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SLURRY FLOWS IN METALLURGICAL PROCESS ENGINEERING - DEVELOPMENT OF TOOLS AND GUIDELINES

Master's thesis for the degree of Master of Science in Technology submitted for inspection, Espoo, 04.04.2014.

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Abstract

Slurry flows are very important for metallurgical process engineering. They are one of the principal methods for material transport in minerals processing plants and thus their accurate engineering is of paramount importance.

This work explains the physical properties of slurries and discusses the differences between settling and non-settling slurries, with main focus being given to settling slurries. The work focuses on transportation of slurries in pipes using centrifugal pumps in short to medium distance that are common inside minerals processing plants. The object is to discuss the subject from a practical perspective, aiming to help process and design engineers who are tasked with designing slurry systems.

A spreadsheet calculation tool was developed. The tool can be used for sizing of pipes and pumps handling settling slurries. The tool calculates critical deposition velocities that need to be achieved in pipe transport to prevent particle settling and pipe blockages. The tool also calculates extra pressure losses caused by the solid particles. The results of the calculation tool are integrated in to a pump data sheet that can be used for the inquiry of pumps. Additionally, a set of design guidelines was developed based on investigated material and personnel interviews. These guidelines give the reader an introduction to slurry transport design and help indentify points that need to be taken into account when designing slurry systems. Both the calculation tool and design guidelines were then applied into a practical case example.

It was found that the existing calculation methods for critical deposition velocity and pressure losses are adequate, but limited in accuracy. Most significant problem with designing slurry systems is not actually the limitations of the available calculation methods, but rather the very limited information available of the material that is being handled. To further improve the accuracy of design, data collection methods from real cases need to be improved.

Keywords Slurry, settling, non-settling, minerals processing, metallurgical, pump, excel, spreadsheet, design

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Abstract of master's thesis

Tekijä Ville Roitto

Työn nimi Lietevirrat metallurgisessa prosessisuunnittelussa – Suunnittelutyökalujen ja –ohjeiden kehitys

Laitos Biotekniikan ja kemian tekniikan laitos

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Tiivistelmä

Lietevirrat ovat hyvin tärkeitä metallurgisessa prosessisuunnittelussa. Lietevirrat ovat usein rikastuslaitoksen päävirtoja, joiden avulla siirretään suuria massoja ja siten niiden tarkka suunnittelu on hyvin tärkeää.

Tässä työssä esitellään lietteiden ominaisuuksia ja käsitellään eroja laskeutuvien ja laskeutumattomien lietteiden välillä. Päähuomio annetaan laskeutuville lietteille. Työ on rajattu lietteiden kuljetukseen rikastuslaitoksille tyypillisissä lyhyehköissä putkistoissa käyttäen keskipakopumppuja. Työn tavoite on käsitellä aihetta käytännönläheisestä näkökulmasta siten, että se helpottaa lietejärjestelmiä suunnittelevien insinöörien työtä.

Työn tuloksena laadittiin taulukkolaskentaohjelmassa toimiva mitoitusohjelma, jota voidaan käyttää lietteitä käsittelevien lietteiden ja pumppujen käsittelemiseen. Työkalu laskee putkistojen kriittisiä virtausnopeuksia, jotka on putkivirtauksessa ylitettävä, jotta vältetään putkistojen tukkeutumiselta laskeutuvien partikkeleiden vuoksi. Työkalu laskee lisäksi lietteiden kiintoaineen aiheuttamia ylimääräisiä dynaamisia painehäviöitä. Laskennan tulokset esitetään automaattisesti pumpun tietolehdellä, jota voidaan käyttää pumppujen hankinnassa. Lisäksi laadittiin kokoelma suunnitteluohjeita, jotka pohjautuvat henkilöstöhaastatteluihin ja tutkittuun kirjallisuusmateriaaliin. Suunnitteluohjeet antavat lukijalle johdannon lietevirtojen suunnitteluun ja auttavat tunnistamaan asioita, jotka on erityisesti otettava huomioon suunnittelussa. Työkalun ja suunnitteluohjeiden toimintaa esitellään käytännönläheisellä esimerkillä.

Työn tuloksena selvisi, että käytettävissä olevat menetelmät kriittisten virtausnopeuksien ja painehäviöiden laskentaan ovat riittäviä, joskin melko epätarkkoja. Suurin ongelma lietejärjestelmien suunnittelussa ei ole niinkään käytettävissä olevien laskentamenetelmien epätarkkuus, vaan käytettävissä olevan tiedon määrä pumpattavasta materiaalista. Jotta suunnittelun tarkkuutta voidaan edelleen kehittää, on tiedonkeräysmenetelmiä todellisista projekteista parannettava.

Avainsanat Liete, laskeutuva, laskeutumaton, mineraalien jalostus, metallurginen, pumppu, excel, laskentaohjema, suunnittelu

FOREWORD

This master's thesis was carried out at the Department of Plant Engineering of Outotec (Finland) Oy during October 2013 – April 2014.

Firstly, I wish to thank my advisors, Merja Hakaste-Härmä and Hanne Ahlfors for all the help and guidance they gave me. Their advice was both invaluable and made my work very easy and pleasant. I would also like to extend my thanks to my supervisor, Professor Jukka Koskinen from the research group of Plant design in the department of Biotechnology and Chemical Technology at the Aalto University School of Chemical Technology.

I would also like to thank the whole department and all my co-workers at Outotec for all the conversations, laughs, coffee and lunch breaks, morning quizzes and also help and guidance that made the whole six months extremely pleasant. Rarely have I experienced such a welcoming and warm atmosphere.

Ville Roitto
Espoo, 4th of April, 2014

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ABBREVIATIONS

A = Area (m^2)

C_D^* = Particle drag coefficient (-)

C_p = Specific heat (J/K)

C_V = Concentration by weight in percent (%)

C_w = Concentration by weight in percent (%)

d_{50} / d_{85}= Particle size at which 50 / 85 % of the solids are finer (µm)

D_i = Inner diameter of the pipe (m)

D_{pi} = Pump impeller diameter (mm)

E_R = Efficiency reduction ratio for centrifugal pumps (-)

f = Fanning friction factor (-)

$f_{L,}$ f_T, f_{TR} = Fanning friction factors in laminar, turbulent and transitional flow (-)

F = Force (N)

F_L = Durand factor (-)

F'_L = Modified Durand factor for Wasp's method (-)

g = Gravitational acceleration (m/s^2)

He = Hedström number (-)

h_f = Head loss of the pipe due to friction (m)

H_M = Mixture (slurry) head (m)

H_R = Head ratio (-)

H_W = Water head (m)

I = Hydraulic gradient (head m water / m pipe)

I_f = Hydraulic gradient for carrier fluid (head m water / m pipe)

I_m = Hydraulic gradient for mixture, or slurry (head m water / m pipe)

I_w = Hydraulic gradient for water (head m water / m pipe)

K = Power law consistency factor (-)

k = Thermal conductivity ($W\ m^{-1}\ K^{-1}$)

K_H = Head reduction factor. K_H = 1- H_R (-)

L = Pipe length. (m)

M = Exponent in stratification-ratio equation (-)

n = Power law behaviour index (-)

n_s = Power index in hindered settling velocity calculation (-)

P_{st} = Start-up pressure resulting from the yield stress. (Pa)

Re_B = Bingham plastic Reynolds number (-)

Re_{mod} = Modified Reynolds number for power law slurries. (-)

$Re_{mod,c}$ = Critical modified Reynolds number for power law slurries (-)

$R^*_{particle}$ = Particle Reynolds number (-)

S_f = Specific gravity of the carrier fluid (-)

S_m = Specific gravity of the mixture (-)

S_s = Specific gravity of solid particles (-)

S_w = Specific gravity of water (-)

t = Time (s)

V = Velocity (m/s)

V_3, V_L, V_C, V_D = Flow velocity at the limit of solids deposition (m/s)

V_{50} = Flow speed in which 50% of solids are suspended by fluid (m/s)

η = Coefficient of rigidity, or non-Newtonian viscosity, or plastic viscosity (Pa·s)

ρ_l = Density of the carrier liquid (kg/m^3)

ρ_l = Density of water (kg/m^3)

ρ_m = Density of the mixture, or slurry (kg/m^3)

ρ_s = Density of the solid particles (kg/m^3)

τ = Shear stress (Pa)

τ_w = Shear stress at the wall of a measurement (Pa)

τ_0 = The yield stress of a Bingham plastic. (Pa)

$V_{incl.}$ = Required additional flow velocity in inclined flow (m/s)

υ_T = Terminal particle settling velocity (m/s)

υ'_T = Hindered settling velocity (m/s)

υ_r = Ratio of the actual viscosity of the carrier liquid to that of water at 20 °C

μ = Viscosity (Pa·s)

ϕ^*_1 = Parameter in particle drag coefficient calculation (-)

Δ_D = Inclination parameter for inclined slurry pipes (-)

1. INTRODUCTION

For ages past, ever since the time of the ancient Romans and Egyptians, slurries have been a part of human life. The river Nile is practically a massive slurry flow that once a year deposits life-giving silt on the riverbanks, creating a narrow strip of rich farmland in the middle of an arid desert. The Romans used slurry flows to their advantage in mining operations in a process known as hushing, where torrential waters are used to move massive amounts of soil to revel mineral veins. In fact, for mineral processing plants, especially ones employing hydrometallurgical processes, the most significant fluid flow mechanic present is the transportation of slurries. After the steps of crushing and comminution, slurry transport becomes the principal method of transferring material from one process step to the next. Combined with the rule of thumb that pumping uses up to 10 % of all the energy in the world and 25 % in a plant (Hurme, 2008), it becomes evident that proper design of slurry systems is vital for not only the proper functionality but also the financial viability of minerals processing plants.

As fate would dictate, slurry systems engineering is far from easy and straightforward. The varying nature of slurries and their significantly different characteristics make it very difficult to create simple and generalized design guidelines and tools for them. It is often the case that the most detailed and well developed methods are not always the best from a practical point of view. It must be kept in mind that much of the actual engineering work that goes into building a minerals processing plant is done with very limited information. Design of minerals processing plants is done based on results obtained from a limited amount of test drills and hence, incomprehensive information. Quality of the ore being excavated varies with time. This is why there is a need for development of guidelines and best practises that can be followed in the absence of better and more detailed information. The shortfall of what could be called very ”scientific” methods is that while they can and do provide more exact and precise results, that precision does not always produce additional value to a process engineer. In addition, often due to lack of time and resources, all the necessary information is not always available to apply them. While slurry systems have been studied quite extensively since the 1950's, they continue to impose challenges from an engineering point of view. This work attempts to alleviate some of those problems by providing both theoretical and practical insight into the world of slurry systems engineering.

1.1. Description of the target company

Outotec Oyj is a Finnish company headquartered in Espoo, which provides technologies and services for the metal and mineral processing industries. The company also provides solutions for industrial water treatment, the utilization of alternative energy sources and the chemical industry. Outotec has a broad selection of technologies, covering the entire process chain from minerals to metals. Outotec aims to develop technologies which utilize natural resources and raw materials efficiently, reduce energy and water consumption, produce less waste and emissions as well as minimize the plant’s lifetime operating costs. Several of Outotec’s technologies are rated as Best Available Techniques (BAT) by EU thanks to their energy-efficiency and low emissions. An overview of Outotec’s technologies can be seen in figure 1.

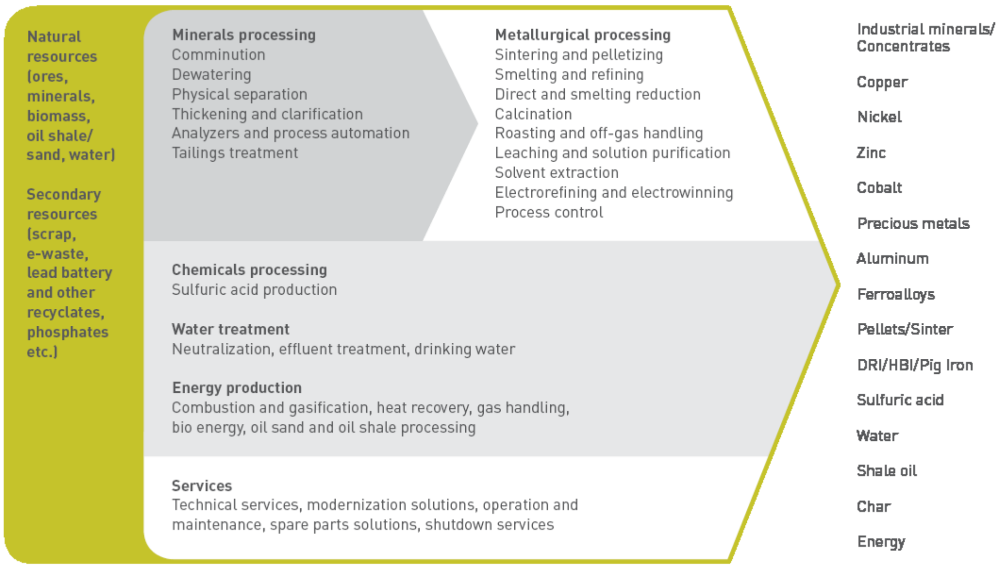

Figure 1. Overview of Outotec's technologies

Outotec was previously a technology division of a Finnish stainless steel producer, Outokumpu, but was sectioned off as a separate company in June 2006 and listed on the Helsinki Stock Exchange shortly afterwards. In February 2007 Outotec was promoted to the benchmark OMX Helsinki 25 index.

As a global company, Outotec operates in six continents and 27 countries. Outotec's operations are clustered into three main regions: the Americas, EMEA (Europe, the Middle East and Africa), and APAC (Asia Pacific). Outotec's business is divided into two business areas, Minerals Processing and Metals, Energy & Water. Outotec's business model is illustrated in figure 2.

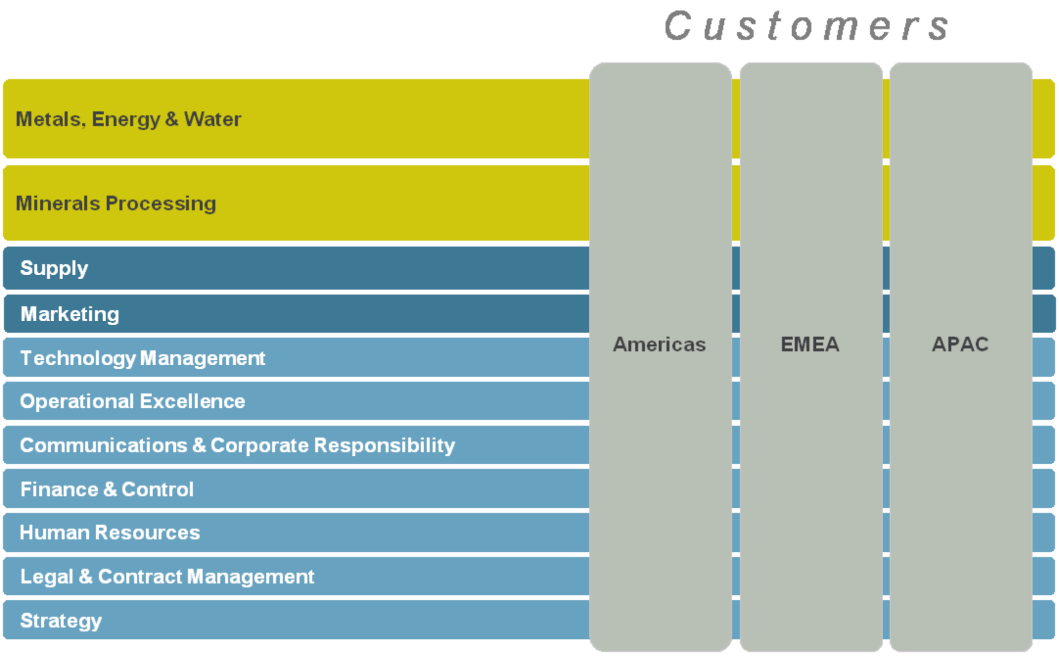

Figure 2. Outotec's business model

This thesis is done for the department of Plant engineering in Outotec's Minerals Processing business line (see figure 2). The department of Plant engineering in Outotec (Finland) Oy (affiliated company of Outotec Oyj) takes care of general process engineering, layout, piping and civil engineering in solution delivery projects. The main task for general process engineering is to be responsible for the "non-metallurgical" part of the process engineering which is needed for each project. Typically this includes, for example, the design of P&I-diagrams, sizing pipelines and calculation of pumps (Hakaste-Härmä, 2013).

1.2. Scope and aims of the work

This thesis will focus on the transportation of solids in a flowing liquid medium within a minerals processing plant. The framework of this thesis is very firmly in the world of process design and piping engineering. Equipments such as grinding mills, thickeners, flotation cells and filters will not be looked into. Reference to them will be made where necessary, but each of them could warrant a work of their own. Centrifugal pumps and pipelines encountered within minerals processing plants are the main focus of this thesis and main attention is given to the practical applications related to the topic. Aim is to give an explanation of the basic principles that affect the design of slurry systems. In the practical part, a calculation tool is developed for the sizing of slurry pipelines and pumps for settling slurries. In addition, a selection of guidelines and best practises are presented concerning topics that are found significant for the design of slurry transportation systems in the target company. Finally, a water treatment unit is developed as an example case of practical application of the topics of the thesis.

Experienced engineers gather vast amounts of engineering know-how during their careers, large amounts of which are not documented anywhere. In most cases this knowledge is transferred to new generations of engineers slowly and orally, or not at all. Documentation of this information in the form of guidelines helps newcomers to adopt the special features of this specific field. In addition, documented guidelines make the use of subcontractors easier; making sure that design is done according to company preferences. Interviews of experienced design engineers are conducted within the target company to identify subjects of interest.

2. PHYSICAL PROPERTIES OF SLURRIES

2.1. Introduction

Slurry is a mixture of solid particles in a carrier liquid. While the solid particles and the carrier liquid can be anything, in practice and in particular in this thesis, the carrier liquid is water unless otherwise stated. When slurries are used to transport material suspended in water, a slurry flow can also be called hydraulic transport, or conveying.

The most important characteristics of slurries are defined by their rheology. Rheology explains the flow of matter, in particular the flow of liquids. It also applies to substances with complex microstructures such as mud, sludge and suspensions, and hence slurries. Understanding the rheology of slurries is essential for proper design and engineering of slurry systems. Slurry rheology is a dynamic property of the microstructure of the slurry and is affected by various attributes such as the shape, size, density and mass fraction of the suspended solid particles and the density and viscosity of the carrier liquid.

This chapter gives an introduction to the characteristics of slurry flows and explains the major physical properties of slurries, as these are important to the efficient design and engineering of slurry systems.

2.2. Viscosity in Newtonian fluids

One of the most important rheological attributes of a liquid is its viscosity. Simplified, viscosity is the quantity that describes a fluid's resistance to flow, as friction forces between particles of the fluid try to prevent particles from moving past each other. Viscosity is defined with an idealized situation known as a Couette flow where a fluid is trapped between a horizontal stationary plate and a horizontal plate moving across the surface of the liquid at a constant speed V_0. The top layer of the liquid will move parallel to the moving plate at the same speed as the moving plate ($V = V_0$). Each differential layer of the liquid will move slower than the layer above it due to frictional forces resisting their relative motion. The fluid will exert a force on the moving top plate opposite to the direction of its motion and therefore an external force is required to keep the top plate moving. (Munson *et al.*, 2002) The Couette flow is illustrated in figure 3.

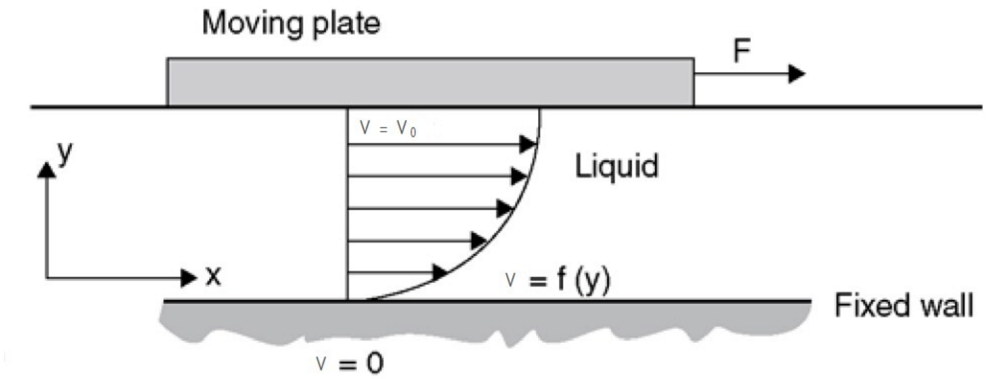

Figure 3. Couette flow for defining viscosity (Anon, 2010).

The external frictional force F is found to be proportional to the speed V_0 and the area A of the plates, and inversely proportional to their separation$y$. This is shown in equation (1).

$$F = \mu A \frac{\partial V}{\partial y} \quad (1)$$

Where:

μ = Dynamic viscosity of the fluid

F = External force

A = Area

V_0 = Speed of the plate

y = Separation of the plates on the y-axis.

A fluid where the viscosity is independent of stress is called a Newtonian fluid after Isaac Newton who expressed the viscous forces by the following differential equation (2).

$$\tau = \mu \frac{\partial V}{\partial y} \tag{2}$$

Where:

τ = Ratio between the force and the ratio, the shear stress.

$\frac{\partial V}{\partial y}$ = Local shear velocity or rate gradient.

The SI unit for viscosity is Pa·s but viscosity is often expressed in centipoises, cP (1 cP = 0,001 Pa·s). For Newtonian fluids the shear stress is directly proportionate to the velocity gradient, or the shearing rate. Additionally, shear stress is zero if the velocity gradient is zero.

2.3. Viscosity in non-Newtonian fluids

For non-Newtonian fluids viscosity is not independent of the shear rate. Viscosity can also be dependent of time. The most common types of non-Newtonian fluids are pseudoplastic (shear thinning), dilatant (shear thickening) and Bingham plastic fluids. For some fluids viscosity is time-dependent. Thixotropic fluids get thinner when agitated or otherwise stressed over time. In contrast, rheopectic fluids get more viscous with time. Time-dependent fluids are, however, less common in slurries but some pastes show thixotropic behaviour. The different viscosity regimes (excluding time-dependent) are presented in figure 4.

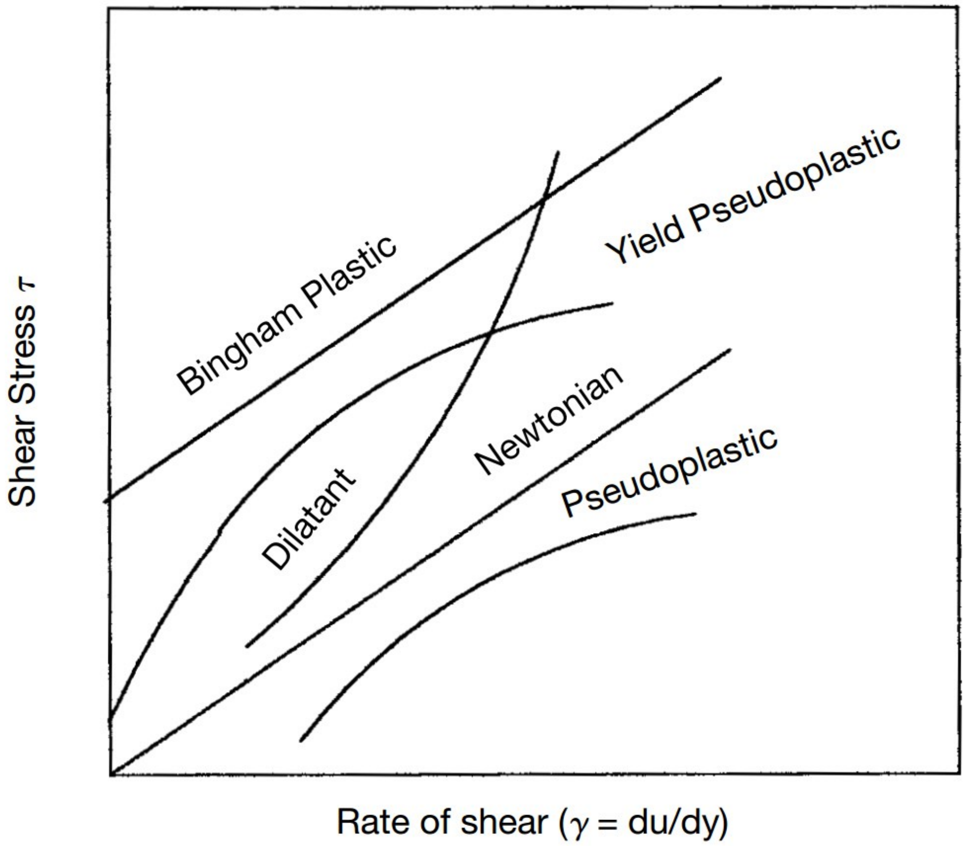

Figure 4. Viscosity regimes (Abulnaga, 2002)

2.3.1. Bingham plastics

Bingham plastics are essentially Newtonian fluids with a yield stress τ_0 (Pa) that needs to be overcome to initiate motion. After the yield stress is overcome, they behave as Newtonian fluids in that their viscosity is constant. However, in the case of non-Newtonian fluids, viscosity is referred to as η (cP) and is called the coefficient of rigidity, or non-Newtonian viscosity, or plastic viscosity. The viscosity curve for Bingham plastics can be characterised with equation (3).

$$\tau_w - \tau_0 = \eta d\gamma/dt \tag{3}$$

Where:

τ_w = Shear stress at the wall of a measurement device (Pa)

dy/dt = Shear rate characteristic to the measurement device (-)

The yield stress can vary from as low as 0.01 Pa for sewage sludge to as high as 1000 MPa for asphalts and bitumen. The coefficient of rigidity, or plastic viscosity, can also be vary drastically, from the viscosity of water to 100 Pa·s of some paints and much higher for asphalts and bitumen. Examples of Bingham plastic slurries are given in table 1 (Abulnaga, 2002).

Table 1. Examples of Bingham plastic slurries (Abulnaga, 2002)

Slurry	Particle size, d_{50} [μm]	Density [kg/m3]	Yield stress [Pa]	Coefficient of rigidity, η [mPa·s]
Fine coal 49% Cw	50% under 40μm		1	5
Coal tails 31% C_w	50% under 70μm		2	60
Copper concentrate 48 % C_w	50% under 35μm		19	18
21.4 % Bauxite	<200μm	1163	8.5	4.1
Gold tails 31 % C_w	50% under 50μm		5	78
18 % Iron oxide	<50μm	1170	0.78	4.5
7.5 % Kaolin clay	Colloidal	1103	7.5	5
Kaolin 32 % C_w	50% under 0.8μm		20	5
58 % Limestone	<160μm	1530	2.5	15
Phosphate tails 37 % C_w	85% under 10μm		28.5	14
14 % Sewage sludge		1060	3.1	24.5
Red mud 39 % C_w	5% under 150μm		23	30
Zinc concentrate 75 % C_w	50% under 20μm		12	31
Uranium tails 58 % C_w	50% under 38μm		4	15

2.3.2. Pseudoplastics

In shear thinning, or pseudoplastic, liquids viscosity is lowered as shear rate increases. They also have an infinitesimal shear stress which is sufficient to initiate motion. Pseudoplastic flow is encountered in slurries where fine particles form loose aggregates. Behaviour of pseudoplastics is difficult to predict accurately, but various empirical equations have been developed. The equations involve at least two empirical factors, one of which is an exponent. Thus, pseudoplastic slurries are often called power-law slurries. The shear stress in pseudoplastic slurries is a function of shear rate according to the following equation (4) (Abulnaga, 2002).

$$\tau_w = K[(d\gamma/dt)^n] \qquad (4)$$

Where
K = Power law consistency factor (Pa·s^n)
n = Power law behaviour index (-)
dy/dt = Shear rate characteristic to the measurement device (-)

n is < 1 for pseudoplastic slurries. The empirical factors can be determined in laboratory testing using a rheogram. For Bingham plastics the coefficient of rigidity is a linear function of the shear rate above the yield stress but in the case of pseudoplastics it is expressed by the following exponential equation (5). (Abulnaga, 2002)

$$\eta = K(d\gamma/dt)^{n-1} \qquad (5)$$

Examples of pseudoplastic slurries and their coefficients are shown in table 2.

Table 2. Examples of pseudoplastic power-law slurries (Heywood, 1996).

Slurry	Particle size, d_{50} [μm]	Range of weight conc. [%]	Range of consistency coefficient K [Ns^n/m^2]	Power law behaviour index, n
Cellulose acetate		1.5 - 7.4	1.4 - 34.0	0.38 - 0.43
Drilling mud, barite	14.7	1.0 - 40.0	0.8 - 1.3	0.43 - 0.62
Sand in drilling mud	180.0	1.0 - 15% sand using drilling mud, with 18% barite	0.72 - 1.21	0.48 - 0.57
Graphite	16.1	0.5 - 5.0	Unknown	Probably 1
Graphite and magnesium hydroxide	5.0	32.2 (4.1 graphite and 28.1 magnesium hydroxide)	5.22	0.16
Flocculated kaolin	0.75	8.9 - 36.3	0.3 - 39.0	0.117 - 0.285
Deflocculated kaolin	0.75	31.3 - 63.7	0.011 - 0.6	0.82 - 1.56
Magnesium hydroxide	5.0	8.4 - 45.3	0.5 - 68.0	0.12 - 0.16
Pulverized fuel ash	38.0	63 - 71.8	3.3 - 9.3	0.44 - 0.46
Pulverized fuel ash	20.0	70.0 - 74.4	2.12 - 0.57	0.48 - 0.57

There is also another class of pseudoplastic slurries, known as yield pseudoplastic slurries. They are effectively very similar to pseudoplastics, except that a yield stress must be overcome at zero shear rate for motion to occur. Thus, they are a combination of Bingham plastics and pseudoplastics. Their shear stress can be determined with a slightly modified pseudoplastic equation that takes in account the yield stress. Yield pseudoplastic behaviour can be seen in some organic sewage sludges and kaolin slurries. (Abulnaga, 2002)

An important characteristic related to yield stress of flocculated slurries is their thinning behaviour under shear. A distinction has to be made between true pseudoplastic fluids, commonly known as shear-thinning, and fluids that are thinned under shear stress but do not recover to higher viscosity after the shear is removed. This is common in, for example, gravity thickeners, where a chemical flocculant is added to promote settling of solid particles by the formation of larger flocs. The formation of flocs also increases the yield stress of the settled fluid, often so much that pumping is no longer possible. Pumping with centrifugal pumps is regarded as very difficult above yield stresses over 150 Pa. (Myllymäki,

2013) As a result, thickeners are often equipped with shear thinning pumps that circulate the flocculated slurry to break down the flocs and lower the yield stress to levels that are acceptable for pumping with centrifugal pumps.

2.3.3. Dilatancy

Dilatant slurries are the opposites of pseudoplastic slurries. In dilatant slurries an increasing shear rate causes the rate of increase of shear stress to rise. That is, dilatants slurries get 'thicker' as shear rates increase. Dilatancy is also referred to as shear thickening. Same equations can be used to describe both dilatants and pseudoplastic slurries, with the exception that the power law behaviour index n is > 1 for dilatants slurries. Dilatant slurries are much rarer than pseudoplastic slurries. (Abulnaga, 2002)

2.4. Density

Density of a slurry is affected by the density of the carrier liquid, density of the solid particles and the concentration of the solid particles. The concentration of the solid particles is often given in percent by weight, as it is more convenient when calculating pipeline throughput tonnages. However, slurry properties in pipeline flow are more related to the volume of solids. Density of slurry using solid percent by weight is defined by the following equation (6) (Wasp, 1977).

$$\rho_m = \frac{100}{\frac{C_W}{\rho_s} + \frac{100 - C_W}{\rho_l}} \tag{6}$$

where

C_w = concentration by weight in percent

ρ_m = density of the mixture, or slurry (kg/m^3)

ρ_l = density of the carrier liquid (kg/m^3)

ρ_s = density of the solid particles. (kg/m^3)

The concentration of solids by volume, C_V, is expressed in percents by the following equation (7) (Wasp, 1977).

$$C_V = \frac{C_w \rho_m}{\rho_s} = \frac{100\,\dfrac{C_w}{\rho_s}}{\dfrac{C_w}{\rho_s} + \dfrac{100 - C_w}{\rho_l}} \tag{7}$$

The concentration of solids by weight, C_W, in percent is conversely expressed by the following equation (8) (Wasp, 1977).

$$C_W = \frac{C_v \rho_s}{\rho_m} = \frac{C_v/\rho_s}{C_v \rho_s + (100 - C_v)} \tag{8}$$

Slurry density can be measured directly in either laboratory testing or using online measurements. However, when measuring settling slurries, care must be taken to ensure that larger particles do not settle out of the sample prior to measurement. In the case of online measuring, flow rates need to be sufficiently high to ensure proper suspension of particles. It is sometimes perhaps better to measure the particle and fluid densities to define the density of the slurry of a given concentration. Conversely, slurry density can be used as a measure of concentration. (Abulnaga, 2002)

2.5. Specific heat

Thomas (1960) developed the following equation (9) to determine slurry heat capacities from the specific heats of the pure solid and liquid components according to concentration by weight.

$$Cp_m = \frac{Cp_s\, Cw_s + Cp_l\, Cw_l}{100} \tag{9}$$

Where:

C_p = Specific heat (J/K)

C_w = Concentration by weight in percent

m, l, s = Subscripts for mixture (slurry), liquid and solids, respectively.

2.6. Thermal conductivity

Similarly as with density measurements, settling inflicts problems to measurements of thermal conductivity. Orr and Dalla Valle (1954) added small quantities of agar to suspensions to solve this issue and derived the following equation (10) to calculate thermal conductivities based on the thermal conductivities of the carrier liquid and solid particles and the volumetric concentration of the solids.

$$k_m = k_l \left[\frac{2k_l + k_s - 2C_v(k_l - k_s)}{2k_l + k_s + C_v(k_l - k_s)} \right] \tag{10}$$

Where:

k = Thermal conductivity (W m^{-1} K^{-1})

C_V = Concentration by volume in percent

m, l, s = Subscripts for mixture (slurry), liquid and solids, respectively.

Despite being derived from slurries stabilized with agar, the equation also applies well to non-gelified slurries in practice. However, heat transfer issues are not very prominent in mineral processing industries and are mostly confined to the nuclear industries, processing of tar sands, feeding slurry to autoclaves and certain emulsion based slurries. (Abulnaga, 2002)

2.7. Flow regimes

When designing slurry systems perhaps the most important attribute that needs to be determined is the settling behaviour of the slurry. Slurries are, in practice, divided into two types based on how the particles settle in the carrier liquid under flowing conditions. All solid particles will settle in any carrier liquid given enough time. All gravity separation methods are based on this fact. In practical applications, however, it is paramount to known how the solid particles behave when the objective is to transport the solid particles using hydraulic conveying, i.e. slurry pumping. Residence times have to also be kept in mind. For example, the residence time of a slurry flowing at 1 m/s in a 100 km pipeline is about 30 hours. This is enough time for particles with a settling velocity of 0.001 mm/s to double in concentration in the lower half of a 200 mm pipe, even though such slurry would be classified as non-settling. (Brown & Heywood, 1991).

In heterogeneous or settling slurries the particles are not properly suspended in the carrier liquid and instead are merely transported along with the liquid. However, at high velocities they may become suspended by turbulence. With heterogeneous slurries care must be taken to ensure that the velocities in pipelines are above the critical settling velocity of the particles to prevent plugging of pipelines. Heterogeneous slurries are typically water based with a large percentage of solids being greater than 100 μm in size. Low content of fines (solids smaller than 40 μm) means that the carrier fluid (water and the fine particles) is essentially similar to water. Homogeneous or non-settling slurries are slurries where the solid particles are suspended in the carrier liquid and they form one continuous phase. Homogeneous slurries form attributes that may differ significantly from those of water or other simple Newtonian liquids. The fine particles increase the viscosity of the fluid (Abulnaga, 2002).

Whether a slurry is settling or non-settling is determined by the particle size and specific gravity of the solid particles. A crude determination between settling and non-settling behaviour can be made using a chart presented in Figure 5 (Bootle, 2002). This is a very rough method and should be treated as such. It only takes into account the average particle size and the specific gravity of the solid particles, while slurry concentration has also an effect on the settling behaviour of solids. For example, high concentrations of fine particles increase the viscosity of the fluid. Higher viscosities help the suspension of larger particles and while figure 5 might quantify a certain slurry or particle as settling, it could very well in practise behave as a non-settling slurry. Vice versa, slurry with a low d_{50} can contain a significant portion of larger particles that could cause problems during low velocity pipe transport. The aim of figure 5 is, thus, merely to serve as a reminder of the domain in which a process engineer should take into account the possibility of solids settling in the slurry. The two different flow regimes and settling in pipelines will be discussed in more detail in the next two chapters.

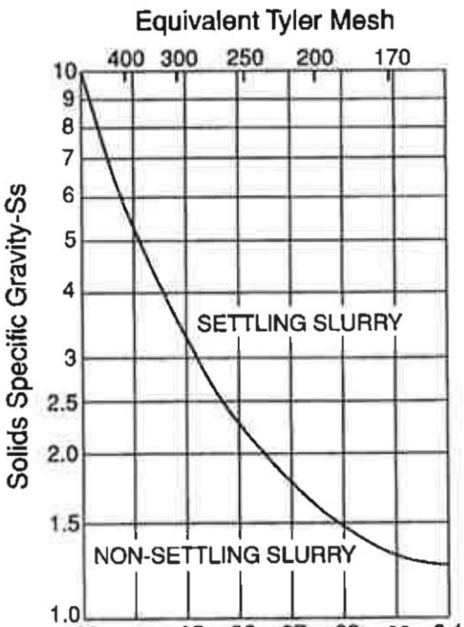

Figure 5. Determining if slurry is settling or non-settling (Bootle, 2002)

2.8. Laboratory testing methods for slurries

Laboratory measurements are commonly used in slurry system engineering to predict pipeline friction losses and yield stresses. However, the amount of measurements that can be made in small scale in a laboratory is usually limited to the specific gravity of the slurry, particle size distribution, viscosity and yield stress. Viscosity and yield stress can only be measured for slurries which are clearly non-settling. Measurement of viscosity for a settling slurry is very difficult, as the solids settle out of the liquid, making accurate measurements practically impossible. Additionally, settling particles do not contribute to the viscosity of the carrier fluid. If the particle size distribution is very wide and the slurry contains significant amount of fines along with coarse particles, viscosity of the carrier liquid and the slowly setting fines (i.e. the supernatant fluid after larger particles have settled out of it) can be measured to provide some indication of the behaviour of the settling slurry. However, for accurate empirical testing of pipeline head losses and pumpability data to be achieved for settling slurries, larger scale pilot-plant flow loop studies have to be employed.

For non-settling slurries, measurement of viscosity and yield stress is common and required. Practically no pipeline design can be made without knowing the viscosity and yield stress of the slurry. Heywood (1991a) points out that despite much work that has been devoted to understanding why slurries have certain rheological properties, it is impossible to predict, with any reasonable degree of accuracy, the rheological properties of a given slurry no matter how well the slurry's physical and chemical properties may have been specified.

Yield stress can be measured using standard viscometers. Pumping with centrifugal pumps becomes difficult above yield stress of 150 Pa (Myllymäki, 2013). The pumpability with centrifugal pumps can also be estimated using a so-called Warman slump ring test. The slump ring test is essentially a metal plate with a set of concentric rings inscribed on the surface. The central ring is 50 mm in diameter and the other rings increase in diameter by 20 mm each. A thin pipe with a 50 mm internal diameter and 50 mm height is placed on the central circle and filled with the slurry. The pipe is then gently lifted off and the slurry is allowed to spread (or slump) onto the metal plate. If the slurry does not spread out to at least the third ring, the slurry is deemed too thick and a centrifugal pump will normally not be able to pump it. (Anon, 2002). The Warman slump ring test is presented in figure 6.

Figure 6. Warman slump ring test

Another similar test is the ASTM C143 Standard Test Method for Slump of Hydraulic-Cement Concrete, which can also be applied to test behaviour and yield stress of non-settling slurries and pastes. The ASTM slump test procedure is presented in figure 7.

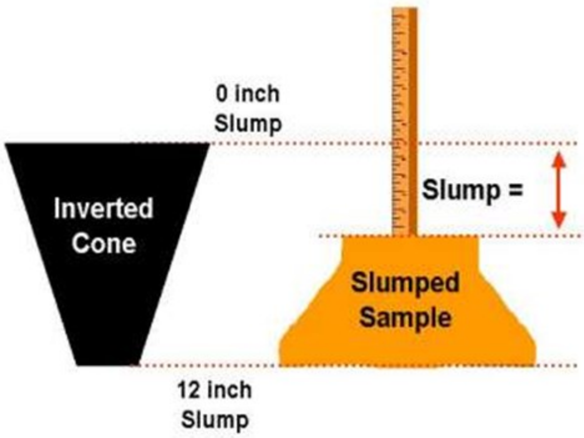

Figure 7. ASTM C143 Standard slump test method

3. FLOW OF SETTLING SLURRIES

For heterogeneous slurries where the solid particles are not properly suspended in the carrying liquid, accurate determination of the settling velocity is perhaps the first and most important step in designing a pipeline, as the settling velocity dictates the diameter of the pipe for a given required flow.

Heterogeneous flows usually consist of fairly large particles transported via a water flow which leads to high friction losses and abrasion. It would, then, seem logical to use large diameter pipes to minimize the friction and allow for lower pump speed, head output and lower wear and horsepower draw. However, due to the settling nature of heterogeneous flows, too low flow speeds will lead to sedimentation of the solid particles. (Abulnaga, 2002)

3.1. Flow regimes for heterogeneous slurry flows

The regimes of flow for Newtonian, heterogeneous settling slurry flows are generally divided in to four flow regimes. The nomenclature for the regimes changes from author to author, but in this chapter, nomenclature used by Abulnaga (2002) will be followed. The four regimes are:

- Flow with stationary bed.
- Flow with a moving bed and saltation (with or without suspension).
- Heterogeneous mixture with all solids in suspension.
- Pseudo-homogeneous or homogeneous mixtures with all solids in suspension

The four different flow regimes are illustrated in figure 8 and figure 9. In figure 8 the regimes are shown with particle size vs. mean flow velocity. In figure 9 the regimes are shown in terms of flow velocity vs. volumetric concentration.

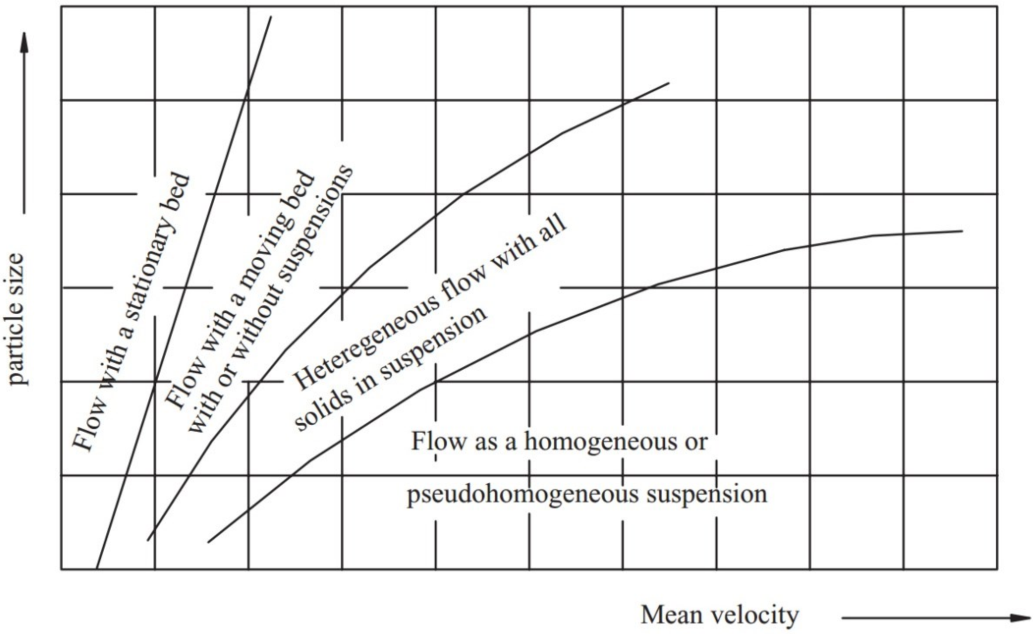

Figure 8. Flow regimes for heterogeneous flow with particle size vs. flow velocity (Abulnaga, 2002)

Figure 8 shows that with increasing mean flow velocity, the flow regime changes from a completely stationary bed to a moving bed. With further increasing flow speeds, the particles become suspended in the carrier liquid. Also, the particle size of the solid particles has an effect on the flow regimes. Larger particles require higher flow speeds to achieve suspension or moving bed. For smaller particle sizes and high mean flow velocities, it is possible to achieve flow that has pseudo-homogeneous or even homogeneous suspension behaviour.

Figure 9 shows the same situation in the terms of velocity vs. volumetric concentration with more accurate flow regimes for low flow speeds. Higher volumetric concentrations at low flow speeds will lead to deposits and even blocking of the pipe. In practice, partial blockage of the pipe will lead to increased flow speeds through the reduced diameter.

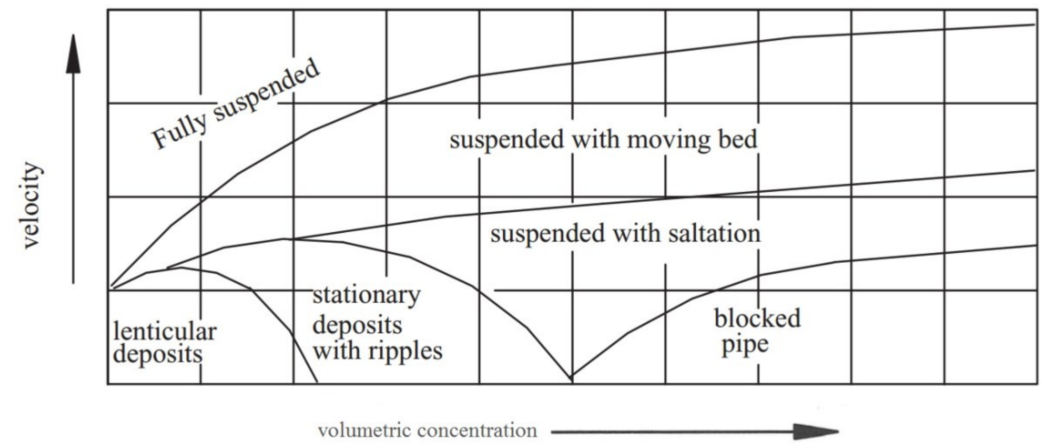

Figure 9. Flow regimes for heterogeneous flow with flow velocity vs. volumetric concentration. (Abulnaga, 2002)

An illustrative sketch of the way particle concentrations vary on the y-axis of a horizontal pipe depending on the volumetric concentration and flow velocity is presented in figure 10.

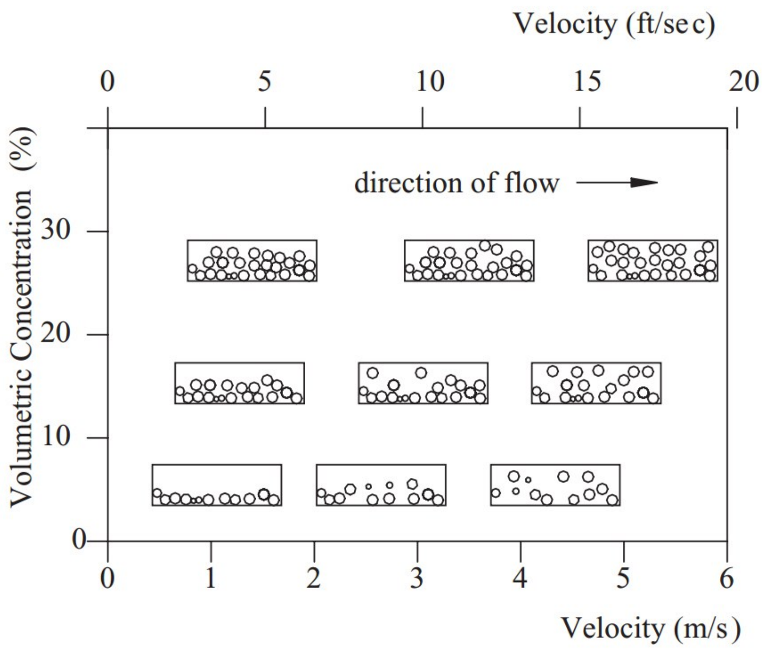

Figure 10. Simplified sketch of particle distribution as a function of volumetric concentration and flow velocity (Abulnaga, 2002).

Selection of an appropriate flow speed is an optimization issue. Higher flow speed prevents settling and sedimentation of solid particles but also increases pumping costs and leads to higher wear in both the pipeline and pump. Higher flow speed also requires faster impeller speeds, which can be very detrimental to pump service life. Larger pipes allow lower pipeline friction losses and wear, but lead to flow speeds that are insufficient to achieve acceptable moving speeds for the solid particles.

3.1.1. Flow with a stationary bed

When the flow speed is low, a bed forms at the bottom of the pipe. Larger particles settle at the bottom with finer particles layering on top of them. The smallest of particles may continue to move, suspended by the flow. If the flow speed is sufficiently low, the pipe will eventually be blocked.

Some flow with saltation and asymmetric suspension does occur above the speed of blockage, as particles are entrained by the flow. Largest particles may creep, roll or tumble on the bottom but in practise the bed in mostly stationary. The larger particles are only moved by inter-granular-contact. In some special cases it might even be beneficial to allow a bed to form on the bottom of the pipe as it reduced the effective cross-sectional area of the pipe. In most engineering specifications, however, it is essential to make sure that flow speeds in slurry pipelines are high enough to prevent stationary beds from forming. (Abulnaga, 2002)

3.1.2. Flow with a moving bed

A moving bed is similar to a stationary bed in that the larger particles settle on the bottom of the pipe. However, with a moving bed the flow speeds are high enough to ensure that the material keeps moving in the pipe. Particles move in the pipe much like sand dunes move in deserts. If the particle size distribution is large, vertical layers of different particle sizes form in a horizontal pipe, with larger particles (or in general particles with faster settling speeds) moving along the bottom of the pipe. Additionally, particles on the upper layers move faster than particles on the lower layers. Particles sliding along the bottom of the pipe cause additional pressure losses and wear on the pipe. (Abulnaga, 2002)

3.1.3. Heterogeneous flows with turbulence suspension

As the flow speeds increase further, turbulence becomes sufficient to move even the largest particles without forming a bed. Particles are being moved by both inter-granular contact and fluid support mechanisms. The flow is still asymmetric, meaning that on average a vertical particle size gradient is present in the pipe. Additionally, particles may and do strike the bottom of the pipe, bouncing back. This leads to increased wear on the bottom of the pipe compared to other parts of the pipe. Pipes need to be designed with this in mind. A practical solution is to rotate the pipes during maintenance to ensure even wear on the pipe. Furthermore, flow speeds in the pipe remain heterogeneous in that finer particles travel somewhat faster. (Abulnaga, 2002)

3.1.4. Suspended homogeneous or pseudo-homogeneous flow

At high velocities, practically all solids may move in a symmetric flow pattern and slurries behave as homogeneous or pseudo-homogeneous flows. In this type of flow, particles are carried by the fluid rather than inter-granular contacts. (Wilson *et al.* 2006) In pseudo-homogeneous flows some degree of particle size segregation is permitted, but otherwise the flow is very close to properly suspended homogeneous flow. Power consumption is linearly proportionate to the static head multiplied by the velocity, but is proportional to the cube of velocity needed to overcome friction losses. Thus, power consumption in pseudo-homogeneous flows speeds for mixtures of coarse and fine particles may be excessive for long pipelines. (Abulnaga, 2002)

3.2. Transitional velocities

The four different flow regimes can also be presented as a graph where pressure drop per meter of pipe is plotted against mean flow velocity. The pressure drop behaviour of the each flow regime varies significantly. The graph is presented in figure 11.

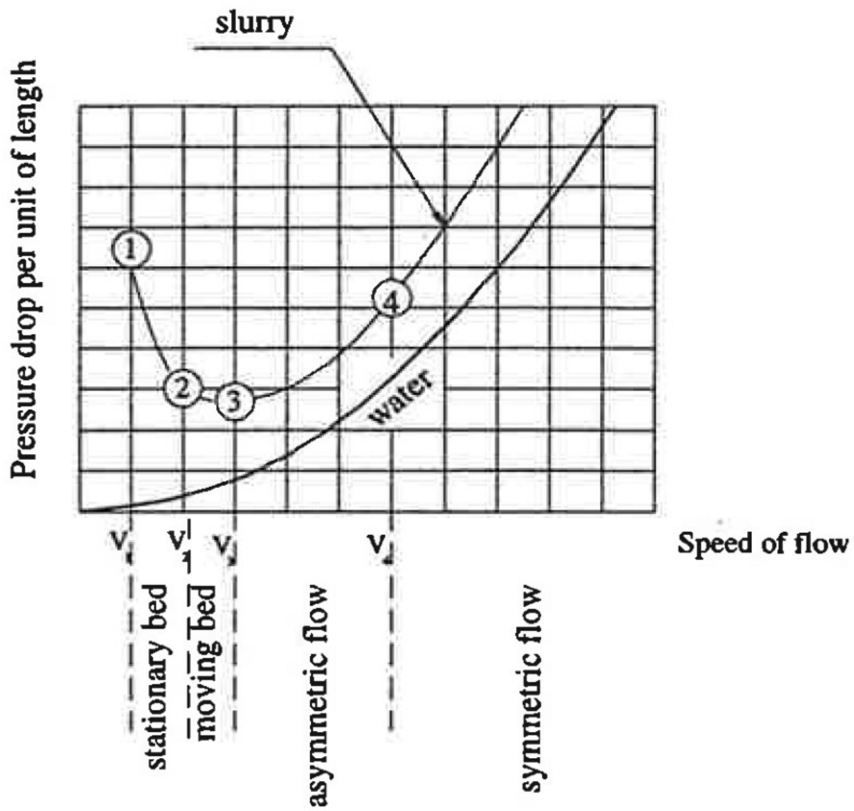

Figure 11. Pressure drop vs. speed of flow for different flow regimes of heterogeneous settling slurries. (Abulnaga, 2002)

The numbers marked on figure 11 represent transitional velocities, which are flow velocities in which one flow regime transforms to the next. As the graph clearly illustrates, lowest pressure drops are achieved at transitional velocity V_3, often also called the limiting velocity V_L, the critical velocity V_C or the deposition velocity V_D. A historical term one may also encounter is the Durand velocity. V_3 is the velocity in which flow speeds are sufficiently high to prevent a moving bed from forming on the bottom of the pipe. At high flow velocities, even settling slurries start developing homogeneous characteristics as turbulence suspends particles. At homogeneous or pseudo-homogeneous flow regimes the pressure drop gradient is very similar to that of water, albeit naturally higher due to the increased density and viscosity of the slurry imposed by the suspended solid particles. (Abulnaga, 2002)

The shape of the curve is very typical for slurries. Below the critical deposition velocity at point 3, solid particles start to increasingly slide along the bottom of the pipe as a moving bed forms. This increases the pressure loss, as shown by the rising curve. As the flow speed drops further, a stationary bed forms and eventually the pipe becomes blocked, stopping flow. This also explains the somewhat illogical situation that may be encountered in piping design, where dynamic pressure losses are actually higher for low flow speeds than higher ones. This may seem unintuitive to an engineer who is used to dealing with clean liquid flows.

From an engineering point of view the flow speed region above V_3 is a very attractive as bed forming from settling particles is not an immediate issue and the pressure drop gradient is at minimum. V_3 becomes perhaps the first variable to be determined when a slurry pipeline is being designed. (Abulnaga, 2002)

Transitional velocities V_1 and V_2 have little practical usage in slurry system engineering and are mostly of interest in lab testing, design of instrumentation and monitoring of start ups. They should not, however be used as a design guideline and as such are not presented in more detail here. (Abulnaga, 2002)

3.2.1. Calculation of critical deposition velocities

The first equation for determining the V_3 (or V_D or V_C) transitional velocity was proposed by Durand and Condolios (1952), which is presented in the following equation (11):

$$V_C = V_3 = F_L\sqrt{2gD_i[(\rho_S - \rho_L)/\rho_L]} \tag{11}$$

Where:
F_L = Durand factor based on solid particle grain size and volume concentration (-)
D_i = Inner diameter of the pipe (m)
g = Gravitational acceleration (m/s^2)
ρ_S = Density of the solids (kg/m^3)
ρ_L = Density of the carrier liquid (kg/m^3)

The Durand factor is presented usually in a graph for single of narrow graded particles. The original graph, based on the work of Durand (1953), is commonly considered to be too conservative for most slurries which are mixtures of particles of different sizes. However, it is still in use and is used by for example Weir, a pump supplier specializing in slurry pumps (Anon, 2009). The Durand's limiting settling velocity parameter diagram for narrow graded particles is presented in appendix A. Weir regard narrow particle size distribution as one where the ratio of particles sizes, expressed as testing screen apertures, does not exceed approximately 2:1 for at least 90 % by weight of the total solids.

As an experimental factor, several other correlations have been proposed, each attempting to improve on the pioneering work of Durand. Reviews of various correlations can be found from literature, for example by Carleton and Cheng (1974) and Turing *et al.* (1987). A modified Durand's limiting settling velocity parameter diagram used by Weir (Anon, 2009) suitable for a more widely graded particle sizes is presented in Appendix B.

Schiller and Herbich (1991) proposed the following equation (12) for the calculation of the Durand factor:

$$F_L = \{(1.3 \cdot C_v^{0.125})[1 - exp(-6.9 \cdot d_{50})]\} \tag{12}$$

Where:
C_V = Concentration by volume in percent
d_{50} = Particle size at which 50 % of the solids are finer (mm).

Wasp and Aude (1970) developed a modified equation, usually known as Wasp's equation, based on the equation by Durand and Condolios (equation 11). They included a ratio between the solid particle diameter and the inner diameter of the pipe. The equation also includes a modified Durand factor, F_L'. Wasp's equation is presented in equation (13).

$$V_C = V_3 = F_L'\sqrt{2gD_i[(\rho_S - \rho_L)/\rho_L]}\left(\frac{d_{50}}{D_i}\right)^{1/6} \tag{13}$$

Where:

$$F_L' = 3.399\ C_V^{0.2156} \tag{14}$$

The results from Wasp's equation for critical deposition velocity are generally lower than those produced by the original Durand formula.

Wilson et al. (2006) use a similar term, the velocity at the limit of stationary deposition, based on Wilson's earlier work in the 1970's. This is a flow speed below which a stationary bed forms in the pipe. They parallel this with Durand's critical deposition velocity. However, this comparison is not entirely accurate. In Durand's model the critical deposition velocity represents a flow speed below which a moving bed forms. As discussed earlier, there is a difference between a moving bed and a stationary bed.

Wilson et al. (2006) found that the velocity at the limit of stationary deposition is concentration dependent, having low values at low concentrations and rising to a maximum value at some intermediate concentration value and then dropping off again at higher concentrations. They used force balance analysis to develop a model for the prediction of the velocities at the limit of stationary deposition, and especially for the maximum velocity, denoted V_{SM}. The problem with the model is that it requires a lot of values that are not available for a process engineer in the basic engineering phase of a project. In addition it requires a lot values only published as graphs, making its usage very cumbersome when there is a need to size possibly hundreds of different pipelines and pumps. The authors also created a nomographic chart representation of it for simpler use, which sacrifices accuracy. The nomogram is presented in appendix C.

3.2.2. Comparison of deposition velocity calculations

Results given by Durand's formula are generally accepted to be very conservative. Especially with large pipe sizes and high volumetric flows, Durand's formula starts suggesting critical deposition velocities that are in practise impossible to achieve without excessive pressure losses and wear. This is what the Wasp's equation tries to adjust with the added ratio. Furthermore, Wilson's V_{SM} values are also always lower than those of Durand's. However, as Warman International ltd. (nowadays part of Weir Minerals) point out in their slurry pumping manual (Anon, 2002), it is possible that Wilson and Durand simply used different criteria for their velocities, making direct comparison difficult.

Durand's method has been used extensively over the years and it is inherently safer than Wilson's method. Obviously the advantage of Wilson's method, if it is accurate, is that larger pipes are selected, leading to less pipe wear and lower dynamic pressure losses. But there simply isn't as much accumulated user experience with Wilson's method. It should be applied with caution until sufficient confidence is accumulated through practical experience.

3.3. Frictional head losses for heterogeneous slurries

For slurry consisting of fairly large settling particles, the estimation of friction losses in pipelines is very difficult. Complex calculation methods for their estimation do exist and they are well described by authors such as Jacobs (2005). They are, however, cumbersome and mostly require data and knowledge not available to a process engineer or a plant designer in the phase of the project where most piping design is conducted. Ever since slurries have been flowing in pipes, engineers and scientists have tried to estimate losses due to solid content with an equal amount of water by correlating various variables such as the volumetric concentration of solids, drag coefficients, terminal velocities of the solids and so forth. (Abulnaga, 2002)

Fortunately, pipeline friction head losses are not very significant in short pipelines usually encountered in minerals processing plants. Estimations of the head losses can be made that are sufficiently accurate for the application. In most cases, simply using the slurry specific gravity for the density of the flowing fluid will provide sufficiently higher friction losses to ensure that the head requirements are well met.

It would take a very brave and experienced (or inexperienced) engineer and a very trusting and merciful plant owner to approve building of a large scale extensive pipeline for slurry transportation based on only calculations made using a model found in a handbook without verifying them with experimentation (Anon, 2002).

3.3.1. Simplified approach for estimating solids effect

Wilson *et al*. (2006) have described a simplified method for estimating the head loss due to the solids in pipeline transport. The method can be used even with limited information available and it can be a useful tool for preliminary design of longer pipelines. A few terms need to be introduced for its usage. The hydraulic gradient, or head loss, is given as meters head of water per metre of pipe and denoted as i, subscript m (i_m) is used to denote the head loss of the mixture (slurry) and subscript f (i_f) is used to denote the head loss of an equivalent flow of the carrier liquid alone. In most cases the carrier liquid is water and i_f can be replaced with i_w, for water. The solids effect is presented as (i_m - i_f) and it represents the additional head loss caused by the solids. (i_m – i_f) is calculated using equation (15):

$$\frac{(i_m - i_f)}{(S_m - S_f)} = 0.22\left(\frac{V}{V_{50}}\right)^{-M} \tag{15}$$

Where:

S_m = The specific gravity of the mixture

S_f = The specific gravity of the carrier fluid (often 1.00, for water).

V = flow speed (m/s)

V_{50} = flow speed (m/s) in which 50% of solids are suspended by fluid.

M = A power exponent.

The power exponent M and the flow velocity in which 50 % of solids are suspended by fluid (V_{50}) can be estimated using equations (16) and (17):

$$V_{50} \approx 3.93\ d_{50}^{0.35}[(S_s - 1)/1.65]^{0.45} \upsilon_r^{-0.25} \qquad (16)$$

Where:
d_{50} = Grain size at which 50 % of the solids are finer (mm)
S_s = The specific gravity of the solid particles
υ_r = The ratio of the actual viscosity of the carrier liquid to that of water at 20 °C

$$M \approx [\ln(d_{85}/d_{50})]^{-1} \qquad (17)$$

Where:
D_{50} = Particle size at which 50 % of the solids are finer (mm)
D_{85} = Particle size at which 85 % of the solids are finer (mm)

In practise when estimating slurries, M has lower and upper limits and should not be allowed to exceed 1.7 or fall below 0.25.

(i_m-i_f) can now be calculated from equation 13. The head losses for equivalent volume flow of the carrier liquid alone, i_f, can be calculated using standard methods for dynamic head losses. It is taken to contain all pipe friction losses as well as head losses in valves and pipe fittings. When i_f is presented as head in meters of water per meter of pipe, the solids effect (i_m-i_f) can be added to it to calculate the head losses for the actual slurry flow, i_m. The slurry flow head losses are also presented as meters of water per meter of pipe and should be converted to total head loss for the whole pipe, as the value obtained for i_m is averaged for the whole pipe. If desired, it can also be converted into units of pressure.

3.4. Effect of solid particles on performance of centrifugal pumps

Solid particles have an adverse effect on the performance of centrifugal pumps. Less research has gone into the analysis of the effect of solids on pump performance than resistance to flow in pipelines, but authors such as Wilson *et al.* (2006) expect the underlying reasons to be partly the same. Only the water part of a slurry generates discharge head in the pump while the solids are not contributing anything. Therefore, there is always a head loss and extra expenditure of power when pumping solids in comparison to pumping water alone. (Anon, 2002)

Slurry pumps, like all pumps, are designed and tested using water as a reference liquid. Pump suppliers produce pump curves for their products that are used in selection of pumps, but these curves practically always only apply for water. Thus, if a plant designer determines the operating point for his slurry application and uses this operating point to select a pump from a water pump curve, the pump will be insufficient for the application. To prevent this, a coefficient generally known as a head ratio, H_R, needs to be applied to the calculated slurry head. The head ratio is always smaller than unity, as a pump is unable to generate equivalent head for slurry as for clear water. The head ratio is defined by dividing the generated head when pumping slurry by the generated head when pumping water (H_M/H_W). In practise it needs to be approximated mathematically and then used to increase the determined slurry head to a larger water head value that is suitable for pump selection. The head ratio depends on the concentration, specific gravity and particle size distribution of the solid particles as well as the pump impeller diameter. The head ratio is hence an attribute of the specific pump.

Various ways exist for the determination of the head ratio. Engin & Gur (2003) evaluated existing correlations and developed their own, improved correlation based on the results. They found the new correlation to provide a closer approximation with experimental data than all other evaluated correlations.

Instead of calculating the head ratio directly, they used the term head reduction factor, K_H, which equals 1-H_R. Their correlation is presented in equation (18).

$$K_H = 2.705 \frac{C_W}{100} (S_S - 1)^{0.64} \left(d_{50}/D_{pi}\right)^{0.313} \tag{18}$$

Where:

C_W = Concentration by weight in percent

S_S = Specific gravity of the solid particles

D_{50} = Particle size at which 50 % of the solids are finer. (mm)

D_{pi} = Pump impeller diameter (mm)

Efficiency of pumps is similarly reduced compared to clear water service. Most authors agree that efficiency is reduced by at least the same amount as the head and efficiency reduction ration, E_R, can be taken to equal H_R. Weir Minerals (Anon, 2009) further reduce E_R compared to H_R when concentration by volume of the solids increases above 20 %. The reductions for different concentrations are presented in table 3.

Table 3. Efficiency reduction factor at high concentrations

Concentration by volume (C_V)	Efficiency reduction factor
20 % < C_V <= 35 %	E_R = (H_R - 0.1653) / 0.8346
35 % < C_V <= 50 %	E_R = (H_R - 0.241) / 0.759
C_V >= 50%	E_R = (H_R - 0.3083) / 0.6918

3.5. Terminal settling velocity

Terminal settling velocity is the speed in which a singular particle settles in a stagnant liquid. Calculations of terminal settling velocities are originally based on the works of Newton (1687) and Stokes (1851). Terminal settling velocity is a function of the particle diameter and density and the viscosity and density of the fluid. Accurate calculations can only be done for single, round particles settling in Newtonian fluids at rest. Such calculations have little practical application for slurry systems engineering, but the results can be generalized to give indication of settling speeds in stagnant fluids. It is of practical significance for example for vertical flow, where flow speeds need to be faster than terminal settling velocities to ensure that particles are transported by the up-flowing liquid.

A useful calculation scheme has been presented by Karamanev (1996). In his method, terminal settling velocities can be calculated through particle drag coefficients and particle Reynolds numbers without the need for iteration. In Karamanev's method, the terminal particle settling velocity υ_T (m/s) is calculated from the particle Reynolds number $R^*_{particle}$ which is obtained from particle drag coefficient C^*_D and parameter ϕ^*_1. They are calculated using the following equations (19) - (22).

$$\phi_1^* = \frac{4}{3}\frac{(\rho_s - \rho_l)\rho_l\, g d_p^3}{\mu_l^2} \tag{19}$$

$$C_D^* = \frac{432}{\phi_1^*}\left(1 + 0.0470\phi_1^{*2/3}\right) + \frac{0.517}{1 + 154\phi_1^{*-1/3}} \tag{20}$$

$$R_{particle}^* = \left(\frac{\phi_1^*}{C_D^*}\right)^{1/2} \tag{21}$$

$$\upsilon_T = R_{particle}^*\frac{\mu_l}{d_p \rho_l} \tag{22}$$

Where:

d_p = The particle diameter (m)

ρ_l = Density of the fluid (kg/m^3)

ρ_s = Density of the particle (kg/m^3)

μ_l = Viscosity of the fluid (Pa·s)

g = Gravitational acceleration (m/s^2)

In real slurries particles settle slower due to hindrance caused by the particles hitting each other. The hindered settling velocity for larger particles can be estimated using the correlation of Richardson & Zaki (1954), presented here in equation (23). The hindered settling velocity is dependent on the volume concentration of solids.

$$v_T' = v_T(1 - C_V)^{n_s} \tag{23}$$

Where:

v_T' = Hindered settling velocity (m/s)

v_T = Terminal settling velocity (m/s)

C_V = Volumetric concentration of solids in decimal points

n_s = Power index

The power index n_s varies depending on the Reynolds number $R^*_{particle}$ of the particle and the ratio between the diameter of the particle and diameter of the container or pipe (d_p/D). Expressions for the value of n_s in different ranges of $R^*_{particle}$ are presented in table 4.

Table 4. Exponents for equation (23) (adapted from Brown, 1991).

Range of Reynolds number $R^*_{particle}$	Expression for exponent n_s
$0.002 < R^*_{particle} \leq 0.2$	$n = 4.65 + 19.5(d/D)$
$0.2 < R^*_{particle} \leq 1$	$n = (4.35 + 17.5(d/D))R^{*\,-0.03}_{particle}$
$1 < R^*_{particle} \leq 200$	$n = (4.45 + 18(d/D))R^{*\,-0.1}_{particle}$
$200 < R^*_{particle} \leq 500$	$n = 4.45 \cdot R^{*\,-0.03}_{particle}$
$500 < R^*_{particle} \leq 7000$	$n = 2.39$

In vertical flow the flow speed needs to be well above the hindered settling velocity of the solid particles for the particles to be hoisted by the up flowing liquid. In literature, factors of up to 4 to 5 are mentioned (Wilson et al. 2006). Fortunately, the hindered settling velocity is usually very small compared to flow speeds in pipes. If the pipeline has any horizontal sections and the flow speed is high enough to avoid settling in those, the flow speed is usually enough for the vertical sections as well.

3.6. Inclined flow

Inclined flows are the most problematic case for slurry flows. An incline in the pipe introduces an axial component to the forces that resist the motion of the particles. In inclined flow, the particles require more vertical forces to prevent settling, leading to higher required flow velocity.

The required increase in flow speed increases with rising inclination angles, reaching a maximum at 30 degrees inclination. The required increase in flow speed can be as high as 50 %. At larger inclination angles, the effect starts to diminish. These values were found by Wilson & Tse (1984) by experimenting with particle sizes between 1 mm and 6 mm. The required additional flow velocity can be estimated by using the following figure 12.

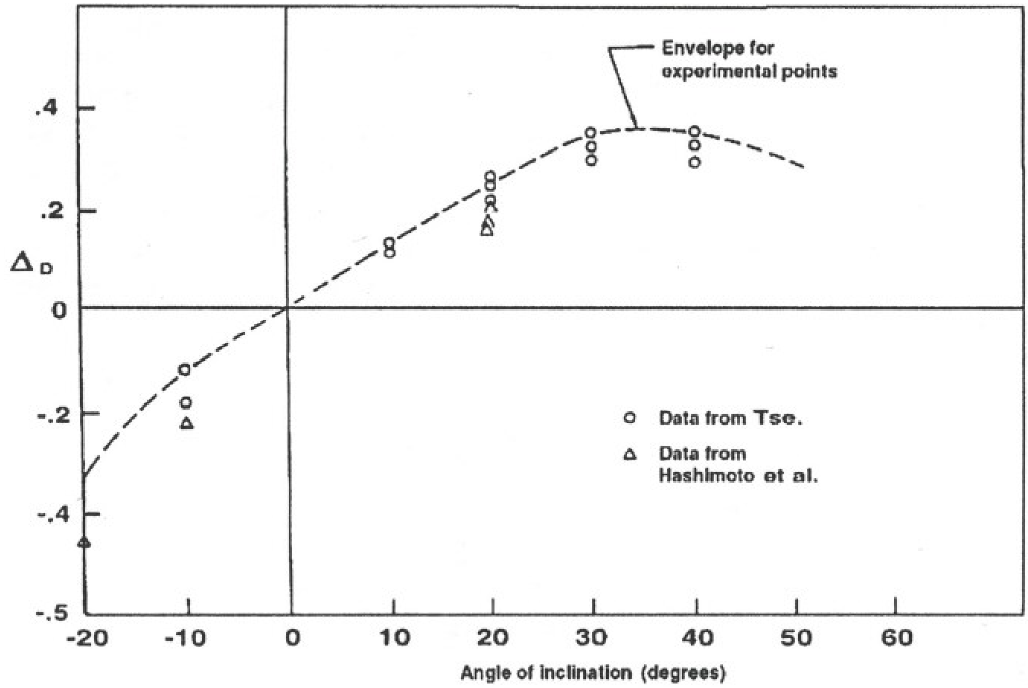

Figure 12. Effect of angle of inclination on deposition velocity (Wilson et al. 2006)

With Δ_D determined from the graph, the additional flow velocity is calculated with equation (24):

$$V_{incl.} = \Delta_D (2g(S_s - 1)D)^{1/2} \qquad (24)$$

Where:

$V_{incl.}$ = The additional velocity to be added to the critical deposition velocity of horizontal flow (m/s)

g = Acceleration of gravity (m/s^2)

S_S = Specific gravity of the solid particles

D = Internal diameter of the pipe (m)

4. FLOW OF NON-SETTLING SLURRIES

For homogeneous flows of non-settling slurries the rheology of the mixture becomes important for calculations of slurry behaviour in pipelines and pumps. For settling slurries the viscosity of the liquid phase could be approximated to be the same, or slightly higher than, as for water. However, increases in viscosities become evident for non-settling slurries. When particle sizes are sufficiently low (significantly below 100 μm, say 40 μm), particles become suspended in the carrier liquid and do not settle out of the liquid in short periods of time. For design purposes, non-settling slurries can be treated as a single viscous phase. Sufficient concentrations of small particles, called fines, can increase the viscosity of water tenfold and change the viscosity regime of the liquid. In fact, most industrial slurries do not follow Newtonian viscosity behaviour, as explained in chapter 2. Most slurries encountered in industrial application, especially in mining and minerals processing, are either Bingham plastics or pseudoplastics with some showing time dependent, usually thixotropic, behaviour. (Abulnaga, 2002)

Non-settling slurries do not require the calculation of a certain critical velocity that needs to be achieved to ensure flow in a pipeline, as settling slurries do. Difficulty of pumping non-settling homogeneous slurries arises from their viscosity and non-Newtonian behaviour. As this is not an issue specific to slurries per se, but rather all viscous and non-Newtonian fluids, only limited focus is given to non-settling slurries in this thesis, primarily on the calculation methods for friction factors.

Determination of friction factors is not quite as straightforward as for water. Several models have been developed over the years for Bingham plastics and pseudoplastics. Every few years, an author will develop a new definition for a "modified Reynolds number" and claim to have found relationships between the solid content of the liquid, the Reynolds number and the friction factor. As these are experimental definitions, a slurry system design engineer should look askance at any model claiming to work universally for all situations. Experimentation becomes vital for accurate design of systems for non-settling slurries and calculation methods should always be checked with experimental results before being applied to large scale pipeline engineering. (Abulnaga, 2002)

Fortunately, friction pressure losses are not dominant in short pipelines. Some equations can be used to determine flow regimes and friction factors using experimental values found in literature. Equations for friction losses are presented in this chapter for Bingham plastic and power law slurries for laminar, transitional and turbulent flow.

4.1. Friction losses for Bingham plastic slurries

Bingham slurries were defined in chapter 2. Their defining feature is a yield stress τ_0 that needs to be overcome to initiate motion. After initiating motion, their viscosity is constant, similarly to Newtonian fluids. However, in the case of Bingham plastics, this constant viscosity is often called the coefficient of rigidity η. The yield stress can be determined in laboratory testing or estimated from published data. Consequence of having a yield stress is that pipelines handling Bingham plastics have a start-up pressure for pumping them. The start-up pressure can be determined using equation (25). (Abulnaga, 2002)

$$P_{st} = \frac{4\tau_0 L}{D_i} \tag{25}$$

Where:

Pst = Start-up pressure resulting from the yield stress. (Pa)

τ_0 = The yield stress of a Bingham plastic. (Pa)

L = Pipe length. (m)

D_i = Inner diameter of the pipe. (m)

To calculate friction factors, required for determination of head losses in pipes due to friction, two dimensionless numbers need to be determined, the Reynolds number and the Hedström number (Hedström, 1952). For fully developed Bingham plastic fluids, the Reynolds number is in fact determined in the same way as for simple Newtonian fluids, as Bingham plastic fluids have a constant viscosity when flowing, just like Newtonian fluids. However, in the case of Bingham plastics, literature usually refers to Bingham Reynolds number Re_B, since the calculation uses the coefficient of rigidity η rather than dynamic viscosity μ, even though in practise they are very similar. Re_B is calculated using equation (26) (Abulnaga, 2002):

$$Re_B = \frac{D_i V \rho_m}{\eta} \tag{26}$$

Where:

D_i = The internal diameter of the pipe (m)

V = Flow velocity (m/s)

ρ_m = density of the slurry (kg/m^3)

η = Coefficient of rigidity (cP)

The Hedström number He is another dimensionless number used to describe the flow conditions, and is calculated using equation (27) (Hedström, 1952).

$$He = \frac{D_i^2 \rho_m \tau_0}{\eta^2} \tag{27}$$

Where:

τ_0 = The yield stress of the Bingham plastic. (Pa)

4.1.1. Laminar flow regime friction losses

To calculate friction losses in the laminar flow regime for Bingham plastic fluids, first the Hedström and Reynolds numbers need to be determined using equations (14) and (15). The dimensionless Fanning friction factor for laminar flow f_L can then be determined using equation (28) (Hedström, 1952).

$$f_L = \frac{16}{Re_B}\left[1 + \frac{He}{6Re_B} - \frac{He^4}{3f_L^3 Re_B^7}\right] \tag{28}$$

The Fanning friction factor can be found on both sides of the equation, but satisfactory accuracy of calculations can be achieved by ignoring the higher-order terms. As this is the Fanning friction factor, care must be taken not to confuse it with the Darcy friction factor.

With the Fanning friction factor determined, head losses due to pipe friction (in meters) can be calculated using the standard Fanning friction head loss equation, presented in equation (29) (Abulnaga, 2002):

$$h_f = \frac{2f_L V^2 L}{gD_i} \tag{29}$$

Where:

h_f = Head loss of the pipe due to friction (m)

f_L = Fanning friction factor for laminar flow

V = fluid flow velocity (m/s)

L = Length of the pipe (m)

D_i = Inner diameter of the pipe (m)

g = Local acceleration of gravity (m/s^2)

4.1.2. Transition from laminar to turbulent flow

The transitional area for change from laminar to turbulent flow is well defined for simple Newtonian fluids, such as water. Flow for such fluids will be laminar at Reynolds numbers below 2100 and turbulent above Reynolds number of approximately 4000. Unfortunately, the limiting Reynolds numbers are difficult to determine for non-Newtonian slurry flows. The equation for Reynolds number includes density and viscosity of the slurry and it could thus be argued that the transitional Reynolds numbers are not very much different for Bingham plastic fluids.

Rough estimates of the velocity in which transition happens have been produced experimentally based on the Hedström number. For example, Hanks and Pratt (1967) have presented a graph for a clay slurry which is presented in figure 13. When the Hedström number can be calculated, the graph can be used to estimate a critical Reynolds number where the transition happens. However, Bingham plastics do not exhibit a sudden transition to turbulent flow. Thus, such graphs should only be used as guidelines to identify roughly the transitional flow speeds. More complex methods have been published in the 1980's by Thomas and Wilson (1987). But these models are very computational and require more experimentally acquired data, making them very impractical to be used in basic engineering and feasibility studies. Their use is confined to very long distance slurry transportation where pipeline friction losses become much more significant.

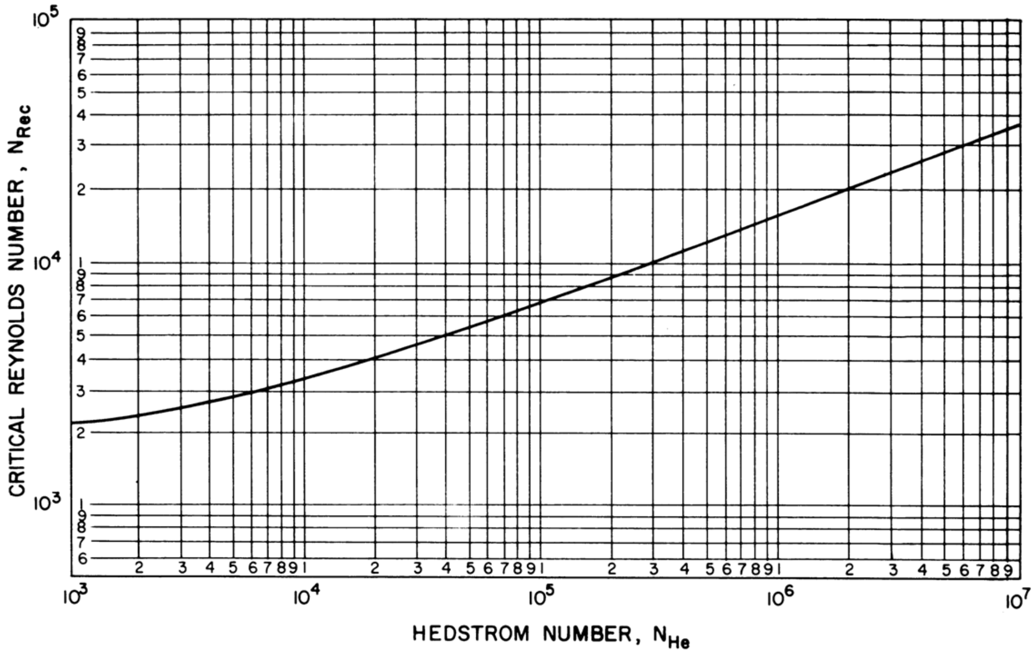

Figure 13. Critical Reynolds number for the determination of transition to turbulent flow for Bingham plastic fluids based on the Hedström number (Hanks & Pratt, 1967)

4.1.3. Turbulent flow regime friction losses

Most commonly cited equation for calculating friction losses for Bingham plastic fluids in the turbulent flow regime is one proposed by Darby and Melson (1981). Their proposal is presented in equation (30):

$$f_T = 10^C {Re_B}^{-0.193} \tag{30}$$

Where

$$C = -1.47 \cdot [1 + 0.146 \cdot exp(-2.9 \cdot 10^{-5} \cdot He)] \tag{31}$$

The equation presented here has been slightly modified by Darby *et al.* (1992) because the original equation over predicts the friction factor in the turbulent flow. Namely, the original value of 1.38 has been replaced by 1.47 in the calculation of C.

Darby and Melson (1981) also proposed a single friction factor expression valid for all flow regimes, combining the equations for friction factors in laminar and turbulent flow, shown here in equation (32):

$$f = [{f_L}^m + {f_T}^m]^{1/m} \tag{32}$$

Where the exponential factor m is calculated using equation (33):

$$m = 1.7 + \frac{40000}{Re_B} \tag{33}$$

The Fanning friction factor equations presented here do not include any factor for the pipe roughness. This is because the effect of pipe roughness's are difficult to predict for varying slurries and in theory the calculations are for smooth pipes only. However, most materials that are used for slurry pipelines are very smooth to begin with (such as HDPE and steel) or they are simply smoothed out and polished by the flow of the solid particles in the slurry. After a few weeks, a stainless steel pipe can very well be much smoother than a new pipe. Furthermore, the effect of the roughness of the pipe on the head loss is very negligible especially on larger pipe diameters.

4.2. Friction losses for power law slurries

Power law slurries were defined in chapter 2. The power law slurries are either pseudoplastic or dilatant fluids. They are jointly known as power law slurries because they follow the same power law equations, just with different power exponents. They do not exhibit a yield stress as Bingham plastic slurries do. Characterization of power law fluids require experimentally determined values, the power law consistency factor K and flow behaviour index n. For pseudoplastic slurries $n > 1$ and dilatants slurries $n < 1$.

4.2.1. Laminar flow regime friction losses

For flow in the laminar regime, Heywood (1991) proposed the following equation (34) for a modified Reynolds number Re_{mod} for power law slurries.

$$Re_{mod} = \frac{\rho_m V D}{K} \left(\frac{4n}{1+3n}\right)^n \left(\frac{D}{8V}\right)^{n-1} \tag{34}$$

Where:

ρ_m = Density of the mixture (kg/m^3)

V = Flow velocity (m/s)

D = internal diameter of the pipe (m)

K = Power law consistency factor (Pa·s^n)

n = Flow behaviour index.

The Fanning friction factor for power law slurries in the laminar flow regime can then be calculated similarly to Newtonian fluids, using equation (35):

$$f_L = \frac{16}{Re_{mod}} \tag{35}$$

4.2.2. Transition from laminar to turbulent flow

Ryan and Johnson (1959) obtained a correlation between the flow behaviour index, n, and the lower critical modified Reynolds number that corresponds to transition from laminar to turbulent flow. Their correlation is shown in equation (36):

$$Re_{mod,c} = \frac{6464n(n+2)^{(n+2/n+1)}}{(1+3n)^2} \tag{36}$$

Darby (1986) also presented another Reynolds number corresponding to the laminar-turbulent transitions, shown here in equation (37):

$$Re_c = 2100 + 875(1-n) \tag{37}$$

The lower critical Reynolds number can be used to indentify when the flow starts transitioning away from laminar flow.

4.2.3. Turbulent flow regime friction losses

Darby (1986) presented a set of empirical equations that are curve-fits that represent results of previous work with reasonable accuracy. Similarly as equations for Bingham plastics presented by Darby and Melson (1981), Darby (1986) proposed a single friction factor for turbulent flow but also a factor for transition flow and a compound factor which combined the friction factors for laminar, transitional and turbulent flow regimes into a single general friction factor. They are presented in equations (38) - (43):

$$Re_p = 2^{3-n} D^n V^{2-n} \rho / K[(3n+1)/n]^n \tag{38}$$

$$f_{TR} = 1.79 \cdot 10^{-4} \cdot exp(-5.24n) Re_p^{(0.414+0.757n)} \tag{39}$$

$$f_T = 0.0682 n^{-1/2} / Re_p^{1/(1.87+2.39n)} \tag{40}$$

$$f = f_L(1-\alpha) + \alpha / (f_T^{-8} + f_{TR}^{-8})^{1/8} \tag{41}$$

$$\alpha = 1/1\left(1 + 4^{-\Delta}\right) \tag{42}$$

$$\Delta = Re_p - Re_c \tag{43}$$

With the friction factor calculated, friction losses in the pipe can be calculated using equation (29).

5. WEAR AND MATERIALS

Possibly as important as accurate sizing of pipes and pumps is the selection of materials that can withstand the corrosive and erosive environment of slurry handling for admissible periods of time. The useful life of most slurry transport systems is limited by erosive wear of their wetted parts.

In this chapter the most common materials used in slurry handling are presented along with description of different wear mechanisms to be used as basis for guidelines that can be used in process and piping engineering. While the selection of appropriate materials for pumps is chiefly left for the supplier of the pumps, wear can be minimized with proper design. Also, the more accurately a buyer can describe their need for specific materials, the better chosen pumps will be supplied. For pipelines the materials are chosen by the design engineer, and wear needs to be one of the principal variables used in selection of piping materials.

5.1. Wear

'Wear' can mean a lot of things, but Miller (1986) defined it in terms of slurry pumping as "the gradual deterioration of any part in the system to the point of danger or uselessness". Another definition is "the progressive volume loss of material from a surface arising from all causes" (Miller, 1986). The two main types of wear are erosion and corrosion. Erosion is wear involving mechanical action by solid particles, or cavitation. Corrosion is a type of wear stemming from chemical or electrochemical action. Both erosion and corrosion can happen simultaneously. It should also be noted that some authors, such as Bootle (2002) and Wilson *et al*. (2006), further classify physical wear as abrasion and erosion. Abrasion is defined as the forcing of hard particles against a wear surface. Abrasion in a slurry pump occurs on the shaft sleeve and between the tight tolerance wear ring section of the impeller and the suction side liner. Abrasion is the most common wear type in slurry pipelines; where even during homogeneous flow larger particles tend to slide more along the bottom of a pipe, causing abrasion. When the flow streamlines are curved, such as in an elbow, abrasion is even more severe because in addition to gravity pulling particles towards the normal of the surface, centrifugal acceleration causes additional force and thus, wear.

Wilson *et al*. (2006) categorize erosion into deformation, cutting and fatigue. These are called particle-impact erosion and they are a consequence of particles hitting surfaces, rather than sliding along it. The basic principles of these erosion types are presented in figure 14.

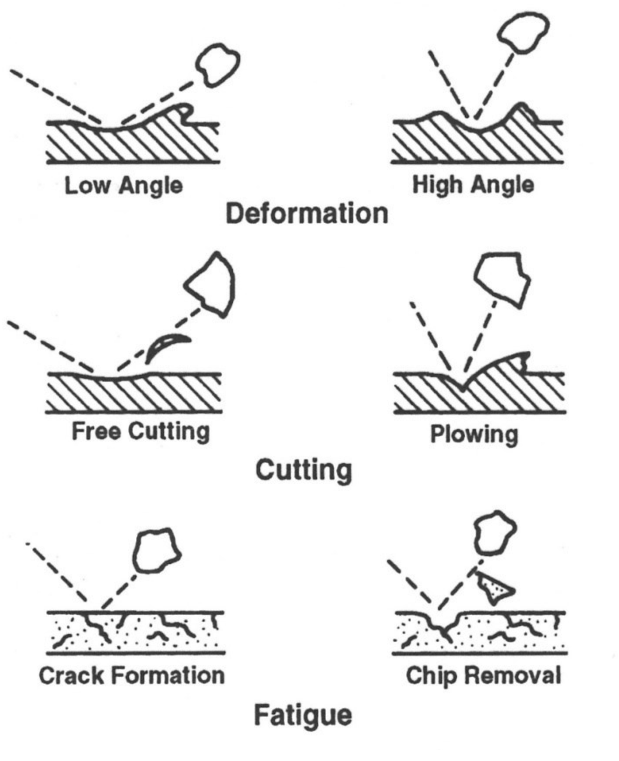

Figure 14. Mechanisms of particle-impact erosion Wilson *et al*. (2006).

The degree of wear depends on various factors, most important of which are the kinetic energy of the particle, the shape of the particle and the slurry concentration. Larger particles in terms of mass have higher kinetic energy than smaller particles, and thus cause more damage. Naturally the flow speed increases the kinetic energy of the particles, and thus increases wear. The shape of the particle is important, as smaller sharp particles have smaller impact areas than large rounded particles. Small impact area leads to high local stress and more severe damage. Increasing slurry concentrations also increases the amount of occurring impacts and thus the amount of wear.

The durability of a material is dependent on the attributes explained above and the type of mechanical impact happening. For example, elastic materials are not very susceptible to fatigue-wear, but low angle strikes and cutting wear are especially wearing on materials such as rubber. On the contrast, very hard and brittle materials, such as Ni-Hard steel, are not very susceptible to low angle particle strikes and abrasion.

A very important factor on wear is the hardness of materials, both of the solid particles in the slurry and of the wear surface. If the wear material is harder than the flowing particles, the particles will be unable to scratch the material effectively. Hardness alone does not eliminate all wear, since there are various mechanisms of wear as mentioned above. There are several scales in which to measure material hardness, such as the Mohs scale, the Brinell scale and the Knoop scale. Figure 15 shows various materials on the three different scales.

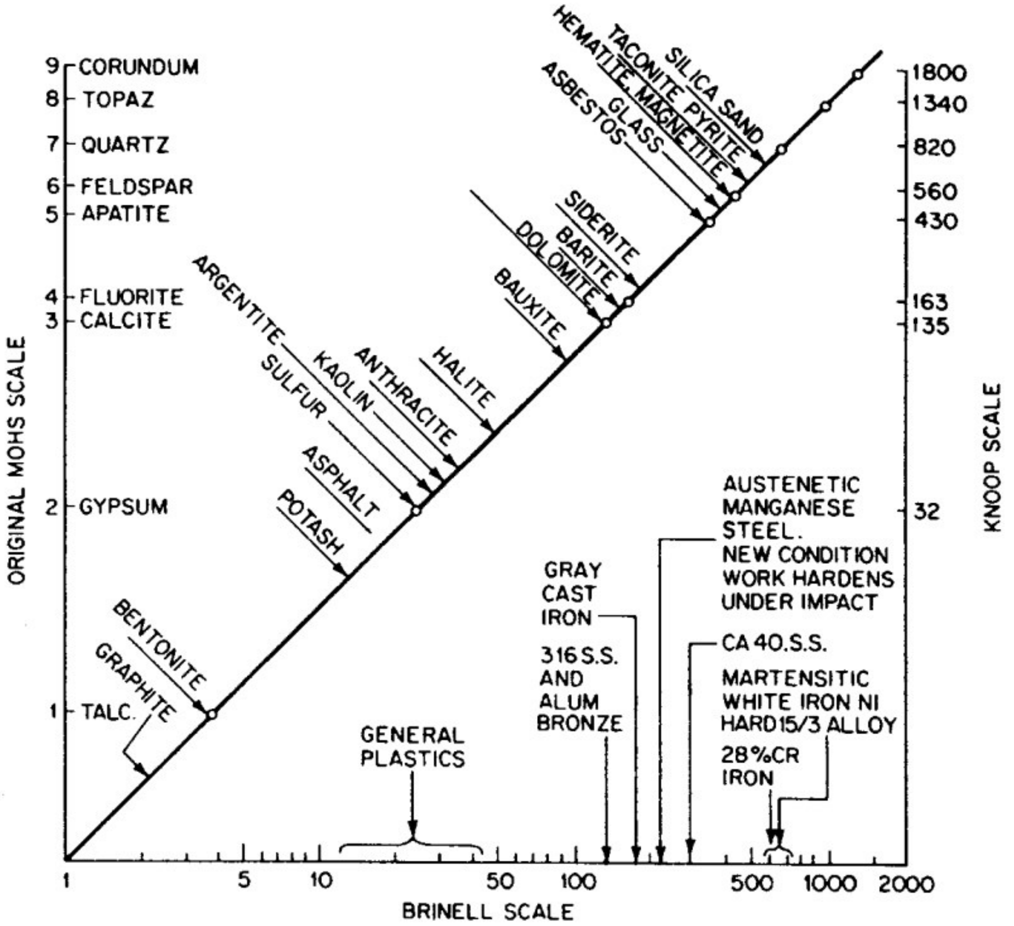

Figure 15. Hardness of various materials (Wilson, 1985).

Abrasion resistance of various materials can be compared with a testing apparatus known as the Miller machine (Miller, 1987). In this test the wear samples are forced to reciprocate for a specific amount of time in sand slurry of specific concentration. The material loss of each sample is measured and then a slurry abrasion resistance number (SAR) can be determined. A high SAR indicates poor resistance to abrasion. Alternatively, a slurry can be tested to determine a Miller number. High Miller number of a slurry indicates highly abrasive slurry. Miller numbers for various slurries are presented in table 5. The SAR and Miller numbers aren't intrinsic qualities of a material, but rather are influenced by a number of variables, such as particle size and shape, both of which can be affected by the method of grinding. For example, the Miller number of alundum is very heavily affected by particle size, as a smaller particle size can increase the abrasiveness by a factor of over 4. This makes the quantitative determination of wear rates very difficult, as the number of variables is very large. This is also why some materials have several SAR numbers.

Table 5. Miller numbers of various materials (Miller 1987).

Material	Miller number
Alundum, 400 mesh	241
Alundum, 200 mesh	1058
Ash	127
Fly ash	14, 83
Bauxite	9, 33, 50, 134
Calcium carbonate	14
Carbon	16
Carborundum, 220 mesh	1284
Clay	36
Coal	6, 10, 21, 28, 57
Copper concentrate	19, 37, 68, 128
Dust, blast furnace	57
Gypsum	41
Iron ore (or concentrate)	28, 64, 122, 234
Kaolin	7, 30
Limestone	22, 39, 46
Limonite	113
Magnetite	64, 71, 134
Mud, drilling	10
Phosphate	68, 74, 84, 134
Pyrite	194
Sand, silica	51, 68, 116, 246
Sewage (digested)	15
Sewage (raw)	25
sulphur	1
Tailings (all types)	24, 91, 217, 644

As most slurry systems handle slurries where the carrier liquid is water, corrosion is usually a significant concern only in chemical and seawater applications. In applications where corrosion is a factor, such as in highly acidic conditions, it can be difficult to indentify as erosion can have a masking effect on the wear caused by corrosion. Both types of wear amplify each other. For example, corrosion can cause the wear surface to become softer or more porous, increasing erosion. And vice versa, particles that scratch the wear surface increase the surface area that is susceptible to corrosion. Erosion can also damage protective coatings, exposing materials that are more easily corroded. Corrosion is practically impossible to quantitatively predict, and prevention of corrosion is limited to qualitative evaluation of the corrosion resistance of materials.

Cavitation affects slurry systems in the same way as all other pumping systems. Solids present in the slurry do not affect the vapour pressure of the liquid and don't directly affect cavitation. However, solids present in the flow increase pressure losses in the suction the same way they cause additional pressure losses on the pressure side. Cavitation may be difficult to indentify in an operating slurry system as normal erosion from solid particles may mask the damage caused by cavitation. Additionally, in water systems cavitation is often identified by the characteristic sound and vibration caused by cavitation, but this too may disappear under the sounds of solids being pumped.

5.2. Materials

Materials used in slurry systems are usually metals, elastomers and plastics. Ceramics can also be considered for some applications, but due to their brittleness and very high cost, they are generally not used in slurry systems and are not suitable at all for high impact or high pressure applications. Ceramic materials can, however, find use in special applications such as control ball valves and composite materials for extremely abrasive cases. Ceramic materials are thus not considered in depth here. Metals (and ceramics) withstand erosion due to their high hardness values. Elastomers withstand erosion due to their ability to absorb energy, thanks to their resilience and tear resistance.

5.2.1. Hard metals

Hard metals most commonly used in wear resistant pump casings and liners are defined by ASTM A532 standard specification for abrasion-resistant cast irons. They fall under classes I, II and III of the standard. They are martensitic white irons (class I), chromium-molybdenum white irons (class II) and high chrome irons (class III). The class I martensitic white irons have been used for abrasion resistant application already for some decades and are often commercially known as Ni-Hard irons, which, as the name would suggest, have a significant nickel content. Their hardness is in the range of 500 – 550 Brinell (540 – 600 HV). The class II and III irons have started to supersede Ni-Hard irons. They contain extremely hard chromium carbides in a martensitic matrix. This gives them high hardness, up to 750 Brinell, but also good corrosion resistance. Chromium carbide is a very inert compound, improving the corrosion resistance. Class III high chrome irons contain less carbon and more chrome than class II irons, which lowers the amount of chromium carbide and thus the hardness, but it also lowers the amount of chrome that is removed from the matrix, improving corrosion resistance and toughness of the matrix itself. They can be hardened to 650 Brinell, or in the case of advanced high chrome irons with extremely high chrome content, up to 700 Brinell. Martensitic white iron is harder than austenitic iron, but also more brittle. Toughness and impact resistance can be improved by lowering the martensite content (Bootle, 2002).

Steel is used as a material where the corrosion resistance of iron is not sufficient. They are not as erosion resistance, but may be necessary for very corrosive or high temperature applications.

Most commonly used metal in slurry pipelines is carbon steel. Carbon steel pipes are comparatively cheap and widely available, but they have fairly bad wear characteristics. Harder metals can be used, but their price is usually too high for wider use. Carbon steel pipes are not very wear resistant, but are sufficient for many applications where slurries are not especially abrasive.

5.2.2. Elastomers and plastics

Elastomers are usually divided into synthetic elastomers and natural rubbers. Elastomers have good wear resistance due to their resilience and tear resistance.

Resilience is described as the ability to deform elastically under impact (Jacobs, 2005). Resilience is important for resisting wear by small particles while tear resistance becomes predominant against larger particles that tend to cut the material. Tear resistance increases with hardness, while resilience decreases (Bootle, 2002). A significant weakness of natural rubber and synthetic elastomers is so called "tramp damage", which refers to any larger or sharper objects present in the flow for any reason. Tramp damage can be caused even by things like trash, tools or even hard hats that have somehow been introduced to the flow. Any oversized tramp material will most likely cause serious damage to the lining. The downside of natural rubber is that it does not withstand heat or some chemicals, such as oils and hydrocarbons. For the same reason rubber lining is not recommended for application where the particle size is widely graded and can vary. Synthetic elastomers can be used in small particle applications, where rubber would be subject to chemical attack, causing swelling or hardening, leading to liner separation or damage (Bootle, 2002). Rubber liners are generally not acceptable for temperatures above 60 °C. Some synthetic elastomers, such as nitrile and Hypalon, can withstand higher temperatures, up to 110 °C in case of Hypalon. The chemical resistance of synthetic elastomers depends on the material. Polyurethane is a harder polymer that is well suited for applications where the tear resistance of rubbers is not sufficient. Polyurethane lacks the thermal stability of rubbers and synthetic elastomers, and is not well suited for high speed applications such as pump impeller liners.

Authors seem to generally prefer elastomer liners over hard metal liners for pumps and pipelines. Most authors, such as Delaroute (1991), Bootle (2002) and Jacobs (2005) all agree that elastomer liners are a very good choice for applications where pump impeller and flow speeds are slow, particle size is moderate and particles aren't especially dense or sharp. What exactly does low speed, moderate size and average density and sharpness mean, varies from author to author. For example Delaroute (1991) recommends elastomer linings for particle sizes up to 5 mm, at least if the particles are rounded. On the other hand, according to Bootle (2002), elastomers are usually used in application with particle diameters not greater than 10 mm, but that they clearly outperform hard metals only for application where particle size is smaller than 250 μm. Elastomer liners also have other limiting factors. The tip speeds of pump impellers are significantly higher than flow speeds and impose limitations to the use of elastomers in impeller liners. Bootle (2002) lists approximate impeller tip speeds limits and corresponding approximate BEP (Best Efficiency Point) head limits for various materials:

- Highly wear resistant soft natural rubber 25.0 m/s 32 m head
- Typical natural rubber 27.5 m/s 39 m head
- Anti-thermal breakdown rubber 30.0 m/s 46 m head
- Nitrile 27.0 m/s 37 m head
- Butyl 30.0 m/s 46 m head
- Hypalon 30.0 m/s 46 m head
- Neoprene 27.5 m/s 39 m head
- Polyurethane 30.0 m/s 46 m head
- Hard metal (impellers) 38.0 m/s 74 m head

High impeller speeds lead to generation of heat and the tip speed limit is a function of the hardness of the materials and its ability to dissipate heat. For hard metals, the tip speed is limited by the ductility of the material. Tip speed wearing is easy to identify as it occurs on the parts with highest speeds, i.e. on the periphery of the impeller and on the side liner next to the impeller tip. Slurry pumps are generally designed to be larger and with slower impeller speeds than water pumps to combat wear, but impeller tip speeds can nevertheless exceed those suitable for rubber in some applications. For example, filter feed pumps that pump against an increasing pressure of the growing filter cake can typically exceed the impeller tip speed limit.

In pipelines elastomers are used as either hoses or metal pipe liners. Elastomer lined steel pipes offer the high structural strength of metal pipes combined with the good abrasion resistance of elastomers. They are often used for high pressure applications. They are, however fairly expensive. Lined steel pipes cannot be welded, as heat will damage the lining. Elastomer hoses are an attractive choice for low pressure, high wear applications and often offer longer lifespan than steel pipes or plastic piping. They are very flexible and thus easy to install and modify even by on-site personnel without extensive training. Their flexibility and erosion resistance also makes them good choices to be used as, for example, piping bends. They also offer lower stocking costs, especially to elastomer lined steel pipes since they do not need to be stocked at specific lengths, but rather can be easily cut to needed lengths. As soft, ductile materials, elastomer pipes can also serve as dampening bellows near pumps.

Plastics are generally only used in pipelines, and in some cases tanks. Commonly used plastics are polyvinylchloride (PVC), chlorinated polyvinylchloride (CPVC), polyethylene (PE), polypropylene (PP) and acrylonitrile butadiene styrene (ABS). Polyethylene is very widely available, is easy to weld and is cheap, making it often the best choice simply from a practical point of view. PVC is similarly cheap and widely available, but cannot be welded. Instead, PVC components need to be cemented, which is a temperature sensitive operation and can be problematic in cold or hot climates. Specialty materials have a significant downside in that they can be very difficult to procure. Plastics are in many ways superior to metals in slurry piping. Their abrasion resistance is much better than most metals and they offer much longer service life. Very large, hard and sharp particles can however cause cutting and gouging of the plastic surface, quickly eroding the material. Plastic pipes produced from are fairly cheap. They are also very resistant to corrosion and are suitable choices for example in applications where sulphuric acid is present, as is quite often the case in minerals processing. Plastics are also significantly lighter than metal pipes. Unfortunately plastic pipes are structurally weaker and do cannot withstand high pressures. They also require much more pipe supporting, as they can only support their own weight under load for very short distances.

6. SPREADSHEET CALCULATION TOOL

A spreadsheet calculation tool was developed. The tool can be used for the design and sizing of slurry pipes and pumps. The tool uses principles and calculation methods presented in this thesis. It is based on an existing Outotec spreadsheet calculation tool which was designed for sizing of pumps for water services (Siltala, 2013). The new tool is an extension of the existing tool, adding slurry functionality by expanding the pressure drop calculations to allow solid particles in the flow. Additionally, the tool calculates estimations for critical deposition velocities in any selected pipe size using two selected methods. The estimations can then be used to evaluate suitability of selected pipe size and flow speed. The new tool was based on the existing tool to simplify workflow within the company.

The tool utilizes the method described in chapter 3.3.1 to calculate the dynamic pressure losses caused by solid particles. First, an equal flow (in volume) of clean water is assumed and the pressure drop is calculated for a specified pipe system using standard praxis. The method described in chapter 3.3.1 is then applied to obtain pressure drops for slurry service.

Both Durand's and Wasp's methods, described in chapter 3.2.1, are used to calculate limiting deposition velocities. Both methods are used to provide flow speed region instead of relying on one method alone. Durand's and Wasp's methods were chosen because they were already used by individual process engineers at Outotec, they were suitable for use in an excel-based calculation tool and especially Durand's method is a widely used, established method with a long history and a lot of accumulated experience. Two methods are used because neither method is verifiably more accurate than the other. This is an issue concerning slurry systems engineering in general. Various methods exist, but to make an informed selection between them, one would need to use extensive lab testing. If laboratory tests are available, one wouldn't need to settle for these methods in the first place. The limiting deposition velocities are then used to evaluate the flow speeds in a selected pipe size to see if the selected pipe is suitable for the slurry service.

Properties of the slurry are based on the mass flow and concentration by weight of the slurry, density of the solid particles and the d_{50} and d_{85} sizes of the solid particles. Further properties, such as density of the slurry, concentration by volume and volumetric flow are calculated using equations described in chapter 2.

The output of the tool is a pump data sheet that can be used when specifying and purchasing pumps for a project. The data sheet contains information that specifies the requirements for the pump, such as information about the fluid, capacity, pressures, head requirements, $NPSH_A$, hydraulic power etc.

Additionally, the tool can be utilized to size pumps also for situations where a single pump has several discharges. This function assists in the determination of the discharge that causes the highest pressure drop for the pump.

The functionally of the calculation tool is best explained by a user guide. A user guide was compiled and it is presented in appendix D.

7. DESIGN GUIDELINES FOR SLURRY TRANSPORT

7.1. General guidelines

7.1.1. Slurry characteristics

Characteristics of the slurry need to be taken in consideration when designing pipelines for slurry service.

For proper design of slurry pipelines, the following characteristics of the slurry need to be known: Particle size in terms of d_{50} and d_{85}, density of the solid particles and concentration by weight of the solid particles.

Settling nature of the slurry shall be determined. Laboratory testing should be used, where possible. In other cases, settling nature can be approximated from practical experience and literature. Use figure 5 for crude determination of the slurry settling nature.

7.1.2. Settling slurries

For settling slurries, flow speeds need to be above limiting deposition velocity of the slurry. Bed forming occurs below this velocity, increasing wear, pressure losses and increasing the risk of pipe blockage. Pipe size needs to be chosen to be small enough to ensure sufficiently high flow speeds. However, wear of wetted parts increases rapidly with increasing flow speeds. Guidelines on maximum flow speeds depend on the particle size and pipe diameter. Flow speeds should not exceed the following guide:

Particle size	Max. velocity
< 0.08 mm	4 m/s
0.08 – 0.9 mm	5 m/s
0.9 – 4.8 mm	6 m/s
> 4.8 mm	6 m/s (< 400 mm pipe diameter)
	8 m/s (> 400 mm pipe diameter)

Limiting deposition velocity can be determined with several methods. The most commonly used methods are Durand's, Wasp's and Wilson's methods. Provided spreadsheet calculation tool uses both Durand's and Wasp's methods. For more information about the methods, refer to chapters 3.2.1 and 3.2.2.

7.1.3. Non-settling slurries

For thick non-settling slurries, determination of the rheology of the slurry is of paramount importance. Rheology of slurries cannot be reliably determined from the characteristics of the slurry. If prior experience or reliable literature data for the specific slurry is not available, laboratory testing should be conducted. Viscosity and regime of the slurry should be determined. For handling and pumping of viscous materials, especially non-Newtonian, refer to published adjustment tables, for example by Hydraulic Institute.

7.1.4. Piping design

When designing slurry pipes, following guidelines should be followed:

- Pipes should be as short as possible to reduce pressure losses.
- Pipes should be as straight as possible to reduce pressure losses and wear
- Pipes should be sloped to facilitate emptying of pipes
- Pipes should be equipped with drain valves and flushing inlets
- Pockets and blind areas should be avoided. If unavoidable, they need to be equipped with a drain valve.
- Pipe bends should be as wide as possible for the layout. Preferably r = 3d bends should be used. Wider bends reduce pressure losses and wear.
- Number of pipe fittings should be kept to a minimum.
- All areas of low velocity should be eliminated from slurry lines to avoid settling of solid particles and pipe blockages.
- Piping shall be arranged and supported to allow easy dismantling for maintenance purposes. Where possible, pipes should also be designed with possibility to rotate them upon their axes to spread wearing caused by sliding beds.

7.2. Guidelines for valves

7.2.1. On/off valves

Usage of valves should be minimized in slurry service. Valves should provide a full-bore, straight-through opening, should not rely on machined surfaces for closure and should not have dead pockets that fill with solids and restrict operation. The most commonly used valves for slurry service are knife gate valves, diaphragm valves, pinch valves and autoball valves. Plug valves an also be used for slurries that are moderately abrasive and have little tendency for scaling or caking. Full port plug valves should be used. They can all be used as isolation valves.

7.2.2. Throttling valves

Use of throttling valves is not recommended for slurry service, but can be done with for example pinch valves and in special cases, wear resistant, ceramic ball valves. They are, however, extremely expensive.

7.2.3. Valves in pump suction line

Usage of valves should be avoided in pump suction lines, but due to the need to isolate the pump, this is usually not possible. Valves in the suction line of a pump should be completely open, straight-through design that causes the least friction to flow when the pump is operational. Their length should also be small, so that they do not unnecessarily make the suction line longer. Knife gate valves are commonly used in pump suction lines.

7.3. Guidelines for pump

7.3.1. Design margins for slurry pumps

Design margin should not be added to system head or pump speed calculations. Rather, power draw or motor selection should be oversized. Variable speed drives (VSD) should be used whenever applicable and financially possible. VSD allows some leeway for inaccuracies of design and when a range of flows is required.

7.3.2. Solids effect

For clarity, system head calculations should be done for the fluid being pumped, i.e. for slurry pumps, slurry head should be calculated. In addition, pump de-rating due to solids present in the slurry needs to be taken into consideration. For more information, refer to chapter 3.4.

7.3.3. Pump operating point

When selecting pumps, the system operating point should not be located far on the 'right side' (i.e. higher Q value) of specified best efficiency point (BEP) of the pump (Myllykangas, 2013). Operating on the right side of BEP can lead to sporadic and unstable operation of the pump. Slurry pumps often have fairly flat pump curves, which can lead to several operation points, as slurries can sometimes have non-linear system curves. Significance of this rule proliferates with increasing slurry density and particle size.

7.3.4. Pump suction line

Pump suction piping should be horizontal or declining and as short as possible. About two meters of liquid level should be maintained above the pump suction line, when possible if NPSH calculations do not require more. When pumping from tanks or sumps that are constantly fed, the suction line inlet should be as far as possible from the sump feed inlet. The sump inlet feed line should also be below liquid level, to prevent swirling and turbulence that could introduce air into the pump suction pipe. Declining suction piping also prevents air bubbles from entering the pump.

7.3.5. Pump service class

When selecting pumps, it is helpful to determine a service class the pump belongs to. Service class is a concept coined by Wilson et al. (2006) and GIW Industries to describe the severity of the slurry service the pump needs to handle. Severity of the slurry, and the pump service class, increases with increasing particle size and slurry specific gravity. Pumps are divided into four service classes. For example, mill discharge and cyclone or screen feed pumps usually belongs to service classes 3 and 4, most tailings pumps to service class 3 and all other process application slurry pumps to service class 2. Figure 16 can be used to determine the service class a pump belongs to.

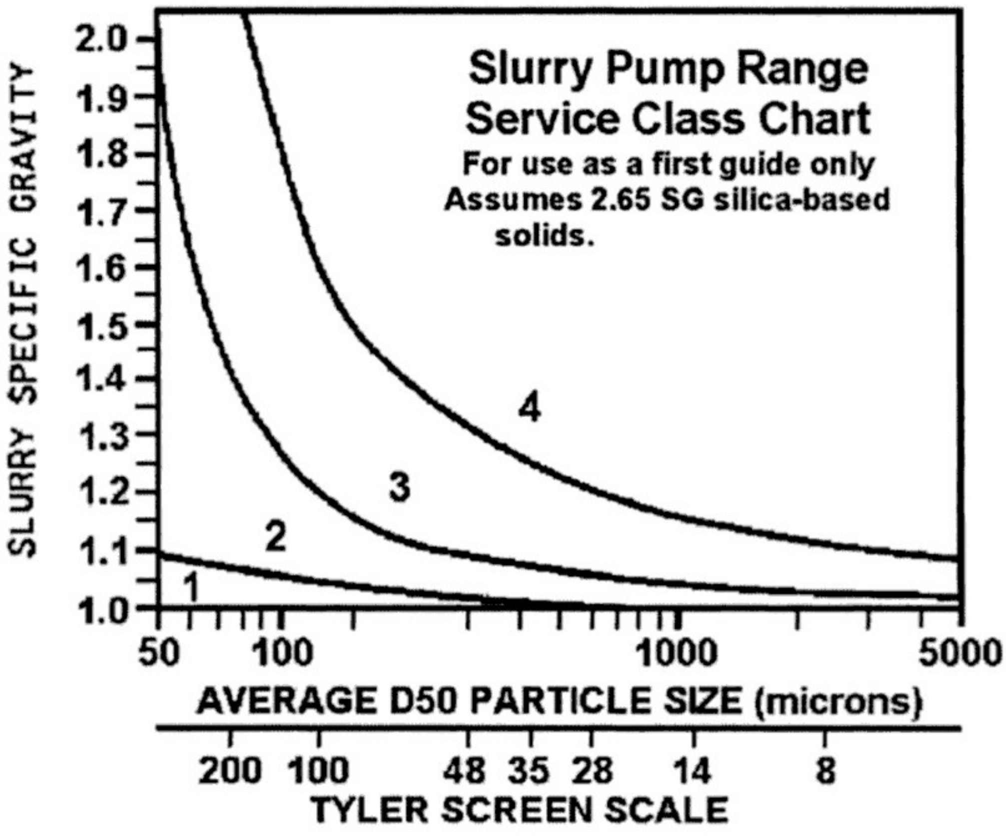

Figure 16. Slurry pump service class chart (Wilson et al. 2006)

The service class and pump geometry impose some limitations or recommendations for the operation of the pump. Recommendations of GIW Industries have been collected into table 6. (Wilson et al. 2006)

Table 6. Recommended operating limits for slurry pumps (Wilson et al. 2006)

		Service class			
	Shell type	1	2	3	4
Maximum dis-charge velocity (m/s)		12	10	8	6
Maximum throat velocity (m/s)		15	12	9	6
Recommended range, percentage of BEP flow rate	Annular (A)	20-120	30-130	40-100	50-90
	Semi-Volute ('C)	30-130	40-120	50-110	60-100
	Near volute (T)	50-140	60-130	70-120	80-110
	Annular/oblique neck (OB)	10-110	20-100	30-90	40-80
Maximum impeller peripheral speed (m/s)	All-metal pump	43	38	33	28
	Rubber-lined pump	28	25	23	20
Maximum head per stage (m)		123	66	52	40

7.4. Guidelines for lime milk systems

Lime milk is extensively used in many mineral processing plants for example for pH control. Thus, lime milk systems are present in many plants. While most design guidelines above apply to lime milk systems as well, certain specifics are clarified here.

- Lime milk is very prone to scaling.
- Lime particles are jagged and only dissolve very little to water, but rather are suspended in the carrying medium, leading to a wearing slurry.
- The slurry concentration should not exceed about 120 g/l.
- Carbon steel should be used for lime milk piping. Though other materials such as polyethylene and stainless steel of material grade 316L are suitable as well.
- Pipes should not be oversized to accommodate future capacity increase.
- Higher temperatures can cause the lime milk solution to become oversaturated as lime solubility to water decreases with increasing temperatures, leading to precipitation and scaling. Large temperature variations should not be allowed for lime milk systems.
- Pipes, pipe fittings and valves should be designed to be as smooth as possible, avoiding all cracks, crevices and blind spots.
- Pinch valves are best suited for lime milk service. They are self cleaning (inhibiting scaling) and do not have crevices for the lime milk to precipitate into.
- Alternating a chlorine solution with the lime milk on a regular basis can eliminate scaling.
- Lime milk line should be flushed with water whenever lime milk feeding is stopped.
- Extensive, large lime milk systems should be equipped with circulation pumps to keep the lime milk moving. Recirculation should be about 200 % of the amount used.
- Addition of polyphosphates in dilution water can inhibit scaling.
- Softened water should be used to inhibit scaling.

8. EXAMPLE CASE

An example case was selected to apply the spreadsheet calculation tool and general design guidelines in practise.

The selected example case is a water treatment unit in a ferrochrome sintering plant. The process values and sizing of the equipment were obtained from actual design cases at Outotec. Accordingly with the topic of this thesis, focus of this example case is not in the sizing or operation of the equipment, but rather in the design of the pipelines and pump for the slurry systems.

The example case consists of a clarifier that is used to treat wastewaters coming from various parts of the sintering plant. Largest wastewater stream comes from gas scrubbers. Main objective of the clarifier is to produce plant water that is recycled back in to the process, mainly to the gas scrubbers. Overflow of the clarifier is used without further treatment. Underflow of the clarifier is treated with a belt filter to remove solid material and to increase the gain of recyclable water.

A process flow sheet, PI-diagrams and a process description were drafted for the case. The diagrams are presented in appendix E. The process description is presented in the following chapter. The scope of the design in this work is limited to the clarifier and belt filter. All lines coming to the area are not sized accurately; as they depend on the specific plant the water treatment unit is attached into. Similarly, the recycling water tank and pumps are not sized.

The slurry is not very dense and particle sizes are small. The d_{50} size is 50 μm and d_{85} size is 100 μm. Density of the solid particles is fairly high, approximately 3000 kg/dm^3. According to the graph in figure 5, the slurry is non-settling when determined from the d_{50} size. However, the d_{85} size is well on the settling side.

Additionally, the d_{50} size is so close to the boundary line, that the slurry is expected to be settling in practise. Furthermore, practical experience from previous cases has shown that ferrochrome slurries settle easily (Kilkki, 2014). Slurry density and concentration before the clarifier are very low. In the clarifier underflow, under normal process conditions, the slurry has a density of 1200 kg/dm^3 and solids concentration by weight of 25.3 %.

Layout for the water treatment unit is designed to be very tight with a small footprint. As a small unit, it is easily adapted and added to various plants. The use of gravity lines is maximized to minimize the amount of pumping and pipe lengths. Clarifier, being the largest equipment, is the core of the process. Most other equipment, specifically the slurry collector, scalping screen, belt filter, filtrate separator and vacuum pump are attached on support structures next and above the clarifier. They are located above the clarifier so that all pumping can be done with the clarifier underflow pumps and gravity is utilized for liquid transport whenever possible. The underflow pipes extend well above the clarifier whence it is divided and fed back into the clarifier and into the belt filter. It is possible to install the filter above the clarifier due to the low amount of solids in the clarifier feed, leading to small and lightly weighted belt filter.

8.1. Process description

Slurries from gas cleaning, filtering area, grinding area and sintering area are pumped separately into a slurry collector (RN01-TK-801). From the slurry collector, slurry flows on to a scalping screen (RN01-VS-801) that separates oversized material (larger than 2 mm) from the slurry. From the screen, slurry flows via a launder into a clarifier (RN01-CL-801).

The clarifier is equipped with a rake and is connected to an automated flocculant feeding system and a sodium hydroxide feeding and mixing system. The clarifier has two underflow pumps (RN01-PU-802/803) one operating and one in stand-by. To thicken the slurry, the clarifier underflow is constantly pumped and circulated back into the clarifier. The underflow circulation line has a take off to a belt filter (RN01-FL-801). The belt filter feed is controlled by a pneumatically actuated pinch valve and a slurry density measurement in the underflow circulation line. Overflow from the clarifier flows by gravity into a recycling water tank (RN01-TK-803).

The slurry taken from the clarifier underflow is fed directly onto a belt filter (RN01-FL-801). The speed of the filter belt is adjusted with a variable speed drive (VSD) controlled motor according to measured filter cake thickness to maintain desired filter cake thickness. The belt filter is located above the clarifier, so that gravitational flows can be used. Minimum elevation of the filter is 3 meters above the clarifier. Vacuum is produced into the belt filter with a liquid ring vacuum pump (RN01-PU-804). There is a filtrate separator tank (RN01-TK-802) between the belt filter and the vacuum pump to prevent filtrate from entering the vacuum pump. Filtrate flows by gravity from the filtrate separator tank into the recycling water tank (RN01-TK-803), located below the filtrate separator and the belt filter. Minimum elevation of the filtrate separator is 10 meters above the liquid level of the recycling water tank to provide hydraulic leg for the vacuum. Filter cake from the belt filter is moved to a filter cake bin (RN01-TK-802) with a conveyor belt (RN01-CV-801). The filter cake bin is equipped with air cannons (RN-AC-801/802) and a disc feeder (RN01-DF-801). From the filter cake bin, the filter cake is conveyed to pelletizing by belt conveyers (RN01-CV-802/803). The first conveyor belt (RN01-CV-801) is equipped with a belt scale.

The filter cloth and belt is washed using plant water network water. The used cloth and belt wash water is drained by gravity into the clarifier. The vacuum pump ring sealing water is also taken from the plant water network. Returning sealing water is drained by gravity into the recycling water tank (RN01-TK-803).

There is a floor sump (RN01-SU-801) in the water treatment area that works as a surge buffer in case of upset conditions. Flushing slurry from the water treatment area also flows into the floor sump. In addition, in case of problems with the filter, filtrate from the filtrate separator (RN01-TK-802) can be directed into the floor sump through a separate line. The floor sump has a sump pump (RN01-PU-801) that pumps slurry from the floor sump into the clarifier.

8.2. Sizing of the slurry pipes

Slurry pipes for the case were sized using the spreadsheet calculation tool presented in chapter 6.1.

The pipes were chosen to be manufactured from high density polyethylene. (HDPE). The slurry is fairly wearing due to high density of the solid particles. However, given the flow speeds, low concentrations of the slurry and small particle size, HDPE pipes are expected to withstand wearing well in the clarifier circulation and filter feed lines. Pipe bends need to be manufactured with long radii, as direct impacts to HDPE pipe walls could lead to high wear rates and penetration.

The pipe sizes are visible in the P&I diagrams and the spreadsheet calculation sheet, which is also used for the sizing of the pumps and presented in appendix F. Appendix F shows most of the pump sizing tool. The tool was not designed to be presented on paper, and few parts are omitted.

The pump suction line is sized at DN 100, which leads to flow speeds that are too low, according to the spreadsheet. However, the suction line is very short as the pumps are located directly below the clarifier, very close to the underflow cone. Thus, the suction line is almost completely declining and particle settling should not pose any problems.

The number of pipe fittings and valves is to be minimized. Valves are only used for isolation of the pumps and the pinch valve that is used for controlling the flow going to the belt filter. Large radius pipe bends are used to minimize pressure losses and their number is kept to a minimum. The result is a pipeline with low pressure losses. In fact, the dynamic pressure losses are small enough that they disappear under the static head.

Accordingly with the design guidelines, all piping is fitted with drain valves and flushing inlets. Valves are knife gate valves and throttling is only used where absolutely necessary. Also, the flow speeds do not exceed the recommended maximum flow velocities, reducing wear.

8.3. Sizing and selection of the slurry pump

The clarifier underflow pumps (RN01-PU-802/803) were sized using the same spreadsheet calculation tool. The spreadsheet calculation sheet and pump data sheets are presented in appendix F. The pump data sheet is the document which would be used in pump procurement and sent to a pump manufacturer. Due to low dynamic pressure losses from the efficiently designed piping, the pump can be fairly accurately sized using only the static system head, resulting in a fairly small and inexpensive pump.

9. DISCUSSION

This work focuses on the flow of slurries in metallurgical process engineering from a practical point of view. This work was done to assist the work of process engineers in the target company's Plant engineering department. The object was the development of tools and guidelines.

Slurry flow engineering has been studied quite extensively since the 1950's, but no huge breakthroughs have been made since. Basic definitions used in slurry engineering have remained somewhat same throughout the years. In metallurgical process engineering the main problem commonly encountered are settling slurries. Settling slurries are mixtures of a liquid, most often water, and solid particles that are too large and dense to be suspended by the liquid itself. As a consequence, flow speeds in slurry pipelines need to be sufficiently high to ensure that solid particles are transported by the turbulent flow. Most research in the field has gone into finding ways to determine this necessary flow speed, usually called the critical deposition velocity. The work was pioneered by Durand and others in the 1950's and has since been improved on by various authors. However, Durand's work remains the principal method.

The situation is similar with evaluation of dynamic pressure losses in settling slurry flows. More accurate and extensive work has been conducted more recently, but the accuracy of the methods is questionable when applied with the limited information available for a process design engineer designing a minerals processing plant.

Non-settling slurries are also looked into, but it is found that most non-settling slurries are in practise very often viscous, non-Newtonian liquids that impose their own challenges to design. However, these are not challenges that result from them being slurries, but rather same challenges concern all viscous liquids and are fairly well known. It is not possible to determine the viscosity of non-settling slurries from the properties of the particles alone. In practise, non-settling slurries should always be tested in a laboratory to find out their viscosity. As such, non-settling slurries were not looked into, apart from introducing a set of formulas for the calculation of friction factors for pipe flow.

In fact, the most significant problem with designing slurry systems is not actually the limitations of the available calculation methods, but rather the very limited information available of the material that is being handled. It is often the case that the engineer designing pipelines and pumps only knows a crude mass balance and one characteristic number of the slurry, usually the d_{50} or even the d_{80} number of the slurry. With such limited information available, it is unreasonable to expect the critical deposition velocity calculations to be extremely accurate. On the other hand the newer, perhaps more accurate, methods can't really be used at all because all the necessary initial data is not available. It is often up to the engineer him- or herself to evaluate which results are closest to the truth. For these reasons, slurry engineering is often as much art, as it is science.

To help interpret this art form, a spreadsheet calculation tool and a set of design guidelines were developed in this work. They can be employed in process and plant engineering for the selection of proper pipe sizes, sizing of pumps and design of pipelines. The tool provides a consistent and traceable calculation for the sizing of slurry pipes and pumps. The guidelines can be used as a basis of design to ensure that special requirements of slurry lines compared to clear liquid lines are taken into account.

To further improve slurry system engineering in the target company beyond the current work, steps would need to be taken to increase the amount of information available to the process engineers. With more information, slurry pipelines could be sized more accurately, avoiding unnecessary overdesign. In general, pipe flow speeds are designed to be too high to ensure that no settling or pipe blockages occur. This leads to increased pumping costs and wearing of pumps and pipelines, translating into higher investment and operating costs. It is unclear, however, how this increased amount of information could be obtained. One option is to try to improve the amount and quality of feedback that is obtained from previous projects. This may be improved in the future, as the target company focuses more on Operation & Maintenance –contracts and thus has more direct access to information about the operation of the plants. How this information is collected and utilized, is a subject of much internal development and perhaps another thesis.

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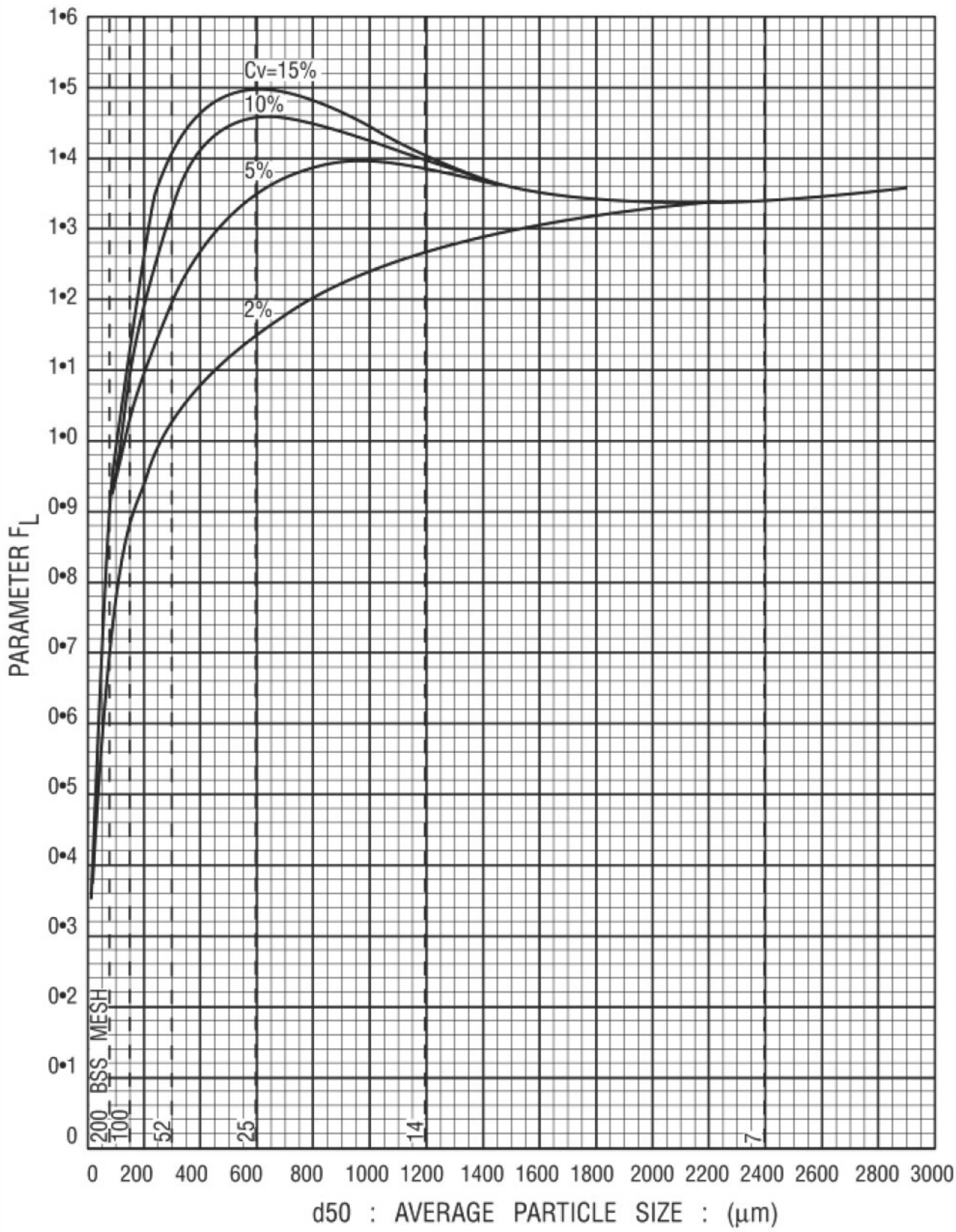
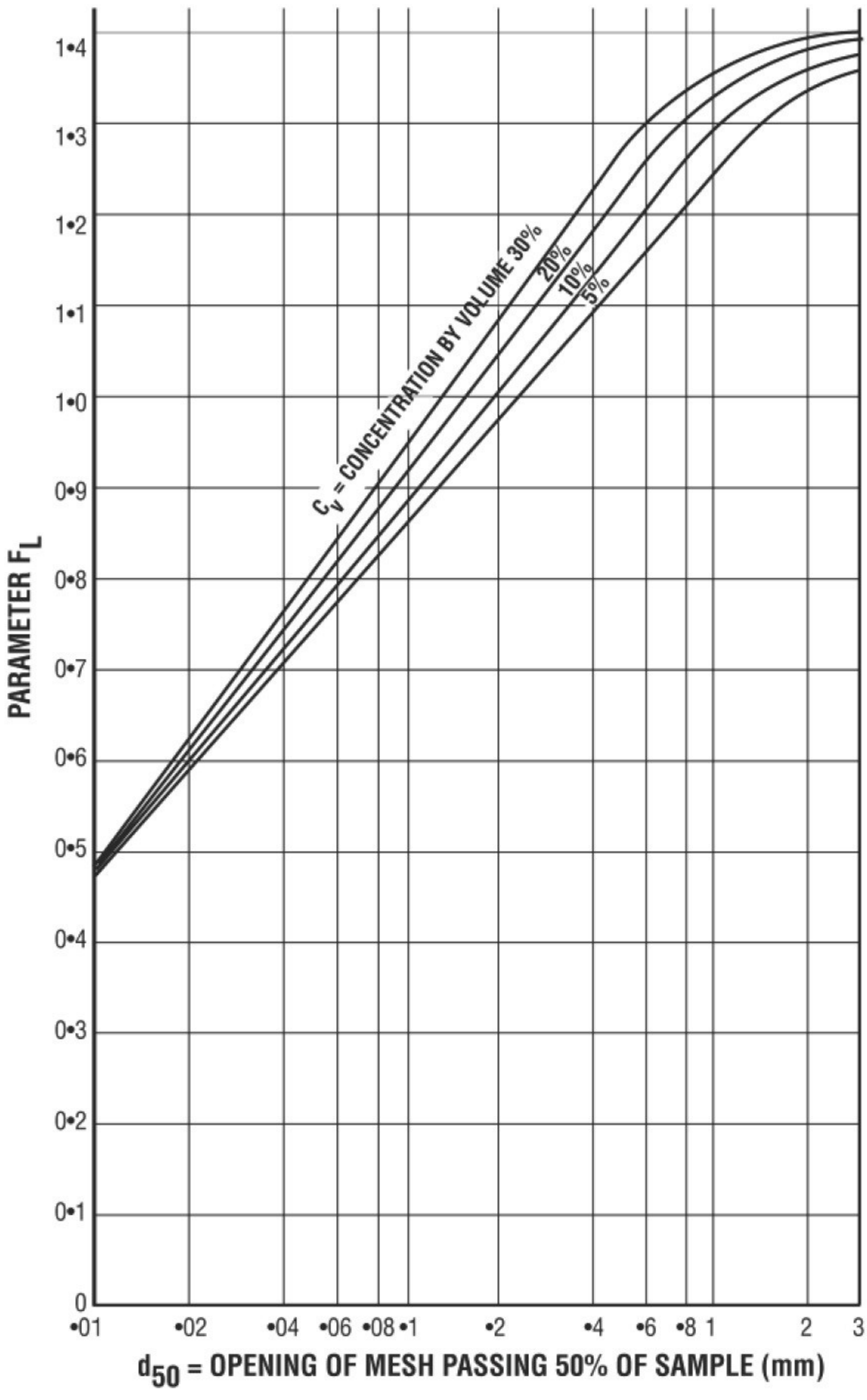
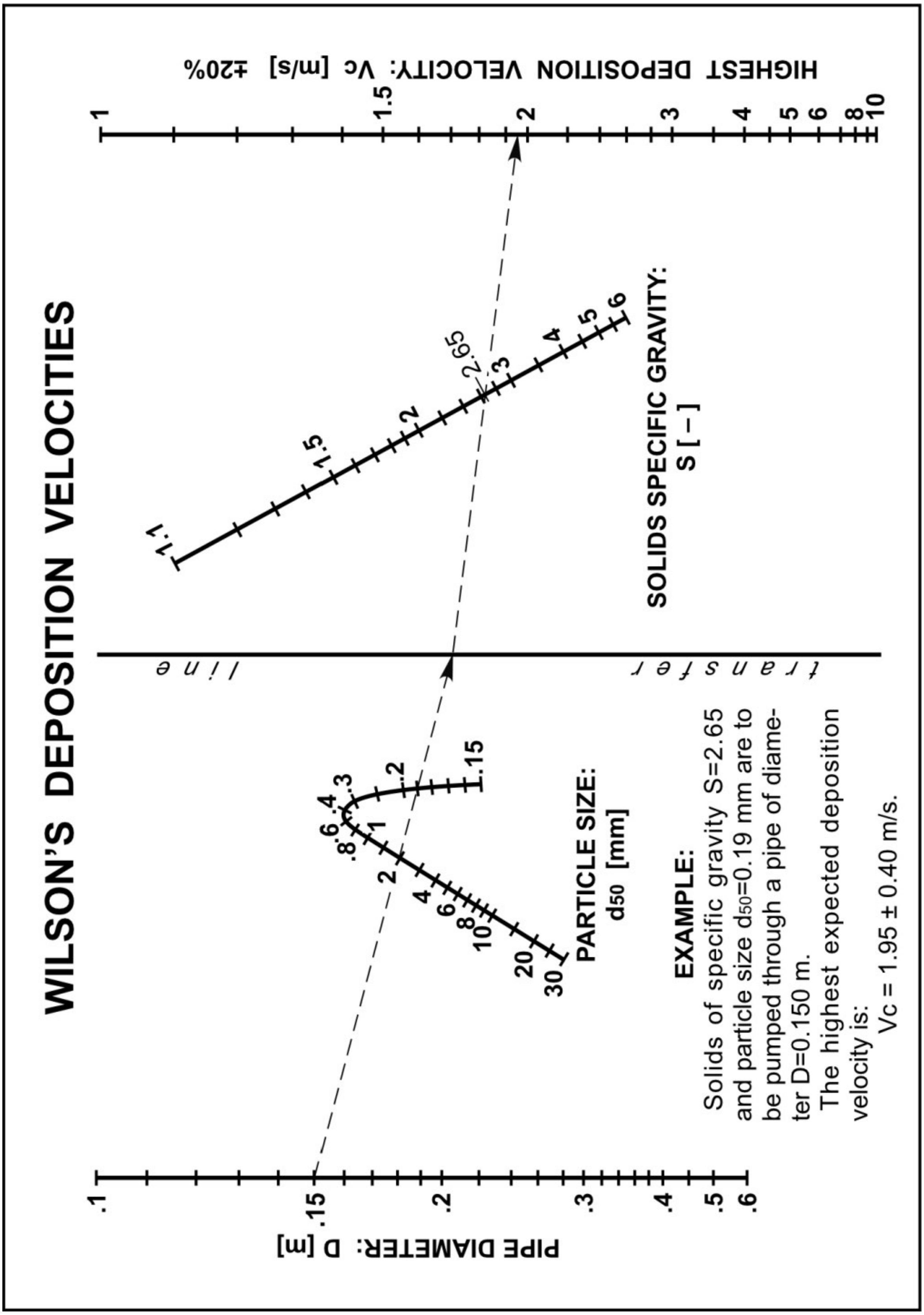
Durand's limiting settling velocity parameter diagram



Modified Durand's limiting settling velocity parameter diagram



Wilson's deposition velocity nomogram



User guide for slurry pump tool

Slurry pump tool is used to evaluate pipeline flow speeds and head losses for settling slurry systems of one pump and up to three separate discharges. It is not recommended for non-settling slurries with viscosities significantly different than water.

Light green colour in the tool indicates cells that are filled up by the user. Light grey cells are cells that contain calculated values based on the inputs of the user. Dark grey cells are constants. Black cells are not in use and may change based on the inputs of the user (for example, choosing "Spec" as the pipe sizing methods blacks out Custom ID cells, indicating they are not in use).

Identification data

Identification data can be input in the ID box, shown in figure 1. ID data that is added here is also used on the pump data sheet.

ID	
Project name	
Customer name	
Plant unit describtion	
Project no.	
Document no.	
Pump tag	
Pump name	
Pump P&I diagram	

Figure 1. ID box for identification data

General process data

General process data includes information that is common to the whole system. Information about the number of discharges, operating conditions, fluid and solids properties and minimum and maximum flow value percentages are input in this section. General process data boxes are presented in figure 2

NUMBER OF DISCHARGES		
#	1	(select)
OPERATING CONDITIONS		
Altitude	0	m
Gravity	9.81	m/s^2
Athmospheric pressure	101.325	kPa
FLUID PROPERTIES		
Fluid	Water	(select)
Temperature	20	°C
Water viscosity	1.00	cP
Water density	998.21	kg/m^3
Water vapor pressure	2.33	kPa
Viscosity (other fluid)		cP
Density (other fluid)		kg/m^3
Vapour pressure (other fluid)		kPa
SOLIDS PROPERTIES		
d_{50}	250	µm
d_{85}	450	µm
Density	2923	kg/m^3
Grading	Wide	(select)
F_L	1.05	
DESIGN VALUES		
MIN	50.0	% (of normal)
MAX	10.0	% (above normal)

Figure 2. General process data

Number of discharges

The number of discharges is selected from a drop down list. The tool supports up to three separate discharges.

Operating conditions

Input the altitude in meters in which the system will operate in, in relation to the sea level. Altitude affects the gravitational acceleration and atmospheric pressure. Atmospheric pressure is automatically used as the default source and destination pressure in the suction and discharge boxes.

Fluid properties

Select the fluid that is the carrier liquid in the slurry. In most cases the fluid is water and only temperature of the fluid is typed in. Rest of the values (viscosity, density and vapour pressure) are calculated based on the temperature of the water. If the carrier liquid is other than water, select "Other" from the drop down list and fill in the values for the viscosity, density and vapour pressure of the fluid.

Solids properties

Input information about the solids present in the slurry. If the d_{85} sizing is not known, it needs to be estimated, as it is required for slurry head loss calculations. If no other value is available, use d_{50} multiplied by a factor of 2.3. Density is the density of the solid particles alone, not the density of the slurry. Grading is selected from a drop down list. The grading represents the particle size distribution of the slurry. The selection affects the method used to calculate Durand's limiting settling velocity factor F_L. Most practical slurries are widely graded. Using narrow grading produces values of F_L and critical deposition velocity that are higher than for wide grading. Narrow grading should only be used if the slurry is known to be very narrow in particle size distribution.

Design values

Input the percentages of minimum and maximum flows in the system in relation to the normal operating situation. The minimum percentage value represents how many percent the minimum flow value is of the normal flow value. The maximum percentage value represents how many percent the maximum (or "design") flow value is above the normal flow value. On the pump data sheet, values based on the normal and maximum (denoted as "design") flow values is presented as the maximum values are of importance for the selection of a pump.

Line

Shown in figure 3, the line section is where the names of the lines in the system are specified. In a simple 1 discharge situation these are the suction and pressure side pipes of a pump. The line name and fluid name are filled in. The fluid name in the suction line is used on the pump data sheet as the name of the slurry in general and should be descriptive.

The line tags 1 and 2 should be reserved for the suction and pressure lines of the pump. If there is more than 1 discharge, the discharge pipelines are built from blocks using the rest of the line tags. This is explained in more detail in a later section.

LINE		
Line tag	Line name	Fluid name
1	Suction line	Slurry
2	pressure line	Slurry
3		

Figure 3 Lines box

Mass balance

Mass balance section, shown in figure 4, is used to fill in the mass balance for the individual lines. The required inputs to be filled in are the total mass flow of the slurry in tonnes per hour and the solids concentration by mass in percent. Rest of the values are calculated and presented next to the inputs. Use the normal flow values. Maximum design values are calculated based on the percentage that was input in the Design values: max –box earlier.

MASS BALANCE						
tph	w/w, %	v/v, %	kg/m³	m³/h	m³/h	m³/h
Slurry total normal mass flow	Slurry concentration by weight	Slurry concentration by volume	Slurry density	Slurry total normal volumetric flow	Slurry total min. volumetric flow	Slurry total max. volumetric flow
900	40.0	20.1	1329.75	676.82	338.41	744.50
900	40.0	20.1	1329.75	676.82	338.41	744.50

Figure 4. Mass balances

Pipeline

Pipeline section, shown in figure 5, is used to fill in information about the pipes.

In the pipe sizing method, user selects between a preset pipe specification and a custom pipe internal diameter. The tool currently supports a limited amount of pipe specifications and a selected group of most commonly used pipe classes are available. If a desired pipe specification and size is not available, choose “Custom” in the pipe sizing method. If “Spec” is selected, pipe specification and size of the pipe is chosen from the Spec. and DN drop down boxes. If “Custom” is selected, the internal diameter of the pipe is manually inserted into the Custom ID section in millimetres. Line length and roughness of the pipe are input in meters. Typical values for roughness are, for example, 0.0003 for cast iron and 0.00003 for stainless steel.

The section includes the calculation of the flow speed in the pipe, critical deposition velocity and checks to evaluate the speeds. The critical deposition velocity is calculated based on both the Durand’s method and Wasp’s modified Durand’s method. The critical deposition velocity represents a limiting flow velocity below which particles start to settle out of the slurry and start forming a moving bed. In optimal situations the flow speed should be above the critical deposition velocity. Durand’s method is quite conservative and yields very high required flow speeds especially with large pipe sizes and high volumetric flows. Durand’s method is thus inherently safer and does not require over sizing. Wasp’s method yields lower results, but requires over sizing. Commonly pipe flow speeds should be at least 20 % higher than suggested by Wasp. This overdesign percent is already calculated into the value shown by the tool. In addition, there is evidence suggesting that the deposition velocities are actually lower for complex slurries that contain solid particles of very varying sizes. Also, if the slurry contains fines (particles < 40 µm) that can increase the viscosity of the carrier liquid, settling of all particles is hindered and actual critical deposition velocity is lower.

Flow speeds are presented for the normal flow, minimum flow and maximum flow situations and the calculations are based on the percentages input in the design values box earlier.

PIPELINE												
(select)	mm			mm	m	m	m/s	m/s	m/s	m/s	m/s	
Pipe sizing method	Custom ID	Spec.	DN	ID	Line length	Rough.	Critical deposition velocity (Durand)	Critical deposition velocity (Wasp)	Norm. flow speed	Min. flow speed	Max. flow speed	High flow speed check for norm. flow
Custom	290			290	2	0.0015	3.21	2.06	3.08	1.54	3.39	OK
Spec		E10H2A	250	269	25	0.0015	3.09	2.01	3.58	1.79	3.94	OK
Spec												

Figure 5. Pipe information

The flow speeds are colour coded based on their value in relation to the value of the critical deposition velocities. A green colour represents a flow speed that is equal or larger than Durand’s critical deposition velocity. A yellow colour represents a flow speed that is 20 % larger than Wasp’s critical deposition velocity. As discussed above, a yellow colour does not necessarily mean the flow speed is too slow. Red colour, however, represents a flow speed that is less than 20 % higher than Wasp’s critical deposition velocity and such flow velocity should not be chosen. As noted above, the 20 % overdesign is present in the value calculated by the tool.

The flow speed check is used to test if the flow speed is too high in normal flow situation. The flow speed limits are based on the particle size of the slurry and are used as a rough guideline. The flow speed check doesn't represent any actual limit to operation, like the settling check does. Higher flow speeds are possible, but lead to increased wear of pipes and other components. The limits are as follows:

Particle size	Max. velocity
< 0.08 mm	4 m/s
0.08 – 0.9 mm	5 m/s
0.9 – 4.8 mm	6 m/s
> 4.8 mm	6 m/s (< 400 mm pipe diameter)
	8 m/s (> 400 mm pipe diameter)

Pipe fittings, valves and other

In the next section, the amount of various pipe fittings and valves is input. They are given as the quantity of each specified pipe fitting or valve. If a particular fitting of valve is not present in the line, leave the cell empty or input 0. These are used to calculate dynamic pressure drop in the line. Part of the pipe fittings and valve area is shown in figure 7

PIPE FITTINGS												VALVES	
pcs.	pcs.	pcs.	pcs.	pcs.	pcs.	pcs.	pcs.	pcs.	pcs.	pcs.	pcs.	pcs.	pcs.
90° Bend, r = 1,5d	90° Bend, r = 3d	45° Bend, r = 1,5d	45° Bend, r = 3d	Tee, straight	Tee, angle	Entry in pipe	Out of the pipe	Reducer (1 size)	Reducer (2 sizes)	Increaser (1 size)	Increaser (2 sizes)	Gate	Globe

Figure 7. Part of the pipe fittings and valve area.

Equipments PD

Input the specific pressure drop in kPa that is caused by equipments such as heat exchangers, measurements and other miscellaneous equipment.

Note: The pressure drop from pipe fittings and valves is corrected from water to slurry service. However, the pressure drops for various equipments given as kPa will not be corrected. Consequently, the pressure drops need to be given directly for slurry service. If pressure drop information is not available for slurry, it needs to be approximated.

Total PD

Calculated here is the total dynamic pressure drop in kPa caused by pipe friction, pipe fittings, valves and other equipment. The pressure drop from friction, fittings and valves is initially calculated for water of equivalent volumetric flow and then corrected for the slurry based on density and particle sizing of the slurry. Total pressure drops are presented for each of the three flow values.

NOTE: Due to the way solid particles cause pressure losses in pipelines, it is possible that the minimum flow situation actually has the highest pressure drop in cases where the slurry is very dense and contains a lot of large particles. This should normally only occur in cases where the minimum flow speed is well below the critical deposition velocity. Below the critical deposition velocity bed forming in pipes causes rapidly increasing pressure losses.

Suction conditions

The suction conditions box includes information about the suction line and conditions. The suction line is presented in figure 8. Information needed to input is the design pressure at source, max. pressure at source, design liquid level, maximum liquid level and the elevation of the pump. The pressures at source are given as absolute pressure in kPa, liquid levels and elevation of the pump in meters. Maximum liquid level and max. pressure at source are used to calculate the shut off pressure of the pump. Minimum static head is calculated from the difference of design liquid level and the elevation of the pump. Minimum static head can be negative. It has a pronounced effect on the performance of the pump and care should be given that the values are selected properly.

The values that are input depend on the situation. If the pump is fed from a pump sump or a vessel the inputs are fairly self explanatory; design liquid level being the lowest liquid level in the vessel that is encountered during normal operation. But for example, if the case is pumps in series, the pressure at source is the discharge pressure of the previous pump and the elevations are zero. To input the elevations a reference level needs to be chosen, which is the lowest point in the whole system. For example, if the pump is the lowest point in the system, elevation of the pump is zero. Elevation from sea level can also be used.

The line tag input is used to select which pipe is used as the suction line. Usually line 1 is used as the pipe suction line. The tool then calculates the rest of the values, most important of which are the suction pressure and NPSHA, which is presented both in kPa and meters. NPSHA stands for Net Positive Suction Head Available. It is used to ensure that no cavitation occurs. Cavitation occurs when the absolute pressure (the suction pressure) at the suction inlet or the pump impeller eye falls below the vapour pressure of the liquid, causing the liquid to boil. Cavitation reduces the efficiency and head of the pump and can even physically damage the pump. Pump manufacturers specify required NPSH values (NPSHR) for their pumps. NPSHA needs to exceed the NPSHR. Typically the easiest way to increase the NPSHA is to increase the minimum static head on the suction side or the design pressure at source.

SUCTION CONDITIONS				
NAME:	Pump sump 301-TK-801			
Design pressure at source	kPa (a)	101		
Max. pressure at source	kPa (a)	150		
Min. liquid level	m	2		
Max.liquid level	m	5		
Elevation of pump	m	0		
Min. static head	m	2		
Min. static pressure	kPa	26		
PRESSURE LOSSES				
line tag	line name	NORM	MIN	MAX
1	Suction line	59	28	69
		NORM	MIN	MAX
Pressure losses	kPa	59	28	69
Suction pressure	kPa	68	99	58
Fluid vapour pressure	kPa	2.33	2.33	2.33
NPSH (AV)	kPa	66	97	56
NPSH (AV)	m	5	7	4

Figure 8. Suction conditions

Discharge conditions, 1 discharge

Presented in figure 9, are the discharge conditions. When only one discharge is selected, only the leftmost discharge condition box is in use.

The required inputs are the (absolute) pressure at destination in kPa and the maximum liquid levels in meters. In a simple situation, such as pumping into a vessel, the pressure at destination indicates the pressure inside the vessel and max. liquid is the max liquid level the pump might have to pump against. In other situations the values need to be adapted accordingly. For example, when pumping into a hydrocyclone that requires a 150 kPa overpressure and is located 20 meters above the chosen reference level, input 250 kPa (When atmospheric pressure is 100 kPa) into pressure at destination and 20 meters into the max. liquid level. The atmospheric pressure presented in the operating conditions box is used by default as the destination pressure. Elevation of pump is automatically obtained from the suction conditions.

DISCHARGE CONDITION					1
NAME:	Discharge 1				
Pressure at destination		kPa (a)	101		
Max. liquid level		m	15		
Elevation of pump		m	0		
Max. static head		m	15		
Max. static pressure		kPa	183		
PRESSURE LOSSES					
line tag	line name		NORM	MIN	MAX
2	pressure line		106	72	121
	Not in use				
	Not in use				
	Not in use				
	Not in use				
	Not in use				
	Not in use				
	Not in use				
SUM OF PRESSURE LOSSES			106	72	121
PRESSURE LOSSES			NORM	MIN	MAX
Fittings+friction			105.5	72.4	121.4
Heat exchangers			0.0	0.0	0.0
Misc. Equipments			0.0	0.0	0.0
Measurements			0.0	0.0	0.0
SUM OF PRESSURE LOSSES			105.5	72.4	121.4
Discharge pressure		kPa	390	357	406
Suction pressure		kPa	124	122	124
Pressure difference		kPa	265	235	281
Head		m	22	19	23
Hydraulic power		kW	53	24	62
Max. suction pressure		kPa	211	211	211
Shut off pressure		kPa	572	535	591

Figure 9. Discharge conditions for one discharge

The line tags are used to select the pipes that are in the discharge side of the pump. In the simplest situation, the only line is number 2, the pressure line pipe. Leave unused line tags empty, as pressure losses for each line are summed to obtain the total dynamic pressure drop for the system. In addition, the pressure drops are divided into different components to ease evaluation and to see what is causing the pressure losses.

The total discharge pressure is then calculated by summing static pressure difference, destination pressure and pressure losses. Total pressure difference required from the pump is obtained by subtracting suction pressure from the discharge pressure. The results are also presented as (slurry) head in meters. Hydraulic power is also calculated. Pump and engine efficiencies are required if total power draw is to be calculated (not supported in this tool). For information, maximal suction pressure and shut off pressure are presented.

Discharge conditions, several discharges

The tool supports up to three individual discharges that are connected to the same pump. The tool can be used to compare three different discharge points to find which one inflicts the highest pressure difference for the pump, being the case that should be used to size the pump.

To compare different discharges, select the appropriate number of discharges from the discharge number selector and define all pipelines. Some pipelines may need to be divided to several parts. See figure 10 for an illustrated example.

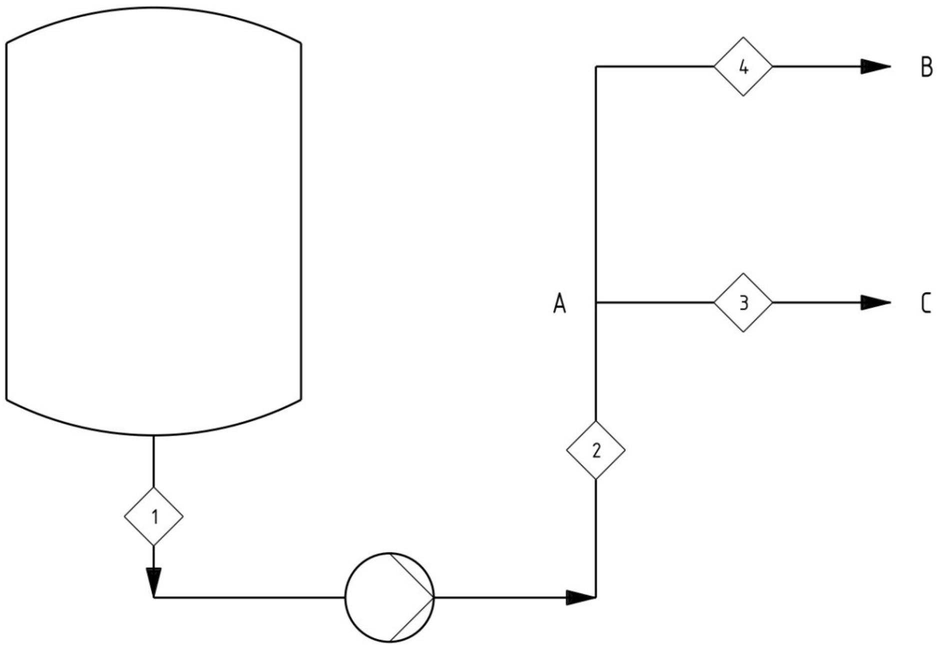


Figure 10. Example flowsheet for several discharges

For the example situation presented in figure 10, pipes 1, 2, 3 and 4 need to be defined in the line section. Line 1 is the suction line. Line 2 from the pump to the branch point A is the pump pressure side discharge line that is common for both discharges. Lines should also be divided into separate parts if the size changes.

Lines 1 and 2 should have the same mass balance information. Similarly, the sum of lines 3 and 4 equals to line 2.

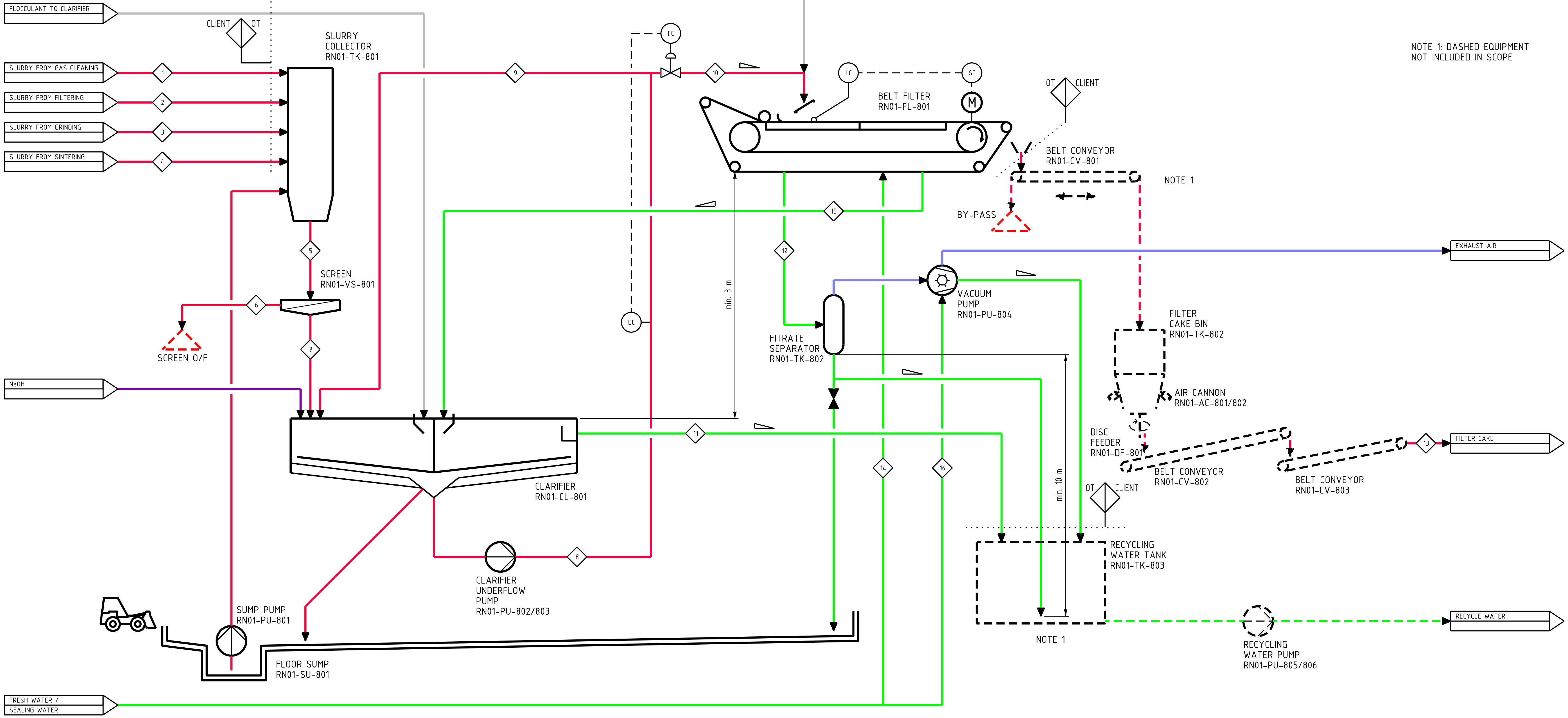
Discharge going to point B will be formed from lines 2 and 4. These line tags are assigned into the first discharge condition box. Discharge going to point C will be formed from lines 2 and 3. These line tags are assigned into the second discharge condition box. Destination pressure and elevation information are input the same way as for single discharge. The tool will automatically determine the sizing case and use data from the corresponding discharge conditions box to print values into the pump data sheet.

Note: When using this tool to design piping systems with more than one discharge, it is important to notice that this can lead to a situation where the pump produces too much head for the lesser discharges. In practice, additional throttling needs to be added to these discharges to balance the system.

Pump data sheet

Values from the calculation sheet are automatically used on the pump data sheet. Some values require user input. Revision control, fluid data and construction requirements in the first pump data sheet page need to be set manually. Additionally, the diagram on the second page of the pump data sheet can be manipulated to approximately illustrate the system.

APPENDIX E (1/4)



STREAM NUMBER	UNIT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
STREAM UNIT		SLURRY FROM GAS CLEANING	SLURRY FROM FILTERING SUMP	SLURRY FROM GRINDING SUMP	SLURRY FROM SINTERING AREA SUMP	TO SCREEN	SCREEN O/F	TO THICKENER	THICKENER UNDERFLOW / SLURRY TO FILTER	THICKENER RECYCLE	BELT FILTER FEED	THICKENER OVERFLOW	FILTRATE FROM BELT FILTER	FILTER CAKE	FILTER BELT/CLOTH WASH WATER	FILTER BELT/CLOTH WASH WATER	VACUUM PUMP SEALING WATER
STREAM CODE		PSL	PSL	PSL		PSL		PSL	PSL	PSL	PSL	WPR		PSL	WFR	WPR	WFR
SOLIDS	t/h	1.4	0.2	0.01	0.002	1.6	0.10	1.5	10.6	9.2	1.5			1.5			
WATER	t/h	212.7	14.0	0.5	0.1	227.3		227.3	31.4	27.0	4.4	230.4	4.3	0.1	7.5	7.5	4.5
NOMINAL FLOW /TOTAL	t/h	214.1	14.2	0.5	0.1	228.7		228.7	42.0	36.1	5.9	230.4	4.3	1.5	7.5	7.5	4.5
NOMINAL FLOW / TOTAL	m3/h	213.0	14.0	0.5	0.1	227.6		227.6	35.0	30.1	4.9	230.4	4.3		7.5	7.5	4.5
SOLID CONTENT	g/l	6.4	15.0	20.0	20.0	7.0		7.0	304.0	304.0	304.0	0.0					
C_W	%	0.64 %	1.48 %	1.98 %	1.98 %	0.69 %		0.65 %	25.3 %	25.3 %	25.3 %						
TEMPERATURE, Max	C	50	30	30	30	50		50	40	40	40	40	40	30			
PRESSURE, Max P (gauge)	kPa	700	400	400	400	By gravity	By gravity	By gravity			By gravity	By gravity			300	By gravity	300
SLURRY DENSITY	kg/l	1.005	1.013	1.01	1.01	1.005		1.005	1.2	1.2	1.2	1	1				
SOLID d-80	mm	0.1	0.07	0.07	0.07	0.1		0.1	0.1	0.1	0.1		0.1				
SOLID d-50	mm	0.05	0.04	0.04	0.04	0.05	2	0.05	0.05	0.05	0.05		0.05				
MOISTURE, max	%													15			
BULK DENSITY	t/m3													2.2			

REV. | NAME DATE PREPARED | NAME DATE CHECKED | NAME DATE APPROVED | REVISION TEXT

STATUS | UNITS | SCALE | SIZE A1

CUSTOMER | PROJECT PHASE Conseptual study | SITE NO

PROJECT NAME | CUSTOMER DOCUMENT NO

REPLACED BY | REPLACES | LANGUAGE English

Outotec

DOCUMENT TITLE
Process flow diagram
Sintering plant (steel belt)
Water treatment

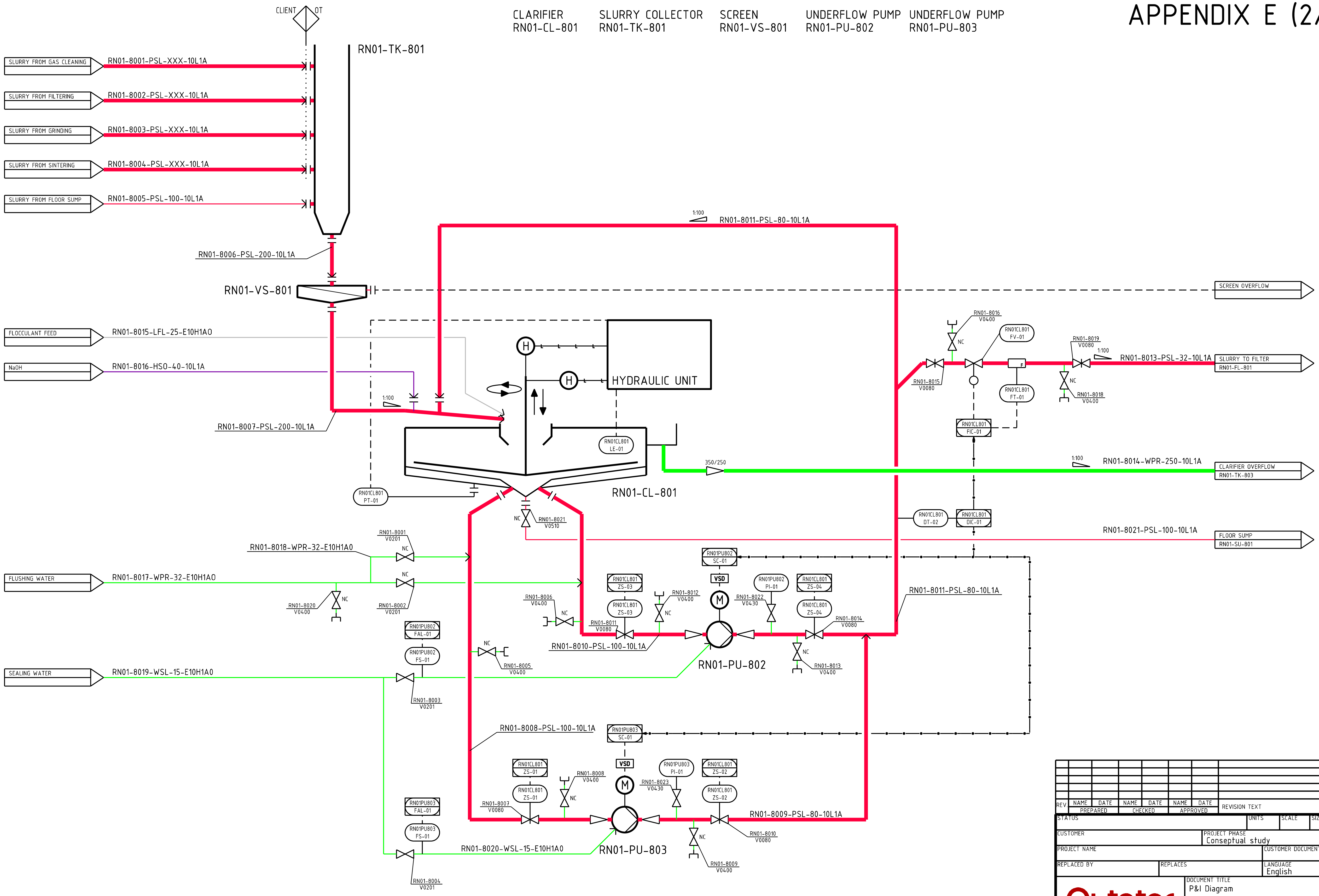
EQUIPMENT NO.

PROJECT ID	PLANT CODE	PLANT UNIT CODE	DOCUMENT TYPE	COUNTING NO	REVISION	SHEET OF SHEETS
–	PSB01	RN01	PFB01	00001		1 / 1

Document ID

APPENDIX E (2/4)

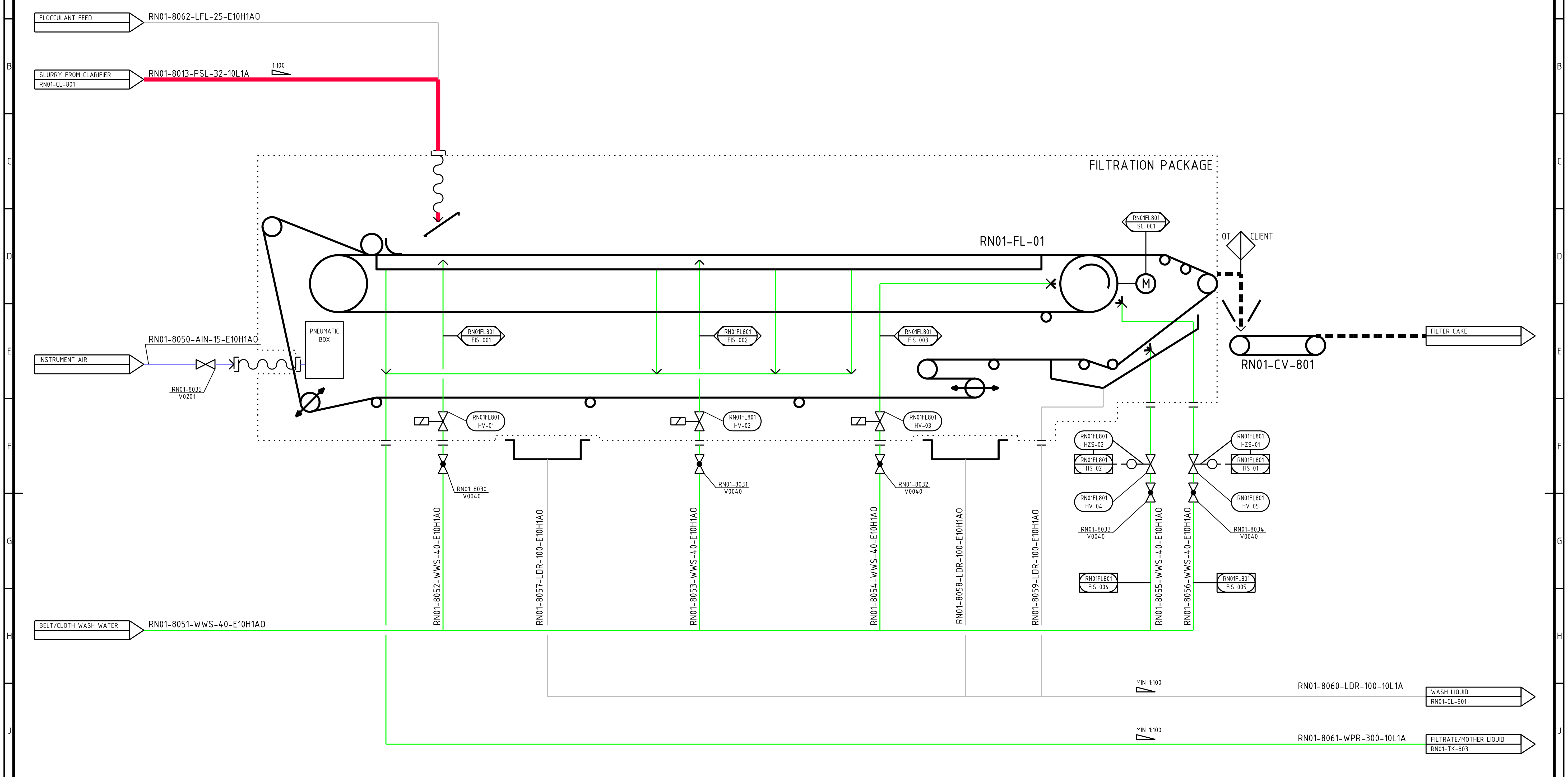
CLARIFIER RN01-CL-801 | SLURRY COLLECTOR RN01-TK-801 | SCREEN RN01-VS-801 | UNDERFLOW PUMP RN01-PU-802 | UNDERFLOW PUMP RN01-PU-803



REV	NAME / DATE (PREPARED)	NAME / DATE (CHECKED)	NAME / DATE (APPROVED)	REVISION TEXT		
STATUS			UNITS	SCALE	SIZE A1	
CUSTOMER		PROJECT PHASE Conseptual study			SITE NO	
PROJECT NAME			CUSTOMER DOCUMENT NO			
REPLACED BY	REPLACES		LANGUAGE English			
Outotec	DOCUMENT TITLE P&I Diagram Sintering plant (steel belt) Water treatment Clarifier RN01-CL-801					
EQUIPMENT NO.						
PROJECT ID –	PLANT CODE PSB01	PLANT UNIT CODE RN01	DOCUMENT TYPE PFB06	COUNTING NO 00001	REVISION	SHEET OF SHEETS 1 / 1

Document ID

APPENDIX E (3/4)



REV | NAME | DATE | NAME | DATE | NAME | DATE | REVISION TEXT
PREPARED | CHECKED | APPROVED

STATUS | UNITS | SCALE | SIZE A1

CUSTOMER | PROJECT PHASE Conseptual study | SITE NO

PROJECT NAME | CUSTOMER DOCUMENT NO

REPLACED BY | REPLACES | LANGUAGE English

Outotec

DOCUMENT TITLE
P&I Diagram
Sintering plant (steel belt)
Water treatment
Belt filter RN01-FL-801

EQUIPMENT NO.

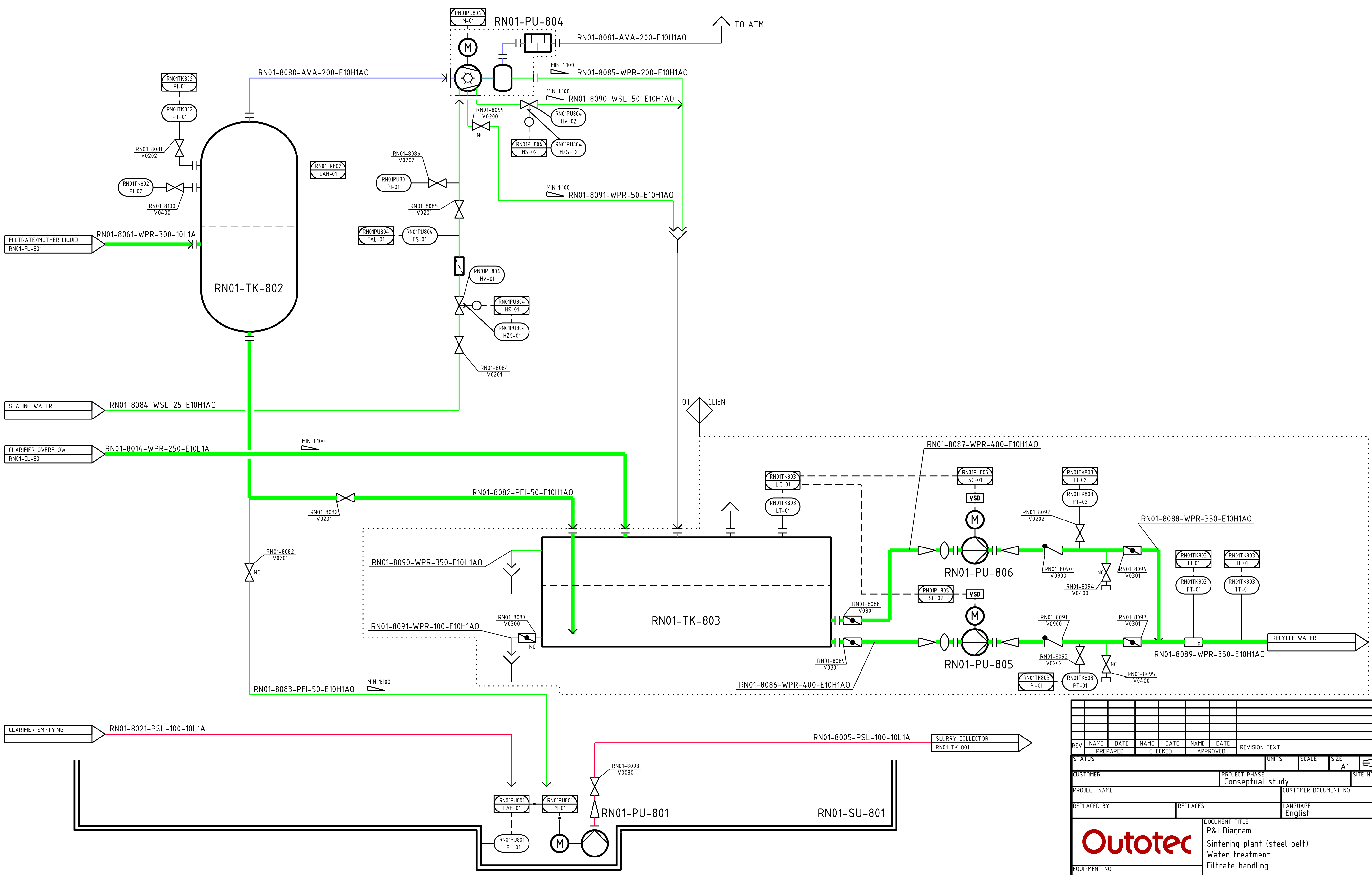
PROJECT ID	PLANT CODE	PLANT UNIT CODE	DOCUMENT TYPE	COUNTING NO	REVISION	SHEET OF SHEETS
-	PSB01	RN01	PFB06	00002		1 / 1

Document ID

Outotec A1
ISO 5457

APPENDIX E (4/4)

FILTRATE SEPARATOR RN01-TK-802 | FLOOR SUMP RN01-SU-801 | SUMP PUMP RN01-PU-801 | VACUUM PUMP RN01-PU-804 | RECYCLING WATER TANK RN01-TK-803 | RECYCLING WATER PUMP RN01-PU-805 | RECYCLING WATER PUMP RN01-PU-806



REV	NAME	DATE	NAME	DATE	NAME	DATE	REVISION TEXT
	PREPARED		CHECKED		APPROVED		

STATUS | UNITS | SCALE | SIZE A1

CUSTOMER | PROJECT PHASE: Conseptual study | SITE NO

PROJECT NAME | CUSTOMER DOCUMENT NO

REPLACED BY | REPLACES | LANGUAGE: English

Outotec

DOCUMENT TITLE: P&I Diagram
Sintering plant (steel belt)
Water treatment
Filtrate handling

EQUIPMENT NO.

PROJECT ID	PLANT CODE	PLANT UNIT CODE	DOCUMENT TYPE	COUNTING NO	REVISION	SHEET OF SHEETS
-	PSB01	RN01	PFB06	00003		1 / 1

Document ID

Outotec

PROCESS DATA FOR SLURRY PUMP CALCULATION

fill up	calculated	constant

ID		
Project name	Sintering water treatment	
Customer name	Outotec	
Plant unit description	Water treatment	
Project no.	-	
Document no.	-	
Pump tag	RN01-PU-802/803	
Pump name	Clarifier underflow pump	
Pump P&I diagram	Sintering_water_treatment_PI_diagram_01	

NUMBER OF DISCHARGES		
#	2	(select)

OPERATING CONDITIONS		
Altitude	0	m
Gravity	9.81	m/s^2
Athmospheric pressure	101.325	kPa

FLUID PROPERTIES		
Fluid	Water	(select)
Temperature	20	°C
Water viscosity	1.00	cP
Water density	998.21	kg/m^3
Water vapor pressure	2.33	kPa
Viscosity (other fluid)		cP
Density (other fluid)		kg/m^3
Vapour pressure (other fluid)		kPa

SOLIDS PROPERTIES		
d_{50}	50	µm
d_{85}	120	µm
Density	2923	kg/m^3
Grading	Wide	(select)
F_L	0.76	

DESIGN VALUES		
MIN	100.0	%
MAX	0.0	%

LINE / MASS BALANCE / PIPELINE

Line tag	Line name	Fluid name	Slurry total normal mass flow (tph)	Slurry concentration by weight (w/w, %)	Slurry concentration by volume (v/v, %)	Slurry density (kg/m^3)	Slurry total normal volumetric flow (m^3/h)	Slurry total min. volumetric flow (m^3/h)	Slurry total max. volumetric flow (m^3/h)	Pipe sizing method (select)	Custom ID (mm)	Spec.	DN	ID (mm)	Line length (m)	Rough. (m)	Critical deposition velocity (Durand) (m/s)	Critical deposition velocity (Wasp) (m/s)	Norm. flow speed (m/s)	Min. flow speed (m/s)	Max. flow speed (m/s)	High flow speed check for norm. flow
1	Suction line	Process slurry	42	25.3	10.4	1197.75	35.07	35.07	35.07	Spec		10L1A01	100	96.8	1	0.0000015	1.45	1.13	1.32	1.32	1.32	OK
2	pressure line	Process slurry	42	25.3	10.4	1197.75	35.07	35.07	35.07	Spec		10L1A01	80	79.2	14	0.0000015	1.31	1.06	1.98	1.98	1.98	OK
3	Clarifier circulation line	Process slurry	36.1	25.3	10.4	1197.75	30.14	30.14	30.14	Spec		10L1A01	80	79.2	13	0.0000015	1.31	1.06	1.70	1.70	1.70	OK
4	Belt filter feed line	Process slurry	5.9	25.3	10.4	1197.75	4.93	4.93	4.93	Spec		10L1A01	32	35.2	2	0.0000015	0.88	0.81	1.41	1.41	1.41	OK
5										Spec												
6										Spec												
7										Spec												
8										Spec												
9										Spec												
10										Spec												
11										Spec												
12										Spec												
13										Spec												
14										Spec												
15										Spec												
16										Spec												
17										Spec												
18										Spec												
19										Spec												
20										Spec												
21										Spec												

PIPE FITTINGS

Line tag	90° Bend, r = 1,5d (pcs.)	90° Bend, r = 3d (pcs.)	45° Bend, r = 1,5d (pcs.)	45° Bend, r = 3d (pcs.)	Tee, straight (pcs.)	Tee, angle (pcs.)	Entry in pipe (pcs.)	Out of the pipe (pcs.)	Reducer (1 size) (pcs.)	Reducer (2 sizes) (pcs.)	Increaser (1 size) (pcs.)	Increaser (2 sizes) (pcs.)
1				1			1	1	1			
2		1					1	1			1	
3		2			1		1	1				
4				2		1	1	1				
5–21												

SUCTION CONDITIONS

NAME: Clarifier RN01-CL-801

Design pressure at source	kPa (a)	101		
Max. pressure at source	kPa (a)	101		
Min. liquid level	m	2.5		
Max.liquid level	m	4.3		
Elevation of pump	m	0		
Min. static head	m	2.5		
Min. static pressure	kPa	29		
PRESSURE LOSSES				
line tag	line name	NORM	MIN	MAX
1	Suction line	2	2	2
		NORM	MIN	MAX
Pressure losses	kPa	2	2	2
Suction pressure	kPa	128	128	128
Fluid vapour pressure	kPa	2.33	2.33	2.33
NPSH (AV)	kPa	126	126	126
NPSH (AV)	m	11	11	11

DISCHARGE CONDITION 1

NAME: Clarifier recycle

Pressure at destination	kPa (a)	101		
Min. liquid level	m	0		
Max. liquid level	m	11		
Elevation of pump	m	0		
Max. static head	m	11		
Max. static pressure	kPa	129		
PRESSURE LOSSES				
line tag	line name	NORM	MIN	MAX
2	pressure line	14	14	14
3	Clarifier circulation line	13	13	13
	Not in use			
	Not in use			
	Not in use			
	Not in use			
	Not in use			
	Not in use			
SUM OF PRESSURE LOSSES		27	27	27
PRESSURE LOSSES		NORM	MIN	MAX
Fittings+friction		26.8	26.8	26.8
Heat exchangers		0.0	0.0	0.0
Misc. Equipments		0.0	0.0	0.0
Measurements		0.0	0.0	0.0
SUM OF PRESSURE LOSSES		26.8	26.8	26.8
Discharge pressure	kPa	257	257	257
Suction pressure	kPa	128	128	128
Pressure difference	kPa	129	129	129
Head	m	11	11	11
Hydraulic power	kW	1.3	1.3	1.3
Max. suction pressure	kPa	152	152	152
Shut off pressure	kPa	337	337	337

DISCHARGE CONDITION 2

NAME: feed to belt filter RN01-FL-801

Pressure at destination	kPa (a)	101		
Min. liquid level	m	0		
Max. liquid level	m	8		
Elevation of pump	m	0		
Max. static head	m	8		
Max. static pressure	kPa	94		
PRESSURE LOSSES				
line tag	line name	NORM	MIN	MAX
2	pressure line	14	14	14
4	Belt filter feed line	6	6	6
	Not in use			
	Not in use			
	Not in use			
	Not in use			
	Not in use			
	Not in use			
SUM OF PRESSURE LOSSES		20	20	20
PRESSURE LOSSES		NORM	MIN	MAX
Fittings+friction		19.9	19.9	19.9
Heat exchangers		0.0	0.0	0.0
Misc. Equipments		0.0	0.0	0.0
Measurements		0.0	0.0	0.0
SUM OF PRESSURE LOSSES		19.9	19.9	19.9
Discharge pressure	kPa	215	215	215
Suction pressure	kPa	128	128	128
Pressure difference	kPa	87	87	87
Head	m	7	7	7
Hydraulic power	kW	1	1	1
Max. suction pressure	kPa	152	152	152
Shut off pressure	kPa	286	286	286

DISCHARGE CONDITION — NOT IN USE

NAME: Discharge 3

Pressure at destination	kPa (a)	101		
Min. liquid level	m	0		
Max. liquid level	m	20		
Elevation of pump	m	0		
Max. static head	m	20		
Max. static pressure	kPa	235		
PRESSURE LOSSES				
line tag	line name	NORM	MIN	MAX
	Not in use			
	Not in use			
	Not in use			
	Not in use			
	Not in use			
	Not in use			
	Not in use			
	Not in use			
SUM OF PRESSURE LOSSES		0	0	0
PRESSURE LOSSES		NORM	MIN	MAX
Fittings+friction		0.0	0.0	0.0
Heat Exchangers		0.0	0.0	0.0
Misc. Equipments		0.0	0.0	0.0
Measurements		0.0	0.0	0.0
SUM OF PRESSURE LOSSES		0.0	0.0	0.0
Discharge pressure	kPa	336	336	336
Suction pressure	kPa	128	128	128
Pressure difference	kPa	208	208	208
Head	m	18	18	18
Hydraulic power	kW	2	2	2
Max. suction pressure	kPa	152	152	152
Shut off pressure	kPa	431	431	431

PUMP SIZING CASE

Discharge	Head (max)
1	11
2	7

MAX HEAD (DESIGN): 11

SIZING CASE

Discharge Condition	1

Outotec	PUMP DATA SHEET	ITEM: *RN01-PU-802/803* Clarifier underflow pump	PAGE 1/2

PROJECT NAME	Sintering water treatment	PLANT UNIT DESC.	Water treatment
		PROJECT NO	-
CLIENT	*Outotec*	DOCUMENT NO	-

REV.	DATE	PROJECT PHASE	PURPOSE OF USE	PREPARED	CHECKED	RELEASED
1						
2						
3						

FLUID DATA			*Rev.*
Fluid	Process slurry		
Corrosive	○ YES ◉ NO	Due to:	
Toxic	○ YES ◉ NO	Due to:	
Hazardous in air	○ YES ◉ NO	Due to:	
Gas present	○ YES ◉ NO	Quality, quantity:	

OPERATING CONDITIONS			*Rev.*	FLOW CONDITIONS			*Rev.*
Temperature	°C	20		Particle size d_{50}	µm	50	
Viscosity of carrier fluid	cP	1.00		Particle size d_{85}	µm	120	
Slurry density	kg/m^3	1198		Normal flow	tph	42	
Solid particle density	kg/m^3	2923		Normal flow	m3/h	35	
Solid conc. by weight	%	25.3		Minimum flow	m3/h	35	
Solid conc. by volme	%	10.4		Design flow	m3/h	35	

SUCTION CONDITIONS				*Rev.*	DISCHARGE CONDITIONS				*Rev.*
Min. liquid level	m	2.5			Max. liquid level	m	11		
Elevation of pump	m	0			Elevation of pump	m	0		
Min. static head	m	2.5			Max. static head	m	11		
Min. static pressure diff.	kPa	29			Max. static pressure diff.	kPa	129		
SUCTION LOSSES		Norm.	Design		PRESSURE LOSSES		Norm.	Design	
Fittings+friction	kPa	2	2		Fittings+friction	kPa	27	27	
Heat exchangers	kPa	0	0		Heat exchangers	kPa	0	0	
Misc. Equipments		0	0		Misc. equipments	kPa	0	0	
Measurements		0	0		Measurements	kPa	0	0	
SUM OF SUCTION LOSSES	kPa	2	2		SUM OF PRESSURE LOSSES	kPa	27	27	
Pressure at source	kPa	101	0		Pressure at liquid level	kPa	101	101	
Suction pressure	kPa	128	128		Discharge pressure	kPa	257	257	
Fluid vapour pressure	kPa	2	2		Suction pressure	kPa	128	128	
NPSH	kPa	126	126		Pressure difference	kPa	129	129	
NPSH	m	11	11		Head (in meters of slurry)	m	11	11	
					Hydraulic power	kW	1.26	1.26	
					Max. suction pressure	kPa	152	152	
					Shut off pressure	kPa	337	337	

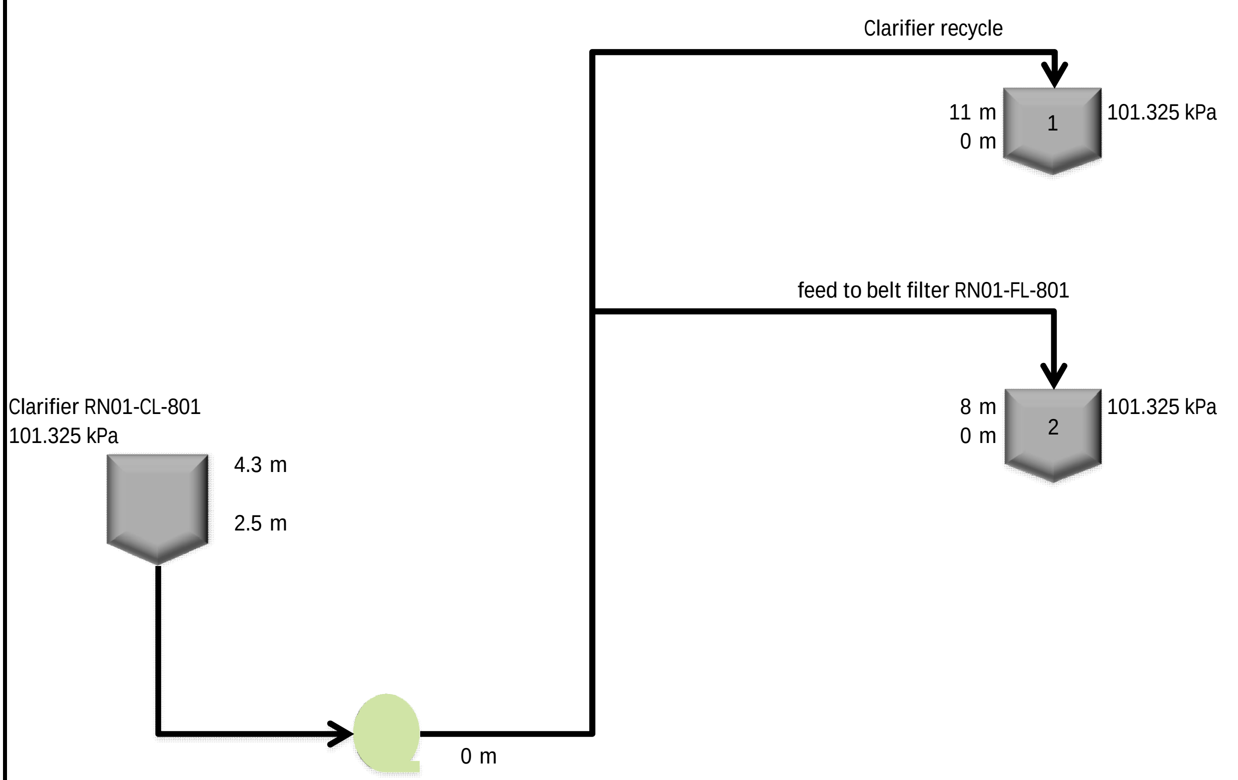
CONSTRUCTION REQUIREMENTS		*Rev.*			*Rev.*
Location	○ INDOORS ◉ OUTDOORS		Driving force	Electricity	
			Frquency controlled	◉ YES ○ NO	
Min. temperature °C	0				
Max. Temperature °C	300		Sealing Type	Packing	
Proposed pump type	Centrifugal pump		Area classification (GAS)	Non-Hazardous area	
Proposed material	Stainless Steel		Area Classification (DUST)	Zone 20	

ADDITIONAL INFORMATION	*Rev.*

Outotec	PUMP DATA SHEET	ITEM *RN01-PU-802/803* Clarifier underflow pump		PAGE 2/2
PROJECT NAME	Sintering water treatment	PLANT SECTION	Water treatment	
		PROJECT NO	-	
CLIENT	*Outotec*	DOCUMENT NO	-	

REV.	DATE	PROJECT PHASE	PURPOSE OF USE	PREPARED	CHECKED	RELEASED
1						
2						
3						

P&I-diagram: Sintering_water_treatment_PI_diagram_01



ADDITIONAL INFORMATION	*Rev.*