristics of a pump when pumping a slurry, from the known clear water performance of the pump and knowledge of the characteristics of the pumped slurry [Burgess & Reizes, 1976].

Table B.4: Burgess and Reizes parameters for research experiments

	Beach Sand	River Sand	Ilmenite	Coarse heavy minerals
ρ_s [kg/m ³]	2670	2640	4630	4360
d_{50} [mm]	0.295	1.29	0.17	0.29
C_v [-]	0 - 0.36	0 - 0.36	0 - 0.25	0 - 0.25
C_w [-]	0 - 0.60	0 - 0.60	0 - 0.60	0 - 0.60
n value	0.333	0.589	0.450	0.561
Pump	Warman 6/4" pump			
$D_{impeller}$ [m]	0.371 (14.625")			
$D_{suction}$ [m]	0.150 (6")			
$D_{discharge}$ [m]	0.100 (4")			
N [RPM]	800 & 1300			

Variables

For the Burgess and Reizes formulation the following variables are used;

- Volumetric concentration, C_v .
- Particle size, d_{50} , in [mm].
- Density of the particle, ρ_s .
- Density of the mixture, ρ_m .

The formulation is empirically fitted to experimental data and is based on the variables stated above. The n value, used in this formulation, is determined with experiments and plotted in graphs. But in more recent studies this n is calculated with empirical fits based on the d_{50} and specific gravity S_s .

Equations

In the paper is stated that for a particular pump the dimensional analysis yields:

$$\frac{gH_m}{N^2 D_{impeller}^2} = H_w \left(\frac{Q}{ND_{impeller}^3}, C_v \text{ or } C_w, \frac{d_{50}}{D_{impeller}}, S_s \right) \quad (\text{B.10})$$

After assuming that the Reynolds number is a function of the slurry characteristics and that its effect will not be separable from those due to the other aspects of the slurry behaviour. After defining the head ratio as indicated in equation 2.7 and according to Stepanoff, the head reduction is independent of flow rate [Stepanoff, 1965]. The resulting head ratio factor, H_r , is based on the following variables according to this paper.

$$H_r = f \left(C_v \text{ or } C_w, \frac{d_{50}}{D_{impeller}}, S_s \right) \quad (\text{B.11})$$

From the functional relationships in equation B.11 indicate that the relative performance of a particular slurry pump is altered only by the parameters; Concentration by volume or weight, C_v or C_w , the average particle size, d_{50} , and the specific gravity of the solids S_s .

Results from the performed experiments by Burgess and Reizes

$$\frac{H_m}{N^2 D_{impeller}^2} = f\left(\frac{Q}{ND_{impeller}^3}\right) \quad (B.12)$$

$$N_s = f\left(\frac{Q}{ND_{impeller}^3}\right) \quad (B.13)$$

The ordinary affinity laws were found to hold provided the concentration was held constant. The head ratio was found to be independent of the flow rate which confirms the results mentioned by Stepanoff. Since the head ratio is independent of $\frac{Q}{ND_{impeller}^3}$ and therefore $\frac{H_m}{N^2 D_{impeller}^2}$, the head ratio is also independent of specific speed. After calculating all the head ratios separately, using the functional relationship of equation B.11, the empirical relationship was developed having the form of;

$$H_r = (1 - C_w)^n \quad (B.14)$$

Where C_w is the concentration of solids in the slurry by weight expressed in a fraction and the parameter n :

$$n = n(S_s, d_{50}) \quad (B.15)$$

The value of n for each solid used was determined by taking the average value of all the test points for that particular solid. The values for the solids used in the experiments are listed in table B.4. There are some data points plotted in a figure in the paper. This plot is not very useful, but there are a few researchers through the years who constructed alternative formulas to calculate the n value for the Burgess and Reizes equation.

According to Engin [Engin & Gur, 2003]:

$$n = (-0.1734 \cdot d_{50}^2 + 0.365d_{50} + 0.027) \cdot S_s \quad (B.16)$$

And according to Peng Cheng [Cheng & Yun, 2013]:

$$n = (0.21 + 0.066 \ln(d_{50})) \cdot S_s \quad (B.17)$$

The formulation of Engin is only applicable to a small range of particle sizes. The formulation of Peng Cheng is far more accurate conform the other models. So the formulation of Peng Cheng will be used to determine the n parameter.

The Burgess and Reizes formulation reads;

$$H_r = \left(1 - \left(C_v \cdot \frac{\rho_s}{\rho_m}\right)\right)^{(0.21 + 0.066 \ln(d_{50})) \cdot S_s} \quad (B.18)$$

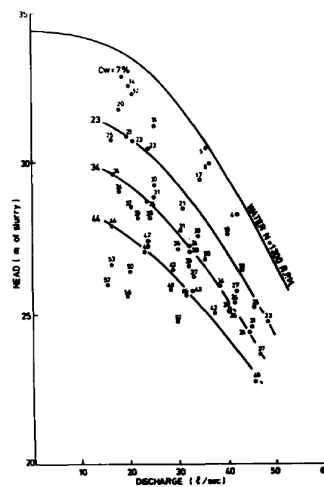


Figure B.4: Burgess and Reizes Head ratio

B.5. CAVE, 1976

As pumps become larger the importance of more exact knowledge of performance increases. The three variables which affect the performance of a centrifugal pump the most during slurry transport are the size, specific gravity and concentration of the transported solids. In the field of mining, the size of solids vary between a few microns to hundreds of millimetres, the specific gravity of the solids from less than 1 to more than 5 and the concentration may go as high as 85 % by weight.

This was the incentive for Cave to perform several tests ranging from 2-inch to 12-inch pumps. Also, the different speeds and flow rates, all concentrations of solids up to 65 % by weight, sizing from 130 to 1300 microns, and solids with specific gravity from 2.6 to 4.7 were covered.

From all the data are the effects of the considered variables examined and their effect on the performance on the centrifugal pump have been determined. The equations derived in this paper are presented to allow estimates of performance to be made for any pump and slurry transported within the range of these tests. An additional extrapolation is made for coarser sizing and other specific gravities to allow a wide range of applications [Cave, 1976].

Table B.5: Details of solid particles used in 4 inch pump tests

Material	Beach Sand	River Sand	Ilmenite	Heavy Minerals
ρ_s [kg/m ³]	2670	2640	4630	4350
d_{50} [μm]	295	1290	170	290
C_v [-]	0 - 0.20	0 - 0.20	0 - 0.20	0 - 0.20
C_w [-]	0 - 0.40	0 - 0.398	0 - 0.535	0 - 0.521
ρ_m [kg/m ³]	1330	1330	1730	1670
$k' (R_H \text{ at } 20\% C_v) [-]$	0.160	0.255	0.282	0.33
H_r [-]	0.840	0.745	0.718	0.665

Variables

For the Cave formulation the following variables are important;

- Particle size, d_{50} , in μm .
- Volumetric concentration, C_v .
- Density of the particle, ρ_s , and the corresponding specific gravity, S_s .
- Density of the mixture, ρ_m

Cave's formulation is empirically fitted to the measured data with the use of the specific gravity, concentration by weight and the particle size.

In this research, the influence of concentration, density and size of the solids is examined. All data presented in this paper are of slurries with narrow size distribution and roughly rounded cubic shapes. Additional is the pump performance affected by pump size, RPM, flow rate, pump and impeller geometry. In this study the effect of pump size, speed and flow rate are investigated.

Cave will discuss the results of the paper of Burgess and Reizes with their 4-inch pump [Burgess & Reizes, 1976]. This discussion leads to a formulation of his theory which he validated with additional experiments. After that Cave reviews some experiments conducted at different test facilities with different size slurry loops.

Equations

The tests of Burgess and Reizes are mentioned in the paper of Cave. They used a 4-inch centrifugal pump and conducted tests at pump speeds of 800 and 1300 rpm, with up to 60 % of solid concentration by weight and flow rates were varied from 34 m³/h to 150 m³/h. A total of 283 test points were taken. After analysing the experimental data the formulation given in Equation B.19 is proven to be the best fit.

Cave's formulation for the head ratio factor reads;

$$H_r = 1 - 0.0385 \cdot (S_s - 1) \left(\frac{S_s + 4}{S_s} \right) \cdot \left(C_v \cdot \frac{\rho_s}{\rho_m} \right) \cdot \ln \left(\frac{d_{50}}{22.7} \right) \quad (\text{B.19})$$

Conclusions

Cave used Equation B.19 to analyse all experiments and came to the following conclusions;

- The relation between head reduction and concentration by weight is practically linear for all four types of slurries.
- Within the range of variables considered, equation B.19 gives an estimate of the head ratio within +/- 10 % accuracy (of the own performed experiments). This holds for any given size and density of solids and any concentration by volume up to 20 %.
- It appears that the head ratio is linear with C_v up to 20 % concentration. At higher concentrations, the head ratio falls more steeply.
- The particle size has a significant influence on the head ratio. For close sized material up to $d_{50} = 1290$ microns its influence is approximately proportional to $\ln(d_{50}/22.7)$.

Table B.6: Cave's calculated data, H_{rt} against measured data from other researchers, H_{rm}

S.G. Solids S_s	C_w	d_{50} [μm]	H_{rm}	H_{rt}	Pump Size inch	Pump Speed RPM	Material
1.49	0.25	2500	0.90	0.92	3	-	Coal
1.49	0.23	7500	0.85	0.91	3	-	
1.49	0.16	12500	0.89	0.93	3	-	
1.49	0.24	12500	0.81	0.89	3	-	
1.49	0.29	12500	0.75	0.87	3	-	
2.65	0.37	400	0.78	0.83	4	-	Crushed ore
2.65	0.68	400	0.54	0.69	4	-	
2.65	0.37	400	0.79	0.83	4	-	
2.65	0.68	400	0.57	0.69	4	-	
2.65	0.37	400	0.76	0.83	4	-	
2.65	0.68	400	0.52	0.69	4	-	
2.63	0.32	750	0.81	0.82	3	1500	Sand
2.63	0.32	750	0.79	0.82	3	1500	
2.63	0.32	750	0.83	0.82	3	1500	
2.63	0.32	750	0.81	0.82	3	1200	
2.63	0.32	750	0.76	0.82	3	1200	
2.63	0.45	750	0.69	0.75	3	1500	
2.63	0.45	750	0.74	0.75	3	1500	
2.61	0.34	8000	0.69	0.69	3	1200	Gravel
2.61	0.32	8000	0.77	0.70	3	1500	
2.61	0.32	8000	0.74	0.70	3	1500	
2.61	0.43	8000	0.64	0.61	3	1500	
2.61	0.43	8000	0.65	0.61	3	1500	
2.64	0.40	105	0.85	0.90	3	1780	Sand Rubber Lined Pump
2.64	0.40	190	0.85	0.87	3	1780	
2.64	0.40	330	0.78	0.83	3	1780	
2.64	0.40	570	0.72	0.80	3	1780	
2.64	0.40	920	0.69	0.76	3	1780	
2.64	0.40	1400	0.67	0.74	3	1780	
2.64	0.40	190	0.89	0.87	3	1780	
2.64	0.40	470	0.84	0.81	3	1780	Sand Metal Lined Pump
2.64	0.40	580	0.82	0.79	3	1780	
2.64	0.40	2000	0.75	0.72	3	1780	

B.6. SELLGREN, 1979

Before this study, there were only a few studies conducted on the solids effect, for which most of the researchers used a narrow particle size distribution. Sellgren determined the effect of some ores and industrial minerals on the performance of a centrifugal pump. The solids were taken directly from in-plant crushing and milling processes, thus covering a wide particle size distribution.[Sellgren, 1979]

Table B.7: Sellgren's parameters for research experiments

	Coarse iron ore	Primary ground ore	Complex ore	Lead ore	Perlite	Crushed granite
ρ_s [kg/m ³]	4150	4003	3395	2672	2341	2676
d_{50} [mm]	1.8	0.25	0.22	0.40	0.35	3.00
d_{max} [mm]	8	1	4	2	2	4
C_v [-]	0.2 - 0.4	0.2 - 0.4	0.2 - 0.4	0.2 - 0.4	0.2 - 0.4	0.2 - 0.4
C_w [-]	0.5 - 0.7	0.5 - 0.7	0.46 - 0.7	0.4 - 0.64	0.37 - 0.6	0.4 - 0.64
Symbol in graphs	A	B	C	D	E	F
Pump	Hydroseal rubber lined Morgardshammar BC-pump with a 3 vane impeller					
$D_{impeller}$ [m]	0.43					
N [RPM]	760 RPM and 1140RPM					

Variables

For the Sellgren formulation the following variables are used;

- Volumetric concentration, C_v .
- Density of the solid, ρ_s , and corresponding specific density, S_s .
- Density of the mixture, ρ_m .
- Weighted drag coefficient, $\bar{C}_D$, determined from measurements. Calculated by eq A.9.

The formulation is an empirical fit to the measured data. This data is obtained with tests where the density of the solids, the particle sizes and concentrations are varied.

Equations

Sellgren agreed with the formulation from Burgess and Reizes, equation B.11. Here it is stated that:

$$H_r = f\left(C_v \text{ or } C_w, \frac{d_{50}}{D_{impeller}}, S_s\right) \quad (\text{B.20})$$

The functional relationships given by Equation B.20 indicate that the performance of a slurry pump of a given impeller diameter is altered by concentration, particle size and density. However, most investigations have dealt with narrow size distributed slurries. It is believed that the depression in head and efficiency will be less for a mixture containing solids of a broad size distribution than that of a mixture of uniform solids with comparable mean particle size. Therefore it is questionable if d_{50} can be used as a representative particle size of slurries covering a considerable range of particles sizes. More generally, the solid particles may be related to characteristic particle sizes, d , and a characteristic particle size distribution, Z .

The influence of the shape, ζ , of the particles on pump performance must also be considered. For example [Widenroth, 1970] reported greater losses for fresh angular particles compared to more rounded particles (particles size 2 to 8 mm).

Sellgren reported that observations of a larger difference in velocity between components inside the pump while leaving the impeller indicates that the performance should be related to a characteristic terminal settling velocity, w_t . The variables discussed previously: d , Z , ζ and w_t are believed to give a better expression of the solid properties than those given by equation B.20 from [Burgess & Reizes, 1976]. The influence of d and w can be expressed by the particle Reynolds number, Re_p , indicated in equation A.18.

With Re_p , ζ and Z the equations B.20 can be adapted in the following form:

$$H_r = f \left(Re_p, Z, \zeta, C_v \text{ or } C_w, \frac{d}{D_{impeller}}, S_s \right) \quad (\text{B.21})$$

Where Re_p , ζ , Z , S_s and d represent characteristic solid properties. The influence of the parameters Re_p , Z and ζ can be related to a representative drag coefficient, C_D . The formulation of Sellgren is determined with 1 slurry pump so the variable $D_{impeller}$ is not investigated. This all will result in:

$$H_r = f (C_D, C_v \text{ or } C_w, S_s) \quad (\text{B.22})$$

With the drag coefficient defined with a rewritten equation A.9. The representative particle diameter is defined as Equation A.4. An average representation of the terminal settling velocity may be defined by the weighted value, $\bar{w}_t$.

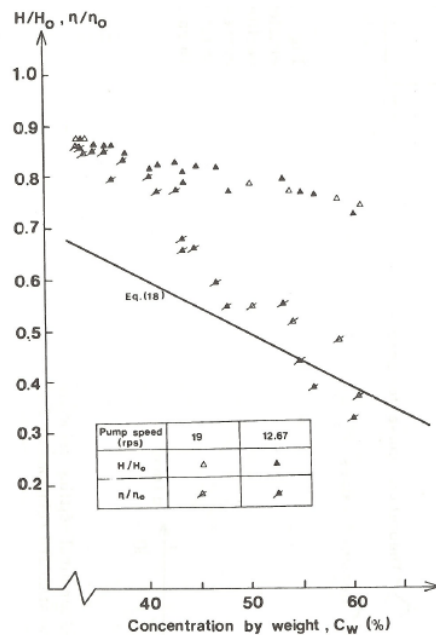
$$\bar{w}_t = \sum_{j=1}^N p_j W_j \quad (\text{B.23})$$

Where W_j is an average value of randomly chosen particles from each fractional part p_j .

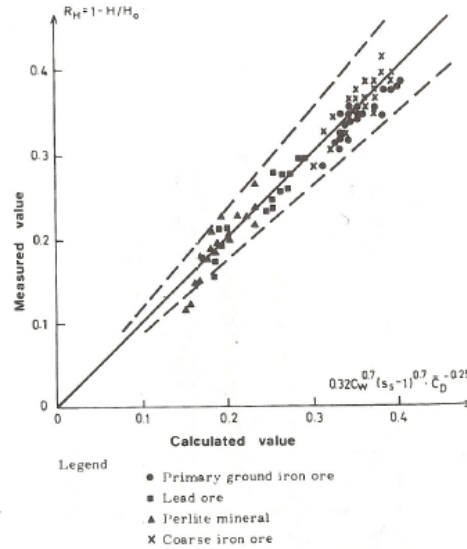
When comparing these statements with previous researchers it is observed that until a concentration of 20% the perlite, lead ore, primary ground iron ore and coarse iron ore agree with the expected trends for example experiments according to [McElvain, 1974]. But for complex ore and the crushed ore, the trend does not comply, and there is a clear drop in the head of approximately 70 % but the efficiency is only reduced by a few percents for the tests with crushed granite.

For higher concentrations, $C_v > 20\%$, it was observed that the solid concentration has a predominant influence on the pump performance. Therefore, the dependence of the solid concentration on the relative reduction in head and efficiency was evaluated in detail.

The ratio in head and efficiency, expressed as H_m/H_w and η_m/η_w , were separately represented as function of C_w and the resulting relationships were graphically represented for concentrations by volume, C_v , ranging from 20 % to 40 %, which corresponds to concentrations by weight, C_w , of 45 % to 70 %. A representative graph is shown in figure B.5a.



(a) Ratio factors for head and efficiency by Sellgren



(b) Accuracy of formulation, dashed lines indicate +/- 15 %

Figure B.5: Head and efficiency ratio's by Sellgren 1979 with accuracy graphs

It can be seen from the figure that the reduction in efficiency diverges from the drop in head for higher concentrations. Sellgren observed that the efficiency drop was more than the drop in head from a concentration by volume of 25 % and more. It is also shown in Figure B.5b that the accuracy of this formulation is within +/- 15 %

It was found by Sellgren that the head reduction is related to the concentration by weight. The efficiency reduction shows a similar relation up until 40% to 60% concentration by weight, than the efficiency drops sharply. Sellgren concluded by this that the efficiency is not correctly described by C_w . All data from this research indicate that the head reduction may be represented by equation B.24.

Sellgren's formulation for the head ratio reads;

$$H_r = 1 - 0.32 \cdot \left(C_v \cdot \frac{S_s}{S_m} \right)^{0.7} \cdot (S_s - 1)^{0.7} \cdot \bar{C}_D^{-0.25} \quad (\text{B.24})$$

Interesting to notice is the function with C_D . An increase in C_D would suggest according to Sellgren in an increase of H_r . The C_D value depends on the shape of the particle, so irregularly shaped particles (with a higher C_D) would result in a higher head ratio.

Conclusions

- Within the range of variables considered, equation B.24 gives an estimate of the head ratio within +/- 15 % accuracy (of the own performed experiments).
- The reduction in efficiency exceeds the reduction in head when mixtures with a C_v is > 20 % are pumped.

B.7. MEZ, 1984

The researcher W. Mez tried to evaluate the research done by Widenroth, Vocadlo, Cave, McElvain, Burgess and Reizes and Sellgren. His research was focussed on the behaviour of centrifugal pumps when pumping coal and gravel in 150 and 300mm centrifugal pumps [Mez, 1984]. He did not develop a new formulation but tried to check the formulations from the researchers mentioned. He also explained how he evaluated the data and which formulas are important.

Table B.8: Mez's parameters for research experiments

	Clean Coal	Raw Coal	Raw Coal 2	Gravel
ρ_s [kg/m ³]	1450	1678	1520 - 1827	2600
d_{50} [mm]	7.61	18.6	13 - 17.6	26.7
d_{max} [mm]	31.5	31.5	63	125
C_v [-]	0 - 0.3	0 - 0.3	0 - 0.4	0.1
C_w [-]	0 - 0.38	0 - 0.42	0 - 0.54	0.22
Pump	ROPU 150/600 K		ROPU 300/825 K	
$D_{impeller}$ [m]	0.65		0.825	
D_{inlet} [m]	0.20		0.35	
D_{outlet} [m]	0.15		0.30	

Equations

The equations used to evaluate the test results are the following;

- For the power input of the pump

$$P_{Pump} = \frac{M_T \cdot N}{9550} \quad (B.25)$$

This equation gives the power input to the pump, P_{Pump} in KW, given torque, M_T , is in Nm and N in RPM.

- For the effective power output of the pump is the following formula used. (Similar to the equations from [Matousek, 2004]).

$$P_{Hydraulic} = \left[(p_d - p_s) + \frac{\rho_m}{2} \cdot (V_{m_d}^2 - V_{m_s}^2) + \rho_m \cdot g \cdot (h_d - h_s) \right] \cdot Q_m \quad (B.26)$$

- For the head developed while pumping a mixture

$$H_m = \frac{P_{Hydraulic}}{\rho_m \cdot g \cdot Q_m} \quad (B.27)$$

- For efficiency ratio

$$\eta = \frac{P_{Hydraulic}}{P_{Pump}} \cdot 100\% \quad (B.28)$$

- And for the solids effect factor

$$R_H = \left(1 - \frac{H_m}{H_w} \right) \quad (B.29)$$

After all the test were performed with help of equations B.25, B.26, B.27, B.28 and B.29 the behaviour for the centrifugal pumps can be determined while transporting solids.

Conclusion

Mez had the following observations after testing and evaluating the models and test data.

- Only the formulations of Cave and Vocablo are accurate for coarse-grained solids.
- A single particle diameter is unable to characterise the effect of wide-ranged grain distributions. The weighted diameter, average drag coefficient or weighted Reynolds number is more useful. This will take the more important parameters in consideration like shape, size, density and concentration. So when the d_{50} is replaced by d_w it results in better results, but the calculated values are below the measured values.
- With increasing solids concentrations, density and grain size the formulations get more accurate. Vocablo is slightly better for coarse grain solids.
- The effect of concentration is linear also when wide-ranged coarse-grained material is pumped.
- The head ratio is proportional to $S_s - 1$
- When solids with wide grained size distributions are pumped at high concentration, the solids effect cannot be separated for each particle size. It is the combination which affects the performances of the pump.

B.8. WILSON, 1987

George Wilson stated in his paper two methods for calculating the head reduction in a centrifugal slurry pump [Wilson, 1987]. The first method is used for non-settling slurries, the second method was for settling slurries. For this thesis, the settling slurry equation will be evaluated.

Table B.9: Wilson's parameters for research experiments

	Various materials
ρ_s [kg/m ³]	1350 - 4700
d_{50} [mm]	0.01 - 4
C_v [-]	0.04 - 0.47
C_w [-]	0.12 - 0.65
Pump	
$D_{impeller}$ [m]	0.076 - 0.508

Variables

For the Wilson formulation the following variables are used;

- Volumetric concentration, C_v .
- Density of the particle, ρ_s , and the corresponding specific gravity, S_s .
- Density of the mixture, ρ_m .
- Particle size, d_{50} , in [m].
- Terminal settling velocity of one particle, w_t , determined with C_D factor or by measurements.

The formulation is an adaptation on the formulation of [Sellgren, 1979]. Wilson has rewritten some terms and has come up with helpful graphs to determine the solids effect.

Equations

Wilson evaluated test data from more than sixty tests performed by Sellgren, Burges and Reizes, Vocadlo, McElvain and Cave. Resulting from this evaluation the settling slurry equation is an adapted formulation of the formulation from [Sellgren, 1979], see equation B.24. The drag coefficient is derived with the assumption that the particles are perfect spheres see equation A.9. This can be written as the terminal velocity, w_t , and expressed in specific density of the solids, S_s . Equation B.24 combined with equation A.9 results in the following definition according to Wilson:

$$H_r = 1 - 0.075 \cdot C_w^{0.7} \cdot (S_s - 1)^{0.45} \cdot w_t^{0.5} \cdot d_{50}^{-0.25} \quad (\text{B.30})$$

If the calculations are reproduced the following equation is formed.

$$H_r = 1 - 0.168266 \cdot C_w^{0.7} \cdot (S_s - 1)^{0.45} \cdot w_t^{0.5} \cdot d_{50}^{-0.25} \quad (\text{B.31})$$

There is a difference in the constant in front of the equation. A possible explanation for this difference is that Sellgren used a weighted C_D factor from fractions of the slurry sample. Wilson used the C_D factor for a given particle size (d_{50}). It is assumed that Wilson recalibrated the equation with a different constant without mentioning this in the paper.

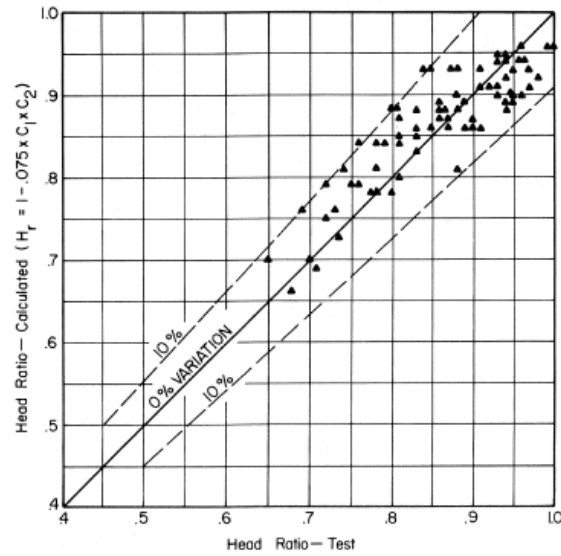


Figure B.6: Accuracy of the proposed formulation

Wilson's formulation for the head ratio factor in this study reads;

$$H_r = 1 - 0.075 \cdot \left(C_v \cdot \frac{\rho_s}{\rho_m} \right)^{0.7} \cdot (S_s - 1)^{0.45} \cdot w_t^{0.5} \cdot d_{50}^{-0.25} \quad (\text{B.32})$$

Conclusions

- Within the range of variables considered, equation B.32 will give an estimate of the head ratio within +/- 10 % accuracy.
- The head ratio appears to be independent of pump size.

Example

Wilson has provided 2 graphs, figures B.7a and B.7b. In these figures the coefficients C_1 and C_2 are determined for multiple materials and concentrations.

$$H_r = 1 - 0.075 \times C_1 \times C_2 \quad (\text{B.33})$$

Where, C_1 and C_2 are calculated by the following equations, or determined with help of figures B.7a and B.7b.

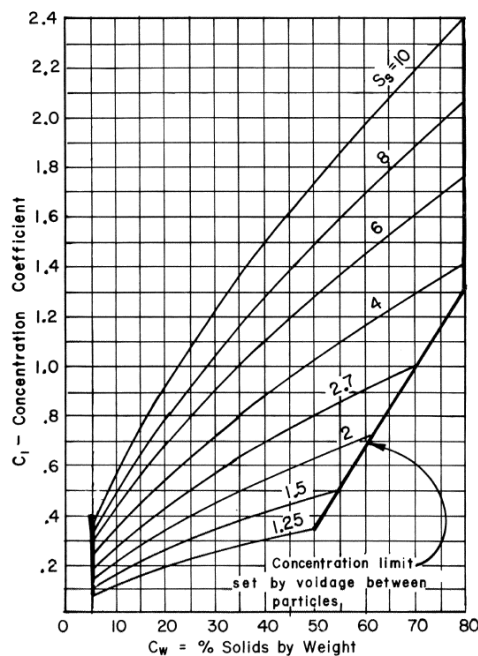
$$C_1 = \left(C_v \cdot \frac{\rho_s}{\rho_m} \right)^{0.7} \cdot (S_s - 1)^{0.45} \quad (\text{B.34})$$

$$C_2 = w_t^{0.5} \cdot d_{50}^{-0.25} \quad (\text{B.35})$$

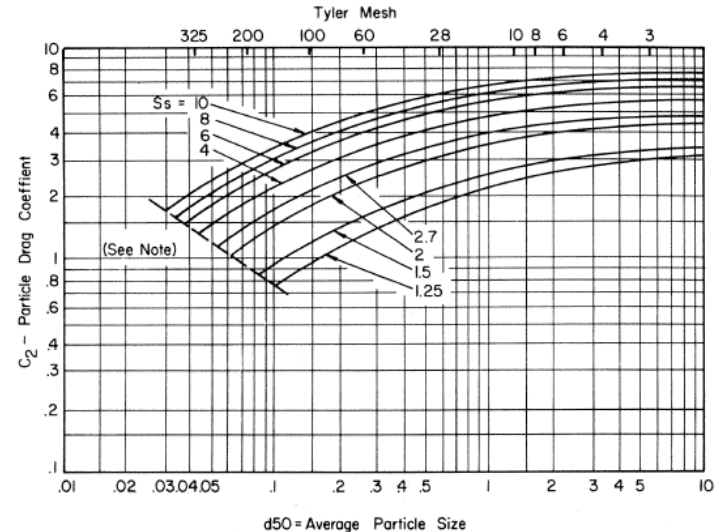
For an example operation, the data from Table B.10 is used. After specifying all parameters the figures are used to determine the head ratio, H_r . The calculated version used a settling velocity of 0.555 m/s which corresponds to a C_D value of 0.07. This C_D is calculated with the settling velocity from the Newton impact equation A.9.

Table B.10: Wilson example calculation

Variable	Graph	Calculations
S_s	2.7	2.7
d_{50}	1	1
C_v	0.20	0.20
C_w	0.40	0.40
C_1	0.7	0.67
C_2	4	4.18
H_r	0.79	0.79



(a) Wilson's coefficient C_1 for different concentrations



NOTE: In this area, slurry can be classed as non-settling and will behave as a Newtonian liquid. Therefore, standard viscosity correction procedures should be used to derate the pump performance after the apparent viscosity has been ascertained.

(b) Wilson's coefficient C_2 for different particle sizes in mm and Tyler mesh

Figure B.7: Wilson coefficients

B.9. SELLGREN AND ADDIE, 1989

Sellgren and Addie have presented research where two sand materials and one gravel material are used. In this research, they evaluated the behaviour of larger centrifugal pumps compared to the small centrifugal pumps usually used in experiments [Sellgren & Addie, 1989]. This research was not intended to formulate a new model, but rather to observe which effect the size of the impeller has on the solids effect.

Several different tests are performed, for example; Influence of different pump designs, effects of high solids concentrations and influence of materials with broad size distributions. In this section, the conclusions of these tests are summarised and relevant information is gathered.

Research results

Sellgren and Addie found that the reduction in efficiency exceeded the reduction in head when the C_w exceeded 40-45%. This is visualised in figure B.8. The conclusion for this is an increase in required power which is no longer proportional to the increase in mixture density.

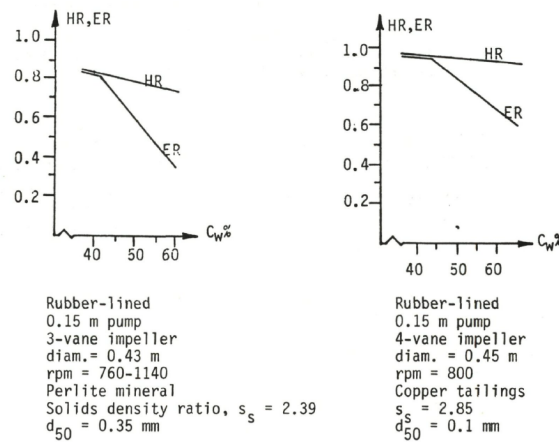


Figure B.8: Efficiency reduction and head reduction

Figure B.8 is summarised in the equations below. Figure B.8 and equation B.36 and B.37 demonstrated that equation 2.2 and 2.10 cannot be taken as universal statements when pumping slurries.

$$E_r(Q_i) < H_r(Q_i) \quad (\text{B.36})$$

or

$$P_{\text{pump;mixture}}(Q_i) > P_{\text{pump;water}}(Q_i) \cdot \frac{\rho_m}{\rho_f} \quad (\text{B.37})$$

After this Sellgren and Addie also found that the particle size distribution was of significant influence to the solids effect. In Figure B.9 is clearly shown that the drop in head ratio is over 40% for iron ore II, while iron ore I has only 15 % drop.

The difference in density cannot explain this significant drop. The d_{50} of the mixtures was similar, while iron ore II contained no fine particles. The results in figure B.9 demonstrate that it is questionable to use the d_{50} as representative solid size.

During these experiments, the flow rate was varied to verify if previous statements about independence were valid. It was with this study confirmed that the solids effect is independent of flow rate, within operational domains of flow rate. This is shown in B.10.

Table 2 Demonstration of the strong influence of the particle size distribution on the reduction in head and efficiency. Experimental result from Vappling (1989). Rubber-lined, 0.15m pump, 4-vane impeller, diameter=0.45m, rpm = 800

Product	Iron ore I	Iron ore II
Solids density ratio	4.11	5.1
Conc. by volume (%)	20	20
Conc. by weight (%)	51	56
Head and efficiency ratio: HR, ER	0.85	0.58

Particle size distributions

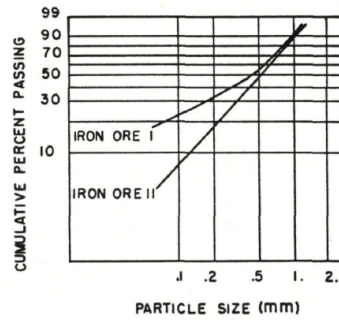


Figure B.9: Particle size distribution with results

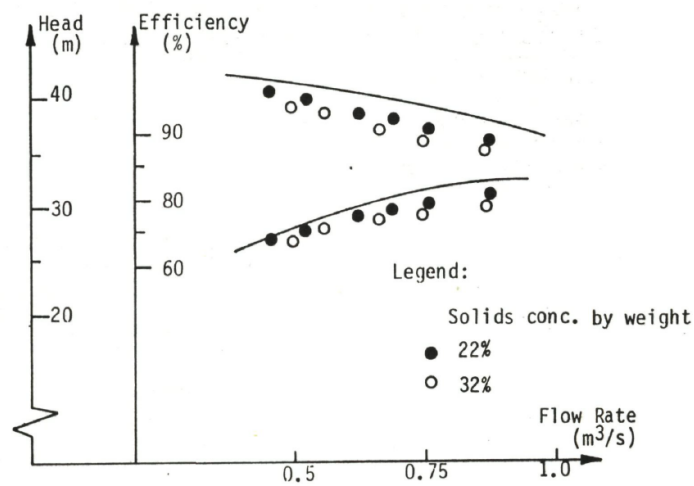


Figure B.10: Head and efficiency ratios vs flow rate, pumping Filtration sand in a 1.1m impeller

In the table B.11 are the results noted of the test where different d_{50} mixtures are pumped. They also tested with a concentration of weight of 22%. These results were not given, but there is stated that a linear relationship is observed between the solids concentration by weight and the reduction in head.

Table B.11: Sellgren and Addie's parameters for research experiments

	Foundry Sand	Filtration Sand	Gravel
ρ_s [kg/m ³]	2650	2650	2650
d_{50} [mm]	0.25	1.5	6
C_v [-]	0.15	0.15	0.15
C_w [-]	0.32	0.32	0.32
Reduction in head R_H [%]	3.5	7.0	10.0
H_r [%]	96.5	93.0	90.0
Reduction in efficiency R_E [%]	3.0	7.0	4.0
E_r [%]	97	93.0	96.0
Pump	4-vane pump impeller		
$D_{impeller}$ [m]	1.2	1.1	1.2
D_{outlet} [m]	0.50	0.45	0.50

An important result of this test is the observation that the solids effect in larger pumps is much smaller than for smaller centrifugal pumps. For example pumping a mixture with a d_{50} of 1.5 mm at a concentration of $C_w = 0.3$, ($C_v = 0.15$), in a small pump results according to [McElvain, 1974] in a R_H of 0.225. When pumping the same mixture in a larger pump the value is 0.07, see table B.11. This is a significant difference in solids effect and concludes the importance to formulate a theory including the impeller size of the pump.

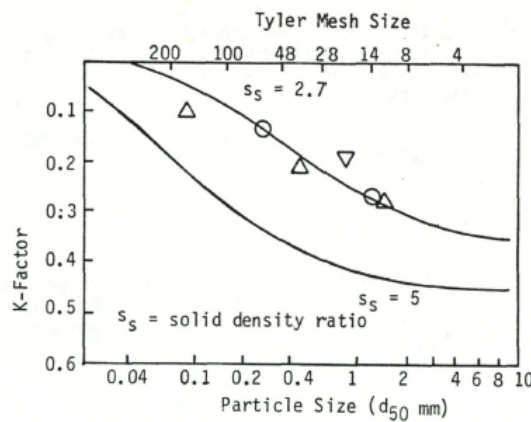


Figure B.11: Comparison of reduction in head for different tests with the curves according to McElvain (1974)

The head reduction data from this study is presented in figure B.12. In this figure the extrapolated lines for smaller pumps correspond approximately to expected reductions according to figure B.11 assuming the curves were for a 0.35m impeller. The inclination of the lines corresponds approximately to 0.9 which mean that the head ratio increases exponentially for $D_{impeller}$ with approximately the value 0.9.

The results of the study conducted by Sellgren and Addie and the data obtained from previous researchers have been evaluated in terms of $d_{50}/D_{impeller}$, see figure B.13. The scatter in this figure is too large to quantify the reduction directly to the ratio of particle to impeller size in a general way. This is presumably due to the different pump sizes and impeller types. Also, the differences in pumped materials, (different densities and sizes) could be responsible for this large scatter. But a general trend is visible where an increase in the ratio particle to impeller size results in larger losses and a lower head ratio.

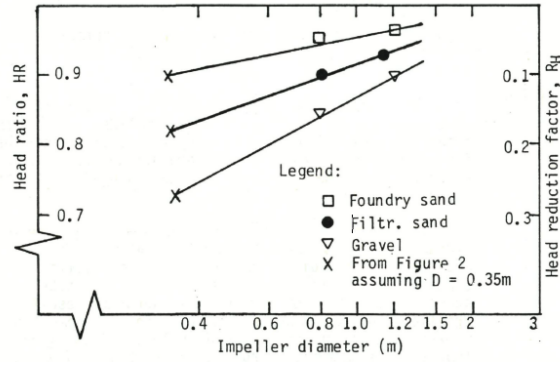


Figure B.12: Head ratio and head reduction factors versus the impeller diameter D pumping the material from this study at a C_w of 0.32

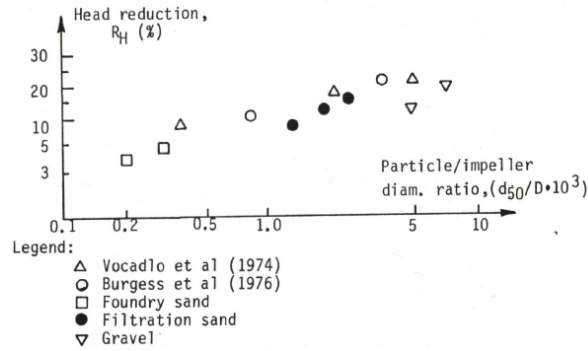


Figure B.13: Head reduction against $d_{50}/D_{impeller}$ by Sellgren and Addie

In the paper is also noted that the particle size distribution has a strong influence on the solids effect. In a mixture with a broad size distribution, the liquid and the finer particles may form a medium in which the separation between the components is reduced. This would improve the process and increase the head ratio.

Sellgren and Addie tried to formulate a theory that would generalize the influence of shape, size, distribution etc. These parameters are related to a dimensionless drag coefficient. When neglecting the influence of rotary speed and the flow rate of a particular pump, the head reduction is stated as;

$$H_r = f(C_D, S_s, C_w, d_{50}/D_{impeller}) \quad (B.38)$$

Sellgren found that the reduction in head was related to C_D^α with $\alpha = -0.25$ [Sellgren, 1979]. The effect of the particle size distribution is accounted for using a weighted drag coefficient. This drag coefficient is related to multiple particle sizes and the fraction of each size suggested by Holzenberg (1980). This all results in the following formulations;

$$H_r = \sum_{i=1}^N H_{r_i} p_i \quad (B.39)$$

Where N is the number of fractions, H_{r_i} the corresponding head reduction per particle size and p_i is the weight fraction of the particle with diameter d_i .

$$H_r \propto \sum_{i=1}^N (\bar{C}_{D_i})^{0.25} p_i \quad (B.40)$$

The formulation of equations B.39 and B.40 expresses relatively well the differences in solids effect for multiple materials. This study indicated that the solids effect could be related linearly to the concentration by weight.

However, there are examples of experiments from GIW where the influence of high concentrations had much less effect on the solids effect in relatively large pumps. Results with a GIW-pump ($D_{impeller} = 0.89m$), performed by Sellgren in 1988, while using a very broad graded material, d_{50} of 0.5 mm and d_{max} of 75 mm, showed a R_H of 5 % while pumping at a C_w of 65-70 %. This study was conducted by Sellgren in 1988, but no references were included in the paper. In this study, narrow graded materials are pumped in high concentrations with a similar pump. This resulted in a larger effect, this demonstrates the complexity of the solids effect problem.

Conclusions

- McElvain's head ratio curves hold for a large variety of slurry types. But is limited to small centrifugal pumps with an impeller diameter less than 0.5m.
- This study demonstrates the effect of pump size on the solids effect. In larger pumps, the solids effect is significantly less.
- The shape of the impeller, type and number of vanes, has a considerable influence on the head ratio. Yet this is not included in the formulation.
- A difference in the reduction of head and efficiency is observed.

B.10. GAHLOT ET AL, 1992

In this paper [Gahlot *et al.*, 1992] two different pumps are used with two different materials. During the experiments, the effect of concentration, specific gravity, particle size distribution and particle size are extensively examined.

Table B.12: Gahlot's parameters for research experiments

	Zinc Tailings	Coal
ρ_s [kg/m ³]	2850	1480
d_{max} [mm]	1	3
d_w [mm]	0.1704	0.9
C_v [-]	0 - 0.50	0 - 0.50
C_w [-]	0 - 0.726	0 - 0.60
Pump	3 vane Rubber lined pump	5 vane Ni-hard metal pump
$D_{impeller}$ [m]	0.28	0.27
D_{outlet} [m]	0.05	0.05
Specific speed N_s	66	89
N [RPM]	1400	1450

Variables

For the Gahlot formulation the following variables are used;

- Volume concentration, C_v .
- Weighted particle size, d_w in [mm].
- Density of the particle, S_s , and the corresponding specific gravity, S_s .
- Density of the mixture, ρ_m .

Gahlot's formulation is fitted on the measured data from the conducted experiments using the specific density of the particle, concentration and weighted particle size.

Equations

During the experiments with the different pumps the speed varied between 1440 and 1500 RPM, this is transferred with the help of the affinity laws to single speeds of 1400 and 1450 RPM. After testing with the materials and pumps mentioned in table B.12, the data from head, efficiency and input power are plotted against the discharge of both water and slurry at different concentrations in the paper.

With the help of these plots the effect of concentration by weight is determined, this appears to be affecting the head reduction in a linear relation to the concentration by weight.

$$R_H \propto C_v \times \frac{\rho_s}{\rho_m} \quad (\text{B.41})$$

The same for the effect of specific gravity, this is stated by [Cave, 1976] as a linear relation with $(S_s - 1)$. This is valid for Stokes flow where the particle Reynolds number is very small. The relation of $(S_s - 1)^{0.72}$ is shown in [Vocadlo *et al.*, 1974] and this is valid for the transition regime of the particle Reynolds number. This is backed in [Sellgren, 1979] where the relation $(S_s - 1)^{0.7}$ is given.

$$R_H \propto (S_s - 1)^{0.72} \quad (\text{B.42})$$

For the effect of size distribution and particle size is Gahlot in agreement with [Sellgren, 1979] that a narrow distribution is represented by the d_{50} , but a broad distribution needs to be represented with a weighted diameter d_w .

After analysing all the individual effects, Gahlot's formulation reads;

$$H_r = 1 - 0.056 \cdot (S_s - 1)^{0.72} \left(\frac{S_s + 3}{S_s} \right) \cdot \left(C_v \frac{\rho_s}{\rho_m} \right) \cdot \ln(50 \cdot d_w) \quad (\text{B.43})$$

In Figure B.14 the measured and predicted values are compared and the accuracy of the formulation is observed. The values are within the range of + 20% and -15 % for these experiments.

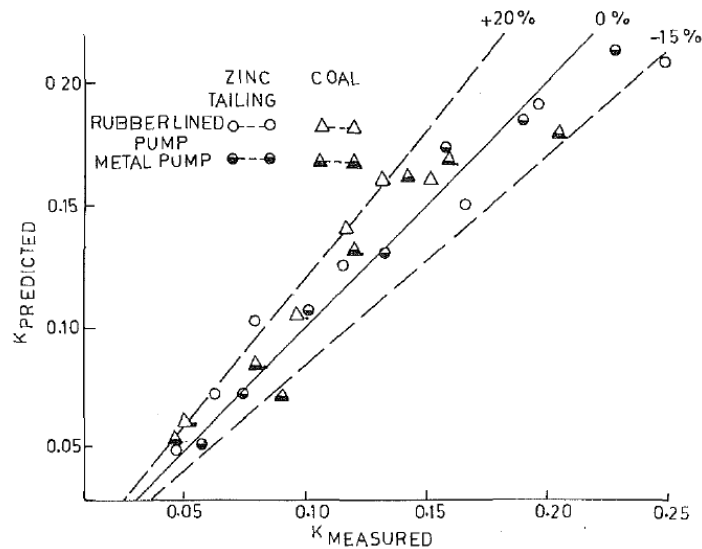


Figure B.14: Accuracy of Gahlot's formulation for head reduction factor

Conclusions

- Gahlot's formulation provides a fairly accurate method to determine the head ratio while handling settling slurries.
- Within the range of variables considered, equation B.43 will give an estimate of the head ratio within + 20% and -15 % accuracy.
- Gahlot's formulation is of similar form as Cave's formulation. The difference is the exponent of the $S_s - 1$ term and the weighted particle size, instead of the d_{50} . The modified formulation is more accurate while pumping broadly graded particle sizes.

B.11. KAZIM ET AL, 1997

Kazim started his research with comparing his experimental data with the predicted reductions according to the previous researchers; [Cave, 1976] with equation B.19 and [Gahlot *et al.*, 1992] with equation B.43. The conclusion after comparing the measured and predicted values was that the accuracy range was from -30 to +20 %. To reduce these differences, Kazim considers the individual effects of particle size, particle size distribution and concentration in his formulation to minimize the deviations between measured and expected reduction values.

Table B.13: Kazim's parameters for research experiments

	Sand Samples					Mild steel	Coal	Zinc	Iron Ore
	A	B/D	C	E	F				
ρ_s [kg/m ³]			2650			6240	1490	5510	4350
d_{50} [mm]	0.18	0.23	0.46	0.23	0.632	0.23	0.185	0.455	0.663
d_w [mm]	0.18	0.23	0.46	0.328	0.46	0.23	0.377	0.482	0.663
C_v [-]	0-0.15	0-0.32	0-0.11	0-0.04	0-0.24	0-0.44	0-0.41	0-0.72	0-0.22
C_w [-]	0-0.33	0-0.55	0-0.25	0-0.10	0-0.45	0-0.25	0-0.55	0-0.55	0-0.15
Re_p	3.66	7.39	35.0	15.88	35.0	17.63	8.62	73.68	112.2
Pump	Ni-hard metal pump								
$D_{impeller}$ [m]	0.27								
D_{outlet} [m]	0.05								
N [RPM]	1000								

Variables

For the Kazim formulation the following variables are used;

- Concentration by volume, C_v .
- Weighted particle size, d_w in [μm].
- Density of the particle, ρ_s , and the corresponding specific gravity, S_s .
- Density of the mixture, ρ_m .

Kazim's formulation is fitted against all available data from various experiments. With the use of the variables stated above, the resulting formulation is more accurate than others available until 1997.

Equations

Kazim specified the same influences as [Gahlot *et al.*, 1992]. So it is interesting to notice that they both agree on the linear relationship of the C_w on the reduction factor. But Kazim has stated that the relation for specific gravity is with the exponent 0.5 instead of 0.72. Also, the distinction between narrow and broad graded solid distributions is in agreement with Gahlot.

The proposed formulation of equation B.44 is tested for a wide range of S_s , (1.48 - 6.238), d_w (0.105 mm - 26.7 mm) and up to a C_w of 0.55. The error in predicted head ratio factors is within +/- 10 % see figures B.15 and B.16.

Kazim's formulation reads;

$$H_r = 1 - 0.13 \cdot \left(C_v \frac{\rho_s}{\rho_m} \right) \cdot \sqrt{S_s - 1} \cdot \ln \left(\frac{d_w}{20} \right) \quad (\text{B.44})$$

Remarks

It should be noted that the proposed correlation has been developed from experimental data of commercial slurries, where the particles are not spherical. It is also interesting to note that the correlation is applicable for rubber and metal lined pumps of different sizes. Hence, because this formulation is fitted to all the experimental data available from previous researchers, the effects of different pumps and solid shape sizes are covered uniquely. This demonstrates a general trend in head ratio, but bear in mind that while the formulation is based on a large data set, the evaluated pumps sizes are still small compared to modern-day dredging pumps.

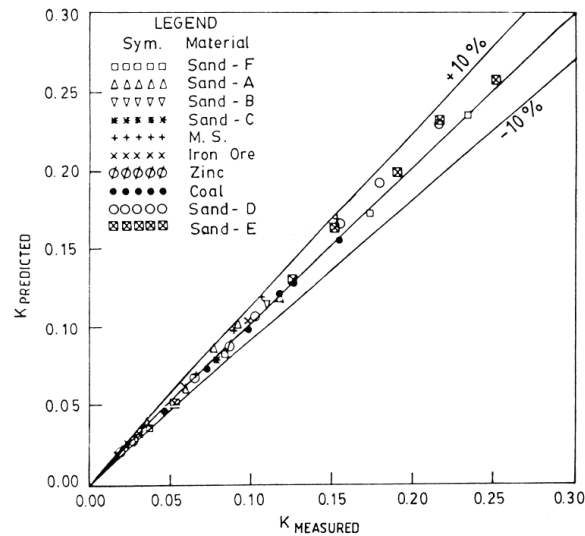


Figure B.15: Kazim's formulation against own experimental data

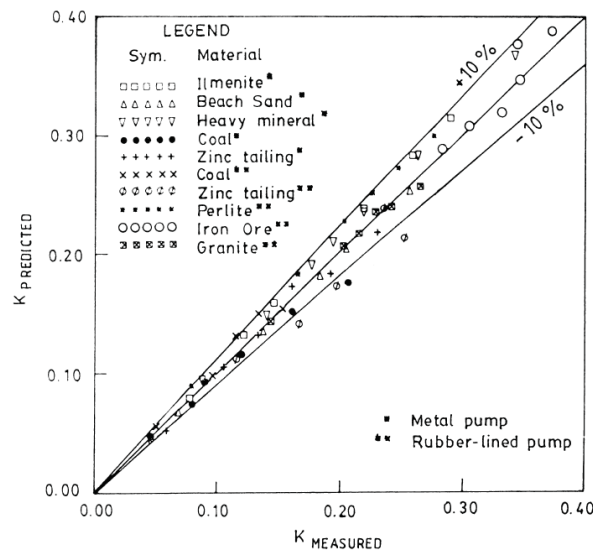


Figure B.16: Kazim's formulation against experimental data from others

Conclusion

Within the range of variables considered, equation B.44 will give an estimate of the head ratio within $\pm 10\%$ accuracy. This accuracy is provided for d_w ranging from 105 to 26700 μm and S_s ranging from 1.48 to 6.238.

B.12. MIEDEMA, 1999

Miedema found a graph of Wilson, figure B.17, in an earlier version of [Wilson *et al.*, 2006] and noticed that the different lines of various pump sizes are only influenced by the impeller diameter. The Stepanoff equation 3.1 is then adapted by Miedema in a form to fit these curves. This is presented in [Miedema, 2015].

Variables

For the Miedema formulation the following variables are used;

- Concentration by volume, C_v .
- Particle size, d_{50} in [mm].
- Impeller diameter, $D_{impeller}$ in [m].
- Specific gravity of the solid, S_s .
- Fraction of particles smaller than $75 \mu m$, X_h .

Equations

The formulation of Miedema is given below, the resemblance with the Stepanoff formulation from equation 3.1 is visible.

$$H_r = 1 - \frac{C_v \cdot (0.466 + 0.4 \log d_{50})}{D_{impeller}} \quad (B.45)$$

To determine if this formulation is a decent fit are in Table B.14 multiple points compared. After analysing this is the conclusion drawn that this formulation is fairly accurate for larger pump sizes (starting from 0.89m). But it is advised to use the formulation developed by Wilson and Sellgren, see section 3.1.3.

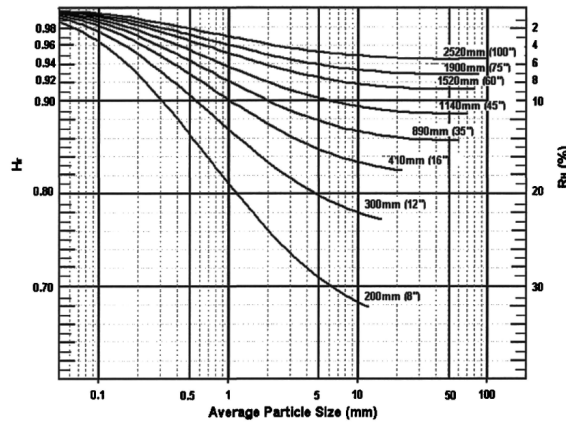


Figure B.17: Solids effect graph for various pump sizes based on test at the GIW Hydraulic Laboratory. $C_v = 15\%$ with $S_s = 2.65$

Wilson also provided 2 correction factors for his graph from [Wilson *et al.*, 2006]. The first to change the specific gravity of the solids relative to the S_s of quartz and the second factor is the correction for the presence of fine particles in the slurry. The second factor is because Wilson observed that the presence of particles finer than $d < 75 \mu m$ will reduce the solids effect. This correction needs the fraction of solids smaller than $75 \mu m$, X_h , as an input value.

$$C_{S.G} = \left[\frac{S_s - 1}{1.65} \right]^{0.65} \quad (B.46)$$

$$C_{X_h} = (1 - X_h)^2 \quad (B.47)$$

These correction factors are also applicable to the formulation from Miedema and will be used if necessary. The final equation for the Miedema formulation is;

$$H_r = 1 - \left(\frac{C_v \cdot (0.466 + 0.4 \log d_{50})}{D_{impeller}} \cdot C_{S.G} \cdot C_{X_h} \right) \quad (\text{B.48})$$

Check formulation with graph

In table B.14 are data points compared from the Wilson graph in figure B.17 and equation B.45. This is done for the available range of d_{50} given in the figure. The difference between the calculated reduction and the reduction according to the graph is fairly large for the smaller impeller sizes.

For example a $D_{impeller} = 0.3$ m, $d_{50} = 10$ mm, the difference is 21% in available head.

If this is compared with an example of $D_{impeller} = 2.52$ m, $d_{50} = 50$ mm, the difference is 1,62 %. For the larger impeller sizes, the formula is better fitted to the suggested curves.

Table B.14: Comparison Miedema's equation with Wilson's graph

d_{50} [mm]	D_{imp} [m]	C_v	$R_{H_{cal}}$	$H_{r_{cal}}$	$R_{H_{graph}}$	$H_{r_{graph}}$	Difference %
0.1	0.3	0.15	0.033	0.967	0.025	0.975	27.6 %
0.5	0.3	0.15	0.173	0.827	0.092	0.908	61.0 %
1	0.3	0.15	0.233	0.767	0.130	0.870	56.7 %
5	0.3	0.15	0.373	0.627	0.200	0.800	60.3 %
10	0.3	0.15	0.433	0.567	0.220	0.780	65.2 %
0.1	0.89	0.15	0.011	0.989	0.015	0.985	-29.7 %
0.5	0.89	0.15	0.058	0.942	0.055	0.945	5.7 %
1	0.89	0.15	0.079	0.921	0.080	0.920	-1.8 %
5	0.89	0.15	0.126	0.874	0.120	0.880	4.6 %
10	0.89	0.15	0.146	0.854	0.130	0.870	11.6 %
50	0.89	0.15	0.193	0.807	0.140	0.860	31.9 %
0.1	1.14	0.15	0.009	0.991	0.010	0.990	-14.1 %
0.5	1.14	0.15	0.045	0.955	0.041	0.959	10.3 %
1	1.14	0.15	0.061	0.939	0.062	0.938	-1.1 %
5	1.14	0.15	0.098	0.902	0.095	0.905	3.2 %
10	1.14	0.15	0.114	0.886	0.105	0.895	8.2 %
50	1.14	0.15	0.151	0.849	0.110	0.890	31.2 %
0.1	1.52	0.15	0.007	0.993	0.005	0.995	26.3 %
0.5	1.52	0.15	0.034	0.966	0.035	0.965	-2.6 %
1	1.52	0.15	0.046	0.954	0.048	0.952	-4.3 %
5	1.52	0.15	0.074	0.926	0.075	0.925	-1.9 %
10	1.52	0.15	0.085	0.915	0.080	0.920	6.6 %
50	1.52	0.15	0.113	0.887	0.085	0.915	28.3 %
0.1	2.52	0.15	0.004	0.996	0.002	0.998	65.1 %
0.5	2.52	0.15	0.021	0.979	0.020	0.980	2.8 %
1	2.52	0.15	0.028	0.972	0.029	0.971	-4.4 %
5	2.52	0.15	0.044	0.956	0.045	0.955	-1.4 %
10	2.52	0.15	0.052	0.948	0.050	0.950	3.0 %
50	2.52	0.15	0.068	0.932	0.052	0.948	26.9 %

Conclusion

After comparing the formulation with the graph, it appears for larger impeller diameters, there is a fairly accurate fit. But this formulation is an attempt to describe all curves, which is not the case. The formulation of Wilson and Sellgren is has a much better correlation with the curves of figure B.17.

B.13. ENGIN AND GUR, 2001

In the paper [Engin & Gur, 2001] is also research performed on the performance of shrouded and unshrouded impellers in a centrifugal pump. The effects of the clearance between the impeller tip and the casing, the effect of the concentration, density and mean diameter of the particle on the pump performance characteristics are investigated.

Table B.15: Engin and Gur's parameters for research experiments 2001

	Casting Sand	Beach Sand	Perlite A	Perlite B
ρ_s [kg/m ³]	2100	2640	2340	2340
d_{50} [mm]	0.4	0.413	0.270	1.390
d_w [mm]	0.4	0.44	0.211	1.147
C_v [-]	0.0272 & 0.159	Not mentioned	0.0380 & 0.0988	0.0379 & 0.1154
C_w [-]	0.0554 & 0.285	Not mentioned	0.0847 & 0.2042	0.0845 & 0.2339
Pump	Metal pump			
$D_{impeller}$ [m]	0.21			
N [RPM]	1250			

Variables

For the Engin and Gur formulation the following variables are used;

- Concentration by volume, C_v .
- Particle size, d_w in [mm].
- Density of the particle, ρ_s , and the corresponding specific gravity, S_s .
- Density of the mixture, ρ_m .

Engin and Gur's 2001 formulation is fitted on experimental data from their experiments. The formulation is based on known variables such as concentration by weight, specific gravity and particle size. The effect of each variable is individually tested.

Observations

The effect of tip clearance was tested with a clearance ranging from 1.25 to 8 mm. The result of these experiments was the confirmation that the pump performance will decrease with increasing clearance between impeller tip and the pump casing. These are extra leakage losses near the tip due to the increase of flow passage.

Equations

The effect of the different solid properties on the performance of the pump is mentioned below. The effect of specific gravity of the pumped material is determined by pumping 2 similar sized solids, d_{50} and d_w are almost equal (so narrow graded), with different specific gravities. The data from these experiments are analysed and Engin and Gur found that the R_H was proportional with the $(S_s - 1)$ to the power 0.64. This is in agreement with the literature study, including [Cave, 1976], [Gahlot *et al.*, 1992] and [Kazim *et al.*, 1997], where the expected power term ranges from 0.5 - 1.

$$R_H \propto (S_s - 1)^{0.64} \quad (\text{B.49})$$

The effect of the concentration on the performances appears to be decreasing linearly with an increasing concentration by weight. This is in agreement with most of the researchers from the past.

$$R_H \propto C_v \times \frac{\rho_s}{\rho_m} \quad (\text{B.50})$$

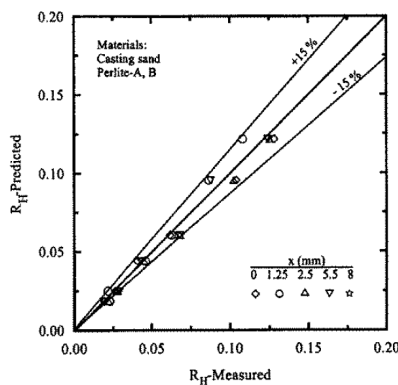
The effect of the particle size is determined by solving the remaining variable to the measured reduction. From the literature, it was noted that the weighted particle size was a more representative particle size than the d_{50} .

$$R_H \propto 0.11 \ln(44d_w) \quad (B.51)$$

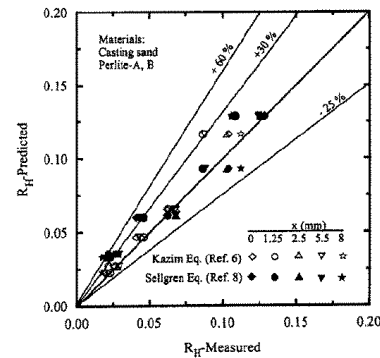
After all variables are investigated, the Engin and Gur 2001 formulation for the head ratio reads;

$$H_r = 1 - 0.11 \cdot \left(C_v \frac{\rho_s}{\rho_m} \right) \cdot (S_s - 1)^{0.64} \cdot \ln(44d_w) \quad (B.52)$$

Equation B.52 results in a maximum deviation of +/- 15 % for all tests performed by Engin and Gur as illustrated in figure B.18a. In figure B.18b is the accuracy of [Sellgren, 1979] and [Kazim *et al.*, 1997] checked with the data from Engin and Gur. In figure B.19 is the formulation tested against the experimental data available from [Vocadlo *et al.*, 1974] and [Cave, 1976]. Here it is observed that the deviation is within the +15 and -20 % range.



(a) Accuracy of eq B.52 with materials from table B.15



(b) Accuracy of the formulation of [Sellgren, 1979] and [Kazim *et al.*, 1997] with materials from table B.15

Figure B.18: Comparing accuracy of formulations

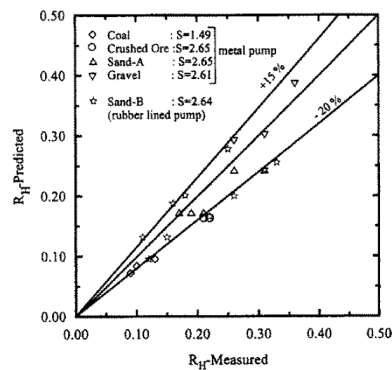


Figure B.19: Accuracy of the proposed formulation against materials from available experiments

Conclusions

- The head ratio is almost independent of tip clearance. This makes it possible to provide a formulation regardless of tip clearance in the pump
- The formulation in equation B.52 provides an accuracy of -20 % + 15 %. Both for own experimental data and data from previous researches.

B.14. OTHER MODELS

In this section are models stated which are found in the literature without further elaboration. These are references and quotes when the papers are not accessible or models consisting of graphs without numerical formulations.

Frazier, 1968

The following formulation is from Frazier dating from 1968, first mentioned in [Gahlot *et al.*, 1992] and later in [Cheng & Yun, 2013]. This equation is based on the specific gravity of the mixture and the volumetric concentration. But neglects the impact of particle size or impeller size. All literature reviewed indicated a dependence of solid size for the solids effect, so this formulation is deemed inadequate to determine the solid effect accurately.

$$H_r = \frac{1 - C_v}{S_m} \quad (\text{B.53})$$

Xijie, 1998

Another formulation is the formulation of He Xijie. This formulation is mentioned in the paper [Cheng & Yun, 2013]. This formula is based on a lot of experimental data and contains the impeller diameter in the formulation, which is interesting to use in comparison with the other formulas.

$$H_r = 1 - \left(\frac{1}{57} + 169.23 \frac{d_{50}}{D_{\text{impeller}}} \cdot S_s \right) \cdot C_v \quad (\text{B.54})$$

Weir Slurry Group Model, 2002

The Weir Slurry Group [Wightley, 2002] uses a graph, shown in figure B.20, to determine the head ratio. It uses the particle size, the specific gravity of the particle, volumetric concentration and impeller size. There is no formulation for this method so each calculation needs to be determined using this graph.

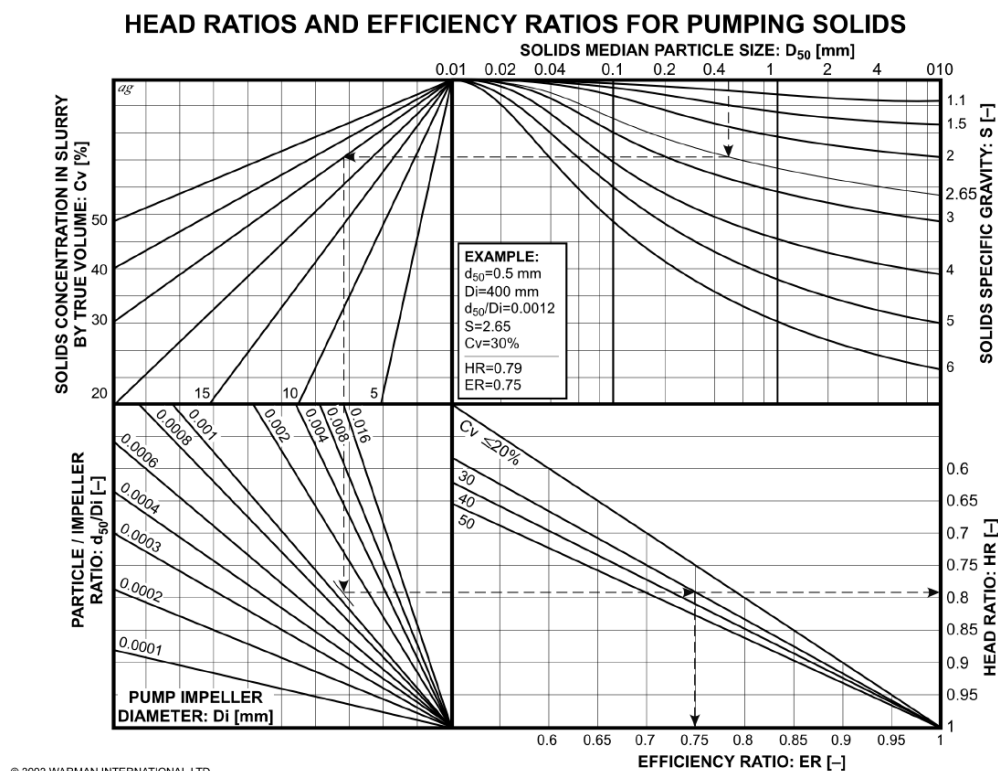


Figure B.20: Weir Slurry Group - Head and efficiency ratios for pumping solids

In the lower right corner it is shown that, for C_v larger than 20 %, there is a difference between the head ratio and efficiency ratio. This is also observed by [Sellgren & Addie, 1989].

C

Inventory of signals and equipment

In this appendix, the signals and equipment mentioned are used for the experiments conducted at the Delft University of Technology. In Table C.1 are the signals ordered as they are presented in the log file after each experiment. In Table C.2 all equipment used is named with specifications if relevant.

Signals	Units	Comments
0	[sec]	Time of datapoint
1	[Volt]	Pressure difference upward leg
2	[Volt]	Pressure difference downward leg
3	[Volt]	Flow rate
4	[Volt]	Temperature of the fluid
5	[Volt]	Pressure difference over the pump
6	[pa]	Pressure difference upward leg
7	[pa]	Pressure difference downward leg
8	[pa/m]	Pressure difference upward leg per meter
9	[pa/m]	Pressure difference downward leg per meter
10	[kg/m ³]	Density fluid
11	[-]	Concentration of solids in the fluid
12	[bar]	Pressure difference over the pump
13	[m ³ /s]	Flow rate
14	[m ³ /h]	Flow rate
15	[m/s]	Flow rate
16	[°Celsius]	Temperature of the fluid

Table C.1: Information of all logged signals in Labview as shown in Log file

Number in Fig. 4.1	Equipment	Specifications	Comments
1	Centrifugal pump	($D_{imp} = 0.4\text{m}$)	Centrifugal pump from Damen
-	Electro drive for the pump	($P_{max} = 132\text{ kW}$)	Electro drive from Siemens
2	Material storage tank		
3	Differential pressure sensors	range 0 - 5 bar	3 sensors (2 for U loop + 1 for pump measurements)
5	Cooling unit		
6&7	Control valves:		Butterfly valves and Gate valves
10	Temperature sensor		
11	Magnetic flow meter		

Table C.2: Information of all equipment used during the experiments

Within the Micromaster 440 display unit is an option to obtain the actual filtered power output at the pump shaft. This R0032 parameter is easily accessed and the information is provided in Figure C.1

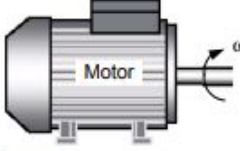
r0032	CO: Act. filtered power	Datatype: Float	Unit: -	Min: - Def: - Max: -	Level 2
P-Group: CONTROL					
Displays motor power (power output at the motor shaft).					
 $P_{\text{mech}} = \omega \cdot M = 2 \cdot \pi \cdot f \cdot M$ $\Rightarrow r0032[\text{kW}] = \frac{1}{1000} \cdot 2 \cdot \pi \cdot \frac{r0022}{60} [1/\text{min}] \cdot r0031[\text{Nm}]$ $r0032[\text{hp}] = 0.75 \cdot r0032[\text{kW}]$					
Dependency: Value is displayed in [kW] or [hp] depending on setting for P0100 (operation for Europe / North America).					

Figure C.1: Power output of frequency drive at pump shaft

D

Pressure sensor calibrations and Density error in the slurry loop

When the slurry loop first started, it was necessary to check if everything was working properly. When starting the centrifugal pump under supervision of lab coordinator Ed Stok, it appeared everything worked except for the density measurement. Ed Stok claimed that the system was completely cleared of particles and only filled with water, yet the density of the mixture was approximately 1050 kg/m³. This was higher than expected with only water, it should be around 1000 kg/m³. After flushing the system at a high flow rate, to make sure all settled solid particles are in suspension, the entire system was drained to make sure the system is clean before starting the experiments.

After refilling the system with clear water and extracting all the air from the system. The slurry loop is starting with clear water conditions. The cleaning didn't resolve all the problems because the density was still more than expected from clear water. This was according to Ed Stok the most accurate measurement of the system because this test set up is used since the research of [Vlasblom *et al.*, 1999]. Previously master students and PhD students conducted tests and they never noticed problems with the concentration measurements.

To verify if everything was correct, and to check where the possible problem where located, a test run was conducted with varying flow rates. The pressures from the two differential pressure sensors located on the U loop were checked. In Figure D.1 is visible that the two DP sensors are measuring different pressures, which result in the noticed density error. The two different differential pressure sensors are supposed to measure identical but opposite pressures for clean water. This due to the principal of the U Loop where the pressure drop in the upward pipe is equal to the pressure drop in the downward pipe. The red line indicates the upward sensor, the blue line indicates the downward sensor, this pressure is multiplied with -1 for convenience. The black line represents the flow rate. At the highest flow rate, the different pressures are 9000 Pa versus 6000 Pa.

After eliminating all possible causes, concerning the pressure sensors and software, the professor responsible for the slurry loop, Prof van Rhee, suggested to start from the beginning and start measuring the construction. With this, a constructional deviation was found near the pressure sensors. The spacing between the sensors located on the U loop where not according to the drawings and due to this the pressure differences are not equal.

The pressure sensor on the upward leg has a spacing of 3.3 m, the sensor on the downward leg has 2.5 m spacing. According to the original construction drawings both spacings were supposed to be 3 m). After changing this error in the parameters of Labview the density was as expected, approximately 1000 kg/m³. After fixing this problem all systems were working accordingly and the slurry loop was ready for testing.

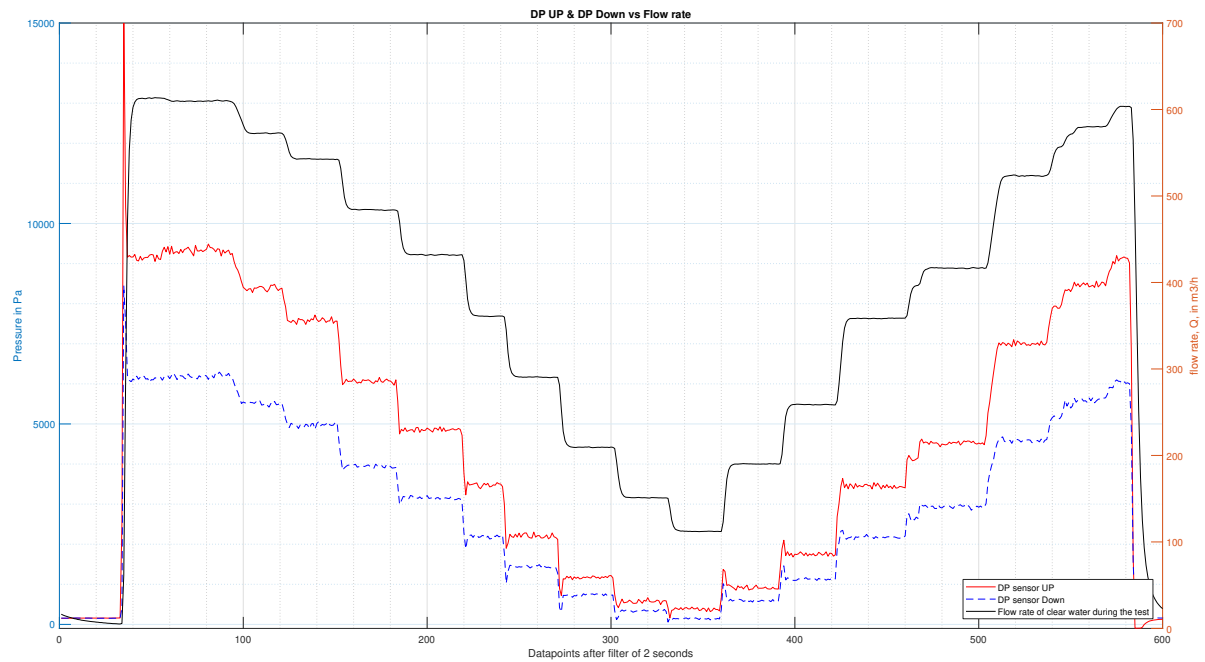


Figure D.1: Differential pressures of Upward and Downward leg compared against flow rate

During all the troubleshooting the differential pressure sensors are checked multiple times, one is even replaced. After determining that the pressure sensors are working properly, the calibrations of the sensors are checked and this calibration curve is used in Labview to convert the volts to corresponding mmH₂O and pascal values. Ed Stok had performed the first calibration with the volts against mmH₂O. This is kept the same and afterwards, the mmH₂O values are converted to pascals.

In figures D.2, D.3 and D.4 the calibration curves with data points are shown for the pressure sensors up, down and over the pump. The trend line is the calibration curve from the last time all sensors are checked. From these figures, it is visible that the sensors have not started to deviate. All points from previous and the recent measurements are all on the same trend line.

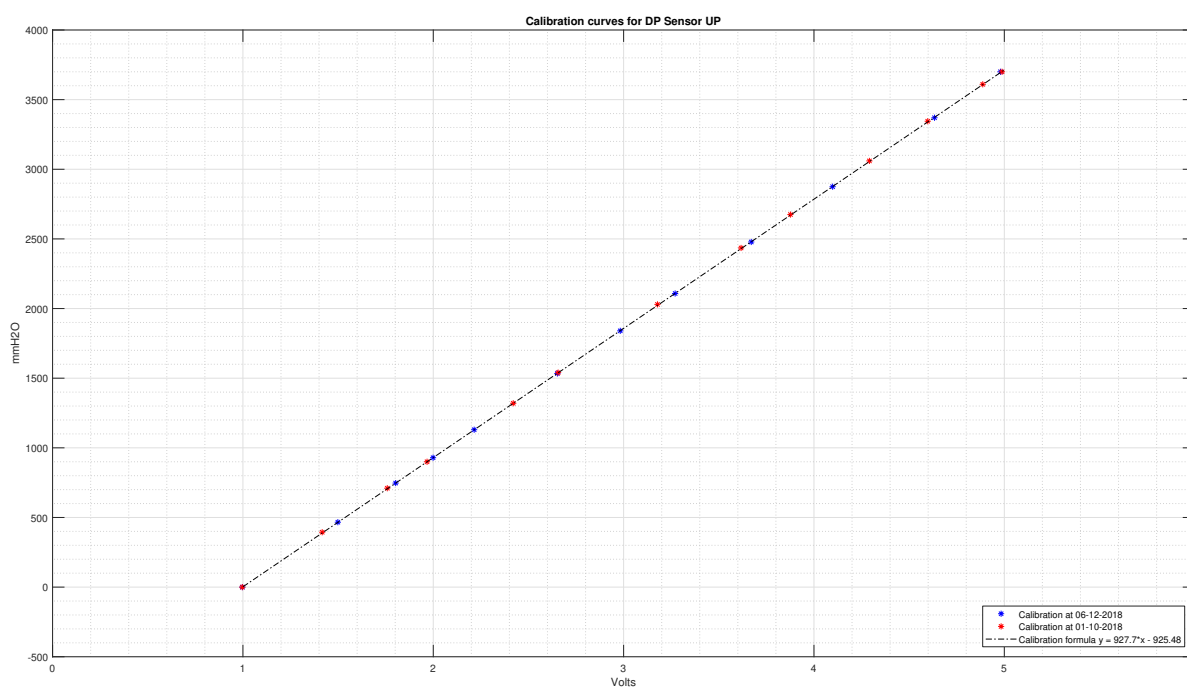


Figure D.2: Calibration curve with measured points of DP sensor UP

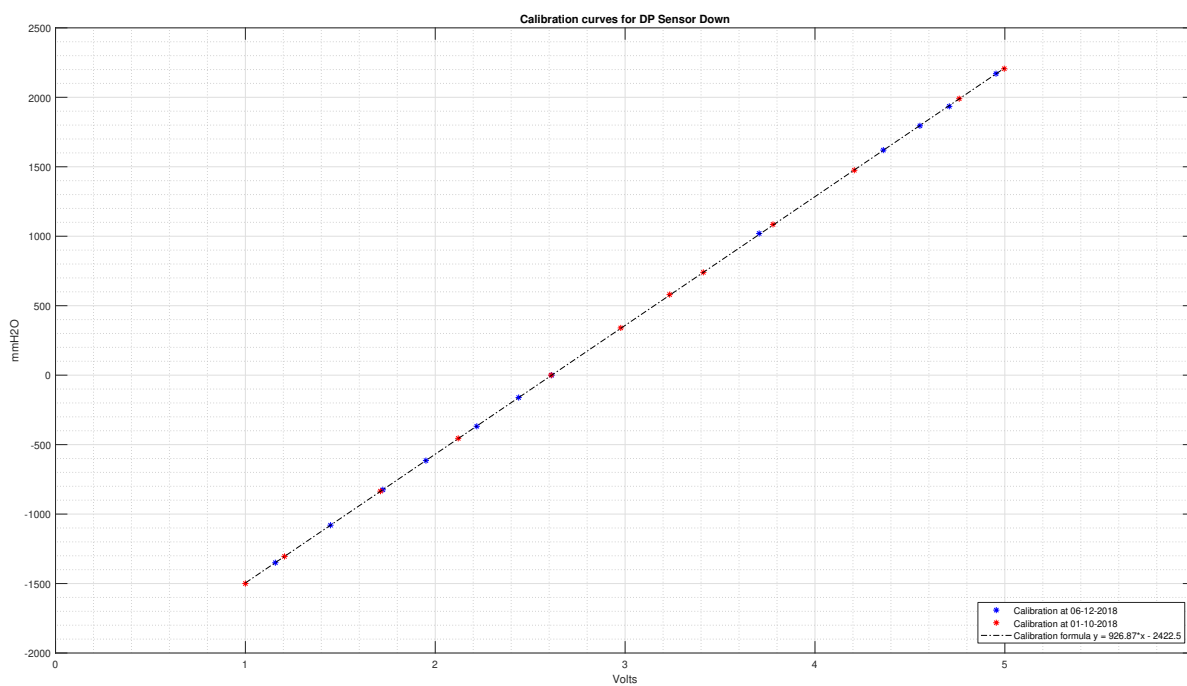


Figure D.3: Calibration curve with measured points of DP sensor Down

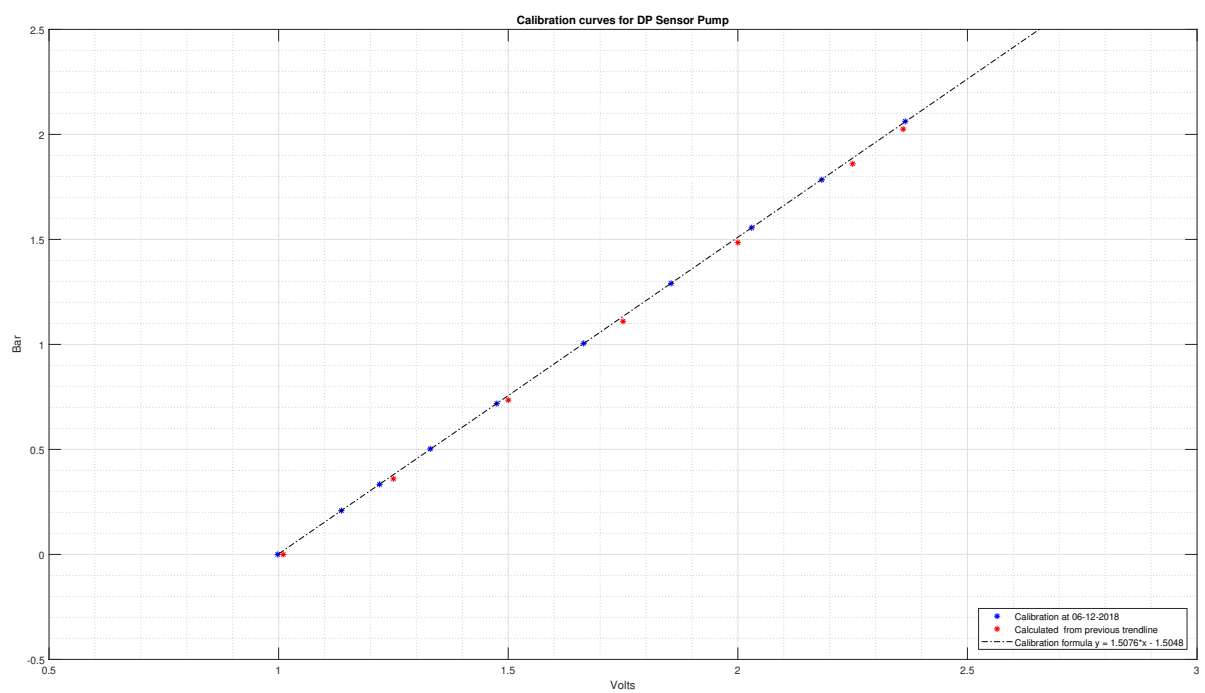


Figure D.4: Calibration curve with measured points of DP sensor Pump

E

Particle Size Distributions of the materials before and after the experiments

Table E.1: PSD of Geba sand before the experiments

Geba -Total measurements Before Testing						
measured [grams]	% of total	% in curve	Sieve size [μm]			
0	0.00%	100.0%	250		>	250
99	5.55%	94.4%	212	212	-	250
226.4	12.70%	81.7%	180	180	-	212
464.7	26.07%	55.7%	150	150	-	180
444.7	24.94%	30.7%	125	125	-	150
461.6	25.89%	4.8%	90	90	-	125
78.4	4.40%	0.4%	63	63	-	90
8	0.45%	0.0%	0		<	63
1782.8	100.00%					

Table E.2: PSD of Geba sand after the experiments

Geba -Total measurements After Testing						
measured [grams]	% of total	% in curve	Sieve size [μm]			
15.8	0.75%	99.25%	250		>	250
15.8	0.75%	98.5%	212	212	-	250
53.1	2.53%	96.0%	180	180	-	212
254.8	12.13%	83.8%	150	150	-	180
794.8	37.84%	46.0%	125	125	-	150
710.7	33.84%	12.2%	90	90	-	125
201.5	9.59%	2.6%	63	63	-	90
53.9	2.57%	0.0%	0		<	63
2100.4	100.00%					

Table E.3: PSD of Dorsilit 9 before the experiments

Dorsilit 9 -Total measurements Before Testing						
measured [grams]	% of total	% in curve	Sieve size [μm]			
0	0.00%	100.0%	250		>	250
99	5.55%	94.4%	212	212	-	250
226.4	12.70%	81.7%	180	180	-	212
464.7	26.07%	55.7%	150	150	-	180
444.7	24.94%	30.7%	125	125	-	150
461.6	25.89%	4.8%	90	90	-	125
78.4	4.40%	0.4%	63	63	-	90
8	0.45%	0.0%	0		<	63
1782.8	100.00%					

Table E.4: PSD of Dorsilit 9 after the experiments

Dorsilit 9 -Total measurements After Testing						
measured [grams]	% of total	% in curve	Sieve size [μm]			
0	0.00%	100.0%	710		>	710
0	0.00%	100.0%	500		>	500
890.4	24.81%	75.2%	355	355	-	500
1885	52.52%	22.7%	212	212	-	355
634.9	17.69%	5.0%	125	125	-	212
101.1	2.82%	2.2%	90	90	-	125
77.6	2.16%	0.0%	0		<	90
3589	100.00%					

Table E.5: PSD of Dorsilit 7 before the experiments

Dorsilit 7 -Total measurements Before Testing						
measured [grams]	% of total	% in curve	Sieve size [μm]			
0.6	0.02%	100.0%	1400	0	>	1400
850.8	32.83%	67.1%	1000	0	>	1000
1469.2	56.69%	10.5%	710	710	-	1000
223.5	8.62%	1.8%	500	500	-	710
32.8	1.27%	0.6%	355	355	-	500
14.8	0.57%	0.0%	0	0	<	355
2591.7	100.00%					

Table E.6: PSD of Dorsilit 7 after the experiments

Dorsilit 7 -Total measurements After Testing						
measured [grams]	% of total	% in curve	Sieve size [μm]			
0	0.00%	100.0%	1400	0	>	1400
801.2	22.37%	77.6%	1000	0	>	1000
2065	57.66%	20.0%	710	710	-	1000
485.5	13.56%	6.4%	500	500	-	710
132.6	3.70%	2.7%	355	355	-	500
96.8	2.70%	0.0%	0	0	<	355
3581.1	100.00%					

F

Centrifugal Pump info

At the Delft University of Technology is a centrifugal pump installed from Damen. There is minimal information known at the TU about this pump, so contact with Damen was made for additional data. Mark Winkelman, manager Research and Development at Damen, was very well willingly to provide all the necessary information for this thesis.

After an interview located at the TU Delft, Mark had a good understanding of the assignment and provided the constant rpm clear water curves for the centrifugal pump for multiple RPMs. With this information the working points of the slurry loop are determined. The specific type of centrifugal pump is the BP1515. Information about the power input was not available, because the electro drive was purchased somewhere else.

Mark also mentioned that the solids effect used at the R & D department of Damen uses an adapted version of the Stepanoff model.

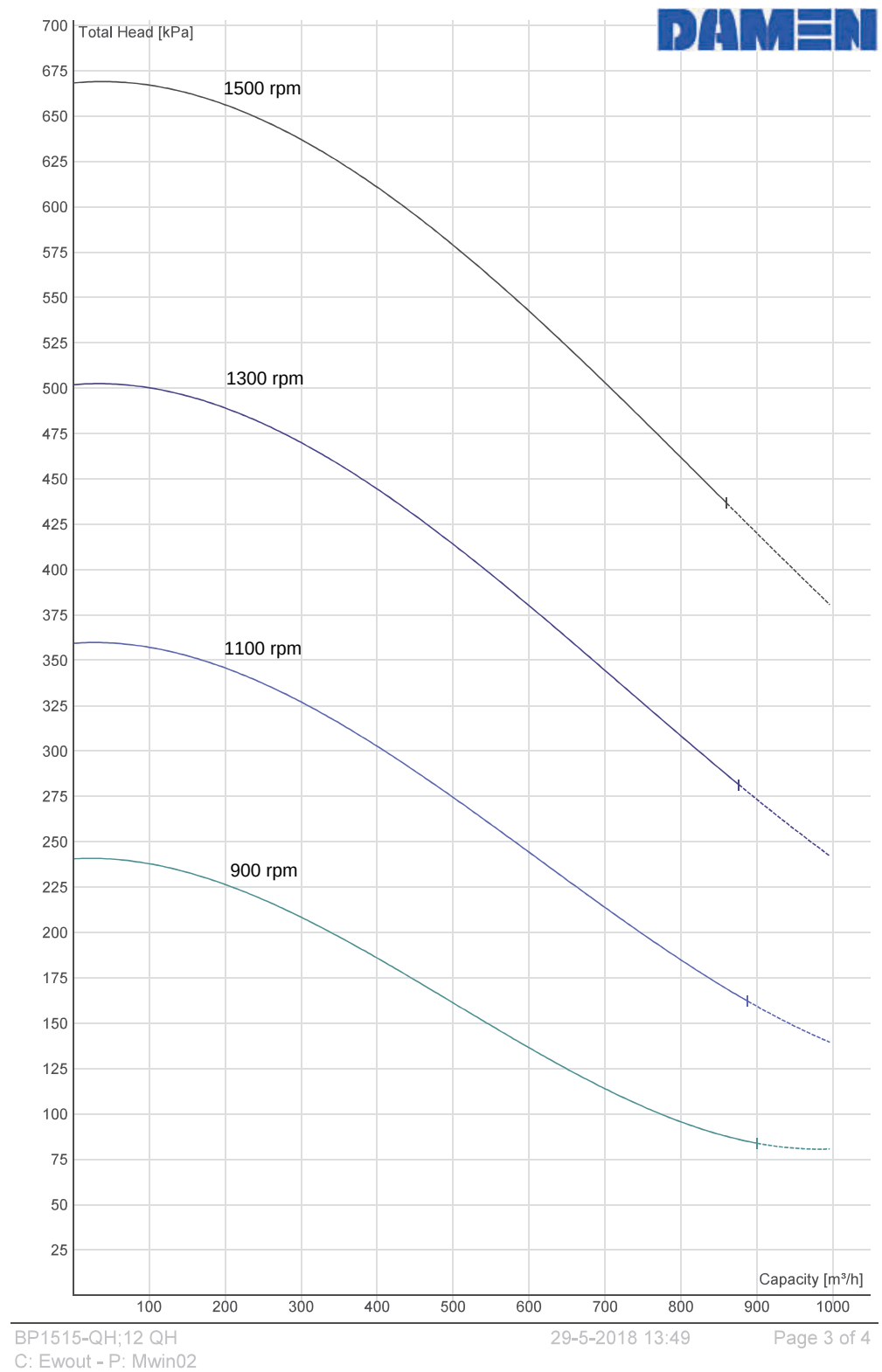
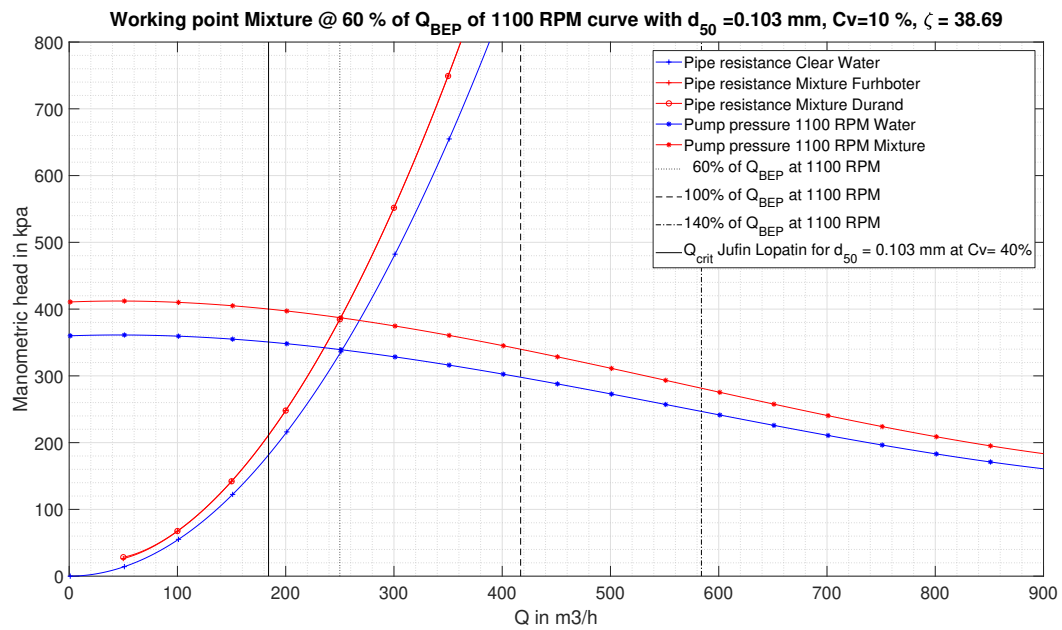
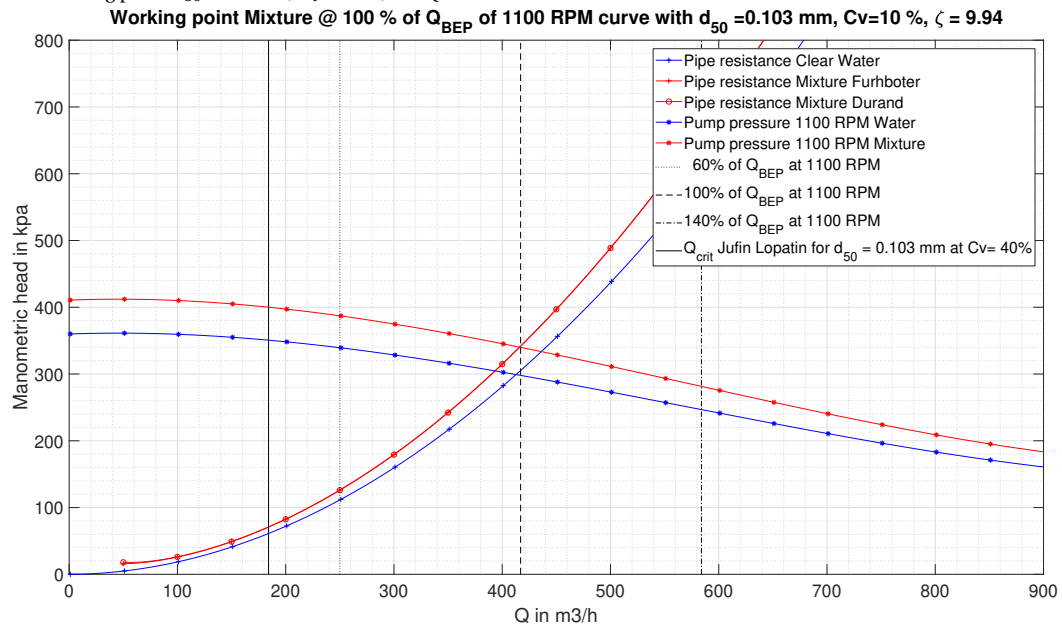
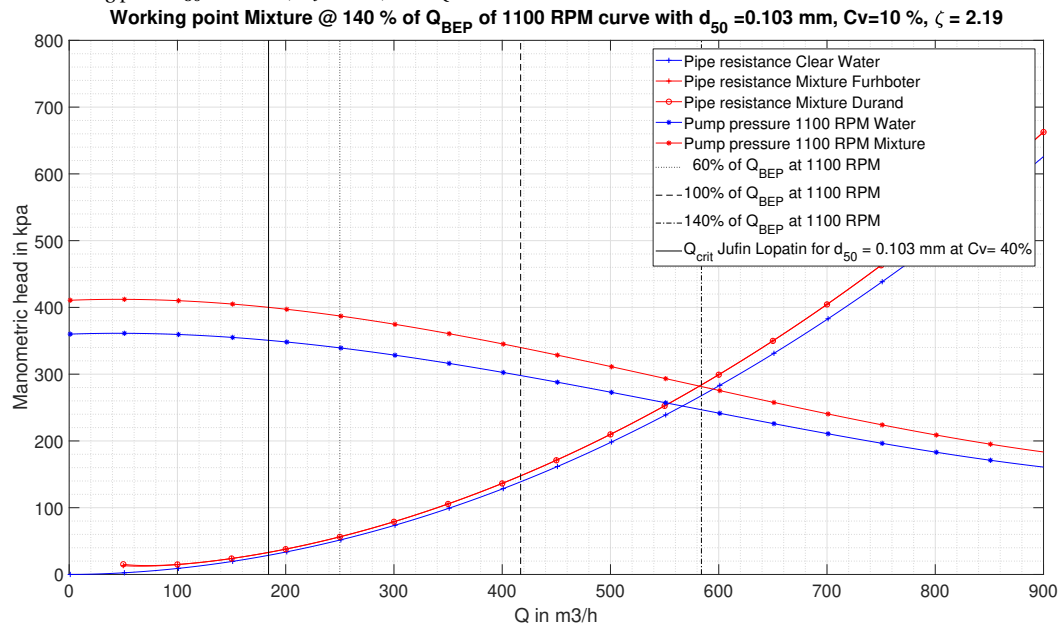
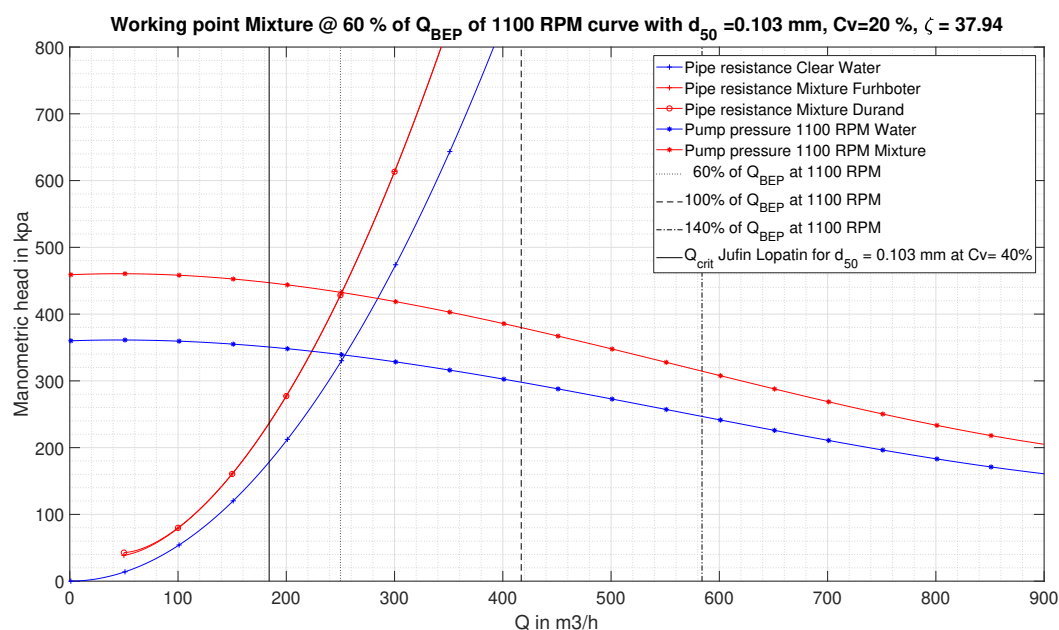
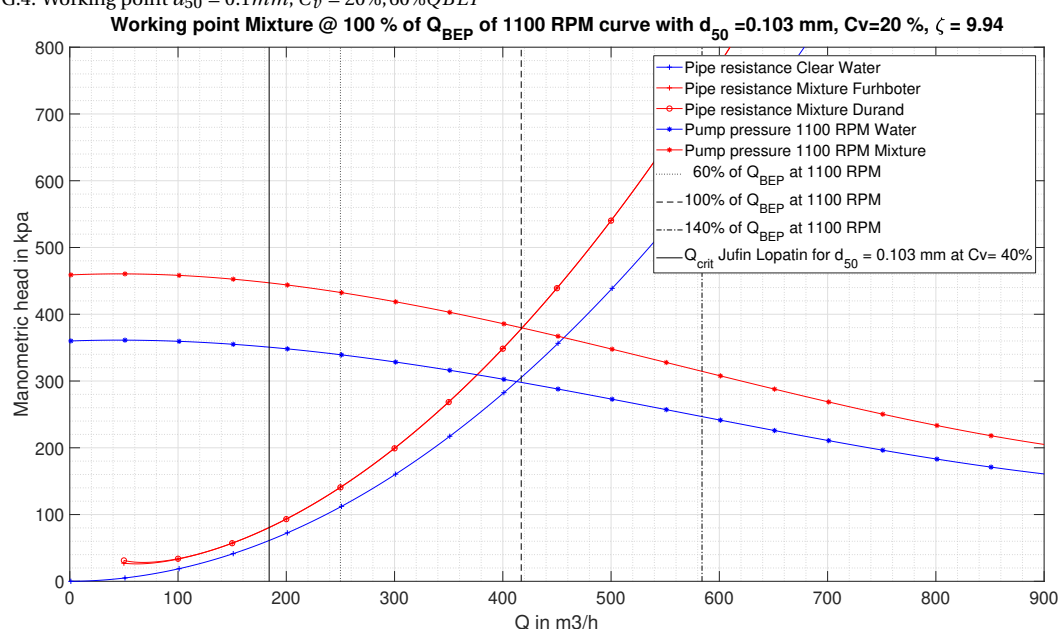
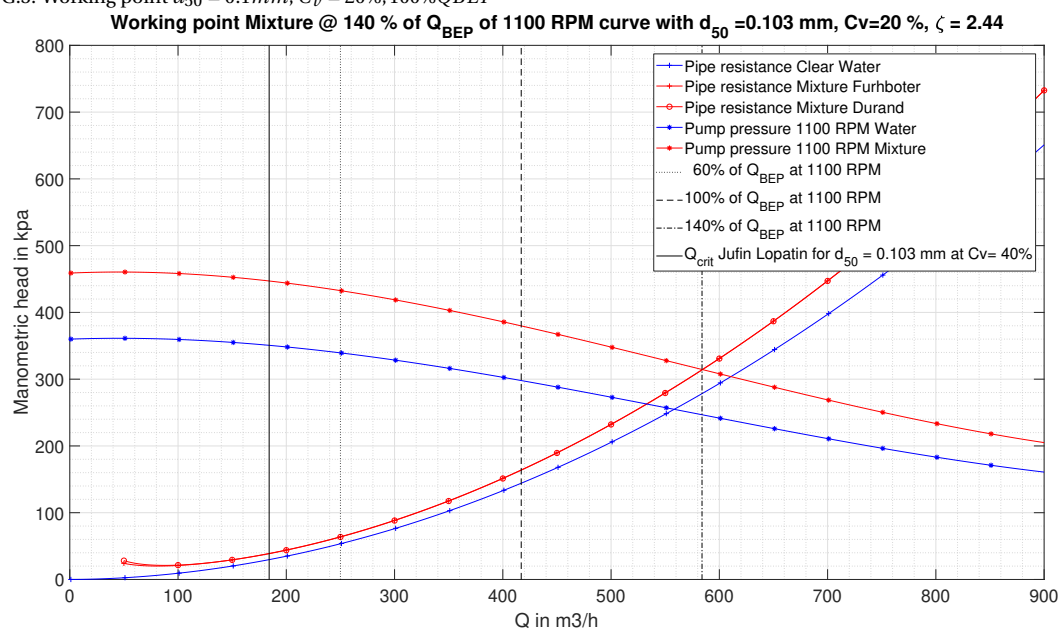


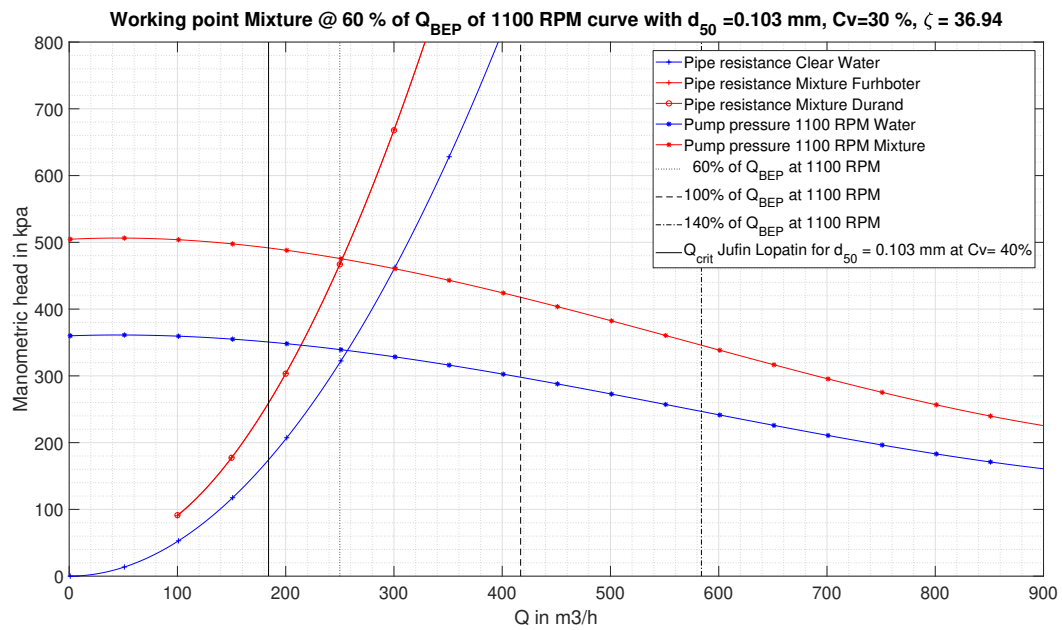
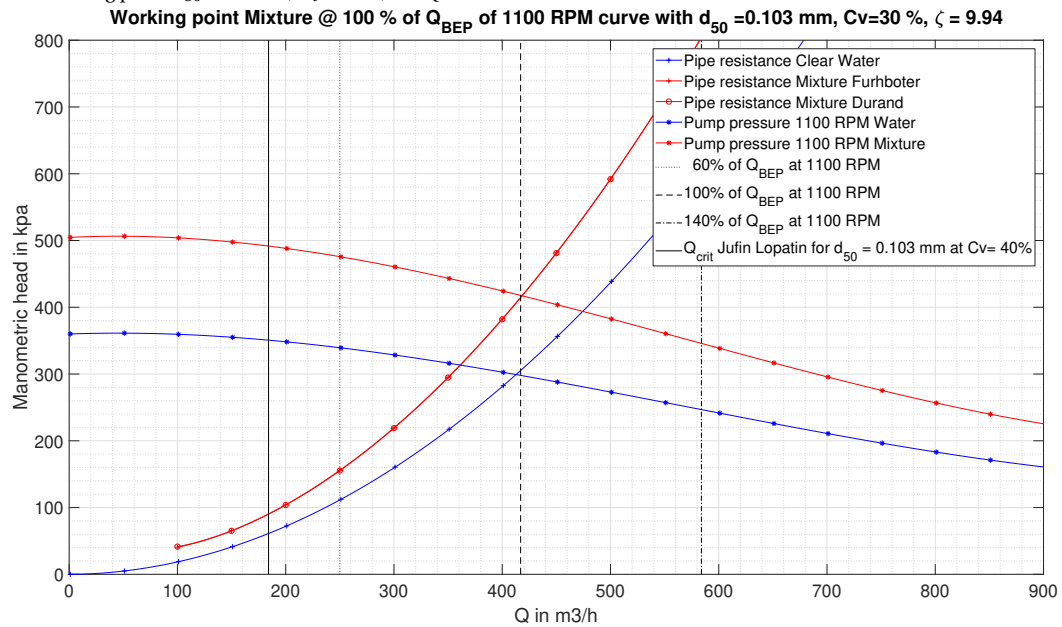
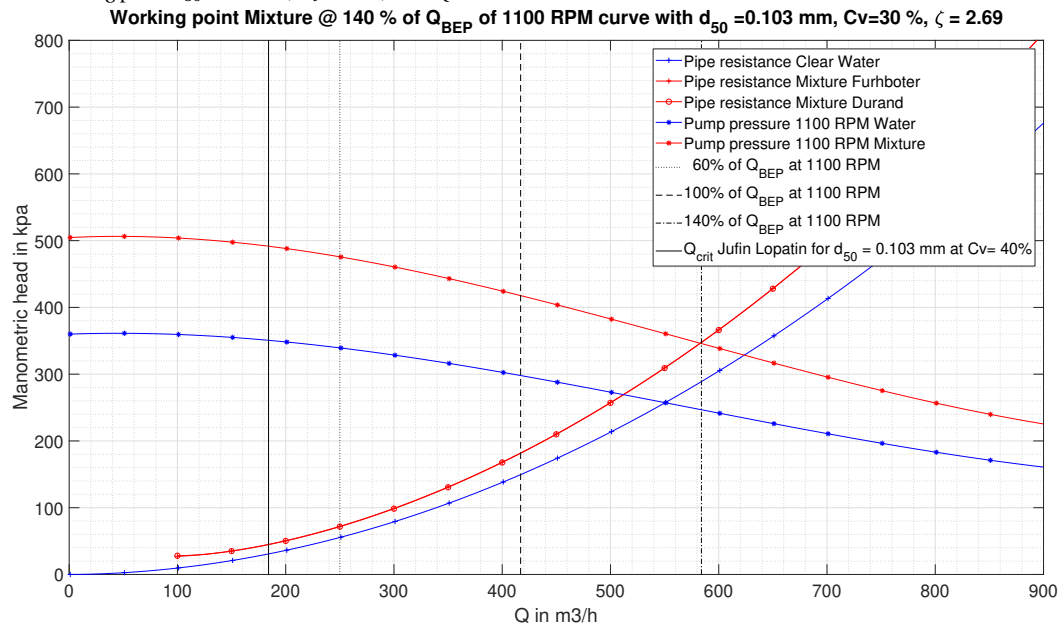
Figure F.1: Pump characteristics Q-H in kPa for multiple rpm settings: 1500, 1300, 1100 and 900 rpm

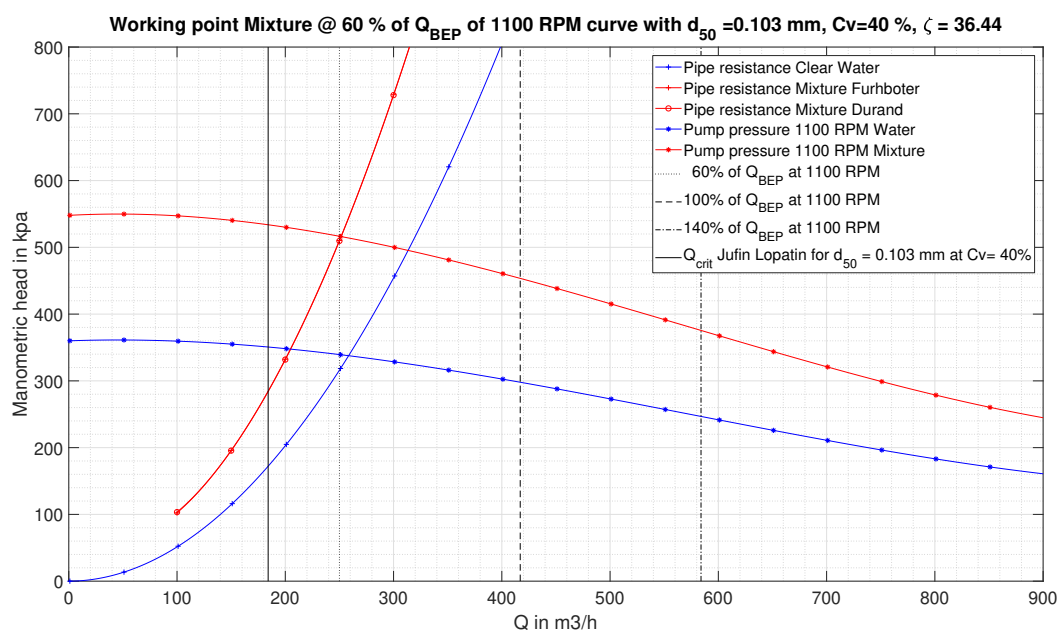
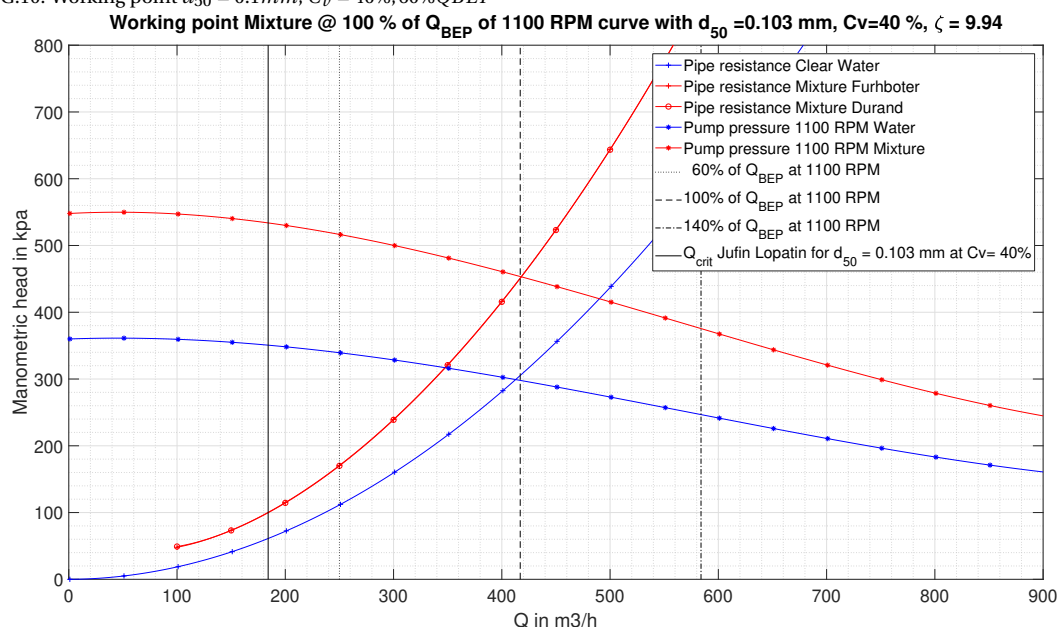
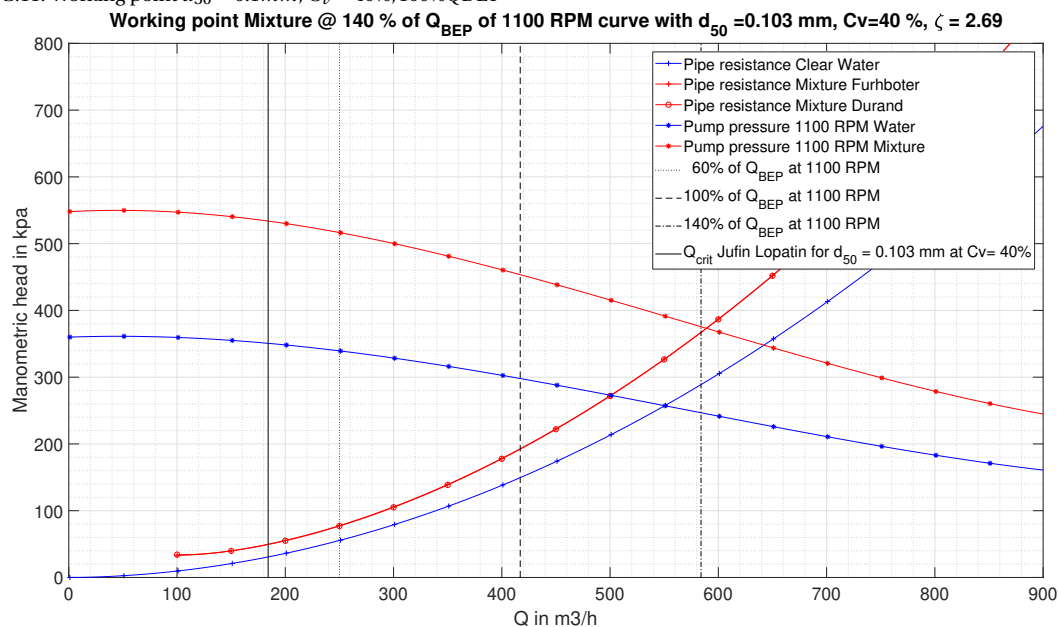
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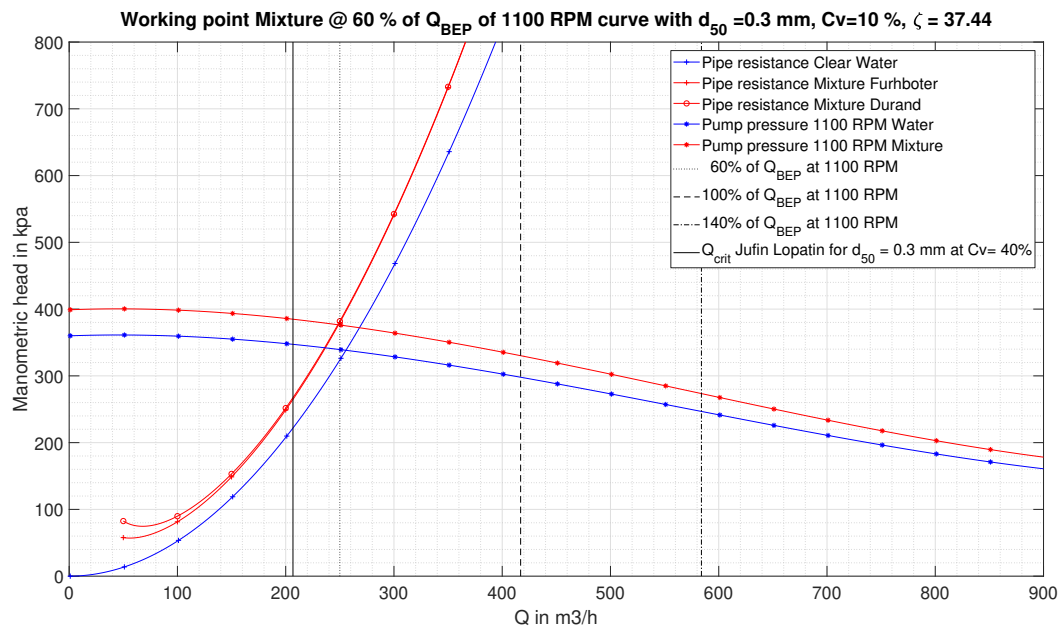
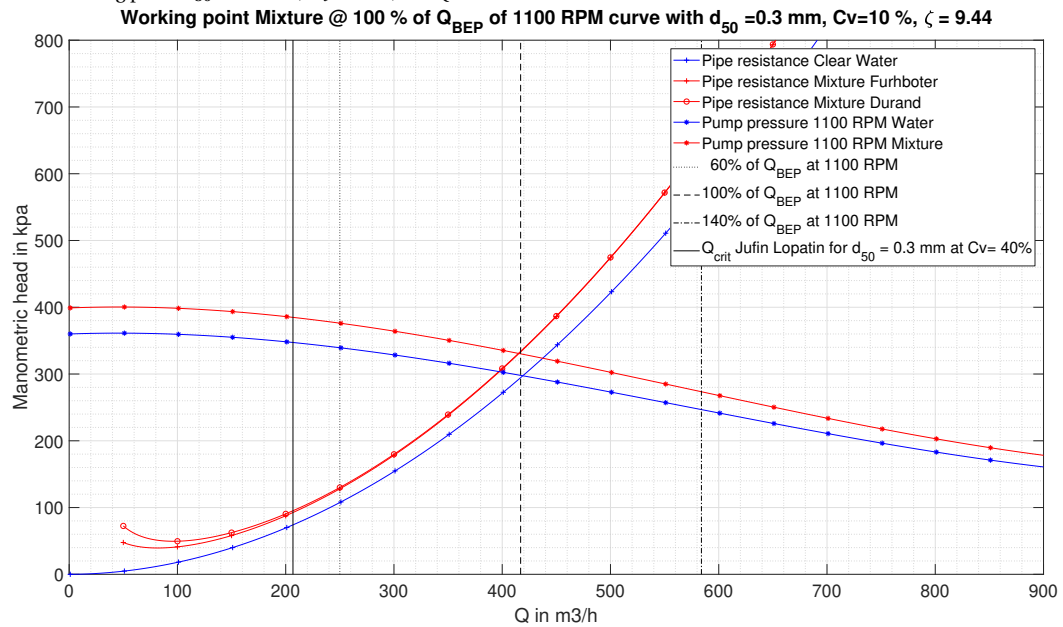
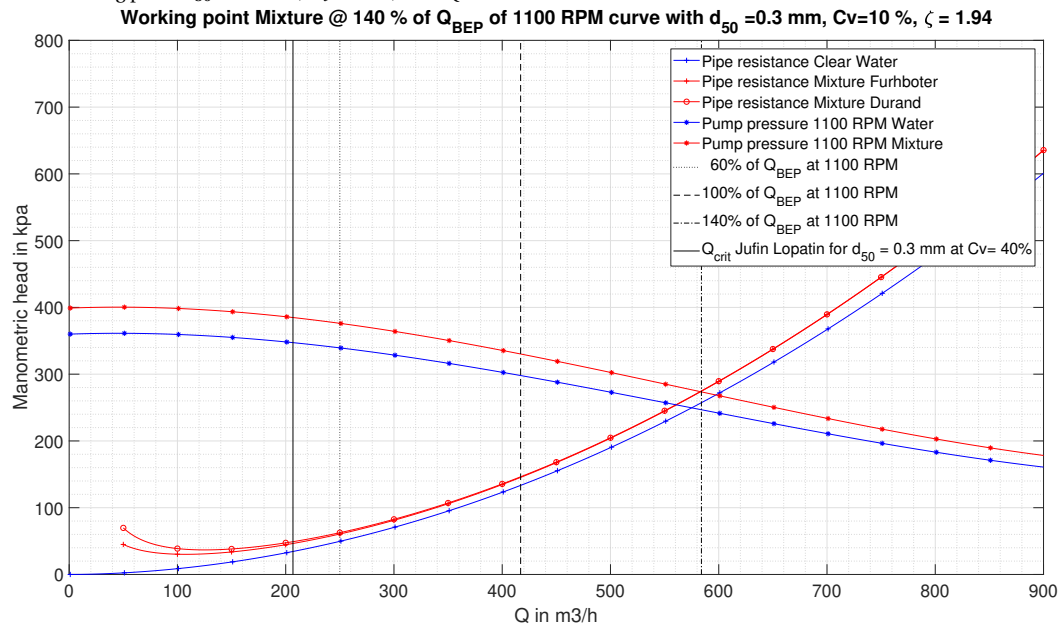
Working points of all test configurations
according to the test plan

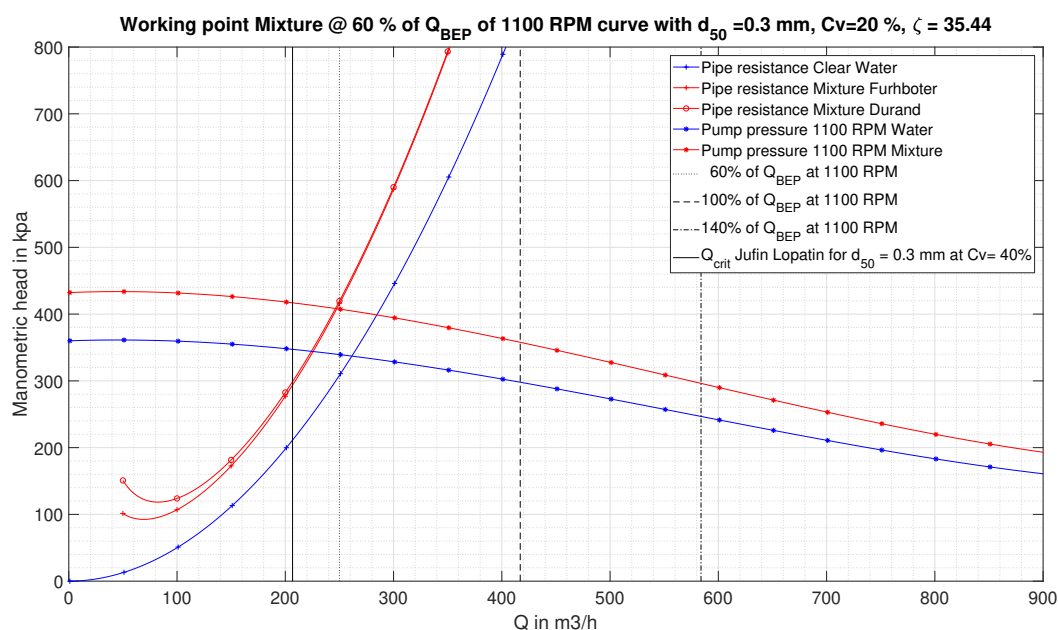
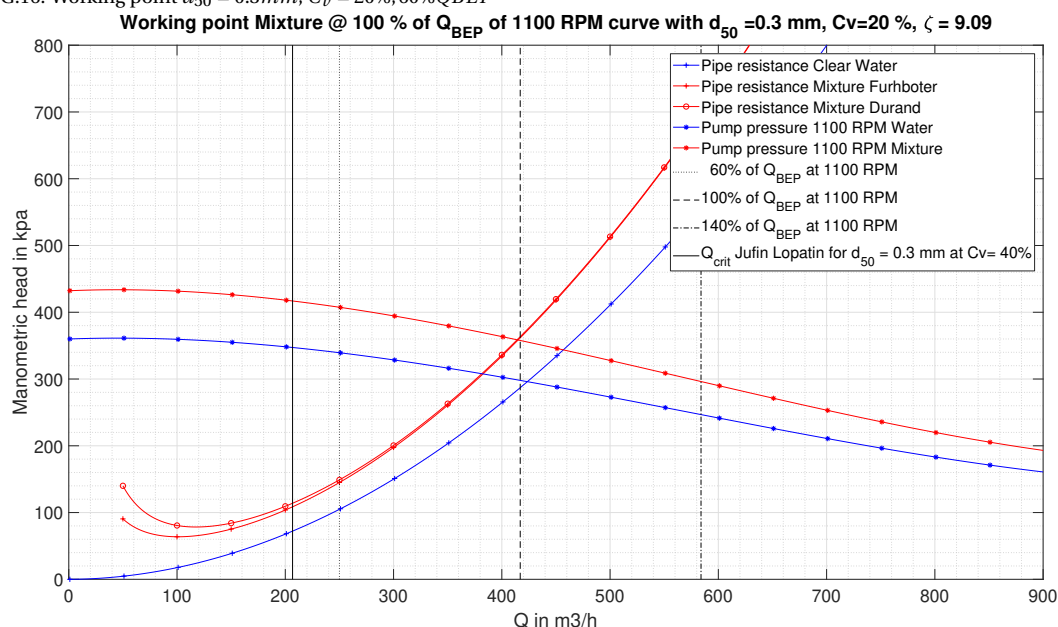
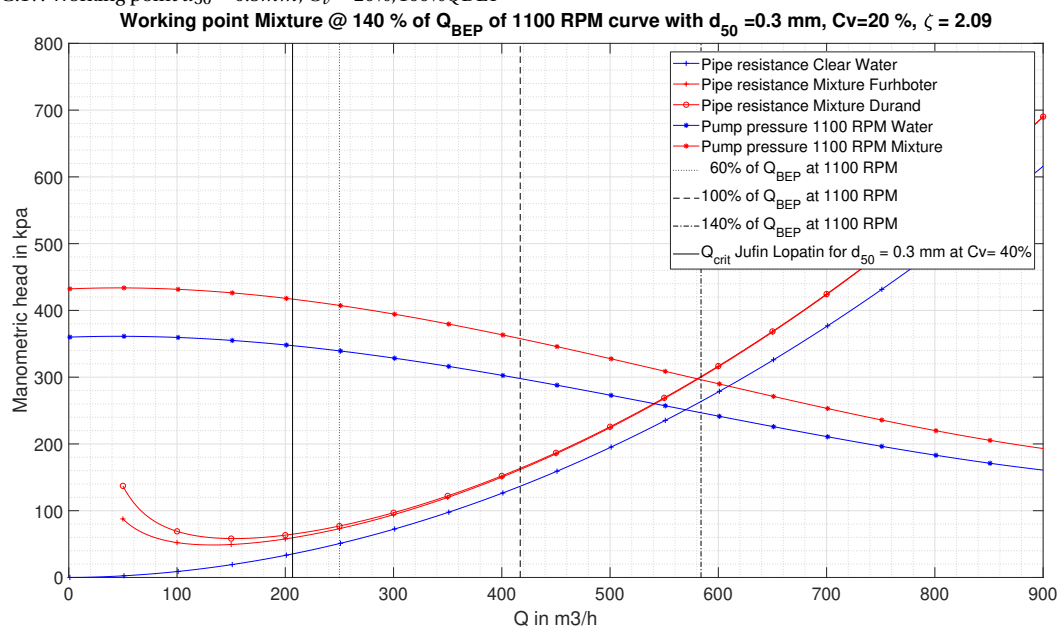
Figure G.1: Working point $d_{50} = 0.1$ mm, $C_v = 10\%$, $60\%Q_{BEP}$ Figure G.2: Working point $d_{50} = 0.1$ mm, $C_v = 10\%$, $100\%Q_{BEP}$ Figure G.3: Working point $d_{50} = 0.1$ mm, $C_v = 10\%$, $140\%Q_{BEP}$

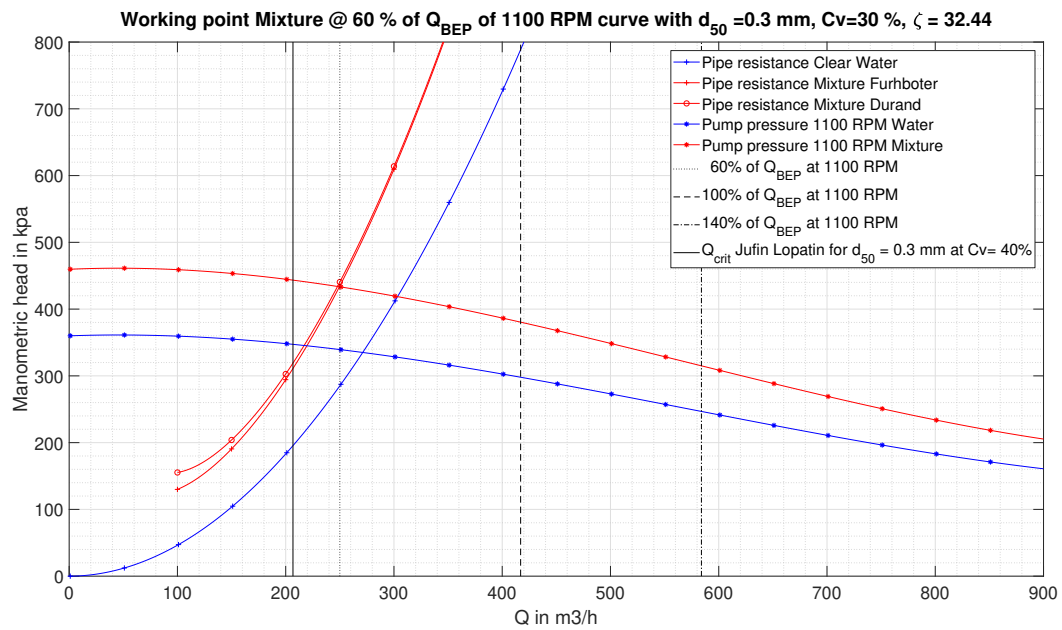
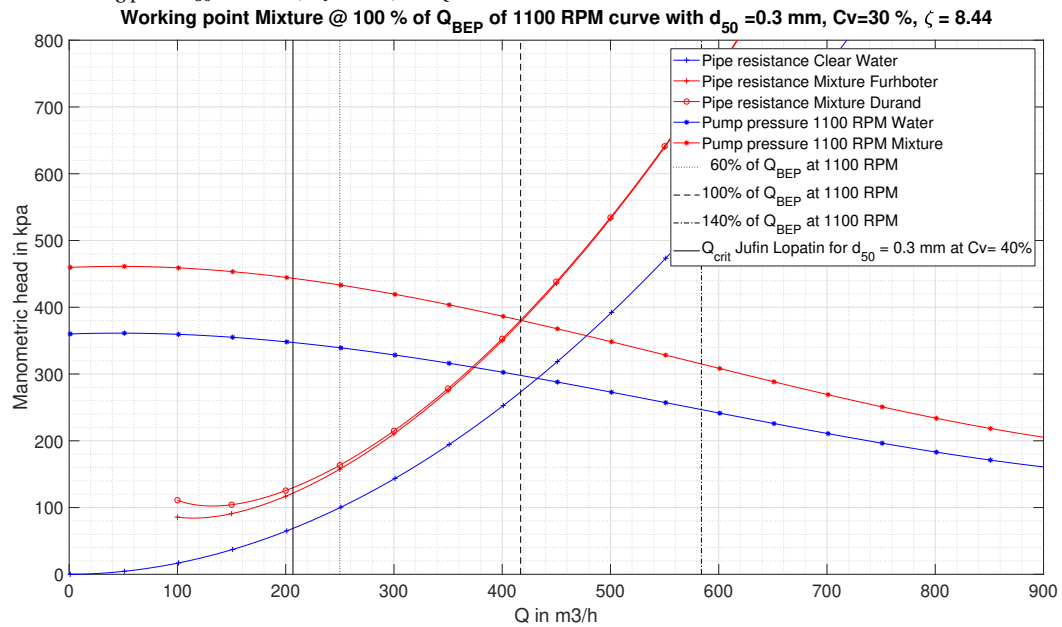
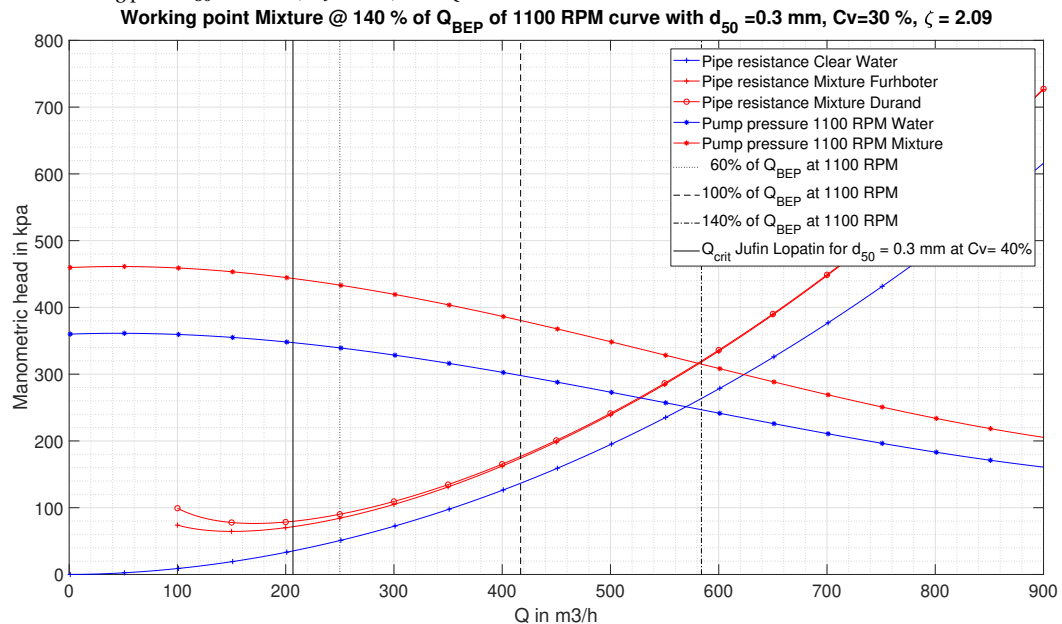
Figure G.4: Working point $d_{50} = 0.1$ mm, $C_v = 20\%$, $60\%Q_{BEP}$ Figure G.5: Working point $d_{50} = 0.1$ mm, $C_v = 20\%$, $100\%Q_{BEP}$ Figure G.6: Working point $d_{50} = 0.1$ mm, $C_v = 20\%$, $140\%Q_{BEP}$

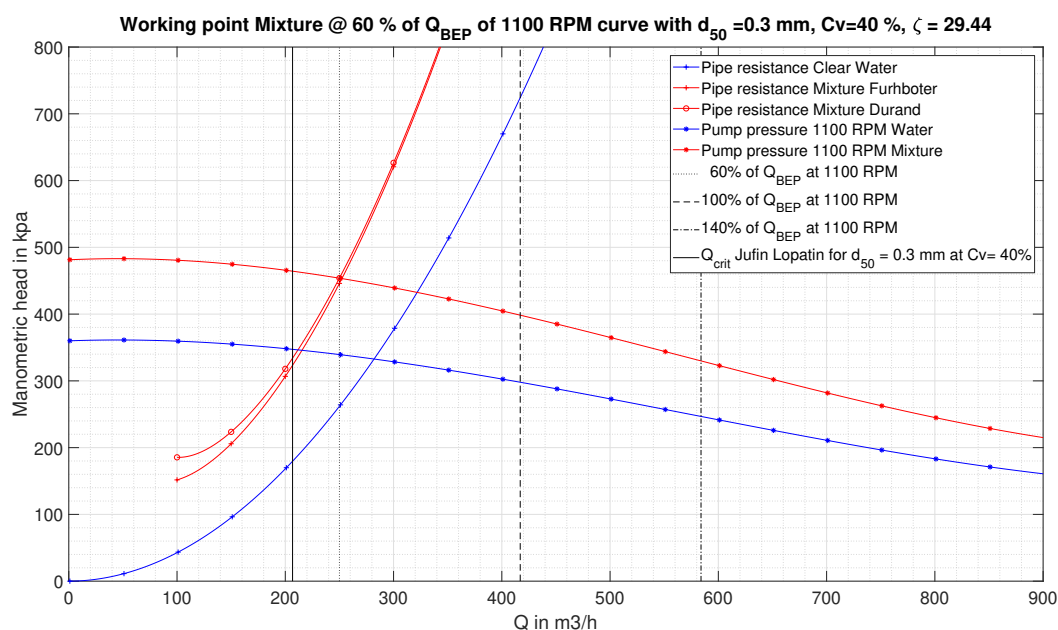
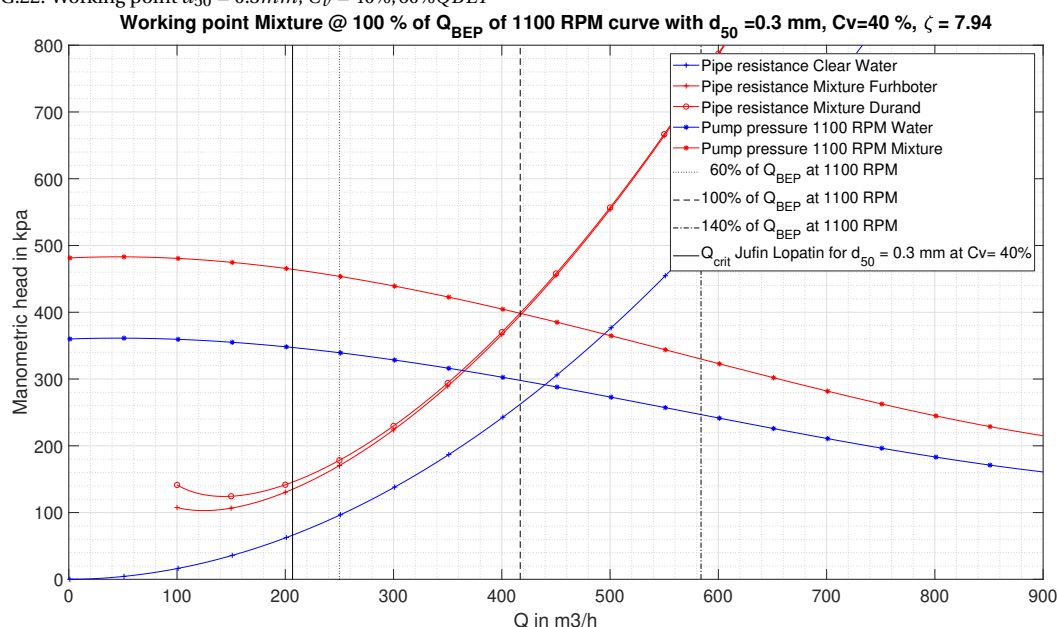
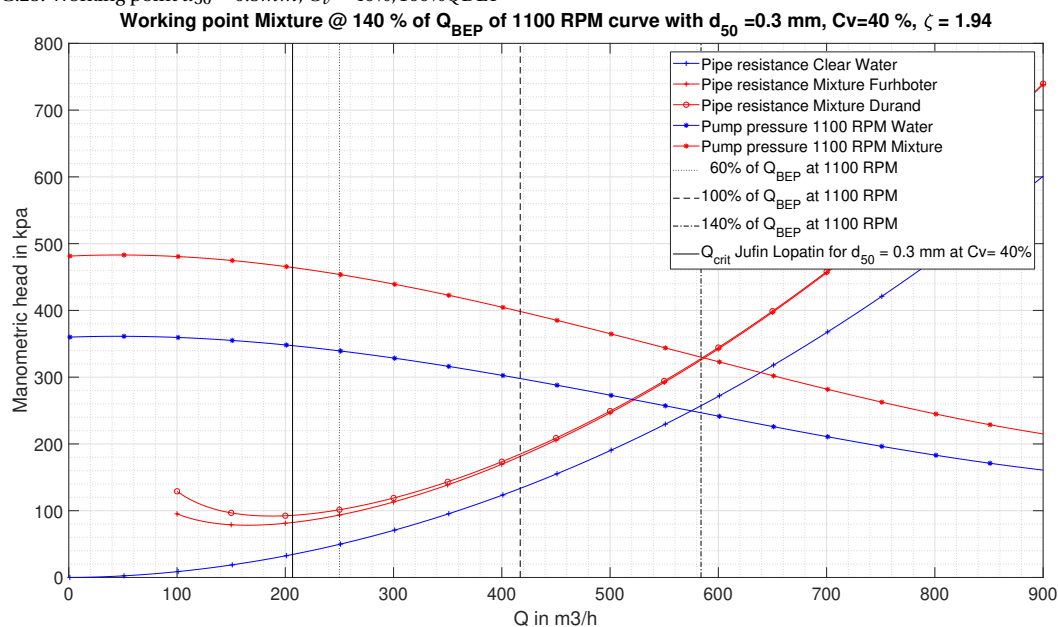
Figure G.7: Working point $d_{50} = 0.1$ mm, $C_v = 30\%$, $60\%Q_{BEP}$ Figure G.8: Working point $d_{50} = 0.1$ mm, $C_v = 30\%$, $100\%Q_{BEP}$ Figure G.9: Working point $d_{50} = 0.1$ mm, $C_v = 30\%$, $140\%Q_{BEP}$

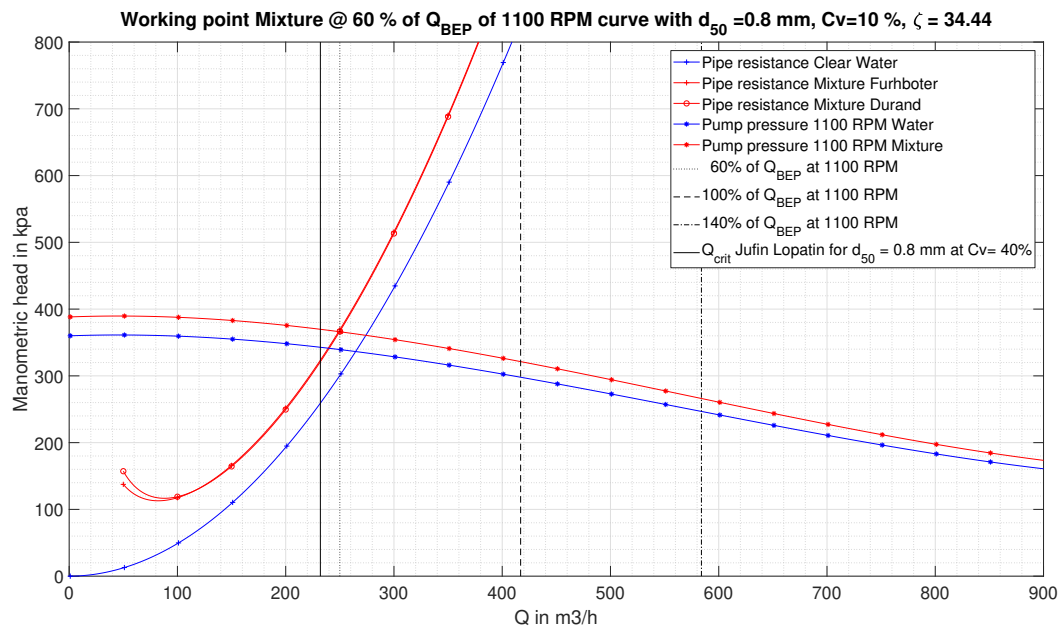
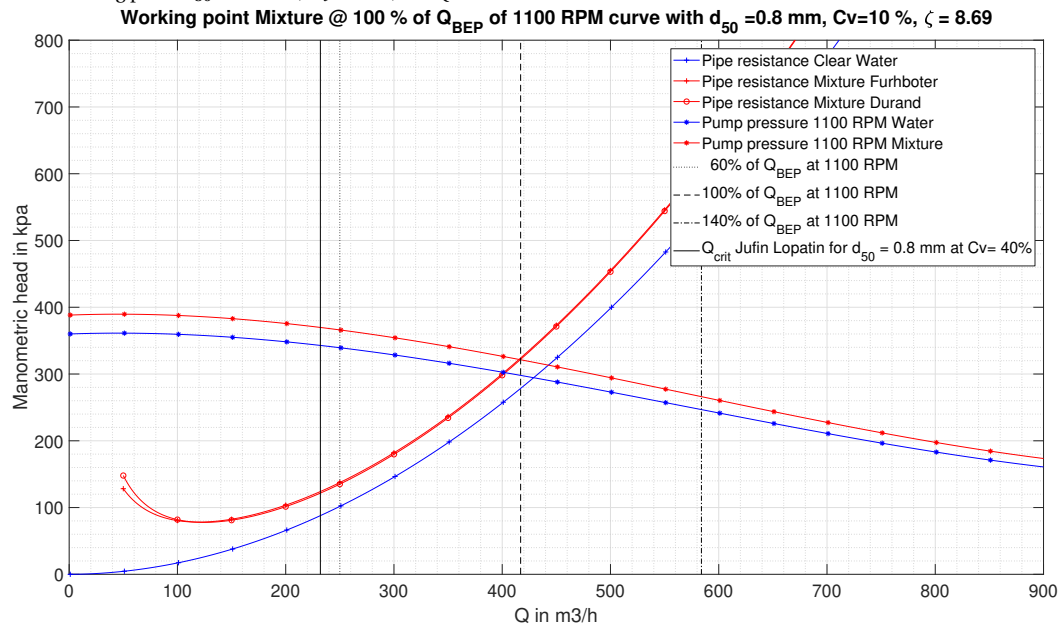
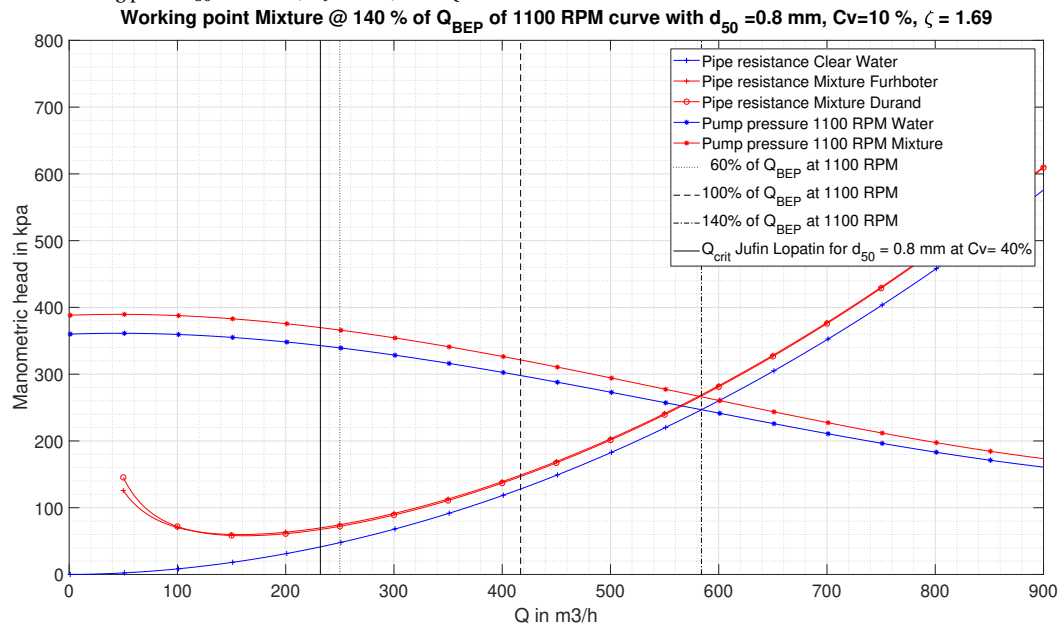
Figure G.10: Working point $d_{50} = 0.1$ mm, $C_v = 40\%$, 60%QBEPFigure G.11: Working point $d_{50} = 0.1$ mm, $C_v = 40\%$, 100%QBEPFigure G.12: Working point $d_{50} = 0.1$ mm, $C_v = 40\%$, 140%QBEP

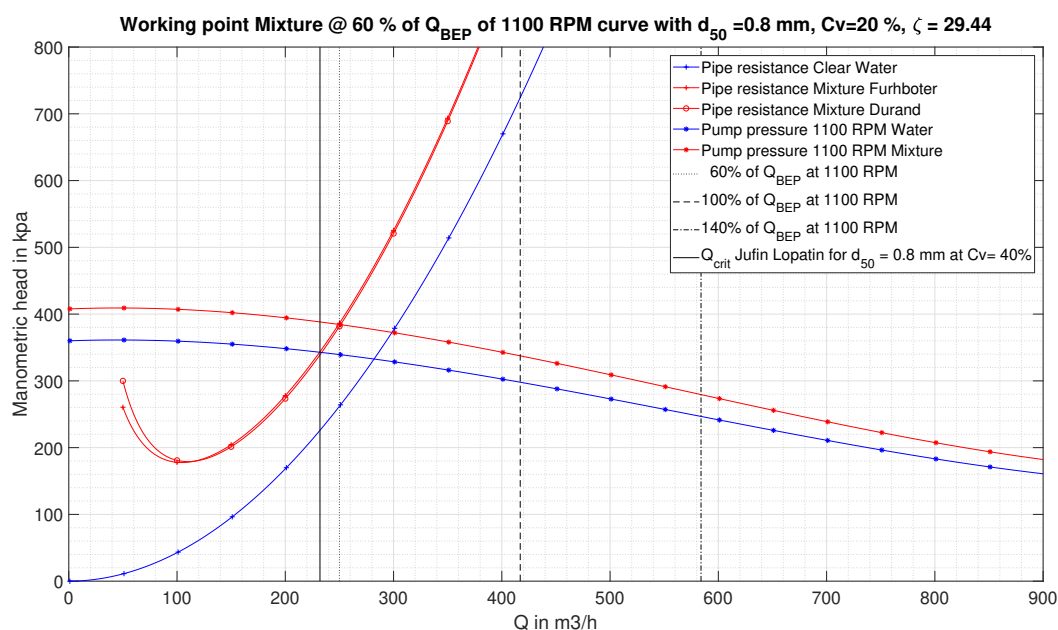
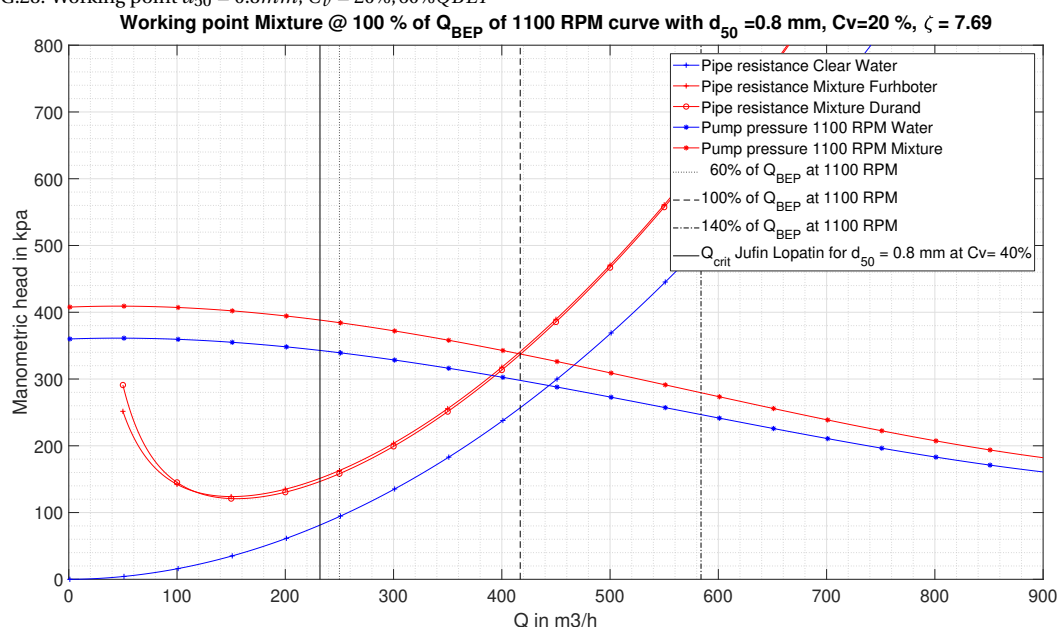
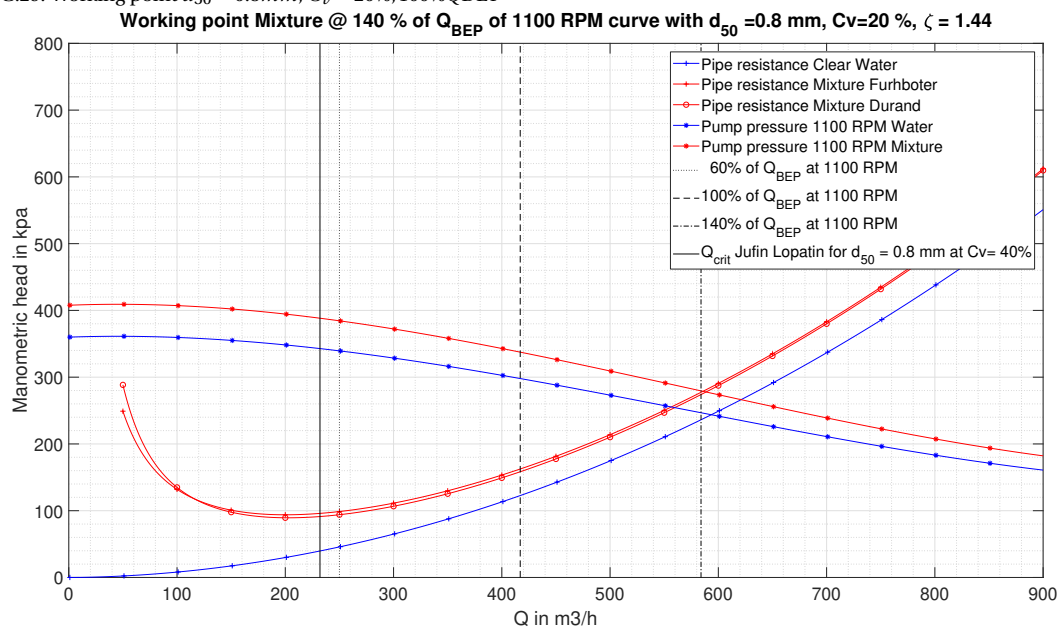
Figure G.13: Working point $d_{50} = 0.3$ mm, $C_v = 10\%$, $60\%Q_{BEP}$ Figure G.14: Working point $d_{50} = 0.3$ mm, $C_v = 10\%$, $100\%Q_{BEP}$ Figure G.15: Working point $d_{50} = 0.3$ mm, $C_v = 10\%$, $140\%Q_{BEP}$

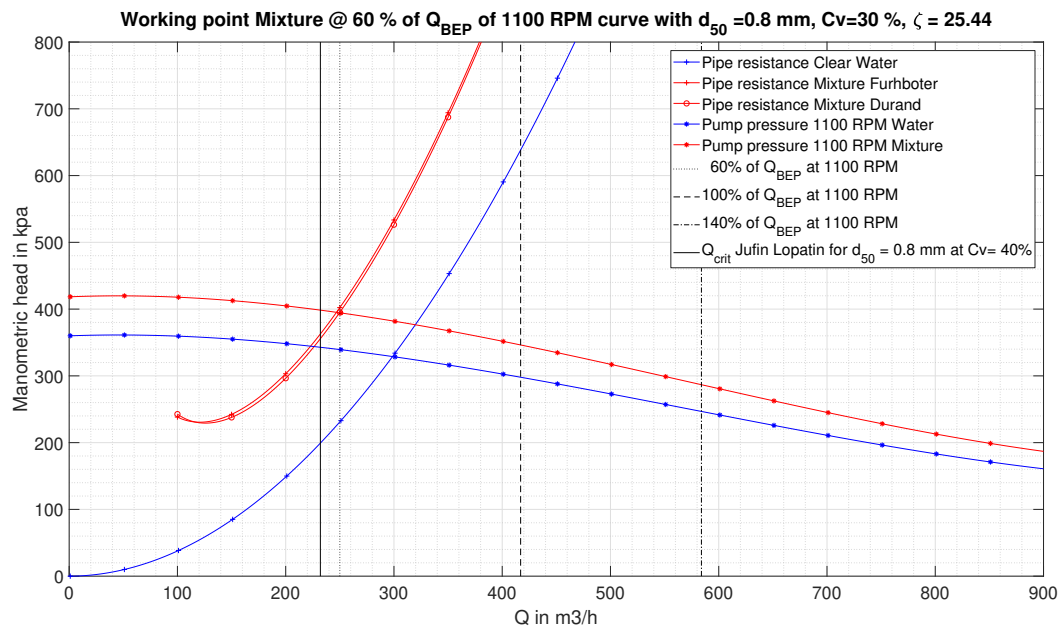
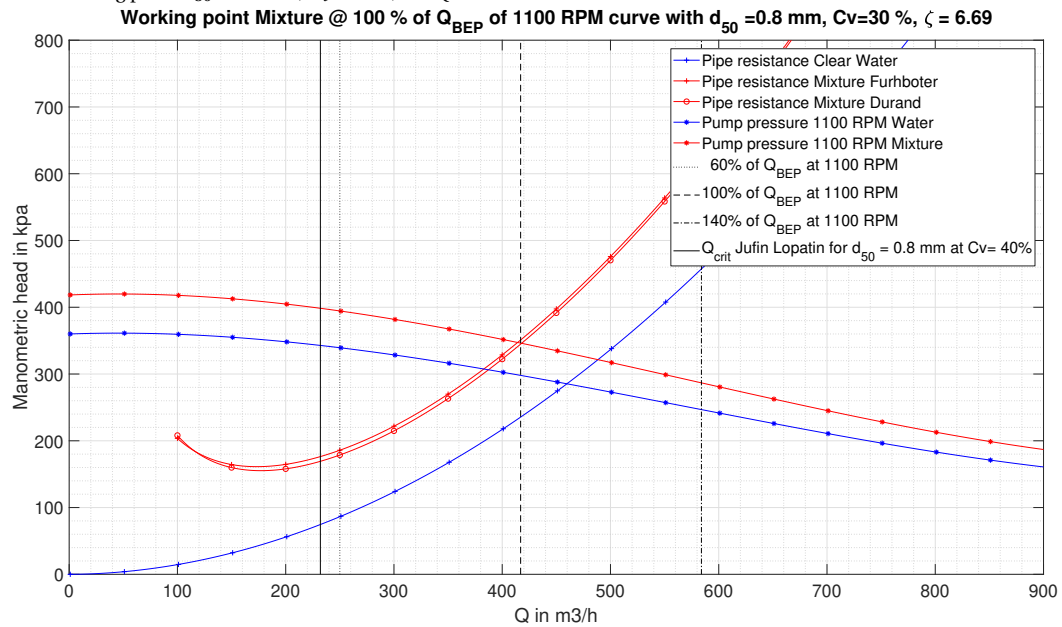
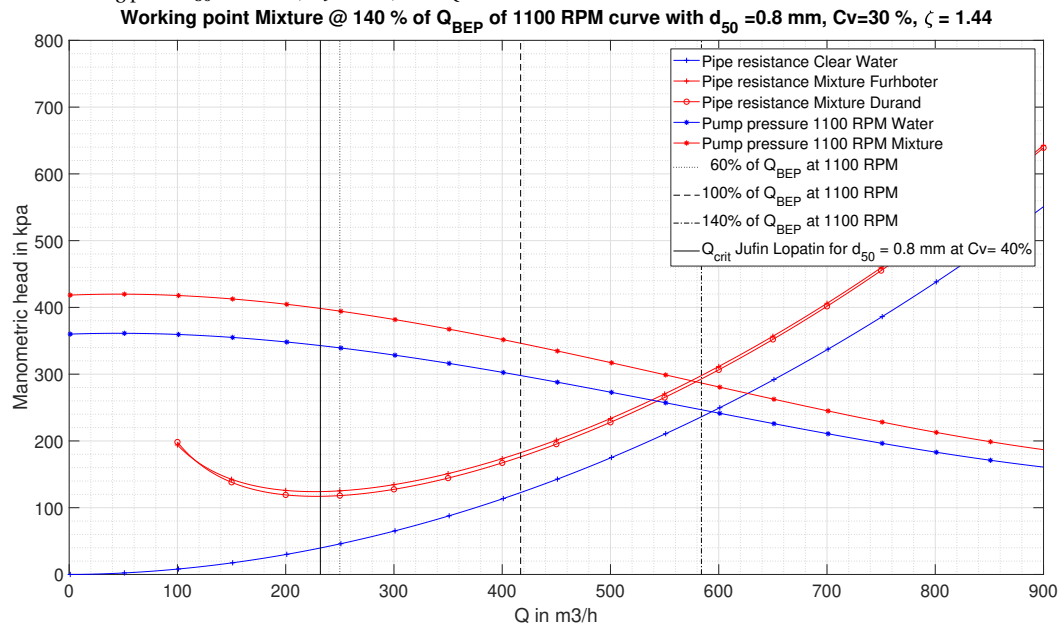
Figure G.16: Working point $d_{50} = 0.3$ mm, $C_v = 20$ %, $60\%Q_{BEP}$ Figure G.17: Working point $d_{50} = 0.3$ mm, $C_v = 20$ %, $100\%Q_{BEP}$ Figure G.18: Working point $d_{50} = 0.3$ mm, $C_v = 20$ %, $140\%Q_{BEP}$

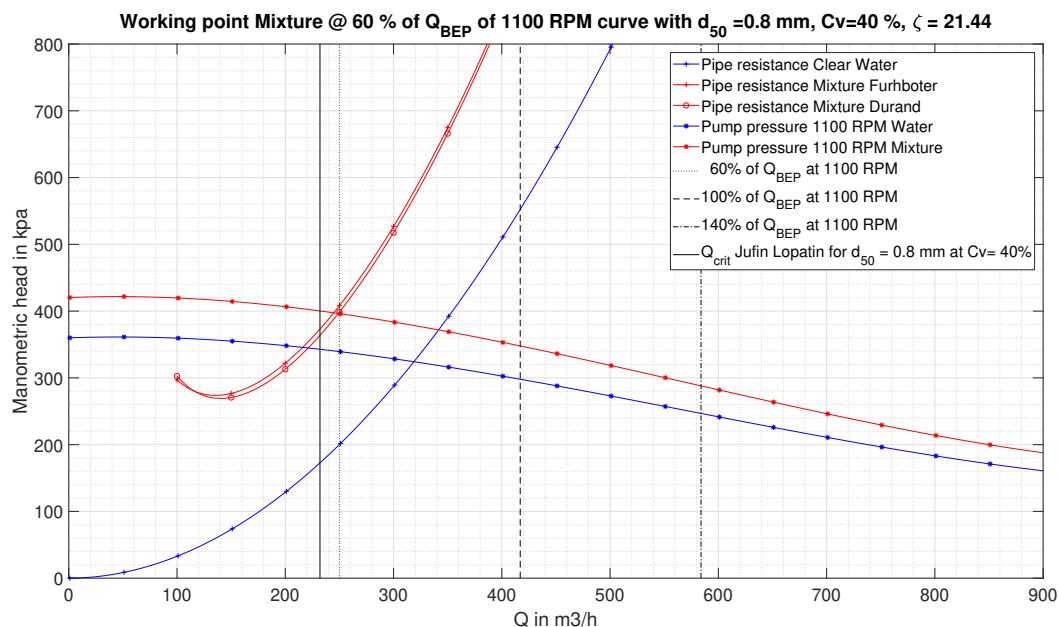
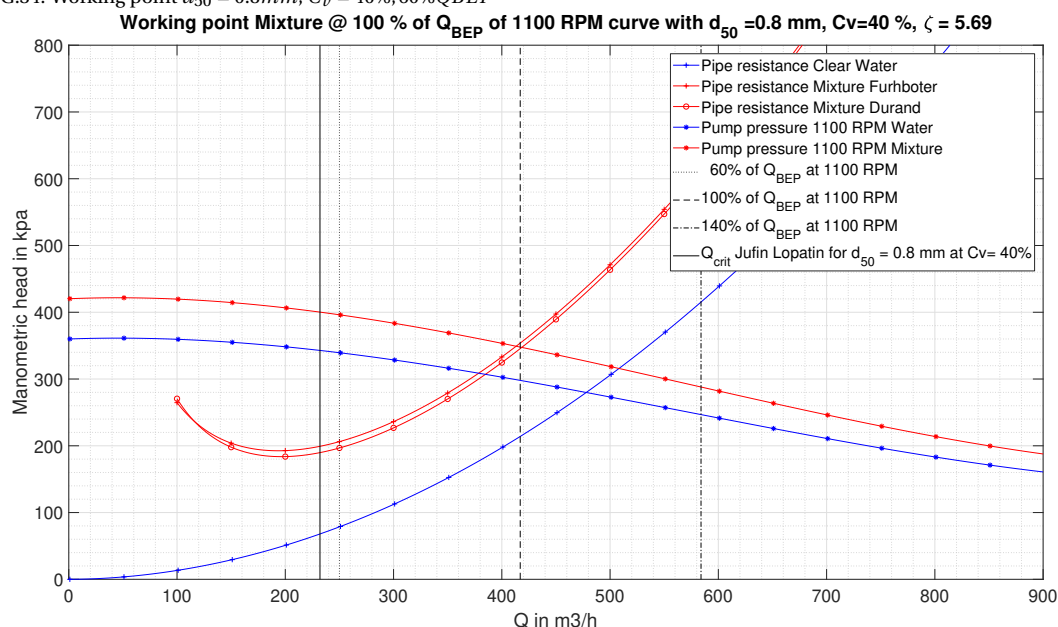
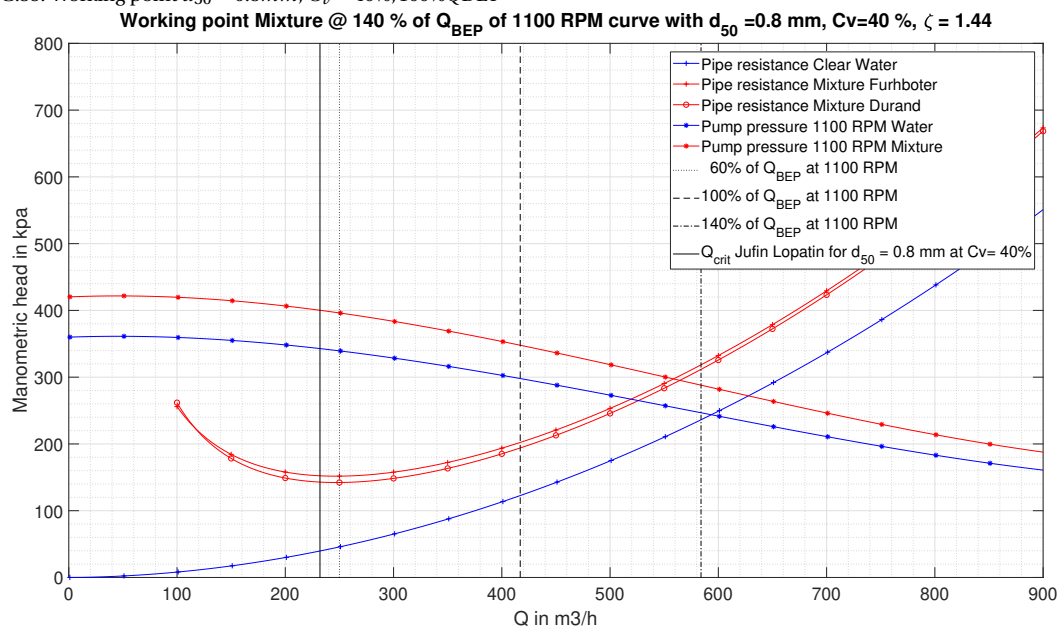
Figure G.19: Working point $d_{50} = 0.3$ mm, $C_v = 30$ %, 60% Q_{BEP} Figure G.20: Working point $d_{50} = 0.3$ mm, $C_v = 30$ %, 100% Q_{BEP} Figure G.21: Working point $d_{50} = 0.3$ mm, $C_v = 30$ %, 140% Q_{BEP}

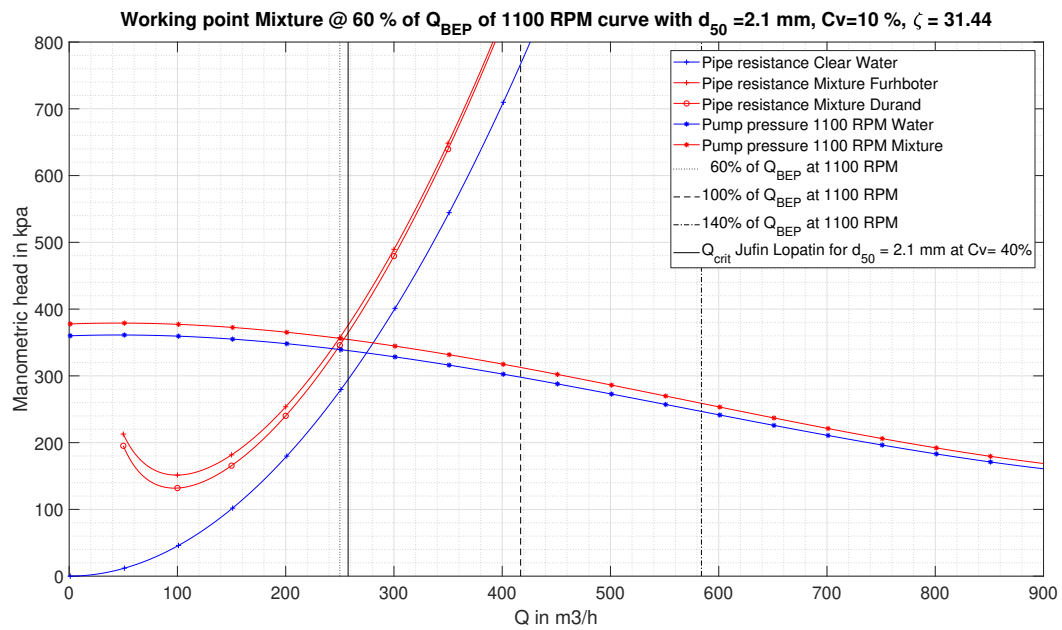
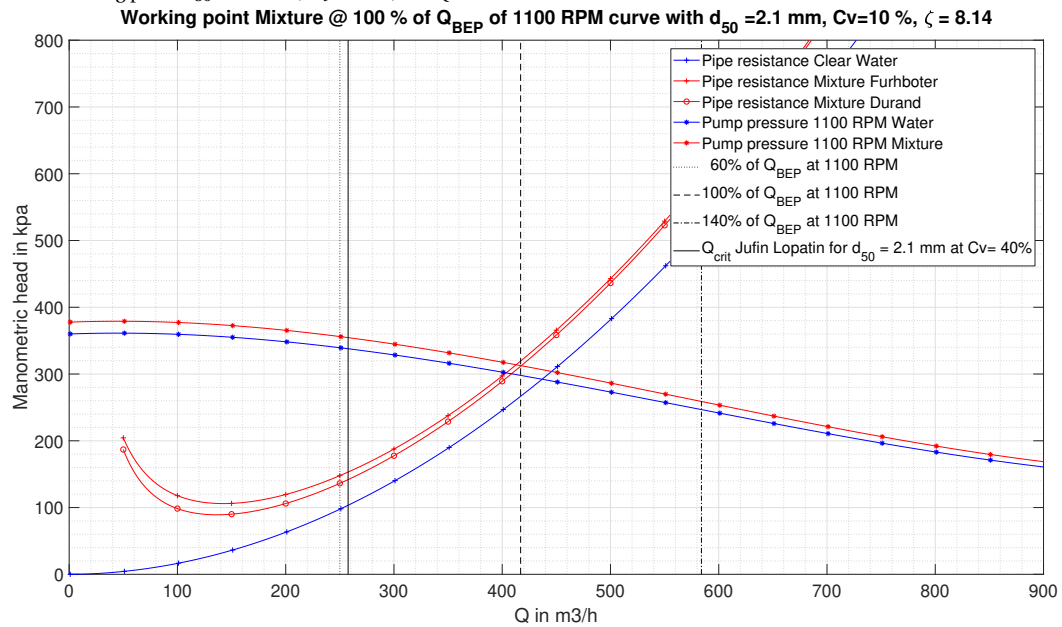
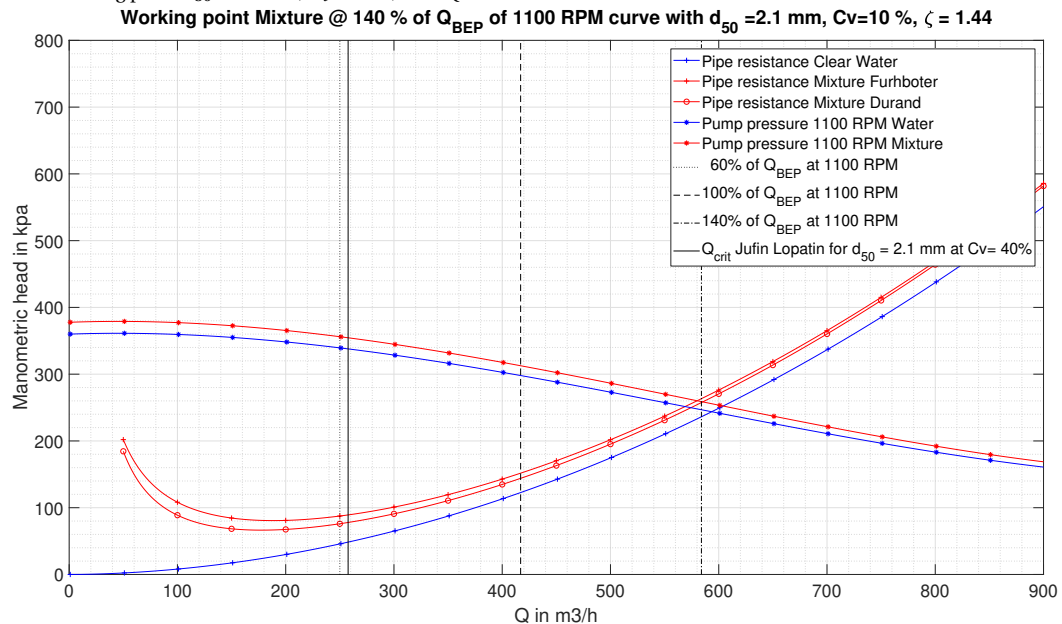
Figure G.22: Working point $d_{50} = 0.3$ mm, $C_v = 40$ %, 60% Q_{BEP} Figure G.23: Working point $d_{50} = 0.3$ mm, $C_v = 40$ %, 100% Q_{BEP} Figure G.24: Working point $d_{50} = 0.3$ mm, $C_v = 40$ %, 140% Q_{BEP}

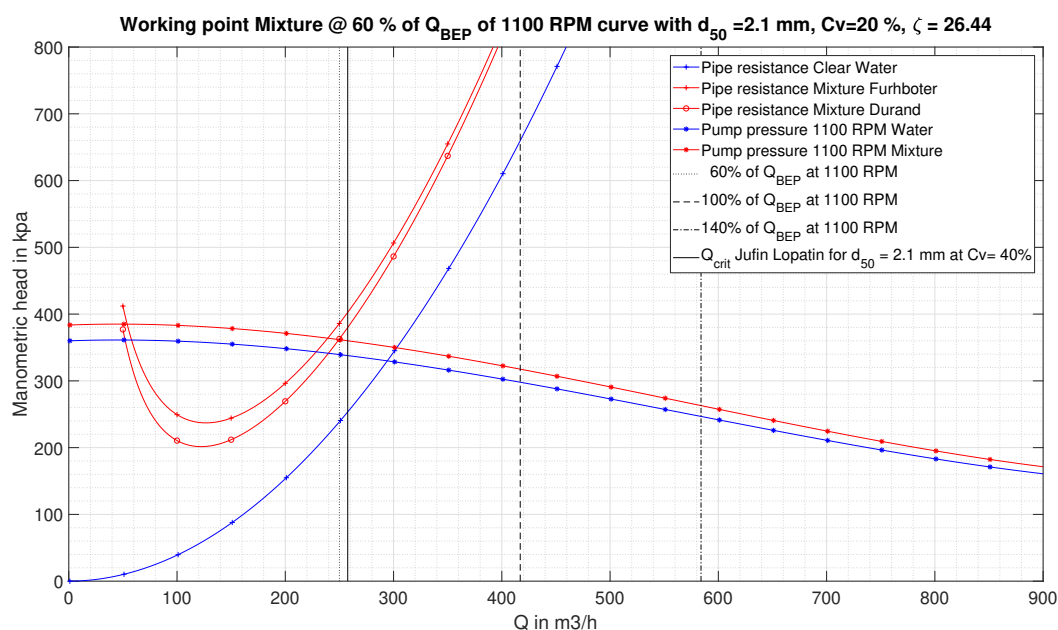
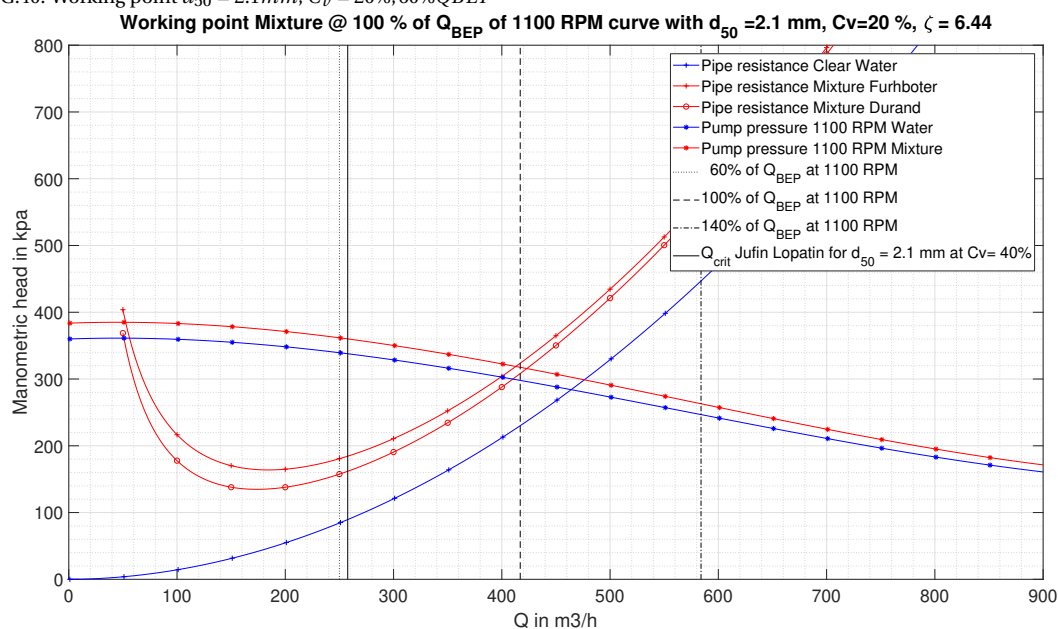
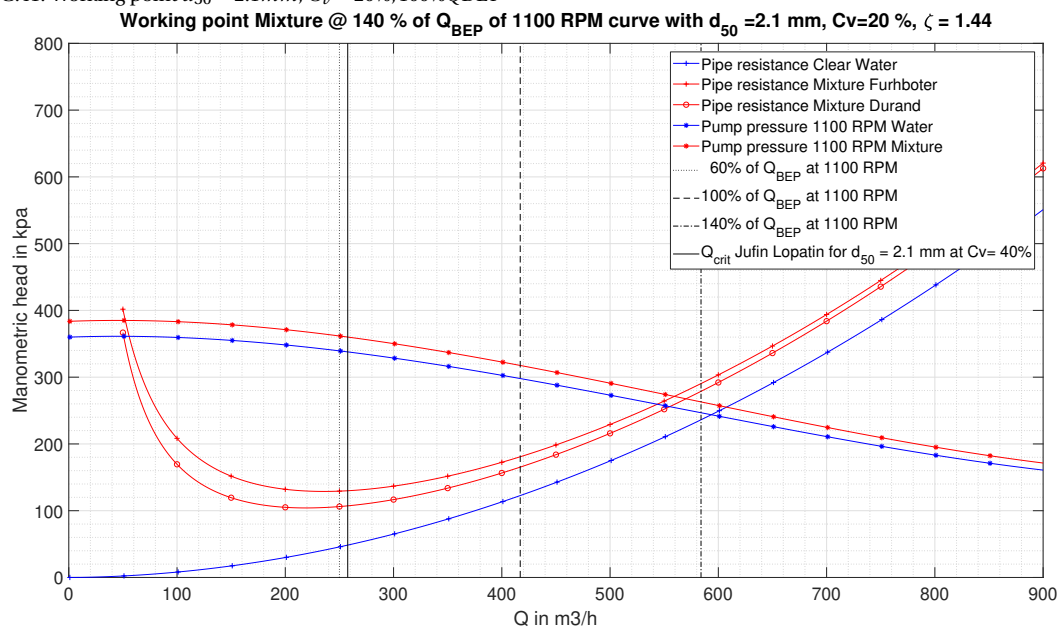
Figure G.25: Working point $d_{50} = 0.8$ mm, $C_v = 10\%$, $60\%Q_{BEP}$ Figure G.26: Working point $d_{50} = 0.8$ mm, $C_v = 10\%$, $100\%Q_{BEP}$ Figure G.27: Working point $d_{50} = 0.8$ mm, $C_v = 10\%$, $140\%Q_{BEP}$

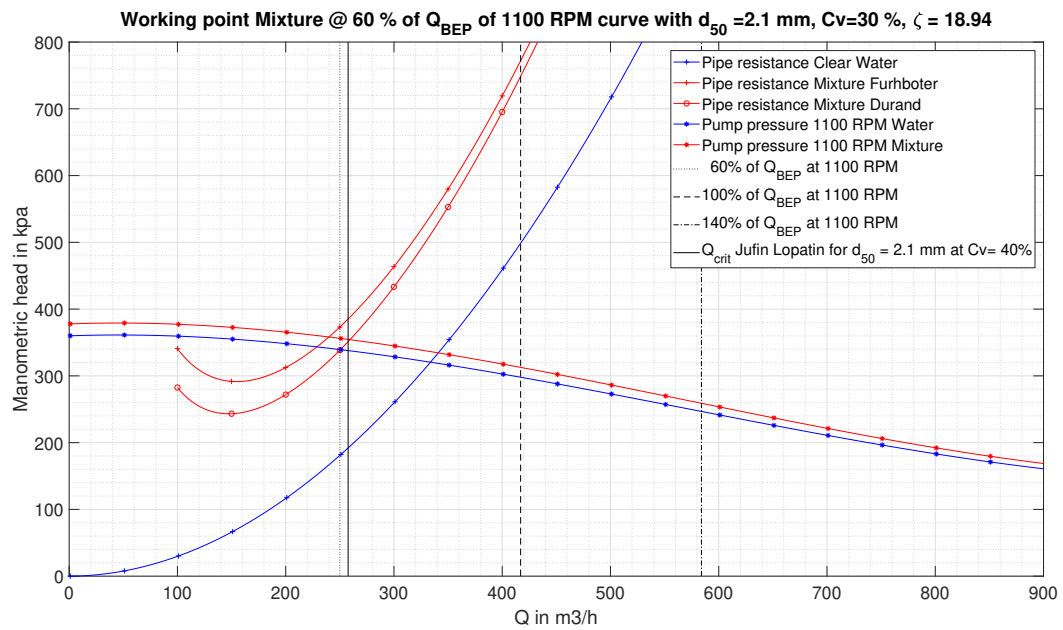
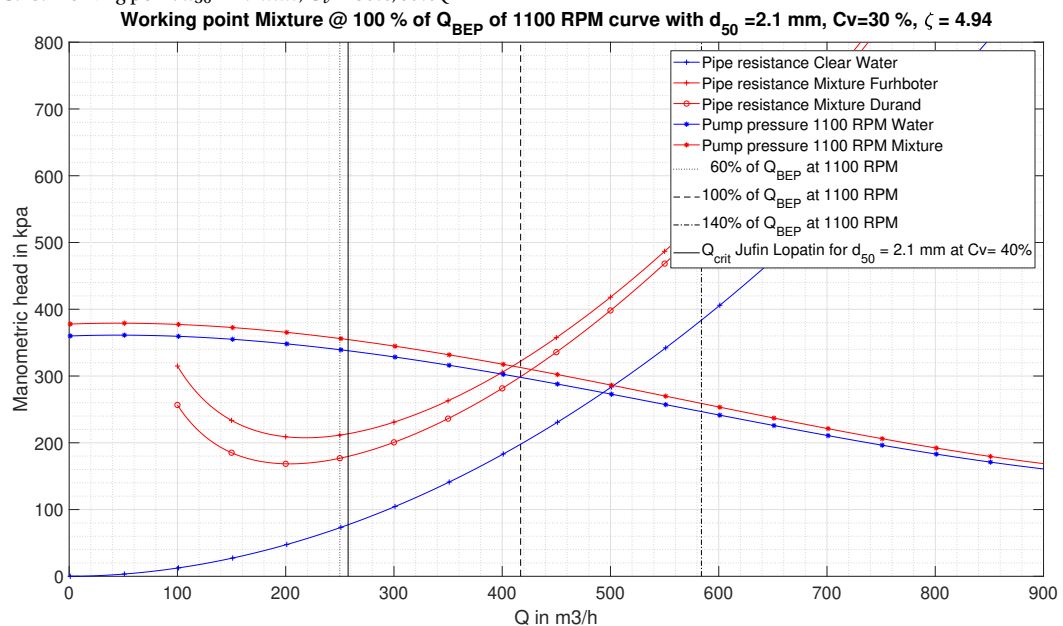
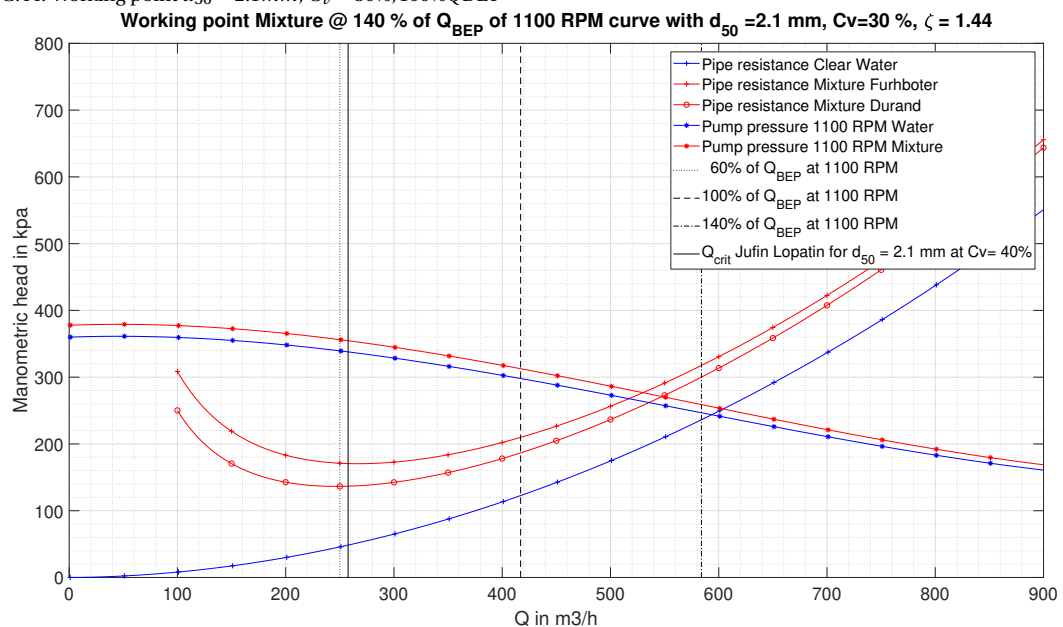
Figure G.28: Working point $d_{50} = 0.8$ mm, $C_v = 20$ %, $60\%Q_{BEP}$ Figure G.29: Working point $d_{50} = 0.8$ mm, $C_v = 20$ %, $100\%Q_{BEP}$ Figure G.30: Working point $d_{50} = 0.8$ mm, $C_v = 20$ %, $140\%Q_{BEP}$

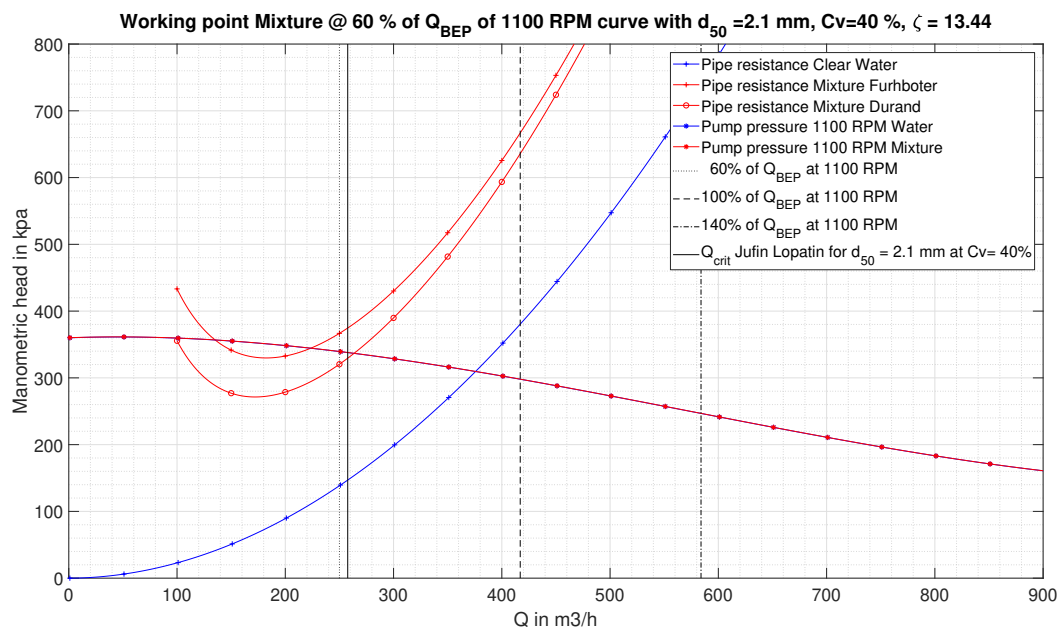
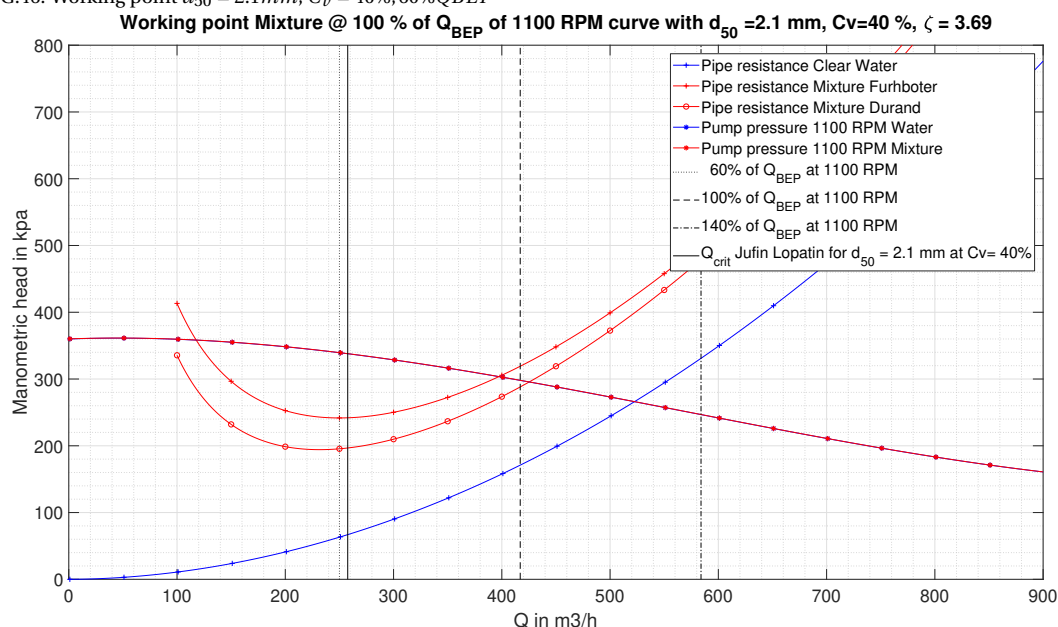
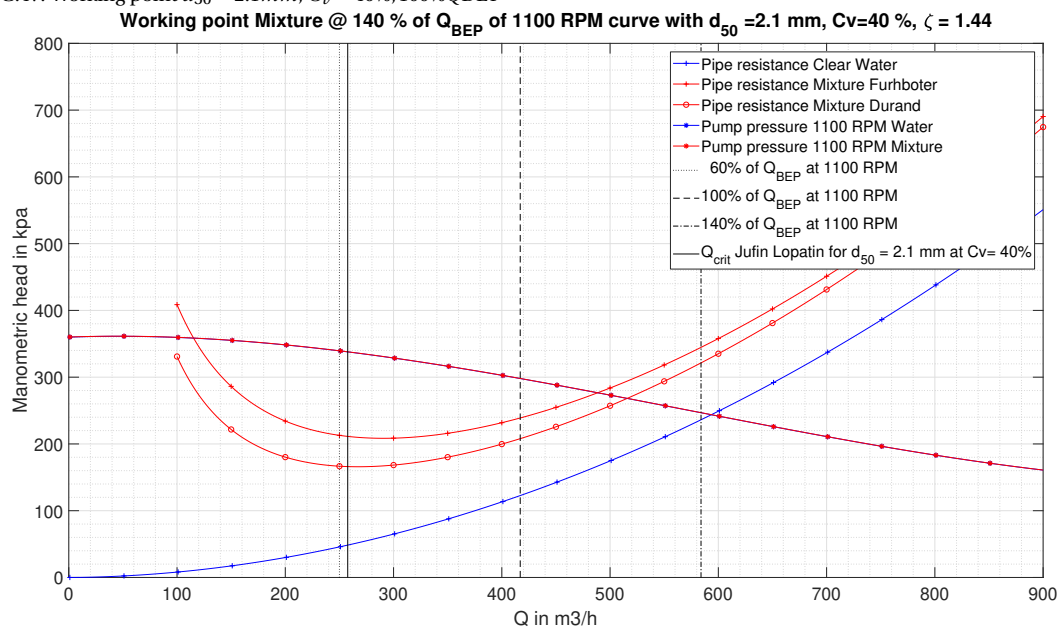
Figure G.31: Working point $d_{50} = 0.8$ mm, $C_v = 30$ %, $60\%Q_{BEP}$ Figure G.32: Working point $d_{50} = 0.8$ mm, $C_v = 30$ %, $100\%Q_{BEP}$ Figure G.33: Working point $d_{50} = 0.8$ mm, $C_v = 30$ %, $140\%Q_{BEP}$

Figure G.34: Working point $d_{50} = 0.8$ mm, $C_v = 40$ %, 60% Q_{BEP} Figure G.35: Working point $d_{50} = 0.8$ mm, $C_v = 40$ %, 100% Q_{BEP} Figure G.36: Working point $d_{50} = 0.8$ mm, $C_v = 40$ %, 140% Q_{BEP}

Figure G.37: Working point $d_{50} = 2.1$ mm, $C_v = 10\%$, $60\%Q_{BEP}$ Figure G.38: Working point $d_{50} = 2.1$ mm, $C_v = 10\%$, $100\%Q_{BEP}$ Figure G.39: Working point $d_{50} = 2.1$ mm, $C_v = 10\%$, $140\%Q_{BEP}$

Figure G.40: Working point $d_{50} = 2.1$ mm, $C_v = 20$ %, 60% Q_{BEP} Figure G.41: Working point $d_{50} = 2.1$ mm, $C_v = 20$ %, 100% Q_{BEP} Figure G.42: Working point $d_{50} = 2.1$ mm, $C_v = 20$ %, 140% Q_{BEP}

Figure G.43: Working point $d_{50} = 2.1$ mm, $C_v = 30$ %, 60% Q_{BEP} Figure G.44: Working point $d_{50} = 2.1$ mm, $C_v = 30$ %, 100% Q_{BEP} Figure G.45: Working point $d_{50} = 2.1$ mm, $C_v = 30$ %, 140% Q_{BEP}

Figure G.46: Working point $d_{50} = 2.1$ mm, $C_v = 40$ %, 60% Q_{BEP} Figure G.47: Working point $d_{50} = 2.1$ mm, $C_v = 40$ %, 100% Q_{BEP} Figure G.48: Working point $d_{50} = 2.1$ mm, $C_v = 40$ %, 140% Q_{BEP}

H

Obtained test data from the slurry loop experiments

In this appendix, all test data is gathered. In the first lines of the table are the average clear water results provided. After this, all mixture data is listed for further analyses and studies. The raw data is saved on multiple locations; the first one is on the computer in the lab, other locations are on a USB drive and in the cloud of the author.

Table H.1.1: Real experimental data of Geba sand at 250 m3/h part 1

Settings				Measured Data							
Type	File Name	flowrate real [m3/h]	Pump Pressure [kpa]	Density temp [kg/m3]	CV temp %	Head temp [m of slurry]	DP Up [pa]	DP Down [pa]	Temperature C	Power [kW]	eta [%]
01-10-2018											
	Average Water combined	250.53	339.67	1008.4	0.51%	34.338	530.44	-366.38	27.73	31.76	74%
Mixture	20181001_007_37_00_hz_250Q_CV10	249.34	388.84	1187.60	11.37%	33.376	2382.10	1297.90	22.55	36.89	73%
Mixture	20181001_008_37_00_hz_250Q_CV_Check	252.32	387.08	1183.70	11.13%	33.334	2352.60	1252.50	22.56	36.87	74%
Mixture	20181001_008_37_00_hz_250Q_CV_Check2	251.65	387.81	1185.70	11.25%	33.341	2368.00	1275.20	22.59	36.87	74%
Mixture	20181001_009_37_00_hz_250Q_CV10	251.05	388.72	1188.20	11.41%	33.349	2390.60	1300.90	22.88	36.89	73%
Mixture	20181001_010_37_00_hz_250Q_CV10	251.16	389.03	1189.50	11.48%	33.339	2402.50	1315.20	23.00	36.87	74%
03-10-2018											
Mixture	20181003_017_37_00_hz_250Q_CV_20	251.96	423.75	1332.80	20.17%	32.410	3867.10	2662.80	27.68	40.34	74%
Mixture	20181003_018_37_00_hz_250Q_CV_20	253.40	423.39	1333.00	20.18%	32.377	3875.90	2658.10	27.26	40.22	74%
Mixture	20181003_019_37_00_hz_250Q_CV_20	252.89	424.38	1333.30	20.20%	32.446	3895.30	2644.50	26.29	40.48	74%
25-10-2018											
Mixture	20181025_023_37_00_hz_250Q_CV_20	249.97	425.77	1332.30	20.14%	32.576	3814.40	2705.00	28.52	39.96	74%
Mixture	20181025_024_37_00_hz_250Q_CV_20	247.52	427.89	1337.40	20.45%	32.614	3857.60	2763.00	28.41	39.96	74%
Mixture	20181025_034_37_00_hz_250Q_CV_20	250.10	428.49	1344.40	20.87%	32.490	3927.70	2830.00	27.97	40.09	74%
Mixture	20181025_035_37_00_hz_250Q_CV_20	249.58	428.68	1342.80	20.78%	32.543	3890.70	2835.20	27.88	40.09	74%
Mixture	20181025_040_37_00_hz_250Q_CV_20	251.65	428.21	1344.90	20.90%	32.456	3946.70	2821.10	28.09	40.02	75%
Mixture	20181025_041_37_00_hz_250Q_CV_20	249.97	428.61	1343.70	20.83%	32.516	3913.50	2829.90	28.00	40.02	74%
26-10-2018											
Mixture	20181026_015_37_00_hz_250Q_CV_10	250.28	382.05	1164.90	9.99%	33.432	2141.60	1094.20	27.16	35.32	75%
Mixture	20181026_016_37_00_hz_250Q_CV_10	249.98	382.23	1165.30	10.02%	33.436	2144.50	1098.20	27.02	35.32	75%
Mixture	20181026_025_37_00_hz_250Q_CV_10	249.56	382.23	1164.30	9.96%	33.465	2127.40	1096.40	26.52	35.75	74%
Mixture	20181026_026_37_00_hz_250Q_CV_10	250.84	381.98	1164.10	9.95%	33.449	2134.40	1085.90	26.38	35.75	74%
Mixture	20181026_027_37_00_hz_250Q_CV_10	250.71	381.94	1164.40	9.96%	33.437	2140.50	1084.90	26.27	35.75	74%
Mixture	20181026_031_37_00_hz_250Q_CV_10	250.91	380.65	1164.50	9.97%	33.321	2122.20	1104.70	25.71	35.81	74%
Mixture	20181026_032_37_00_hz_250Q_CV_10	250.63	380.80	1165.30	10.02%	33.311	2134.50	1108.30	25.67	35.81	74%
Mixture	20181026_050_37_00_hz_250Q_CV_30	251.35	461.02	1489.10	29.64%	31.559	5476.50	4119.10	28.39	44.60	72%
Mixture	20181026_051_37_00_hz_250Q_CV_30	251.61	461.72	1491.50	29.79%	31.556	5506.10	4136.50	28.34	44.60	72%
Mixture	20181026_054_37_00_hz_250Q_CV_30	250.34	464.76	1504.50	30.58%	31.490	5647.00	4250.50	27.91	44.86	72%
Mixture	20181026_055_37_00_hz_250Q_CV_30	250.40	465.34	1506.70	30.71%	31.483	5674.60	4266.50	27.89	44.86	72%
Mixture	20181026_065_37_00_hz_250Q_CV_30	250.23	467.21	1520.20	31.53%	31.329	5829.10	4378.10	29.21	45.63	71%
Mixture	20181026_066_37_00_hz_250Q_CV_30	249.42	467.77	1522.00	31.64%	31.329	5842.10	4399.60	29.11	45.63	71%
Mixture	20181026_067_37_00_hz_250Q_CV_30	249.78	467.98	1521.80	31.62%	31.347	5819.50	4419.10	29.02	45.63	71%

Table H.2: Real experimental data of Geba sand at 250 m3/h part 2

Settings			Measured Data								
Type	File Name	flowrate real [m3/h]	Pump Pressure [kpa]	Density temp [kg/m3]	CV temp %	Head temp [m of slurry]	DP Up [pa]	DP Down [pa]	Temperature C	Power [kW]	eta [%]
29-10-2018											
	Average Water combined	250.53	339.67	1008.4	0.51%	34.338	530.44	-366.38	27.73	31.76	74%
Mixture	20181029_018_37_00_hz_250Q_CV_40	250.70	480.35	1609.20	36.92%	30.428	6805.40	5147.10	32.09	48.02	70%
Mixture	20181029_019_37_00_hz_250Q_CV_40	249.44	481.20	1612.40	37.12%	30.422	6859.90	5154.70	32.00	48.02	69%
Mixture	20181029_020_37_00_hz_250Q_CV_40	253.19	480.31	1616.90	37.39%	30.281	6957.70	5146.20	31.84	48.02	70%
Mixture	20181029_021_37_00_hz_250Q_CV_40	251.48	481.25	1620.10	37.58%	30.280	6981.90	5185.20	31.65	48.02	70%
Mixture	20181029_027_37_00_hz_250Q_CV_40	250.97	483.92	1624.70	37.86%	30.362	7044.70	5212.40	30.28	48.24	70%
Mixture	20181029_028_37_00_hz_250Q_CV_40	251.06	484.37	1626.60	37.98%	30.355	7070.00	5223.80	30.16	48.24	70%
Mixture	20181029_029_37_00_hz_250Q_CV_40	250.36	484.79	1625.90	37.93%	30.394	7048.30	5231.00	30.04	48.24	70%
Mixture	20181029_030_37_00_hz_250Q_CV_40	249.62	484.95	1621.50	37.67%	30.487	6966.50	5228.20	29.86	48.24	70%
Mixture	20181029_042_37_00_hz_250Q_CV_40	251.31	484.38	1624.80	37.87%	30.389	7063.30	5196.00	30.26	48.17	70%
Mixture	20181029_043_37_00_hz_250Q_CV_40	251.08	484.80	1624.60	37.85%	30.419	7033.10	5221.80	30.17	48.17	70%
Mixture	20181029_044_37_00_hz_250Q_CV_40	249.98	485.44	1632.40	38.33%	30.314	7178.00	5228.90	30.07	48.17	70%

Table H.3: Real experimental data of Geba sand at 417 m³/h part 1

Settings			Measured Data								
Type	File Name	flowrate real [m3/h]	Pump Pressure [kpa]	Density temp [kg/m3]	CV temp %	Head temp [m of slurry]	DP Up [pa]	DP Down [pa]	Temperature C	Power [kW]	eta [%]
Average Water combined											
01-10-2018		416.92	287.60	1020.3	1.23%	28.736	1433.75	-1035.79	28.42	42.46	79%
Mixture	20181001_011_37_00_hz_417Q_CV10	416.36	332.31	1196.00	11.88%	28.323	3281.30	563.43	23.82	48.98	78%
Mixture	20181001_012_37_00_hz_417Q_CV10	417.14	332.12	1196.70	11.92%	28.291	3279.20	580.02	24.55	48.86	79%
Mixture	20181001_013_37_00_hz_417Q_CV10	416.72	332.59	1197.40	11.96%	28.314	3271.80	601.42	26.30	48.96	79%
Mixture	20181001_017_37_00_hz_417Q_CV10	415.88	335.27	1206.40	12.51%	28.329	3371.50	678.94	27.62	48.60	80%
03-10-2018											
Mixture	20181003_014_37_00_hz_417Q_CV_20	415.21	358.02	1335.10	20.31%	27.335	4688.20	1886.60	28.52	53.90	77%
Mixture	20181003_015_37_00_hz_417Q_CV_20	415.80	358.18	1334.80	20.29%	27.354	4692.50	1876.60	28.28	53.50	77%
Mixture	20181003_016_37_00_hz_417Q_CV_20	416.59	358.10	1333.80	20.23%	27.368	4699.20	1850.90	28.07	53.55	77%
Mixture	20181003_020_37_00_hz_417Q_CV_20	411.88	360.84	1334.40	20.27%	27.565	4693.00	1868.50	26.07	53.50	77%
Mixture	20181003_021_37_00_hz_417Q_CV_20	416.76	358.14	1334.70	20.28%	27.353	4721.50	1845.50	26.43	53.30	78%
25-10-2018											
Mixture	20181025_025_37_00_hz_417Q_CV_20	416.13	367.73	1349.90	21.21%	27.769	4808.00	2058.00	28.04	53.75	79%
Mixture	20181025_026_37_00_hz_417Q_CV_20	416.16	368.18	1349.90	21.21%	27.803	4800.50	2065.20	27.96	53.75	79%
Mixture	20181025_031_37_00_hz_417Q_CV_20	419.05	366.17	1350.00	21.21%	27.649	4821.20	2045.00	28.30	54.01	79%
Mixture	20181025_032_37_00_hz_417Q_CV_20	416.92	367.11	1349.80	21.20%	27.724	4808.90	2053.50	28.19	53.97	79%
Mixture	20181025_033_37_00_hz_417Q_CV_20	416.95	367.26	1350.10	21.22%	27.729	4807.90	2060.60	28.18	53.97	79%
Mixture	20181025_036_37_00_hz_417Q_CV_20	418.44	366.84	1348.70	21.13%	27.726	4785.50	2056.70	27.53	53.88	79%
Mixture	20181025_037_37_00_hz_417Q_CV_20	418.96	366.33	1347.90	21.08%	27.704	4780.10	2046.50	27.31	53.88	79%
Mixture	20181025_042_37_00_hz_417Q_CV_20	417.20	367.48	1348.50	21.12%	27.779	4757.00	2080.00	27.64	54.03	79%
Mixture	20181025_043_37_00_hz_417Q_CV_20	416.71	367.48	1347.80	21.08%	27.793	4754.50	2068.50	27.56	54.03	79%
Water	20181025_046_37_00_hz_417Q_CV_00	417.81	286.95	1021.30	1.29%	28.641	1442.00	-1023.40	26.91	41.89	80%
26-10-2018											
Mixture	20181026_013_37_00_hz_417Q_CV_10	417.59	324.65	1168.20	10.19%	28.329	3011.90	287.35	27.62	47.83	79%
Mixture	20181026_014_37_00_hz_417Q_CV_10	418.06	324.77	1168.10	10.19%	28.342	3010.80	288.19	27.50	47.83	79%
Mixture	20181026_017_37_00_hz_417Q_CV_10	416.70	325.10	1168.20	10.19%	28.368	3011.90	287.65	26.58	47.82	79%
Mixture	20181026_018_37_00_hz_417Q_CV_10	417.71	325.17	1168.40	10.21%	28.369	3018.00	285.50	26.45	47.82	79%
Mixture	20181026_019_37_00_hz_417Q_CV_10	417.01	325.08	1168.30	10.20%	28.364	3016.40	285.27	26.25	47.82	79%
Mixture	20181026_023_37_00_hz_417Q_CV_10	417.78	324.90	1167.90	10.18%	28.358	3015.50	278.29	26.71	47.82	79%
Mixture	20181026_024_37_00_hz_417Q_CV_10	417.85	324.86	1167.90	10.18%	28.354	3013.60	280.40	26.70	47.82	79%
Mixture	20181026_028_37_00_hz_417Q_CV_10	416.09	325.40	1166.90	10.12%	28.426	3017.30	257.44	25.87	47.82	79%
Mixture	20181026_029_37_00_hz_417Q_CV_10	417.32	324.94	1166.90	10.12%	28.386	3027.00	247.67	25.72	47.82	79%
Mixture	20181026_030_37_00_hz_417Q_CV_10	417.29	324.91	1167.10	10.13%	28.378	3028.40	249.34	25.70	47.82	79%
Mixture	20181026_047_37_00_hz_417Q_CV_30	416.62	388.89	1485.90	29.45%	26.679	6271.10	3261.40	28.30	59.30	76%

Table H.4: Real experimental data of Geba sand at 417 m³/h part 2

Settings			Measured Data								
Type	File Name	flowrate real [m3/h]	Pump Pressure [kpa]	Density temp [kg/m3]	CV temp %	Head temp [m of slurry]	DP Up [pa]	DP Down [pa]	Temperature C	Power [kW]	eta [%]
Average Water combined											
26-10-2018											
Mixture	20181026_048_37_00_hz_417Q_CV_30	415.94	389.20	1487.20	29.53%	26.677	6289.50	3268.50	28.36	59.30	76%
Mixture	20181026_049_37_00_hz_417Q_CV_30	417.10	389.64	1489.70	29.68%	26.662	6313.90	3294.30	28.38	59.30	76%
Mixture	20181026_052_37_00_hz_417Q_CV_30	417.12	392.75	1504.00	30.55%	26.619	6470.60	3417.00	28.19	59.84	76%
Mixture	20181026_053_37_00_hz_417Q_CV_30	417.66	393.24	1507.20	30.74%	26.596	6509.10	3441.80	28.00	59.84	76%
Mixture	20181026_056_37_00_hz_417Q_CV_30	417.50	395.33	1521.70	31.62%	26.483	6685.20	3551.50	27.81	59.89	77%
Mixture	20181026_057_37_00_hz_417Q_CV_30	416.36	395.59	1522.40	31.66%	26.488	6678.20	3570.70	27.74	59.89	76%
Mixture	20181026_058_37_00_hz_417Q_CV_30	416.30	395.84	1522.70	31.68%	26.499	6681.50	3574.00	27.77	59.89	76%
Mixture	20181026_062_37_00_hz_417Q_CV_30	417.87	396.74	1525.20	31.83%	26.516	6729.80	3573.80	29.34	60.71	76%
Mixture	20181026_063_37_00_hz_417Q_CV_30	417.09	397.05	1525.40	31.84%	26.533	6727.70	3580.70	29.26	60.71	76%
Mixture	20181026_064_37_00_hz_417Q_CV_30	416.59	397.59	1525.20	31.83%	26.573	6717.40	3586.70	29.23	60.71	76%
Mixture	20181026_068_37_00_hz_417Q_CV_30	417.82	396.79	1526.40	31.90%	26.499	6755.20	3573.50	28.19	59.75	77%
Mixture	20181026_069_37_00_hz_417Q_CV_30	416.09	396.88	1526.40	31.90%	26.505	6745.40	3581.90	28.06	59.75	77%
29-10-2018											
Mixture	20181029_014_37_00_hz_417Q_CV_40	413.84	405.57	1629.90	38.18%	25.365	8047.50	4311.00	32.90	63.81	73%
Mixture	20181029_015_37_00_hz_417Q_CV_40	415.81	405.07	1627.50	38.03%	25.371	8008.00	4304.40	32.56	63.81	73%
Mixture	20181029_015_37_00_hz_417Q_CV_41	418.03	404.32	1628.70	38.10%	25.306	8048.00	4286.80	32.68	63.81	74%
Mixture	20181029_016_37_00_hz_417Q_CV_40	416.83	405.68	1625.70	37.92%	25.437	7981.70	4294.50	32.45	63.81	74%
Mixture	20181029_017_37_00_hz_417Q_CV_40	415.76	405.82	1624.60	37.85%	25.463	7954.90	4299.20	32.29	63.81	73%
Mixture	20181029_022_37_00_hz_417Q_CV_40	417.10	406.62	1625.80	37.93%	25.495	7869.10	4409.80	30.98	64.03	74%
Mixture	20181029_023_37_00_hz_417Q_CV_40	414.17	406.95	1624.30	37.84%	25.539	7837.60	4410.50	30.85	64.03	73%
Mixture	20181029_024_37_00_hz_417Q_CV_40	417.42	405.72	1624.10	37.82%	25.465	7859.30	4385.50	30.70	64.03	73%
Mixture	20181029_025_37_00_hz_417Q_CV_40	418.05	405.98	1623.90	37.81%	25.485	7860.50	4381.20	30.61	64.03	74%
Mixture	20181029_026_37_00_hz_417Q_CV_40	417.49	405.67	1624.40	37.84%	25.457	7883.90	4367.70	30.52	64.03	73%
Mixture	20181029_031_37_00_hz_417Q_CV_40	417.19	409.84	1628.10	38.07%	25.660	7917.00	4405.70	29.49	64.05	74%
Mixture	20181029_032_37_00_hz_417Q_CV_40	414.92	411.31	1626.70	37.98%	25.775	7878.60	4417.40	29.30	64.05	74%
Mixture	20181029_033_37_00_hz_417Q_CV_40	416.77	410.96	1627.00	38.00%	25.748	7902.00	4399.60	29.13	64.05	74%
Mixture	20181029_038_37_00_hz_417Q_CV_40	417.39	410.26	1627.10	38.01%	25.703	7923.00	4380.70	30.37	63.89	74%
Mixture	20181029_039_37_00_hz_417Q_CV_40	414.71	412.55	1625.60	37.92%	25.870	7864.60	4409.30	30.45	63.89	74%
Mixture	20181029_040_37_00_hz_417Q_CV_40	418.17	411.04	1625.80	37.93%	25.772	7893.00	4385.50	30.35	63.89	75%
Mixture	20181029_041_37_00_hz_417Q_CV_40	417.78	411.23	1625.60	37.92%	25.787	7884.80	4390.00	30.34	63.89	75%
Mixture	20181029_045_37_00_hz_417Q_CV_40	416.77	413.03	1631.30	38.26%	25.809	7963.70	4422.30	29.48	64.03	75%
Mixture	20181029_046_37_00_hz_417Q_CV_40	418.04	412.87	1631.20	38.25%	25.801	7975.10	4408.20	29.37	64.03	75%
Mixture	20181029_047_37_00_hz_417Q_CV_40	418.03	412.56	1629.10	38.13%	25.815	7935.70	4406.80	29.31	64.03	75%

Table H.5: Real experimental data of Geba sand at 584 m³/h part 1

Settings			Measured Data								
Type	File Name	flowrate real [m3/h]	Pump Pressure [kpa]	Density temp [kg/m3]	CV temp %	Head temp [m of slurry]	DP Up [pa]	DP Down [pa]	Temperature C	Power [kW]	eta [%]
01-10-2018											
Mixture	20181001_014_37_00_hz_584Q_CV10	582.10	254.54	1210.20	12.74%	21.44	4436.70	-312.16	28.11	57.48	72%
Mixture	20181001_015_37_00_hz_584Q_CV10	583.52	254.04	1212.00	12.85%	21.37	4464.00	-304.89	28.23	58.39	71%
Mixture	20181001_016_37_00_hz_584Q_CV10	583.65	254.34	1213.40	12.93%	21.37	4472.70	-286.53	28.33	58.39	71%
Mixture	20181001_018_37_00_hz_584Q_CV10	583.19	255.35	1217.70	13.19%	21.38	4540.40	-268.51	27.55	58.65	71%
02-10-2018											
Mixture	20181002_009_37_00_hz_584Q_CV_20	584.88	274.51	1326	19.76%	21.10	5675.10	721.17	25.71	63.84	70%
Mixture	20181002_010_37_00_hz_584Q_CV_20	582.48	275.42	1322.8	19.56%	21.22	5598.60	734.95	28.35	63.84	70%
03-10-2018											
Mixture	20181003_011_37_00_hz_584Q_CV_20	584.38	275.81	1347.00	21.03%	20.87	5967.20	840.52	25.52	64.32	70%
Mixture	20181003_012_37_00_hz_584Q_CV_20	583.00	274.21	1346.20	20.98%	20.76	5966.50	826.43	26.92	64.49	68%
Mixture	20181003_013_37_00_hz_584Q_CV_20	581.99	272.84	1347.50	21.06%	20.64	5974.40	843.99	28.12	64.43	68%
05-10-2018											
Mixture	20181005_011_37_00_hz_584Q_CV25	581.26	295.31	1459.90	27.87%	20.62	7149.10	1875.10	27.35	69.87	68%
Mixture	20181005_012_37_00_hz_584Q_CV25	581.88	296.24	1470.70	28.53%	20.53	7248.30	1986.10	28.75	70.64	68%
Mixture	20181005_013_37_00_hz_584Q_CV25	582.95	297.59	1483.90	29.33%	20.44	7387.30	2106.80	30.17	70.78	68%
Mixture	20181005_014_37_00_hz_584Q_CV30	581.44	299.45	1494.60	29.98%	20.42	7494.40	2209.50	31.00	71.40	68%
Mixture	20181005_015_37_00_hz_584Q_CV30	582.81	299.86	1503.20	30.50%	20.33	7591.20	2280.90	31.54	72.19	67%
Mixture	20181005_016_37_00_hz_584Q_CV30	581.51	301.33	1510.80	30.96%	20.33	7667.70	2354.50	31.98	72.53	67%
Mixture	20181005_017_37_00_hz_584Q_CV30	581.48	302.60	1523.00	31.70%	20.25	7804.50	2457.60	32.59	72.78	67%
25-10-2018											
Mixture	20181025_021_37_00_hz_584Q_CV_20	584.15	275.37	1334.50	20.27%	21.03	5728.40	833.75	28.88	63.84	70%
Mixture	20181025_022_37_00_hz_584Q_CV_20	585.07	275.60	1334.90	20.30%	21.05	5737.10	834.55	28.94	63.84	70%
Mixture	20181025_027_37_00_hz_584Q_CV_20	586.58	276.78	1357.40	21.66%	20.79	5960.90	1051.10	27.98	65.10	69%
Mixture	20181025_028_37_00_hz_584Q_CV_20	586.72	276.94	1356.00	21.58%	20.82	5972.90	1012.40	28.15	65.10	69%
Mixture	20181025_029_37_00_hz_584Q_CV_20	584.69	277.69	1353.70	21.44%	20.91	5964.40	975.16	28.35	65.10	69%
Mixture	20181025_030_37_00_hz_584Q_CV_20	585.05	277.78	1353.20	21.41%	20.93	5955.00	974.88	28.48	65.10	69%
Mixture	20181025_038_37_00_hz_584Q_CV_20	582.46	278.98	1360.10	21.82%	20.91	6029.90	1034.70	27.28	64.84	70%
Mixture	20181025_039_37_00_hz_584Q_CV_20	585.78	278.90	1351.10	21.28%	21.04	5930.20	958.39	28.57	64.84	70%
Mixture	20181025_039_37_00_hz_584Q_CV_21	582.66	279.11	1351.20	21.28%	21.06	5933.40	957.74	28.70	64.84	70%

Table H.6: Real experimental data of Geba sand at 584 m3/h part 2

Settings			Measured Data								
Type	File Name	flowrate real [m3/h]	Pump Pressure [kpa]	Density temp [kg/m3]	CV temp %	Head temp [m of slurry]	DP Up [pa]	DP Down [pa]	Temperature C	Power [kW]	eta [%]
26-10-2018											
Average Water combined		584.00	219.71	1015.6	0.95%	22.06	2475.48	-2169.30	28.30	50.09	71%
Mixture	20181026_011_37_00_hz_584Q_CV_10	584.51	246.28	1165.70	10.04%	21.54	4098.50	-847.97	28.03	57.11	70%
Mixture	20181026_012_37_00_hz_584Q_CV_10	584.80	246.50	1165.90	10.05%	21.55	4100.10	-844.29	27.92	57.11	70%
Mixture	20181026_020_37_00_hz_584Q_CV_10	585.19	244.69	1164.00	9.94%	21.43	4076.30	-859.55	26.15	56.98	70%
Mixture	20181026_021_37_00_hz_584Q_CV_10	583.40	245.56	1164.10	9.95%	21.50	4076.60	-856.69	26.29	56.98	70%
Mixture	20181026_022_37_00_hz_584Q_CV_10	584.54	245.85	1164.20	9.95%	21.53	4078.70	-856.49	26.47	56.98	70%
Mixture	20181026_034_37_00_hz_584Q_CV_10	584.52	236.67	1163.80	9.93%	20.73	4078.40	-864.03	25.13	56.75	68%
Mixture	20181026_035_37_00_hz_584Q_CV_10	583.47	240.12	1162.40	9.84%	21.06	4040.10	-853.76	25.29	56.75	69%
Mixture	20181026_036_37_00_hz_584Q_CV_10	585.51	240.80	1162.40	9.84%	21.12	4039.30	-852.03	25.41	56.75	69%
Mixture	20181026_045_37_00_hz_584Q_CV_30	583.51	297.84	1500.80	30.35%	20.23	7507.20	2317.90	28.00	71.81	67%
Mixture	20181026_046_37_00_hz_584Q_CV_30	584.59	297.77	1501.70	30.41%	20.21	7525.50	2318.70	28.17	71.79	67%
Mixture	20181026_059_37_00_hz_584Q_CV_30	584.80	305.83	1541.00	32.79%	20.23	7979.00	2636.00	28.26	71.89	69%
Mixture	20181026_060_37_00_hz_584Q_CV_30	581.95	305.81	1540.20	32.74%	20.24	7968.20	2630.60	28.95	71.89	69%
Mixture	20181026_061_37_00_hz_584Q_CV_30	584.88	305.53	1540.60	32.76%	20.22	7977.40	2630.10	29.14	71.89	69%
Mixture	20181026_070_37_00_hz_584Q_CV_30	582.92	303.27	1546.40	33.12%	19.99	8112.70	2607.90	28.27	71.75	68%
Mixture	20181026_071_37_00_hz_584Q_CV_30	584.51	302.50	1547.30	33.17%	19.93	8138.20	2600.40	28.50	71.75	68%
Mixture	20181026_072_37_00_hz_584Q_CV_30	586.21	303.03	1546.20	33.10%	19.98	8100.30	2615.30	28.69	71.75	69%
Mixture	20181026_073_37_00_hz_584Q_CV_30	584.58	302.96	1544.20	32.98%	20.00	8039.80	2637.60	28.87	71.75	69%
29-10-2018											
Mixture	20181029_005_37_00_hz_584Q_CV_30	581.66	301.30	1505.80	30.65%	20.40	7507.00	2417.80	30.12	71.41	68%
Mixture	20181029_006_37_00_hz_584Q_CV_30	583.02	301.40	1506.90	30.72%	20.39	7523.60	2422.70	30.21	71.41	68%
Mixture	20181029_007_37_00_hz_584Q_CV_30	585.29	304.05	1531.30	32.20%	20.24	7797.50	2625.60	31.97	71.41	69%
Mixture	20181029_008_37_00_hz_584Q_CV_30	583.62	305.48	1532.80	32.29%	20.32	7818.30	2634.40	32.03	71.41	69%
Mixture	20181029_010_37_00_hz_584Q_CV_40	581.60	309.95	1651.30	39.47%	19.13	9304.80	3473.20	32.91	77.04	65%
Mixture	20181029_011_37_00_hz_584Q_CV_40	580.53	310.80	1653.00	39.58%	19.17	9308.10	3503.30	32.96	77.04	65%
Mixture	20181029_012_37_00_hz_584Q_CV_40	582.19	310.54	1652.60	39.55%	19.15	9315.50	3488.80	32.98	77.04	65%
Mixture	20181029_013_37_00_hz_584Q_CV_40	583.29	310.21	1654.50	39.67%	19.11	9346.50	3494.60	32.97	77.04	65%
Mixture	20181029_034_37_00_hz_584Q_CV_40	581.44	318.35	1642.10	38.92%	19.76	9208.40	3389.00	29.04	71.55	72%
Mixture	20181029_035_37_00_hz_584Q_CV_40	583.66	314.12	1643.40	38.99%	19.48	9284.10	3338.80	29.75	71.55	71%
Mixture	20181029_036_37_00_hz_584Q_CV_40	585.44	312.92	1642.50	38.94%	19.42	9278.60	3326.60	29.88	71.55	71%
Mixture	20181029_037_37_00_hz_584Q_CV_40	583.27	312.89	1643.20	38.98%	19.41	9300.00	3320.50	30.03	71.55	71%
Mixture	20181029_048_37_00_hz_584Q_CV_40	585.24	313.71	1648.30	39.29%	19.40	9298.00	3422.00	29.14	71.41	71%
Mixture	20181029_049_37_00_hz_584Q_CV_40	584.63	314.13	1649.20	39.35%	19.42	9299.10	3437.70	29.23	71.41	71%
Mixture	20181029_050_37_00_hz_584Q_CV_40	583.08	314.35	1649.90	39.39%	19.42	9300.90	3450.40	29.35	71.41	71%

Table H.7: Real experimental data of Dorsilite 9 at 250 m³/h part 1

Settings				Measured Data							
Type	File Name	flowrate real [m3/h]	Pump Pressure [kpa]	Density temp [kg/m3]	CV temp %	Head temp [m of slurry]	DP Up [pa]	DP Down [pa]	Temperature C	Power [kW]	eta [%]
Average Water combined											
		250.03	342.46	1020.68	1.25%	34.20	711.06	-305.33	27.99	31.75	75%
30-11-2018											
Mixture	20181130_013_37_00_hz_250Q_CV_20	249.39	404.68	1331.50	20.09%	30.981	3794.40	2709.80	27.38	39.83	70%
Mixture	20181130_014_37_00_hz_250Q_CV_20	251.28	404.71	1331.60	20.10%	30.981	3809.00	2697.10	27.25	39.83	71%
Mixture	20181130_015_37_00_hz_250Q_CV_20	250.21	405.07	1331.70	20.10%	31.007	3800.80	2706.60	27.08	39.83	71%
Mixture	20181130_017_37_00_hz_250Q_CV_20	249.96	405.37	1331.60	20.10%	31.032	3805.40	2701.20	26.56	39.89	71%
Mixture	20181130_018_37_00_hz_250Q_CV_20	249.78	405.48	1331.50	20.09%	31.043	3809.50	2695.30	26.39	39.89	71%
Mixture	20181130_029_37_00_hz_250Q_CV_30	251.48	438.45	1503.40	30.51%	29.729	5537.00	4339.00	30.34	45.17	68%
Mixture	20181130_030_37_00_hz_250Q_CV_30	250.73	438.69	1503.70	30.53%	29.739	5543.50	4339.90	30.13	45.17	68%
Mixture	20181130_033_37_00_hz_250Q_CV_30	249.15	439.94	1503.90	30.54%	29.820	5543.00	4344.00	28.92	45.25	67%
Mixture	20181130_034_37_00_hz_250Q_CV_30	251.86	439.91	1504.20	30.56%	29.812	5557.30	4335.70	28.46	45.25	68%
Mixture	20181130_034_37_00_hz_250Q_CV_30_1	251.03	439.95	1504.60	30.58%	29.807	5552.20	4347.10	28.27	45.25	68%
Mixture	20181130_035_37_00_hz_250Q_CV_30	250.62	440.06	1504.00	30.55%	29.826	5554.00	4335.30	28.09	45.25	68%
03-12-2018											
Mixture	20181203_015_37_00_hz_250Q_CV_25	249.26	422.76	1404.60	24.52%	30.681	4588.50	3349.50	27.22	41.89	70%
Mixture	20181203_016_37_00_hz_250Q_CV_25	248.58	423.04	1404.80	24.53%	30.697	4588.90	3352.90	27.20	41.89	70%
Mixture	20181203_019_37_00_hz_250Q_CV_25	249.41	422.92	1404.70	24.53%	30.691	4592.50	3347.30	26.80	41.89	70%
Mixture	20181203_020_37_00_hz_250Q_CV_25	249.27	423.08	1405.10	24.55%	30.693	4595.10	3353.70	26.76	41.89	70%
Mixture	20181203_033_37_00_hz_250Q_CV_15	251.50	386.12	1249.70	15.13%	31.495	3062.90	1836.10	26.25	37.51	72%
Mixture	20181203_034_37_00_hz_250Q_CV_15	249.56	386.60	1248.90	15.08%	31.555	3039.80	1844.10	26.21	37.51	71%
Mixture	20181203_037_37_00_hz_250Q_CV_15	252.18	386.19	1249.40	15.12%	31.509	3057.00	1837.10	25.78	37.56	72%
Mixture	20181203_037_37_00_hz_250Q_CV_15_1	248.48	386.91	1249.50	15.12%	31.565	3042.70	1852.20	25.96	37.56	71%
Mixture	20181203_038_37_00_hz_250Q_CV_15	251.47	386.35	1249.10	15.10%	31.529	3055.00	1832.60	25.47	37.56	72%
Mixture	20181203_044_37_00_hz_250Q_CV_10	251.15	368.62	1162.20	9.83%	32.332	2204.30	978.03	25.98	35.32	73%
Mixture	20181203_045_37_00_hz_250Q_CV_10	251.32	368.73	1162.30	9.84%	32.339	2204.40	979.63	25.92	35.32	73%
Mixture	20181203_048_37_00_hz_250Q_CV_10	249.80	369.00	1162.30	9.84%	32.362	2196.30	988.18	25.55	35.28	73%
Mixture	20181203_049_37_00_hz_250Q_CV_10	249.45	369.17	1162.20	9.83%	32.380	2195.90	986.37	25.49	35.28	73%
04-12-2018											
Mixture	20181204_011_37_00_hz_250Q_CV_35	248.64	447.33	1546.70	33.13%	29.482	5991.10	4736.10	34.68	46.02	67%
Mixture	20181204_012_37_00_hz_250Q_CV_35	249.53	447.27	1546.70	33.13%	29.478	5998.90	4726.50	34.56	46.02	67%
Mixture	20181204_015_37_00_hz_250Q_CV_35	251.69	447.69	1548.90	33.27%	29.464	6033.00	4735.70	35.05	46.41	67%
Mixture	20181204_016_37_00_hz_250Q_CV_35	250.97	447.76	1548.70	33.25%	29.472	6035.50	4730.40	34.86	46.41	67%
Mixture	20181204_023_37_00_hz_250Q_CV_25	249.91	418.19	1395.20	23.95%	30.554	4490.50	3263.30	30.96	41.25	70%
Mixture	20181204_024_37_00_hz_250Q_CV_25	250.27	418.44	1395.60	23.98%	30.564	4498.40	3263.70	30.69	41.25	71%
Mixture	20181204_027_37_00_hz_250Q_CV_25	249.69	419.16	1395.90	23.99%	30.610	4500.60	3267.20	29.12	41.16	71%
Mixture	20181204_028_37_00_hz_250Q_CV_25	249.49	418.97	1396.10	24.01%	30.591	4507.30	3263.60	28.94	41.16	71%

Table H.8: Real experimental data of Dorsilit 9 at 417 m3/h part 1

Measured Data											
Type	File Name	flowrate real [m3/h]	Pump Pressure [kpa]	Density temp [kg/m3]	CV temp %	Head temp [m of slurry]	DP Up [pa]	DP Down [pa]	Temperature C	Power [kW]	eta [%]
15-11-2018											
	Average Water combined	417.05	287.58	1016.2	0.98%	28.847	1477.89	-1159.54	27.90	42.08	79%
Mixture	20181115_015_37_00_hz_417Q_CV_10	416.26	315.56	1164.20	9.95%	27.630	2947.30	273.57	25.81	47.44	77%
Mixture	20181115_016_37_00_hz_417Q_CV_10	417.13	315.82	1161.80	9.81%	27.710	2895.80	279.40	25.56	47.44	77%
Mixture	20181115_017_37_00_hz_417Q_CV_10	416.16	315.89	1161.60	9.79%	27.721	2900.90	270.09	25.51	47.44	77%
Mixture	20181115_018_37_00_hz_417Q_CV_10	415.85	315.99	1162.00	9.82%	27.720	2905.00	273.71	25.46	47.44	77%
Mixture	20181115_021_37_00_hz_417Q_CV_10	417.83	315.74	1161.70	9.80%	27.706	2912.60	260.63	25.66	47.44	77%
Mixture	20181115_022_37_00_hz_417Q_CV_10	417.76	315.80	1161.60	9.79%	27.713	2912.00	258.87	25.64	47.44	77%
Mixture	20181115_022_37_00_hz_417Q_CV_10_1	415.51	315.86	1161.80	9.81%	27.714	2911.50	262.28	25.66	47.44	77%
Mixture	20181115_026_37_00_hz_417Q_CV_10	417.78	315.53	1163.20	9.89%	27.651	2933.30	268.85	26.13	47.44	77%
Mixture	20181115_027_37_00_hz_417Q_CV_10	418.24	315.55	1163.20	9.89%	27.653	2930.10	272.33	26.14	47.44	77%
Mixture	20181115_028_37_00_hz_417Q_CV_10	417.48	315.94	1162.90	9.87%	27.694	2923.20	272.17	26.12	47.44	77%
Mixture	20181115_029_37_00_hz_417Q_CV_10	418.09	315.14	1163.00	9.88%	27.622	2939.70	257.55	26.02	47.44	77%
Mixture	20181115_030_37_00_hz_417Q_CV_10	416.29	316.48	1163.10	9.88%	27.737	2923.40	276.80	25.83	47.44	77%
Mixture	20181115_044_37_00_hz_417Q_CV_20	416.58	346.54	1331.10	20.07%	26.538	4603.80	1893.00	28.43	52.98	76%
Mixture	20181115_045_37_00_hz_417Q_CV_20	417.88	346.72	1331.50	20.09%	26.544	4608.80	1895.20	28.36	52.98	76%
Mixture	20181115_046_37_00_hz_417Q_CV_20	416.58	346.91	1332.50	20.15%	26.539	4621.00	1902.30	28.18	52.98	76%
Mixture	20181115_049_37_00_hz_417Q_CV_20	415.82	348.69	1329.70	19.98%	26.731	4577.90	1890.40	28.10	52.98	76%
Mixture	20181115_050_37_00_hz_417Q_CV_20	417.82	348.70	1329.50	19.97%	26.736	4579.80	1885.80	28.05	52.98	76%
Mixture	20181115_053_37_00_hz_417Q_CV_20	416.69	349.01	1329.50	19.97%	26.760	4583.30	1882.40	0.00	52.72	77%
Mixture	20181115_054_37_00_hz_417Q_CV_20	416.67	349.10	1329.30	19.96%	26.771	4582.30	1879.20	0.00	52.72	77%
Mixture	20181115_055_37_00_hz_417Q_CV_20	415.87	349.24	1329.60	19.98%	26.775	4582.00	1883.80	0.00	52.72	77%
16-11-2018											
Mixture	20181116_014_37_00_hz_417Q_CV_30	416.63	373.51	1496.20	30.07%	25.447	6340.40	3395.00	28.79	59.55	73%
Mixture	20181116_015_37_00_hz_417Q_CV_30	417.94	373.36	1495.80	30.05%	25.444	6347.30	3379.80	28.77	59.55	73%
Mixture	20181116_016_37_00_hz_417Q_CV_30	417.97	373.33	1495.70	30.04%	25.444	6348.60	3376.60	28.76	59.37	73%
Mixture	20181116_019_37_00_hz_417Q_CV_30	416.09	374.91	1495.50	30.03%	25.555	6350.20	3370.60	28.69	59.65	73%
Mixture	20181116_020_37_00_hz_417Q_CV_30	417.52	374.88	1495.60	30.04%	25.551	6354.50	3368.40	28.64	59.65	73%
Mixture	20181116_023_37_00_hz_417Q_CV_30	417.62	376.99	1496.40	30.08%	25.681	6357.10	3381.50	29.82	59.45	74%
Mixture	20181116_024_37_00_hz_417Q_CV_30	416.74	376.40	1496.20	30.07%	25.644	6371.70	3364.70	29.57	59.39	73%
Mixture	20181116_034_37_00_hz_417Q_CV_40	415.47	386.29	1646.00	39.15%	23.923	7949.90	4725.00	31.71	65.23	68%
Mixture	20181116_034_37_00_hz_417Q_CV_40_2	417.40	385.63	1647.10	39.22%	23.866	7986.80	4708.50	31.67	65.23	69%
Mixture	20181116_035_37_00_hz_417Q_CV_40	418.14	384.85	1648.00	39.27%	23.805	8017.10	4696.10	31.54	65.23	69%
Mixture	20181116_035_37_00_hz_417Q_CV_40_2	414.35	385.85	1647.70	39.25%	23.871	7999.00	4708.60	31.63	65.23	68%
Mixture	20181116_036_37_00_hz_417Q_CV_40	416.00	385.53	1648.40	39.30%	23.841	8016.30	4705.60	31.45	65.23	68%
Mixture	20181116_039_37_00_hz_417Q_CV_40	416.51	384.71	1647.90	39.27%	23.798	8019.50	4692.80	31.31	65.48	68%
Mixture	20181116_040_37_00_hz_417Q_CV_40	417.86	385.79	1648.40	39.30%	23.857	8019.30	4701.80	30.76	65.48	68%
Mixture	20181116_043_37_00_hz_417Q_CV_40	418.23	387.61	1648.30	39.29%	23.971	8025.40	4695.20	30.21	65.34	69%
Mixture	20181116_043_37_00_hz_417Q_CV_40_2	414.86	388.11	1648.40	39.30%	24.001	8016.60	4705.80	30.53	65.34	68%
Mixture	20181116_044_37_00_hz_417Q_CV_40	417.14	388.64	1648.30	39.29%	24.035	8015.60	4703.80	30.10	65.34	69%
Mixture	20181116_044_37_00_hz_417Q_CV_40_2	416.76	388.62	1648.60	39.31%	24.029	8021.30	4704.10	30.02	65.34	69%

Table H.9: Real experimental data of Dorsilir 9 at 417 m³/h part 2

Settings			Measured Data								
Type	File Name	flowrate real [m3/h]	Pump Pressure [kpa]	Density temp [kg/m3]	CV temp %	Head temp [m of slurry]	DP Up [pa]	DP Down [pa]	Temperature C	Power [kW]	eta [%]
19-11-2018											
Mixture	20181119_013_37_00_hz_417Q_CV_15	416.44	339.81	1263.40	15.96%	27.417	3933.80	1234.30	30.44	50.70	78%
Mixture	20181119_014_37_00_hz_417Q_CV_15	416.10	339.80	1265.30	16.08%	27.375	3964.40	1241.70	30.47	50.70	77%
Mixture	20181119_017_37_00_hz_417Q_CV_15	416.57	339.70	1264.80	16.05%	27.378	3959.40	1235.50	30.60	50.66	78%
Mixture	20181119_018_37_00_hz_417Q_CV_15	418.39	339.75	1264.60	16.04%	27.387	3953.40	1237.50	30.55	50.66	78%
Mixture	20181119_021_37_00_hz_417Q_CV_10	416.56	320.79	1166.30	10.08%	28.038	2974.30	288.37	27.52	47.34	78%
Mixture	20181119_022_37_00_hz_417Q_CV_10	416.19	320.87	1166.60	10.10%	28.037	2985.60	283.55	27.38	47.34	78%
Mixture	20181119_025_37_00_hz_417Q_CV_10	417.65	320.09	1167.60	10.16%	27.945	3009.20	278.59	26.83	47.44	78%
Mixture	20181119_026_37_00_hz_417Q_CV_10	418.04	320.54	1167.80	10.17%	27.980	2997.10	295.38	26.87	47.44	78%
20-11-2018											
Mixture	20181120_013_37_00_hz_417Q_CV_25	416.99	363.67	1417.60	25.31%	26.151	5527.20	2665.30	29.78	56.72	74%
Mixture	20181120_014_37_00_hz_417Q_CV_25	418.32	363.74	1416.20	25.22%	26.182	5487.90	2678.10	29.71	56.72	75%
Mixture	20181120_014_37_00_hz_417Q_CV_25_1	417.20	363.75	1416.20	25.22%	26.182	5488.10	2676.80	29.63	56.72	74%
21-11-2018											
Mixture	20181121_011_37_00_hz_417Q_CV_25	417.29	363.92	1429.00	26.00%	25.960	5623.00	2793.30	28.59	57.23	74%
Mixture	20181121_012_37_00_hz_417Q_CV_25	417.07	363.54	1429.80	26.05%	25.918	5665.00	2767.50	28.43	57.23	74%
Mixture	20181121_017_37_00_hz_417Q_CV_20	417.74	348.13	1339.50	20.58%	26.493	4754.50	1906.20	28.21	53.50	76%
Mixture	20181121_018_37_00_hz_417Q_CV_20	416.98	347.93	1339.80	20.59%	26.472	4760.10	1906.60	28.09	53.50	75%
Mixture	20181121_021_37_00_hz_417Q_CV_20	416.84	347.71	1338.40	20.51%	26.483	4741.80	1897.10	28.36	53.68	75%
Mixture	20181121_022_37_00_hz_417Q_CV_20	415.61	347.81	1338.30	20.50%	26.492	4740.20	1897.20	28.29	53.68	75%
Mixture	20181121_029_37_00_hz_417Q_CV_40	415.88	382.40	1666.30	40.38%	23.394	8184.20	4889.20	34.12	66.00	67%
Mixture	20181121_029_37_00_hz_417Q_CV_40_1	418.59	381.03	1664.10	40.25%	23.341	8173.40	4857.00	33.61	66.00	67%
Mixture	20181121_029_37_00_hz_417Q_CV_40_3	415.41	381.30	1657.50	39.85%	23.450	8085.70	4814.70	30.95	66.00	67%
Mixture	20181121_030_37_00_hz_417Q_CV_40	418.45	379.58	1658.80	39.93%	23.326	8120.00	4806.10	31.44	66.00	67%
Mixture	20181121_030_37_00_hz_417Q_CV_40_2	417.48	382.72	1666.80	40.41%	23.406	8187.70	4895.70	34.18	66.00	67%
Mixture	20181121_033_37_00_hz_417Q_CV_40	415.68	384.76	1669.50	40.58%	23.493	8212.10	4924.40	34.58	66.02	67%
Mixture	20181121_033_37_00_hz_417Q_CV_40_1	416.79	385.01	1669.90	40.60%	23.502	8215.50	4927.00	34.43	66.02	68%
Mixture	20181121_034_37_00_hz_417Q_CV_40	418.69	385.34	1670.30	40.62%	23.517	8232.80	4919.40	33.68	66.02	68%
Mixture	20181121_034_37_00_hz_417Q_CV_40_1	416.94	385.64	1670.00	40.61%	23.539	8236.70	4909.00	33.45	66.02	68%

Table H.10: Real experimental data of Dorsilit 9 at 417 m3/h part 3

Settings			Measured Data								
Type	File Name	flowrate real [m3/h]	Pump Pressure [kpa]	Density temp [kg/m3]	CV temp %	Head temp [m of slurry]	DP Up [pa]	DP Down [pa]	Temperature C	Power [kW]	eta [%]
Average Water combined											
		417.05	287.58	1016.2	0.98%	28.847	1477.89	-1159.54	27.90	42.08	79%
22-11-2018											
Mixture	20181122_011_37_00_hz_417Q_CV_35	417.62	381.68	1596.30	36.14%	24.373	7430.30	4268.30	30.72	63.38	70%
Mixture	20181122_012_37_00_hz_417Q_CV_35	418.01	381.67	1596.00	36.12%	24.377	7433.20	4260.90	30.70	63.38	70%
Mixture	20181122_015_37_00_hz_417Q_CV_35	415.81	382.42	1596.70	36.16%	24.415	7412.80	4294.30	31.49	63.21	70%
Mixture	20181122_015_37_00_hz_417Q_CV_35_1	415.52	382.62	1596.20	36.13%	24.435	7401.20	4295.80	31.39	63.21	70%
Mixture	20181122_015_37_00_hz_417Q_CV_35_2	418.43	382.12	1596.50	36.15%	24.398	7417.70	4285.00	31.28	63.21	70%
Mixture	20181122_015_37_00_hz_417Q_CV_35_3	416.81	381.70	1596.80	36.17%	24.367	7438.10	4271.00	31.12	63.21	70%
Mixture	20181122_016_37_00_hz_417Q_CV_35	414.71	382.51	1596.50	36.15%	24.423	7427.40	4275.20	31.04	63.21	70%
Mixture	20181122_019_37_00_hz_417Q_CV_40	419.10	387.35	1657.00	39.82%	23.829	8105.90	4784.80	31.18	65.87	68%
Mixture	20181122_019_37_00_hz_417Q_CV_40_1	414.48	388.65	1657.90	39.87%	23.896	8111.20	4797.20	31.00	65.87	68%
Mixture	20181122_019_37_00_hz_417Q_CV_40_2	416.45	388.09	1659.50	39.97%	23.839	8146.70	4792.20	30.81	65.87	68%
Mixture	20181122_020_37_00_hz_417Q_CV_40	415.43	388.34	1660.50	40.03%	23.840	8159.20	4800.00	30.65	65.87	68%
Mixture	20181122_020_37_00_hz_417Q_CV_40_1	415.88	388.34	1660.50	40.03%	23.840	8158.00	4801.70	30.52	65.87	68%
Mixture	20181122_011_37_00_hz_417Q_CV_35	417.62	381.68	1596.30	36.14%	24.373	7430.30	4268.30	30.72	63.38	70%
Mixture	20181122_012_37_00_hz_417Q_CV_35	418.01	381.67	1596.00	36.12%	24.377	7433.20	4260.90	30.70	63.38	70%
Mixture	20181122_015_37_00_hz_417Q_CV_35	415.81	382.42	1596.70	36.16%	24.415	7412.80	4294.30	31.49	63.21	70%
Mixture	20181122_015_37_00_hz_417Q_CV_35_1	415.52	382.62	1596.20	36.13%	24.435	7401.20	4295.80	31.39	63.21	70%
Mixture	20181122_015_37_00_hz_417Q_CV_35_2	418.43	382.12	1596.50	36.15%	24.398	7417.70	4285.00	31.28	63.21	70%
Mixture	20181122_015_37_00_hz_417Q_CV_35_3	416.81	381.70	1596.80	36.17%	24.367	7438.10	4271.00	31.12	63.21	70%
Mixture	20181122_016_37_00_hz_417Q_CV_35	414.71	382.51	1596.50	36.15%	24.423	7427.40	4275.20	31.04	63.21	70%
Mixture	20181122_019_37_00_hz_417Q_CV_40	419.10	387.35	1657.00	39.82%	23.829	8105.90	4784.80	31.18	65.87	68%
Mixture	20181122_019_37_00_hz_417Q_CV_40_1	414.48	388.65	1657.90	39.87%	23.896	8111.20	4797.20	31.00	65.87	68%
Mixture	20181122_019_37_00_hz_417Q_CV_40_2	416.45	388.09	1659.50	39.97%	23.839	8146.70	4792.20	30.81	65.87	68%
Mixture	20181122_020_37_00_hz_417Q_CV_40	415.43	388.34	1660.50	40.03%	23.840	8159.20	4800.00	30.65	65.87	68%
Mixture	20181122_020_37_00_hz_417Q_CV_40_1	415.88	388.34	1660.50	40.03%	23.840	8158.00	4801.70	30.52	65.87	68%
30-11-2018											
Mixture	20181130_011_37_00_hz_417Q_CV_20	416.73	349.26	1333.50	20.21%	26.698	4676.20	1866.20	27.47	53.50	76%
Mixture	20181130_012_37_00_hz_417Q_CV_20	416.79	349.30	1333.60	20.22%	26.700	4678.70	1866.10	27.40	53.50	76%
Mixture	20181130_016_37_00_hz_417Q_CV_20	415.96	349.69	1334.50	20.27%	26.711	4688.60	1875.20	26.44	53.55	75%
Mixture	20181130_016_37_00_hz_417Q_CV_20_1	415.34	349.70	1334.70	20.28%	26.708	4684.90	1881.00	26.44	53.55	75%
Mixture	20181130_016_37_00_hz_417Q_CV_20_2	418.01	348.78	1334.40	20.27%	26.644	4698.70	1862.30	26.45	53.55	76%
Mixture	20181130_027_37_00_hz_417Q_CV_30	417.19	372.91	1509.10	30.85%	25.189	6456.60	3531.40	31.14	59.68	72%
Mixture	20181130_028_37_00_hz_417Q_CV_30	416.36	372.89	1508.60	30.82%	25.196	6464.30	3514.70	31.05	59.68	72%
Mixture	20181130_031_37_00_hz_417Q_CV_30	417.68	372.92	1507.90	30.78%	25.210	6453.40	3510.70	29.16	59.68	72%
Mixture	20181130_032_37_00_hz_417Q_CV_30	417.97	372.89	1508.20	30.80%	25.203	6461.00	3509.70	29.02	59.68	73%

Table H.1.1: Real experimental data of Dorsilitt 9 at 417 m³/h part 4

Settings			Measured Data								
Type	File Name	flowrate real [m3/h]	Pump Pressure [kpa]	Density temp [kg/m3]	CV temp %	Head temp [m of slurry]	DP Up [pa]	DP Down [pa]	Temperature C	Power [kW]	eta [%]
03-12-2018											
	Average Water combined	417.05	287.58	1016.2	0.98%	28.847	1477.89	-1159.54	27.90	42.08	79%
Mixture	20181203_013_37_00_hz_417Q_CV_25	416.43	362.24	1404.30	24.50%	26.295	5427.90	2504.30	27.11	56.07	75%
Mixture	20181203_014_37_00_hz_417Q_CV_25	415.19	362.43	1405.80	24.59%	26.280	5471.40	2490.00	27.11	56.07	75%
Mixture	20181203_017_37_00_hz_417Q_CV_25	415.16	363.14	1406.20	24.62%	26.324	5487.10	2483.40	26.87	55.95	75%
Mixture	20181203_018_37_00_hz_417Q_CV_25	418.05	362.00	1406.00	24.61%	26.245	5499.20	2466.20	26.71	55.95	75%
Mixture	20181203_031_37_00_hz_417Q_CV_15	415.43	334.19	1249.50	15.12%	27.264	3926.80	968.81	26.04	50.40	77%
Mixture	20181203_032_37_00_hz_417Q_CV_15	418.18	333.84	1248.20	15.04%	27.264	3899.60	970.24	26.12	50.40	77%
Mixture	20181203_035_37_00_hz_417Q_CV_15	417.56	334.11	1249.60	15.13%	27.255	3933.30	964.52	26.05	50.40	77%
Mixture	20181203_036_37_00_hz_417Q_CV_15	416.92	334.03	1249.20	15.10%	27.257	3926.70	961.82	25.98	50.40	77%
Mixture	20181203_042_37_00_hz_417Q_CV_10	416.42	317.49	1162.00	9.82%	27.852	3055.50	122.54	25.90	47.44	77%
Mixture	20181203_043_37_00_hz_417Q_CV_10	415.05	317.77	1160.60	9.73%	27.910	3032.70	117.58	25.93	47.44	77%
Mixture	20181203_046_37_00_hz_417Q_CV_10	418.34	317.06	1161.50	9.79%	27.826	3063.30	104.60	25.74	47.44	78%
Mixture	20181203_047_37_00_hz_417Q_CV_10	417.90	316.89	1161.30	9.78%	27.816	3059.80	104.97	25.60	47.44	78%
04-12-2018											
Mixture	20181204_009_37_00_hz_417Q_CV_35	418.65	377.91	1552.50	33.48%	24.813	6981.30	3858.70	33.30	61.62	71%
Mixture	20181204_010_37_00_hz_417Q_CV_35	419.17	377.90	1553.30	33.53%	24.800	6991.10	3864.60	33.61	61.62	71%
Mixture	20181204_010_37_00_hz_417Q_CV_35_1	417.47	377.87	1553.20	33.53%	24.800	6989.40	3864.30	34.00	61.62	71%
Mixture	20181204_013_37_00_hz_417Q_CV_35	418.54	378.46	1553.60	33.55%	24.832	6994.90	3866.60	34.53	61.62	71%
Mixture	20181204_014_37_00_hz_417Q_CV_35	418.65	379.16	1553.80	33.56%	24.875	6991.90	3874.30	34.67	61.62	72%
Mixture	20181204_021_37_00_hz_417Q_CV_25	415.71	358.30	1397.10	24.07%	26.143	5378.80	2412.20	31.82	55.30	75%
Mixture	20181204_022_37_00_hz_417Q_CV_25	416.13	358.67	1398.20	24.13%	26.149	5403.80	2408.40	31.62	55.30	75%
Mixture	20181204_025_37_00_hz_417Q_CV_25	416.75	359.67	1397.10	24.07%	26.243	5387.70	2403.00	29.61	55.30	75%
Mixture	20181204_026_37_00_hz_417Q_CV_25	416.79	359.70	1396.80	24.05%	26.250	5385.70	2400.00	29.41	55.30	75%

Table H.12: Real experimental data of Dorsilit 9 at 584 m3/h part 1

Settings			Measured Data								
Type	File Name	flowrate real [m3/h]	Pump Pressure [kpa]	Density temp [kg/m3]	CV temp %	Head temp [m of slurry]	DP Up [pa]	DP Down [pa]	Temperature C	Power [kW]	eta [%]
Average Water combined 584 m3/h											
Average Water combined 574 m3/h											
Average Water combined 557 m3/h											
15-11-2018											
Mixture	20181115_011_37_00_hz_584Q_CV_10	584.89	236.36	1165.30	10.02%	20.68	4113.80	-870.08	25.39	56.46	68%
Mixture	20181115_012_37_00_hz_584Q_CV_10	584.45	236.75	1164.80	9.99%	20.72	4095.70	-861.54	25.48	56.46	68%
Mixture	20181115_013_37_00_hz_584Q_CV_10	585.24	236.71	1164.60	9.98%	20.72	4091.80	-862.53	25.53	56.46	68%
Mixture	20181115_014_37_00_hz_584Q_CV_10	585.26	236.61	1164.80	9.99%	20.71	4094.40	-860.66	25.58	56.46	68%
Mixture	20181115_019_37_00_hz_584Q_CV_10	584.33	237.06	1166.80	10.11%	20.71	4110.90	-838.06	25.36	56.54	68%
Mixture	20181115_020_37_00_hz_584Q_CV_10	584.10	237.15	1167.20	10.13%	20.71	4118.30	-837.21	25.46	56.54	68%
Mixture	20181115_023_37_00_hz_584Q_CV_10	584.37	237.22	1167.00	10.12%	20.72	3990.50	-713.72	25.56	56.54	68%
Mixture	20181115_024_37_00_hz_584Q_CV_10	583.13	237.36	1167.30	10.14%	20.73	4001.00	-719.11	25.62	56.54	68%
Mixture	20181115_025_37_00_hz_584Q_CV_10	585.99	237.24	1166.60	10.10%	20.73	3992.10	-723.68	25.67	56.54	68%
Mixture	20181115_025_37_00_hz_584Q_CV_10_1	583.18	237.21	1166.40	10.08%	20.73	3982.00	-717.22	25.73	56.54	68%
Mixture	20181115_041_37_00_hz_584Q_CV_20	583.35	258.80	1333.00	20.18%	19.79	5812.90	720.14	28.21	63.55	66%
Mixture	20181115_041_37_00_hz_584Q_CV_20_1	585.87	259.06	1331.10	20.07%	19.84	5781.80	715.38	27.68	63.84	66%
Mixture	20181115_041_37_00_hz_584Q_CV_20_2	585.42	258.99	1331.00	20.06%	19.84	5779.10	715.21	27.88	63.84	66%
Mixture	20181115_042_37_00_hz_584Q_CV_20	584.67	258.72	1332.30	20.14%	19.80	5787.90	731.30	28.26	63.84	66%
Mixture	20181115_043_37_00_hz_584Q_CV_20	585.19	260.04	1330.20	20.01%	19.93	5677.30	800.93	28.45	63.84	66%
Mixture	20181115_043_37_00_hz_584Q_CV_20_1	582.39	260.18	1330.70	20.04%	19.93	5683.00	804.70	28.41	63.84	66%
Mixture	20181115_047_37_00_hz_584Q_CV_20	583.27	260.16	1339.10	20.55%	19.80	5815.60	838.30	27.99	63.75	66%
Mixture	20181115_048_37_00_hz_584Q_CV_20	583.65	260.13	1339.40	20.57%	19.80	5831.20	828.07	28.08	63.75	66%
Mixture	20181115_051_37_00_hz_584Q_CV_20	585.36	259.56	1329.80	19.99%	19.90	5842.00	628.57	27.85	63.81	66%
Mixture	20181115_051_37_00_hz_584Q_CV_20_1	585.54	259.59	1331.70	20.10%	19.87	5865.20	642.65	27.87	63.81	66%
Mixture	20181115_052_37_00_hz_584Q_CV_20	585.02	259.71	1334.10	20.25%	19.84	5896.70	657.49	27.93	63.81	66%
Mixture	20181115_056_37_00_hz_584Q_CV_20	583.59	260.76	1334.60	20.28%	19.92	5824.00	741.39	28.34	63.78	66%
Mixture	20181115_057_37_00_hz_584Q_CV_20	583.34	260.68	1334.40	20.27%	19.91	5832.30	728.29	28.41	63.78	66%
16-11-2018											
Mixture	20181116_011_37_00_hz_584Q_CV_30_1	585.89	276.34	1506.50	30.70%	18.70	7746.70	2190.10	27.66	72.19	62%
Mixture	20181116_011_37_00_hz_584Q_CV_30	585.19	278.85	1505.10	30.61%	18.89	7682.30	2227.70	28.25	72.19	63%
Mixture	20181116_012_37_00_hz_584Q_CV_30	584.31	282.26	1506.70	30.71%	19.10	7675.90	2264.90	28.56	71.81	64%
Mixture	20181116_013_37_00_hz_584Q_CV_30	583.42	282.61	1505.90	30.66%	19.13	7649.70	2276.50	28.71	71.89	64%
Mixture	20181116_017_37_00_hz_584Q_CV_30	584.73	283.04	1512.50	31.06%	19.08	7803.70	2251.10	28.87	71.67	64%
Mixture	20181116_018_37_00_hz_584Q_CV_30	584.08	283.69	1510.70	30.95%	19.14	7768.10	2251.70	28.99	71.67	64%
Mixture	20181116_021_37_00_hz_584Q_CV_30	584.43	283.08	1500.20	30.32%	19.23	7651.40	2162.30	30.15	71.56	64%
Mixture	20181116_022_37_00_hz_584Q_CV_30	584.07	282.90	1500.10	30.31%	19.22	7649.80	2162.20	30.35	71.56	64%
Mixture	20181116_031_37_00_hz_584Q_CV_40	576.95	293.48	1639.30	38.75%	18.25	9040.50	3503.50	30.16	78.63	60%
Mixture	20181116_031_37_00_hz_584Q_CV_40_1	578.80	293.97	1651.70	39.50%	18.14	9233.60	3552.00	30.30	78.63	60%

Table H.13: Real experimental data of Dorsilit 9 at 584 m³/h part 2

Settings			Measured Data								
Type	File Name	flowrate real [m3/h]	Pump Pressure [kpa]	Density temp [kg/m3]	CV temp %	Head temp [m of slurry]	DP Up [pa]	DP Down [pa]	Temperature C	Power [kW]	eta [%]
Average Water combined 584 m3/h		584.32	219.69	1006.3	0.38%	22.25	2473.93	-2349.50	28.13	50.16	71%
Average Water combined 574 m3/h		574.26	225.98	1011.3	0.69%	22.78	2564.63	-2342.13	25.93	49.63	73%
Average Water combined 557 m3/h		558.96	230.20	1010.6	0.64%	23.22	2404.42	-2197.28	27.35	49.33	72%
16-11-2018											
Mixture	20181116_031_37_00_hz_584Q_CV_40_2	575.77	294.22	1654.70	39.68%	18.13	9270.60	3574.30	30.50	78.63	60%
Mixture	20181116_032_37_00_hz_584Q_CV_40	576.69	294.34	1653.80	39.62%	18.14	9226.50	3600.70	30.79	78.63	60%
Mixture	20181116_033_37_00_hz_584Q_CV_40	572.74	294.47	1655.20	39.71%	18.14	9228.10	3627.80	31.06	78.63	60%
Mixture	20181116_037_37_00_hz_584Q_CV_40	573.90	295.00	1660.20	40.01%	18.11	9378.70	3573.90	31.44	78.63	60%
Mixture	20181116_038_37_00_hz_584Q_CV_40	575.33	295.00	1659.00	39.94%	18.13	9354.80	3575.50	31.61	78.63	60%
Mixture	20181116_041_37_00_hz_584Q_CV_40	574.84	295.71	1660.00	40.00%	18.16	9396.90	3552.30	30.81	78.45	60%
Mixture	20181116_042_37_00_hz_584Q_CV_40	578.64	295.70	1660.90	40.05%	18.15	9409.30	3557.40	30.72	78.45	61%
19-11-2018											
Mixture	20181119_011_37_00_hz_584Q_CV_15	585.09	255.00	1260.90	15.81%	20.62	5058.20	59.66	28.50	60.70	68%
Mixture	20181119_012_37_00_hz_584Q_CV_15	584.58	256.28	1260.50	15.79%	20.73	5048.10	62.77	29.65	60.70	69%
Mixture	20181119_015_37_00_hz_584Q_CV_15	584.42	254.71	1267.40	16.21%	20.49	5131.20	115.81	30.43	60.70	68%
Mixture	20181119_016_37_00_hz_584Q_CV_15	584.06	255.06	1265.00	16.06%	20.55	5069.50	129.08	30.46	60.70	68%
Mixture	20181119_019_37_00_hz_584Q_CV_10	584.30	242.95	1164.00	9.94%	21.28	4063.60	-846.46	28.69	56.46	70%
Mixture	20181119_020_37_00_hz_584Q_CV_10	581.83	243.16	1164.20	9.95%	21.29	4058.40	-837.07	28.29	56.46	70%
Mixture	20181119_023_37_00_hz_584Q_CV_10	584.15	241.30	1160.20	9.71%	21.20	3940.10	-796.80	26.82	56.72	69%
Mixture	20181119_024_37_00_hz_584Q_CV_10	584.83	241.60	1161.80	9.81%	21.20	3969.30	-794.80	26.77	56.72	69%
Mixture	20181119_027_37_00_hz_584Q_CV_10	585.43	242.38	1162.40	9.84%	21.26	3990.00	-804.27	26.64	56.46	70%
Mixture	20181119_028_37_00_hz_584Q_CV_10	585.59	242.39	1162.80	9.87%	21.25	3991.50	-797.03	26.65	56.46	70%
20-11-2018											
Mixture	20181120_011_37_00_hz_584Q_CV_25	584.72	275.14	1420.50	25.48%	19.74	6715.50	1535.50	29.38	68.32	65%
Mixture	20181120_012_37_00_hz_584Q_CV_25	584.15	275.17	1420.60	25.49%	19.75	6721.30	1529.90	29.50	68.32	65%
Mixture	20181120_015_37_00_hz_584Q_CV_25	584.49	275.05	1420.30	25.47%	19.74	6732.90	1512.80	29.52	68.26	65%
Mixture	20181120_016_37_00_hz_584Q_CV_25	581.80	274.82	1419.70	25.44%	19.73	6726.80	1508.50	29.58	68.26	65%
Mixture	20181120_016_37_00_hz_584Q_CV_26	585.02	274.99	1418.60	25.37%	19.76	6710.50	1501.80	29.65	68.26	65%
21-11-2018											
Mixture	20181121_009_37_00_hz_584Q_CV_25	583.64	272.75	1435.30	26.38%	19.37	6878.80	1662.60	28.62	68.68	64%
Mixture	20181121_010_37_00_hz_584Q_CV_25	584.65	272.65	1436.30	26.44%	19.35	6886.50	1674.30	28.65	68.68	64%
Mixture	20181121_013_37_00_hz_584Q_CV_25	584.84	272.25	1435.40	26.39%	19.33	6867.30	1674.30	28.26	68.75	64%
Mixture	20181121_014_37_00_hz_584Q_CV_25	583.27	275.09	1427.80	25.93%	19.64	6706.10	1687.70	29.10	68.75	65%
Mixture	20181121_014_37_00_hz_584Q_CV_25_1	586.01	272.33	1434.30	26.32%	19.35	6859.30	1661.50	28.23	68.75	64%
Mixture	20181121_014_37_00_hz_584Q_CV_25_2	582.94	275.41	1429.30	26.02%	19.64	6729.40	1694.30	28.61	68.75	65%
Mixture	20181121_015_37_00_hz_584Q_CV_20	585.12	260.72	1341.30	20.68%	19.81	5877.70	818.97	28.56	64.04	66%
Mixture	20181121_016_37_00_hz_584Q_CV_20	583.83	261.08	1343.00	20.79%	19.82	5838.60	890.22	28.34	64.04	66%
Mixture	20181121_019_37_00_hz_584Q_CV_20	584.17	261.04	1338.80	20.53%	19.88	5834.10	812.88	27.96	63.98	66%
Mixture	20181121_020_37_00_hz_584Q_CV_20	584.73	260.69	1339.70	20.59%	19.84	5851.30	813.21	28.06	64.04	66%

Table H.14: Real experimental data of Dorsilit 9 at 584 m3/h part 3

Settings			Measured Data								
Type	File Name	flowrate real [m3/h]	Pump Pressure [kpa]	Density temp [kg/m3]	CV temp %	Head temp [m of slurry]	DP Up [pa]	DP Down [pa]	Temperature C	Power [kW]	eta [%]
Average Water combined 584 m3/h Average Water combined 574 m3/h Average Water combined 557 m3/h		584.32	219.69	1006.3	0.38%	22.25	2473.93	-2349.50	28.13	50.16	71%
		574.26	225.98	1011.3	0.69%	22.78	2564.63	-2342.13	25.93	49.63	73%
		558.96	230.20	1010.6	0.64%	23.22	2404.42	-2197.28	27.35	49.33	72%
21-11-2018											
Mixture	20181121_027_37_00_hz_560Q_CV_40	558.07	305.89	1644.40	39.05%	18.96	8933.00	3710.10	28.60	77.34	61%
Mixture	20181121_028_37_00_hz_560Q_CV_40	558.38	306.27	1648.90	39.33%	18.93	8970.60	3760.60	29.26	77.34	61%
Mixture	20181121_031_37_00_hz_560Q_CV_40_2	555.77	307.93	1676.00	40.97%	18.73	9297.10	3965.40	34.45	78.02	61%
Mixture	20181121_032_37_00_hz_560Q_CV_40_2	554.53	307.96	1676.40	40.99%	18.73	9306.40	3964.10	34.63	78.02	61%
22-11-2018											
Mixture	20181122_009_37_00_hz_560Q_CV_35	559.95	307.06	1604.50	36.64%	19.51	8546.60	3312.70	29.61	75.02	64%
Mixture	20181122_010_37_00_hz_560Q_CV_35	562.68	305.16	1605.70	36.71%	19.37	8577.40	3306.70	30.40	75.02	64%
Mixture	20181122_010_37_00_hz_560Q_CV_35_1	559.91	305.93	1605.10	36.67%	19.43	8556.10	3316.90	30.58	75.02	63%
Mixture	20181122_013_37_00_hz_560Q_CV_35	558.47	304.99	1604.90	36.66%	19.37	8552.10	3316.00	30.82	75.02	63%
Mixture	20181122_014_37_00_hz_560Q_CV_35	559.91	304.59	1605.10	36.67%	19.34	8556.10	3316.70	31.22	75.02	63%
Mixture	20181122_017_37_00_hz_560Q_CV_40	559.22	307.96	1654.50	39.67%	18.97	9099.00	3741.90	31.80	78.12	61%
Mixture	20181122_018_37_00_hz_560Q_CV_40	559.85	308.21	1656.00	39.76%	18.97	9111.50	3758.70	31.97	78.12	61%
30-11-2018											
Mixture	20181130_009_37_00_hz_584Q_CV_20	584.71	261.97	1333.40	20.21%	20.03	5877.50	664.67	26.84	63.94	67%
Mixture	20181130_010_37_00_hz_584Q_CV_20	582.19	263.21	1333.40	20.21%	20.12	5860.00	680.56	27.13	63.94	67%
Mixture	20181130_010_37_00_hz_584Q_CV_20_1	582.24	262.56	1333.10	20.19%	20.08	5878.30	657.79	27.47	63.94	66%
Mixture	20181130_010_37_00_hz_584Q_CV_20_2	583.87	262.52	1333.80	20.23%	20.06	5885.20	663.98	27.59	63.94	67%
Mixture	20181130_026_37_00_hz_584Q_CV_30	584.29	283.21	1515.90	31.27%	19.04	7707.60	2415.10	30.99	72.28	64%
03-12-2018											
Mixture	20181203_011_37_00_hz_584Q_CV_25	584.74	272.69	1406.90	24.66%	19.76	6693.70	1289.90	26.79	67.80	65%
Mixture	20181203_012_37_00_hz_584Q_CV_25	585.07	272.58	1404.50	24.52%	19.78	6642.50	1294.60	26.82	67.80	65%
Mixture	20181203_021_37_00_hz_584Q_CV_25	583.38	267.83	1408.70	24.77%	19.38	6759.40	1259.70	26.63	67.55	64%
Mixture	20181203_022_37_00_hz_584Q_CV_25	585.80	267.96	1407.70	24.71%	19.40	6770.20	1228.70	26.85	67.55	65%
Mixture	20181203_029_37_00_hz_584Q_CV_15	583.22	251.47	1243.80	14.78%	20.61	5030.90	-248.41	25.54	60.03	68%
Mixture	20181203_030_37_00_hz_584Q_CV_15	583.85	250.91	1244.20	14.80%	20.56	5038.40	-247.82	25.75	60.03	68%
Mixture	20181203_030_37_00_hz_584Q_CV_15_1	582.74	251.62	1243.30	14.75%	20.63	5016.50	-242.48	25.64	60.03	68%
Mixture	20181203_039_37_00_hz_584Q_CV_10	584.04	239.69	1153.30	9.29%	21.19	4127.70	-1119.50	25.46	56.46	69%
Mixture	20181203_040_37_00_hz_584Q_CV_10	583.90	239.66	1152.60	9.25%	21.20	4111.10	-1117.30	25.51	56.46	69%
Mixture	20181203_041_37_00_hz_584Q_CV_10	582.89	239.54	1152.90	9.27%	21.18	4119.70	-1119.40	25.67	56.46	69%
04-12-2018											
Mixture	20181204_007_37_00_hz_560Q_CV_35	561.54	306.27	1547.70	33.19%	20.17	7833.90	2911.20	32.31	72.45	66%
Mixture	20181204_008_37_00_hz_560Q_CV_35	559.07	306.11	1548.80	33.26%	20.15	7837.10	2930.30	32.54	72.45	66%
Mixture	20181204_017_37_00_hz_560Q_CV_35	561.88	302.90	1558.70	33.86%	19.81	8102.20	2859.10	34.32	72.19	65%
Mixture	20181204_018_37_00_hz_560Q_CV_35	560.43	303.31	1557.90	33.81%	19.85	8068.80	2876.40	34.15	72.19	65%
Mixture	20181204_019_37_00_hz_584Q_CV_25	585.51	270.33	1397.80	24.11%	19.71	6514.40	1289.60	32.18	66.26	66%
Mixture	20181204_020_37_00_hz_584Q_CV_25	583.29	270.66	1399.50	24.21%	19.71	6577.70	1260.10	31.78	66.26	66%

Table H.1.5: Real experimental data of Dorsilit 7 at 250 & 333 m³/h part 1

Settings				Measured Data							
Type	File Name	flowrate real [m3/h]	Pump Pressure [kpa]	Density temp [kg/m3]	CV temp %	Head temp [m of slurry]	DP Up [pa]	DP Down [pa]	Temperature C	Power [kW]	eta [%]
	Average Water 250 m3/h	250.96	341.23	1021.42	1.30%	34.06	724.87	-304.74	29.46	31.95	74%
	Average Water 333 m3/h	334.06	317.43	1026.20	1.59%	31.53	1160.55	-646.29	31.33	37.64	78%
20-12-2018											
Mixture	20181220_011_37_00_hz_333Q_CV_30	332.41	344.67	1485.90	29.45%	23.645	5919.20	3614.20	28.97	52.50	61%
Mixture	20181220_012_37_00_hz_333Q_CV_30	332.32	344.85	1485.50	29.42%	23.664	5916.30	3609.30	28.88	52.50	61%
Mixture	20181220_017_37_00_hz_333Q_CV_20	332.99	335.47	1335.00	20.30%	25.616	4329.50	2243.20	25.91	46.41	67%
Mixture	20181220_018_37_00_hz_333Q_CV_20	333.39	335.37	1335.30	20.32%	25.602	4339.60	2239.40	25.88	46.41	67%
Mixture	20181220_023_37_00_hz_333Q_CV_10	332.73	324.30	1178.60	10.82%	28.049	2710.40	793.05	24.78	41.89	72%
Mixture	20181220_024_37_00_hz_333Q_CV_10	333.02	324.27	1179.00	10.85%	28.037	2719.80	792.59	24.73	41.89	72%
Water	20181221_005_37_00_hz_250Q_CV_00	250.14	341.88	1024.40	1.48%	34.020	739.93	-261.86	32.98	31.90	74%
Water	20181221_006_37_00_hz_250Q_CV_00	250.32	341.89	1024.60	1.49%	34.014	748.11	-265.26	32.86	31.90	75%
23-01-2019											
Mixture	20190123_015_37_00_hz_250Q_CV_10	249.43	350.11	1192.20	11.65%	29.935	2463.20	1307.60	30.29	35.71	68%
Mixture	20190123_016_37_00_hz_250Q_CV_10	250.39	350.17	1192.70	11.68%	29.928	2466.70	1313.20	30.05	35.71	68%
Mixture	20190123_019_37_00_hz_250Q_CV_10	249.55	350.72	1193.50	11.73%	29.955	2470.70	1326.60	28.42	35.48	69%
Mixture	20190123_020_37_00_hz_250Q_CV_10	250.03	350.74	1194.90	11.81%	29.922	2496.50	1327.30	28.22	35.48	69%
Mixture	20190123_029_37_00_hz_250Q_CV_15	250.83	356.32	1278.20	16.86%	28.417	3351.10	2107.70	27.43	38.29	65%
Mixture	20190123_030_37_00_hz_250Q_CV_15	251.44	356.20	1279.10	16.92%	28.387	3368.60	2106.50	27.29	38.29	65%
Mixture	20190123_033_37_00_hz_250Q_CV_15	254.74	355.92	1277.30	16.81%	28.405	3361.20	2079.30	26.05	38.56	65%

Table H.16: Real experimental data of Dorsililt 7 at 417 m3/h part 1

Settings			Measured Data								
Type	File Name	flowrate real [m3/h]	Pump Pressure [kpa]	Density temp [kg/m3]	CV temp %	Head temp [m of slurry]	DP Up [pa]	DP Down [pa]	Temperature C	Power [kW]	eta [%]
14-12-2018											
	Average Water combined	417.46	288.32	1018.81	1.14%	28.848	1544.51	-1175.34	29.65	42.45	79%
Mixture	20181214_013_37_00_hz_417Q_CV_25	416.06	307.23	1426.90	25.87%	21.948	5885.20	2490.70	28.69	56.46	63%
Mixture	20181214_014_37_00_hz_417Q_CV_25	416.17	307.37	1426.80	25.87%	21.960	5871.70	2501.40	28.69	56.46	63%
Mixture	20181220_009_37_00_hz_417Q_CV_30	420.70	309.68	1496.50	30.09%	21.094	6619.20	3122.00	29.50	58.76	62%
Mixture	20181220_009_37_00_hz_417Q_CV_30_2	418.41	311.72	1496.90	30.12%	21.228	6628.30	3120.60	28.44	58.89	62%
Mixture	20181220_010_37_00_hz_417Q_CV_30	418.48	310.03	1498.60	30.22%	21.089	6656.30	3126.40	29.44	58.76	61%
Mixture	20181220_010_37_00_hz_417Q_CV_30_2	418.54	311.80	1496.60	30.10%	21.237	6629.50	3113.20	28.32	58.89	62%
Mixture	20181220_015_37_00_hz_417Q_CV_20	417.01	305.45	1344.80	20.90%	23.153	4976.00	1789.30	25.97	52.59	67%
Mixture	20181220_015_37_00_hz_417Q_CV_20_2	418.45	305.02	1343.50	20.82%	23.143	4947.40	1791.10	25.78	52.78	67%
Mixture	20181220_016_37_00_hz_417Q_CV_20	415.99	305.86	1345.00	20.91%	23.181	4954.90	1813.80	25.95	52.59	67%
Mixture	20181220_016_37_00_hz_417Q_CV_20_2	416.36	305.65	1343.60	20.82%	23.189	4938.00	1804.00	25.74	52.78	67%
Mixture	20181220_021_37_00_hz_417Q_CV_10	417.18	295.09	1179.70	10.89%	25.498	3196.40	328.51	24.96	47.44	72%
Mixture	20181220_022_37_00_hz_417Q_CV_10	416.58	295.14	1180.30	10.93%	25.490	3225.60	311.89	24.91	47.44	72%
23-01-2019											
Mixture	20190123_009_37_00_hz_417Q_CV_10	415.68	297.27	1199.20	12.07%	25.269	3369.00	539.67	32.55	48.64	71%
Mixture	20190123_010_37_00_hz_417Q_CV_10	417.15	296.87	1200.20	12.13%	25.214	3390.70	536.29	31.99	48.64	71%
Mixture	20190123_013_37_00_hz_417Q_CV_10	417.48	296.70	1201.20	12.19%	25.179	3404.20	544.26	30.90	48.88	70%
Mixture	20190123_014_37_00_hz_417Q_CV_10	416.97	296.77	1201.60	12.22%	25.176	3409.50	545.51	30.66	48.88	70%
Mixture	20190123_017_37_00_hz_417Q_CV_10	417.91	297.37	1201.50	12.21%	25.229	3412.50	540.18	29.09	48.76	71%
Mixture	20190123_018_37_00_hz_417Q_CV_10	416.63	297.51	1201.70	12.22%	25.237	3417.00	539.75	28.92	48.76	71%
Mixture	20190123_023_37_00_hz_417Q_CV_15	415.99	303.43	1293.10	17.76%	23.920	4405.40	1344.40	27.62	51.58	68%
Mixture	20190123_024_37_00_hz_417Q_CV_15	415.98	303.54	1293.10	17.76%	23.928	4405.90	1344.10	27.51	51.58	68%
Mixture	20190123_027_37_00_hz_417Q_CV_15	414.61	304.64	1292.70	17.74%	24.023	4391.70	1350.60	27.32	51.42	68%
Mixture	20190123_028_37_00_hz_417Q_CV_15	416.69	303.73	1293.10	17.76%	23.943	4420.90	1329.20	27.27	51.42	68%
Mixture	20190123_031_37_00_hz_417Q_CV_15	417.47	304.00	1293.00	17.76%	23.967	4426.60	1321.10	26.58	51.89	68%
Mixture	20190123_032_37_00_hz_417Q_CV_15	417.34	304.14	1292.90	17.75%	23.979	4425.70	1321.90	26.48	51.89	68%

Table H.1.7: Real experimental data of Dorsilit 7 at 500+ m3/h part 1

Settings			Measured Data								
Type	File Name	flowrate real [m3/h]	Pump Pressure [kpa]	Density temp [kg/m3]	CV temp %	Head temp [m of slurry]	DP Up [pa]	DP Down [pa]	Temperature C	Power [kW]	eta [%]
Average Water combined	584 m3/h	584.69	219.15	1000.52	0.03%	22.33	2508.11	-2497.78	30.09	50.47	71%
	560 m3/h	560.73	230.79	1007.68	0.47%	23.35	2520.65	-2369.98	24.59	49.54	73%
	545 m3/h	544.63	237.60	1011.08	0.67%	23.95	2407.78	-2189.88	24.42	49.27	73%
	500 m3/h	500.88	254.54	1016.10	0.98%	25.54	2017.50	-1702.05	32.37	47.05	75%
14-12-2018											
Mixture	20181214_011_37_00_hz_505Q_CV_25	504.73	263.51	1420.10	25.46%	18.92	6475.50	1767.50	28.29	62.39	59%
Mixture	20181214_012_37_00_hz_505Q_CV_25	506.47	263.45	1420.20	25.47%	18.91	6475.60	1769.60	28.55	62.39	59%
Mixture	20181214_015_37_00_hz_505Q_CV_25	507.06	266.51	1419.10	25.40%	19.14	6463.90	1758.60	28.78	62.26	60%
Mixture	20181214_016_37_00_hz_505Q_CV_25	507.26	266.11	1419.70	25.44%	19.11	6468.00	1767.40	28.83	62.26	60%
Mixture	20181220_007_37_00_hz_500Q_CV_30	497.33	271.29	1485.70	29.44%	18.61	7032.30	2497.20	30.48	64.89	58%
Mixture	20181220_008_37_00_hz_500Q_CV_30	498.19	271.08	1486.20	29.47%	18.59	7043.60	2495.70	30.13	64.89	58%
Mixture	20181220_013_37_00_hz_500Q_CV_20	500.36	267.60	1339.70	20.59%	20.36	5463.30	1200.70	26.26	58.02	64%
Mixture	20181220_014_37_00_hz_500Q_CV_20	499.88	267.68	1339.70	20.59%	20.37	5464.10	1200.10	26.10	58.02	64%
Mixture	20181220_019_37_00_hz_500Q_CV_10	500.01	261.64	1179.70	10.89%	22.61	3769.50	-243.09	25.14	52.34	69%
Mixture	20181220_020_37_00_hz_500Q_CV_10	500.78	261.86	1179.50	10.88%	22.63	3762.60	-241.14	25.04	52.34	70%
23-01-2019											
Mixture	20190123_007_37_00_hz_560Q_CV_10	562.73	232.32	1194.90	11.81%	19.82	4421.80	-597.21	32.77	56.13	65%
Mixture	20190123_008_37_00_hz_560Q_CV_10	563.72	232.11	1194.90	11.81%	19.80	4422.00	-598.60	32.58	56.13	65%
Mixture	20190123_011_37_00_hz_560Q_CV_10	565.37	232.17	1195.90	11.87%	19.79	4446.20	-603.18	31.62	56.24	65%
Mixture	20190123_011_37_00_hz_560Q_CV_10_2	560.47	234.93	1196.40	11.90%	20.02	4405.30	-552.21	31.53	56.24	65%
Mixture	20190123_012_37_00_hz_560Q_CV_10	561.60	234.90	1197.00	11.94%	20.00	4406.50	-541.45	31.45	56.24	65%
Mixture	20190123_021_37_00_hz_545Q_CV_15	543.93	244.45	1288.10	17.46%	19.35	5326.00	325.88	27.82	59.08	63%
Mixture	20190123_022_37_00_hz_545Q_CV_15	545.78	244.39	1287.50	17.42%	19.35	5308.20	332.48	27.73	59.08	63%
Mixture	20190123_025_37_00_hz_545Q_CV_15	544.75	244.28	1286.80	17.38%	19.35	5295.40	332.24	27.36	59.08	63%
Mixture	20190123_026_37_00_hz_545Q_CV_15	545.19	244.24	1286.80	17.38%	19.35	5299.50	327.22	27.32	59.08	63%

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Slurry loop photos

In this appendix, several pictures of the test set up are shown. Some to give an impression of the slurry loop (figures I.1, I.2, I.3 and I.4). Others to visualise the degree of damage the mixtures have caused. The gate valves are heavily damaged by excessive wear, see figure I.5 and I.6. Furthermore are the welds of the transition piece worn out, which results in leakage in front of the pump. In figure I.9 and I.10 are before and after pictures shown of this damage.



Figure I.1: Back view of the centrifugal pump with discharge pipe



Figure I.2: Side view of the centrifugal pump with electro drive



Figure I.3: Overview of the test set up with storage tank and U loop sections



Figure I.4: Top view of the horizontal part of the slurry loop

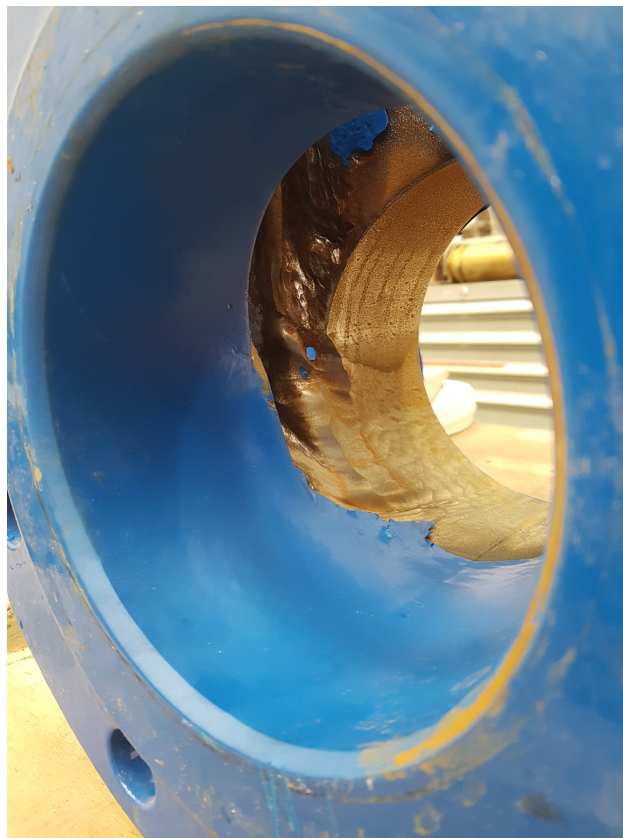


Figure I.5: Gate valve with worn out inner house



Figure I.6: Gate valve with worn out rubber slide piece



Figure I.7: Worn out descending bend with reinforcements before the weld



Figure I.8: Worn out descending bend with reinforcements after the weld



Figure I.9: Worn out weld located on the transition pipe between the storage tank and the suction pipe



Figure I.10: Repair weld located on the transition pipe between the storage tank and the suction pipe

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