Norwegian University of Life Sciences
Faculty of Environmental Science and Technology
Department of Mathematical Science and Technology

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# Pressurized sewage systems and self-cleansing process

Petar Popovic

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**Abstract**

This master thesis explores the performance of pressurized sewage systems and its effect on self-cleansing of distribution pipes. Pressure sewage systems are mostly applied in non-urban areas where these systems connect and distribute wastewater from household to the main sewage pipeline. The biggest concern for these distribution systems is the possible accumulation of sediments in the sewer pipes, although it is a common phenomenon.

The main goal of this thesis is to demonstrate that pressurized sewage systems can achieve the self-cleansing process even with velocities that are lower than defined by standards.

The test was conducted at Norwegian University of Life Sciences (NMBU) in Ås, Norway. In this project, observation of wastewater distribution through Environment One (E/One) grinder pump and pressurized pipes was conducted and analyzed.
This project was designed to reproduce the real setting as close as possible from the wastewater tank, which represents wastewater source in this case, to the gravitational sewer as a final recipient.

Through the analysis, the thesis argues that pressurized sewer system represents a potentially good solution for wastewater distribution in non-urban areas. These systems are achieving self-cleansing effect in pipes, which makes them efficient, self-sustainable and safe for the purpose of distributing wastewater from household to the main sewer.

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## Part 1: Introduction

### 1. Introduction

Wastewater distribution system is one of the fundamental elements of urban and rural infrastructure. The main purpose of wastewater distribution networks is to safely convey wastewater from the households to the final recipient, which in most cases is wastewater treatment plant. The type of wastewater distribution system has impact on the selection of final recipient. Distribution systems are divided into two groups: conventional (centralized) and pressurized (decentralized) sewage systems. Pressurized sewage systems represents decentralized sewage system that mostly used to deliver/convey wastewater from household to a gravitational system from where wastewater is later distributed to the treatment plant. The main characteristics of this system are independence from gravity and smaller diameter pipes while movement of fluid in conventional sewage system is totally dependent on the presence of gravity. Also, conventional systems consist of bigger diameter pipes and usually they are installed/placed on higher depth with the compulsory inclination. Therefore, main sewage lines in urban areas are conventional type while pressurized sewage system is more optimal to rural areas.
Distribution of wastewater is considered safe when the system does not leak or pollute the surrounding environment. However, the biggest concern for all distribution systems is accumulation of sediments in the sewer pipes, which often affects flow characteristics inside the pipes.

The accumulation of sediments within the pipes mostly occurs within the gravitational pipes at lower flow velocities. Sedimentation in sewage pipes causes reduction in cross section of the pipe, which also changes the flow capacity within the pipe itself. Besides sedimentation, hydrogen sulfide ($H_2S$) can also be present in sewers. This gas is toxic and it is one of the main factors that may cause corrosion in the pipes. These problems are causing serious damage to wastewater distribution systems, causing leakage of pipes, and increasing the maintenance cost of the system. Undesirable leakages of sewage pipes are also a threat to the environment.

While conventional/gravity sewage system has these issues, pipe leakage is practically impossible for pressurized sewer systems unless the pipes are physically damaged on purpose, because accidental damages occur very rarely for this system.

In this thesis, pressurized sewer systems will be analyzed along with the self-cleansing effect in the pipes. The self-cleansing effect depends on the following parameters such as, constant flow and an adequate velocity of liquid that runs through the pipe, shear stress. This effect also prevents possible corrosion of the pipes. The project aims to investigate possible accumulation of sediments on the bottom of the pipes during daily operation of the pump.
Based on this analysis, further objective of the project is to revaluate the current national standard for self-cleansing of pipes in pressurized sewage systems. In Norway, generally accepted standard for minimum velocity is 0.7 m/s (Norsk Standard, 1997).

Thus, this master thesis points out the main advantages of the pressure sewer system and challenges the defined standards regarding the required velocities for self-cleansing by answering the following research question:

Is it possible to achieve self-cleansing process/effect within a pressurized sewage system with the velocity under 0.6-0.7 m/s for SDR11 PE 40, 50 and 63mm pipes?

To find an answer to this problem, the performance of both gravitational and pressurized sewage systems has been analyzed. Both the criteria and the method of testing will be described and documented in this report. All influential parameters and elements that play an important role in the following test have been defined, for the purposes of better understanding. This project only refers for the distribution of household wastewater through pressurized sewage systems, which means that storm water is excluded.
The results of study are based on observation method where the performance of pressurized sewage system and self-cleansing were followed for the period from 4th of August to 17th of September.

Lastly, this master thesis contains a theoretical and a practical part: theoretical part discusses relevant theories and practical part analyzes and describes the test procedure.

The problem of accumulation of sediments in pipes is widespread in all sewer systems and it is my hope that this project will contribute to further discussion, which might eventually lead to revising the defined National Standards/requirements for self-cleansing and the required minimum velocity for pressurized sewage systems.
This is the main reason why I have decided to study this topic, to point out the weakness of current defined velocity standard for self-cleansing, and to inform people that current requirements are not following the latest knowledge and technology. Therefore the requirement for self-cleansing velocity in pressurized sewage system needs to get reevaluated.

## Part 2: Theory

### 2. Wastewater

According to Jacobsen (2002), wastewater represents a high rate system for microbiological transformations. Generally, wastewater is considered to be a complex microbiological system and the diversity of microorganisms in sewers is massive. Microorganisms are therefore classified into specific classes that can be found in sewage biofilm, sewer sediments and water phase. The size of organic matter fractions varies.

Interaction between microorganisms and organic matter within the sewer is constant. Therefore it is important to understand the significance of microorganisms in the sewer and its processes.

Wastewater represents the flow of used water that was generated within the community. Wastewater or sewage originates from household wastes, animal and human wastes, industrial wastewaters, storm runoff and groundwater infiltration (Lin, 2007). Main sources of domestic wastewater in a community are considered to be residential areas and commercial districts (Tchobanoglous, 2003). In 1980, the Water Pollution Control Federation defined that wastewater is approximately 99.94% water by weight, while the remaining 0.06% represents material dissolved or suspended in water (Tchobanoglous, 2003).

Looking back through history, according to ¨Wastewater Engineering Treatment and Reuse¨ from 2003 by Tchobanoglous, prior to 1940's most municipal wastewater was generated from domestic sources. After 1940's, rapid industrial growth significantly increased the amount of wastewater produced. This wastewater was later distributed through the municipal collection systems along with domestic wastewater (Tchobanoglous, 2003). The composition of industrial wastewater differs from the domestic wastewater and contains higher concentrations of heavy metals, the presence of which significantly changes the characteristics of wastewater. The addition of industrial wastewater to the domestic wastewater sewer systems resulted in occurrence of new organic compounds, and it was approximated that around 10.000 new organic compounds were generated every year (Tchobanoglous, 2003). The following elements, which are present in wastewater, are considered to be pollutants: suspended solids, inorganic solids, nutrients, metals, pathogenic microorganisms and biodegradable dissolved organic compounds (Templeton, 2011).

### 2.1. Wastewater quality

Wastewater quality plays an important role in sewers and sewer processes. The sewer is a reactor for primarily microbial processes (Jacobsen, 2002). It also impacts later treatment wastewater processes within the treatment plant. As Jacobsen (2002) stated, the quality of wastewater is closely related to the microbial biodegradability of organic matter.

The composition of municipal wastewater varies from place to place and in certain locations the composition of wastewater also varies with time (Henze, 2008).
The composition of typical municipal wastewater with minor contribution of industrial wastewater is shown in the following table (table 2.1):

**Table 2.1: Typical composition of raw municipal wastewater (Henze, 2008)**

| Parameter | High | Medium | Low |
|---|---|---|---|
| COD total | 1200 | 750 | 500 |
| COD soluble | 480 | 300 | 200 |
| COD suspended | 720 | 450 | 300 |
| BOD | 560 | 350 | 230 |
| VFA | 80 | 30 | 10 |
| N total | 100 | 60 | 30 |
| Ammonia | 75 | 45 | 20 |
| P total | 25 | 15 | 6 |
| Ortho P | 15 | 10 | 4 |
| TSS | 600 | 400 | 250 |
| VSS | 480 | 320 | 200 |

The following table 2.2, presents the elements of wastewater and its impact on both environment and human health.

**Table 2.2: Constituents present in domestic wastewater (Henze et 2001)**

| **Wastewater constituents** | | |
|---|---|---|
| Microorganisms | Pathogenic bacteria, virus and worms eggs | Risk when bathing and eating shellfish |
| Biodegradable organic materials | Oxygen depletion in rivers, lakes and fjords | Fish death, odours |
| Other organic materials | Detergents, pesticides, fat, oil, coloring solvents, phenols, cyanide, nitrogen, phosphorus | Toxic effect, aesthetic inconveniences, bioaccumulation in the food chain |
| Nutrients | Nitrogen, phosphorus, ammonium | Eutrophication, oxygen depletion, toxic effect |
| Metals | Hg, Pb, Cd, Cr, Cu, Ni | Toxic effect, bio-accumulation |
| Other inorganic materials | Acids, for example hydrogen sulphide, bases | Corrosion, toxic effect |
| Thermal effects | Hot water | Changing living conditions for flora and fauna |
| Odour | Hydrogen sulphide | Aesthetic inconvenience, toxic effect |
| Radioactivity | | Toxic effect, accumulation |

The quality of wastewater is important:

- For mechanical treatment of wastewater (removal of oxygen consuming substances of wastewater BOD and COD, which affect the subsequent treatment procedure)
- For purposes of denitrification and phosphorus removal
- In-sewer presence of gases such as hydrogen sulfide ($H_2S$) and its fermentation represent a serious threat to the pipes (causing corrosion) and the environment (due to toxicity).

Jacobsen (2002) states that wastewater represents a matrix that includes a large variety of microorganisms and organic matter that varies with time and space.
Redox conditions are of great importance within the sewer network for:

- Microbial community
- Microbial processes

- Sewer itself
- Treatment processes
- Environment

### 2.1.1. Wastewater characteristics

Proper understanding of chemical, biological and physical characteristics of wastewater has a direct bearing on the design, operation, treatment and disposal of wastewater (Lin, 2007). The nature of wastewater, which in this case refers to its physical, biological and chemical characteristics, depends on water usage within the community and industry, as well as the weather (Lin, 2007). In ¨Introduction to Wastewater Treatment¨ from 2011 by M. Templeton it is defined that biodegradable organic compounds in wastewater are mainly composed of:

- Proteins (amino acids)
- Carbohydrates (cellulose, sugar, starch)
- Lipids (fats, oils)

Basically all of the above listed elements contain carbon and they can be biologically converted to carbon dioxide (Templeton, 2011). For wastewater treatment it is recommended to remove these biodegradable materials from wastewater in order to avoid higher oxygen demand in later water flow.

#### 2.1.1.1. Physical properties of wastewater

Fresh wastewater is characterized by gray color and musty odor, which is not considered to be unpleasant. The color of wastewater gradually changes over time, from gray to black. With time, foul and unpleasant odors will develop as a consequence of septic sewage. The temperature and solids content in wastewater are considered to be the most important physical characteristics of wastewater. These two characteristics play an important role in wastewater treatment processes as well. The temperature affects biological activities and chemical reactions of the wastewater. On the other hand, the presence of total suspended solids, settleable solids and volatile suspended solids does affect the operation and size of the distribution and treatment units (Lin, 2007).

**Solids** consist of matter present in suspended or dissolved form in both water and wastewater. Solids are divided into several different fractions. The concentration of solids in wastewater represents useful information, which characterizes the wastewater. The concentration of solids in wastewater also determines the manner of control of the wastewater treatment process (Lin, 2007).

**Total solids** (TS) represent the sum of total suspended solids and total dissolved solids. In the Water and Wastewater Calculations Manual from 2007 by Lin (p.534), total solids are defined as the material remaining in the evaporation dish after it has been dried for at least 1 hour (or overnight, which is considered preferable) in an oven at 103°C to 105°C and is calculated according to Standard Methods.

**Total suspended solids** (TSS) represent non-filterable residue. A total suspended solid is a quality parameter of great importance for both water and wastewater. TSS is also considered to be a wastewater treatment effluent standard. Determination of the TSS value is usually done, by a process of filtering a well-mixed sample through a 0.2μm pore size (Lin, 2007).

**Total dissolved solids** (TDS) represent filterable residues. In wastewater, TDS ranges from 250 to 850 mg/L. The value of TDS can be determined by filtration of a well-mixed sample through a standard glass fiber filter of 2.0∓m pore size. The filtrate is later evaporated for at least 1 hour in an oven at 180°C. The increase in dish weight will indicate the amount of total dissolved solids (Lin, 2007).

**Fixed and volatile solids** are determined from the residue of TS, TSS or TDS tests which are later ignited to constant weight at 550°C. The actual weight loss on ignition represents volatile solids. The solids remaining after this process represent fixed total solids. From the volatile portion of solids it is possible to roughly estimate the amount of organic matter present in the solid fraction of the wastewater. This is useful data for controlling wastewater treatment plant operations. It is important to know that determination of volatile and fixed solids does not precisely distinguish between organic and inorganic matter. The process of determination of organic matter can be done through tests for biochemical oxygen demand (BOD), chemical oxygen demand (COD) and total organic carbon (TOC) (Lin, 2007).

A **settleable solid** represents material settling out of suspension within a defined amount of time. Settled solids can be expressed in weight (mg/L) or volume (mL/L). As shown by Lin (2007), determination of settleable solids can be done by different methods:

1. Imhoff cone or
2. Gravimetric method

#### 2.1.1.2. Chemical properties of wastewater

Both suspended and dissolved solids in wastewater contain inorganic and organic material.
Organic matter in wastewater includes:

- Fats
- Carbohydrates
- Proteins
- Pesticides and other agricultural chemicals
- Volatile organic compounds
- Grease
- Surfactants

On the other hand, inorganic matter in wastewater includes:

- Nutrients (nitrogen and phosphorous)
- Heavy metals
- pH
- Alkalinity
- Chlorides
- Sulfur

Certain gases (such as methane, hydrogen sulfide, carbon dioxide, and oxygen) are also present in wastewater (Lin, 2007). Normal ranges for nitrogen levels in raw domestic wastewater are as follows:

1. For total nitrogen from 25 to 85 mg/L (sum of organic nitrogen, ammonia, nitrate, nitrite)
2. Ammonia nitrogen from 12 to 50 mg/L
3. Organic nitrogen from 8 to 35 mg/L (WEF 1996a).

Concentration levels of organic nitrogen can be determined by the Total Kjeldahl Nitrogen (TKN) analysis. This analysis measures the sum of both organic and ammonia nitrogen, allowing for subsequent measurement of organic nitrogen by subtracting ammonia nitrogen from the TKN measurement (Lin, 2007).

The total phosphorus concentration in raw wastewater varies from 2 to 20mg/L. Concentrations of organic phosphorus range from 1 to 5mg/L, while concentrations of inorganic phosphorous range from 1 to 15mg/L (Lin, 2007). Nitrogen and phosphorus are considered crucial elements for biological growth and reproduction of microorganisms during the wastewater treatment process.

Organic content in wastewater can be measured using several methods:

1. Five- day biochemical oxygen demand ($BOD_5$)
   $BOD_5$ analysis measures the amount of oxygen required to oxidize sample organic matter during 5 days of biological stabilization at 20°C. In the United States, $BOD_5$ for domestic raw wastewater lies in the range between 100 and 250mg/L (Lin, 2007).

2. Total organic carbon (TOC), which is defined as an amount of carbon that is bound in an organic compound.

3. Chemical oxygen demand (COD) is defined according to the ¨Water and Wastewater Calculations Manual¨ from 2007 by Lin as a measurement of oxygen equivalent of organic matter content of a sample that is susceptible to oxidation by a strong chemical oxidant. The COD test is useful for controlling and monitoring wastewater treatment processes.

Results of the COD test are obtained much faster than those of the BOD tests. For comparison, a COD test takes 3 to 4 hours, whereas a BOD test takes 5 days. The results of COD tests are also useful for monitoring and controlling wastewater treatment processes. The results of COD analysis are usually higher than values for BOD. For instance, the ratio of nitrogen (N), phosphorus (P) and carbon (C) in wastewater is very important for biological treatment processes. For example, the commonly accepted BOD/N/P ratio for biological treatment is 100/5/1 (Lin, 2007).

#### 2.1.1.3. Biological characteristics of wastewater

Main microorganisms in wastewater are bacteria, protozoa, fungi, viruses, microscopic plants and animals. According to the ¨Water and Wastewater Calculations Manual¨ from 2007 by Lin, presence of certain organisms in wastewater such as viruses, pathogenic bacteria and fungi is considered threatening and dangerous, and their presence in wastewater represents a public concern. Still, most microorganisms are considered to have beneficial effects on the biological wastewater treatment process.

In most cases, pathogenic organisms are excreted by humans from the gastrointestinal tract and later discharged into wastewater. Cholera, typhoid and diarrhea are some of the waterborne diseases caused by pathogenic organisms in wastewater. The concentration of pathogenic organisms in wastewater is considered low in density and that represents a problem, due to the fact that such organisms are difficult to isolate and identify. Indicator bacteria such as total coliform (TC), fecal coliform (FC) and fecal streptococcus (FS) are applied as an indicator of pathogenic organisms (Lin, 2007).

### 2.2. Wastewater quantity

The amount of wastewater produced per person/household is influenced by a number of factors. Economics, climate, lifestyle and water use are just some of the factors that impact the quantity of wastewater. In general the quantity value varies from country to country. The typical average wastewater flow rate from one household in the US is approximately 265 L or around 70 gallons per capita per day. Municipal wastewater is mostly generated from water supply. Around 60-85% of water consumed ends up as wastewater (Lin, 2007).

The determination of wastewater flow rate is usually determined based on population and average per capita consumption of water (Tchobanoglous, 2003). According to the ¨Wastewater Engineering Treatment and Reuse¨ from 2003 by Tchobanoglous, the wastewater flow rate depends on the quality and quantity of water supply, rate structure, economics and social characteristics of the community. AWWARF case study report conducted in Waterloo, Cambridge and Ontario shows how average annual water use varies from place to place (AWWA Research Foundation, 2005). In Waterloo and Cambridge, annual water use per household was approximately 69 900 gallons (264 600 liters). This equates to an average water consumption per household per day of 725 L/d. In Ontario, survey results showed annual water consumption of around 301 100 gallons (1 139 787 L) per household.

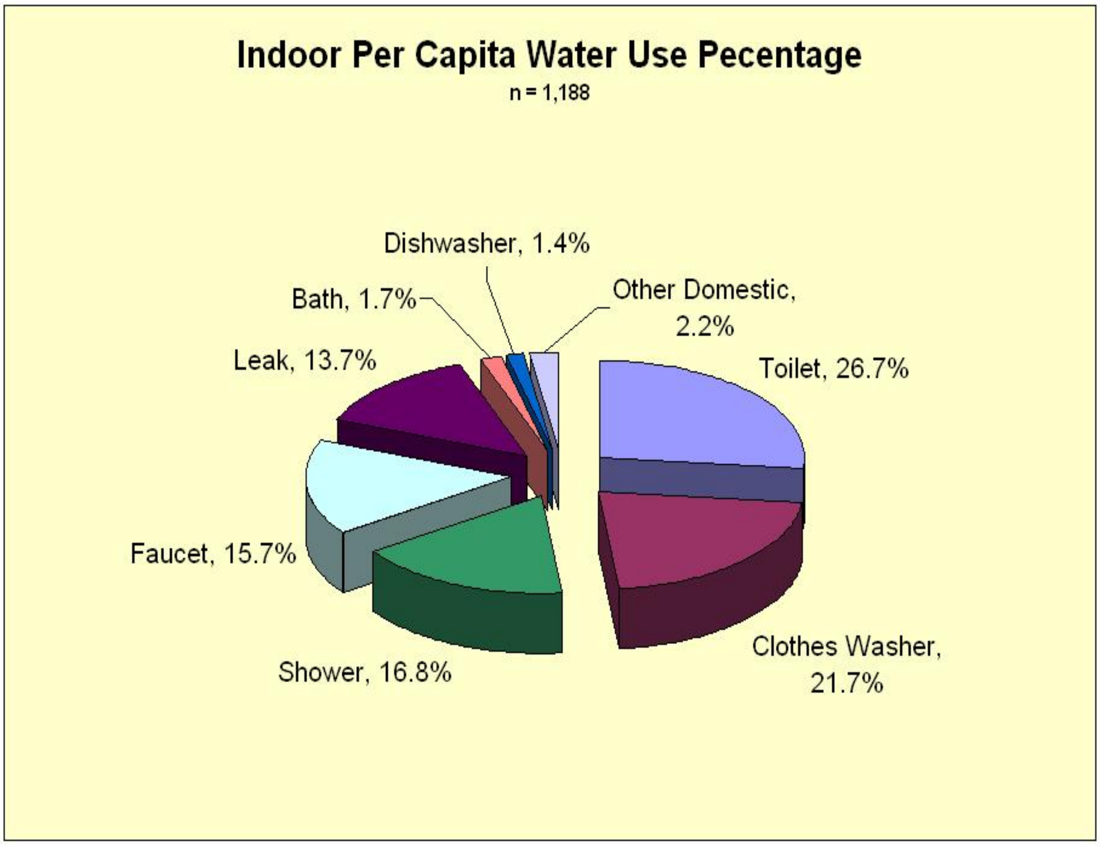


**Figure 2.1: Daily indoor per capital water use percentage (AWWARF)**

**Table 2.3: Typical wastewater flow rates in the USA (Tchobanoglous, 2003)**

| Household size, no. of persons | Flowrate (gal/cap *d) | | Flowrate (l/cap*d) | |
|---|---|---|---|---|
| | Range | Typical | Range | Typical |
| 1 | 75-130 | 97 | 285-490 | 365 |
| 2 | 63-81 | 76 | 225-385 | 288 |
| 3 | 54-70 | 66 | 194-335 | 250 |
| 4 | 41-71 | 53 | 155-268 | 200 |
| 5 | 40-68 | 51 | 150-260 | 193 |
| 6 | 39-67 | 50 | 147-253 | 189 |
| 7 | 37-64 | 48 | 140-244 | 182 |
| 8 | 36-62 | 46 | 135-233 | 174 |

### 2.2.1. Quantity of wastewater constituent concentrations

Tchobanoglous (2003) claims that all three characteristics of wastewater: physical, chemical and biological, vary throughout the day. The quality of the analyses greatly depends on representative samples.

**Table 2.4: Quantity of waste discharge by individuals on dry weight basis in the USA (Tchobanoglous, 2003)**

| | Value, Ib/capital*d | | | Value, g/capital*d | | |
|---|---|---|---|---|---|---|
| Constituent | Range | Typical without ground-up kitchen waste | Typical with ground-up kitchen waste | Range | Typical without ground-up kitchen waste | Typical with ground-up kitchen waste |
| BOD | 0.11-0.26 | 0.18 | 0.22 | 50-120 | 80 | 100 |
| COD | 0.3-0.65 | 0.42 | 0.48 | 110-295 | 190 | 220 |
| TSS | 0.12-0.33 | 0.2 | 0.25 | 60-150 | 90 | 110 |
| NH | 0.01-0.026 | 0.017 | 0.019 | 5-12 | 7.6 | 8.4 |
| Organic N | 0.009-0.022 | 0.012 | 0.013 | 4-10 | 5.4 | 5.9 |
| TKN | 0.02-0.048 | 0.029 | 0.032 | 9-21.7 | 13 | 14.3 |
| Organic P | 0.002-0.004 | 0.0026 | 0.0028 | 0.9-1.8 | 1.2 | 1.3 |
| Inorganic P | 0.004-0.006 | 0.0044 | 0.0048 | 1.8-2.7 | 2.0 | 2.2 |
| Total P | 0.006-0.01 | 0.007 | 0.0076 | 2.7-4.5 | 3.2 | 3.5 |
| Oil and grease | 0.022-0.088 | 0.661 | 0.075 | 10-40 | 30 | 34 |

# 3. Fluid

## 3.1. General

In ¨Mechanics of Fluids¨ by Bernard Massey, fluid is defined as a substance that will deform continuously as long as tangential force is applied to the area on which it acts. This applied force is known as a shear force. On the other hand, shear stress can be defined as the ratio of shear force and the area to which this force is applied (Massey, 2006).

In situations where fluid has no movement, both shear force and shear stress are equal to zero. With fluids, shear forces will form only in situations where movement between layers exists.

Differences between solids and fluids are usually clear. Unlike fluids, solids can resist shear force while at rest (Massey, 2006).

Sometimes, differences between fluids and solids are difficult to distinguish. For instance, some fluids such as thick tar or pitch do not flow easily and in certain situations they may behave more like solids than fluids.

But in general, the main difference between solids and fluids is clear. Any fluid, regardless of its viscosity value, will flow under the action of a net shear force. Net shear force needs to exceed a certain value in order to achieve flowing of solids and, if this condition is not fulfilled, the internal forces within the material will increase and this will only increase resistance to movement (Massey, 2006).

For fluid movement, the only force that opposes movement of one layer over another is a force that occurs only when movement of layers takes place (Massey, 2006).

Deformation of the fluid happens continuously and it will be active as long as the shear force is applied. With removal of the applied force, due to the weak intermolecular attractive forces, fluid loses its original shape.

### 3.1.1. Liquids

Fluids include both liquids and gases. Liquids are characterized by their definite volume, which oscillates with temperature and pressure changes (Massey, 2006). Intermolecular attractive forces in liquids are not as strong as those in solids but the attractive forces in liquids are strong enough to hold the molecules together. Weaker binding of molecules gives them greater mobility. The molecules will have mobility as long as the applied force is active.

### 3.1.2. The continuum

When talking about fluid, it is important to regard it as a continuum. In concise terms, continuum represents a continuous distribution of matter without empty space. Vast numbers of molecules and small distances between them are the only reasons why fluid is considered to be a continuum. If these conditions are not met, this approach would be considered incorrect (Massey, 2006). Properties of fluids are described through attributes such as viscosity, temperature, and pressure.

## 3.2. Properties of fluids

There are three states of matter: solid, liquid and gas. The difference between liquids and gases is noticeable in many ways but there are also certain common characteristics that make them different from solids. In ¨Fluid Mechanics¨ from 2000 by John F. Douglas, it is stated that both liquids and gases are considered fluids, which lack the ability of solids and their permanent resistance to a deforming force. Fluid flow under deforming forces will be present as long as the force is applied. Fluid cannot retain any unsupported shape; it flows under its own weight (gravity) and it takes the shape of any solid body with which it comes into contact (Douglas, 2000).

### 3.2.1. Shear stress in a moving fluid

Shear stress can be developed only in situations where fluid has movement. The movement of fluid particles relative to each other will create differences in velocity, which also causes transformation of the fluid’s original shape to a distorted form. In situations where fluid velocity is the same at every point, no shear stresses will be generated because of the fact that all fluid particles are at rest relative to each other (Douglas, 2000).

When fluid is in contact with a boundary, fluid velocity will be the same as the boundary as a result of this contact and the adherence of the fluid to the boundary. The velocity value in this case is always considered to be zero (Douglas, 2000).

Shear stress is defined as the force that acts over a certain area. It is represented by the Greek symbol $\tau$. The deformation (shear strain) that forms as a consequence of the shear stress influence is measured through the angle $\Phi$. In most cases the deformation angle $\Phi$ is proportional to the value of shear stress (Douglas, 2000). The shear strain value is not the same for liquids and solids. Permanent resistance of solids to shear stress implies that the value of the deformation angle $\Phi$ will be fixed for a given value of shear stress $\tau$. Strain is a function of the applied stress. With solids it is not possible to exceed the elastic limit. In solids, removal of the applied force means that the deformation will disappear. However, the same cannot be said for fluids. The value of the deformation angle $\Phi$ in a fluid will continuously increase with time. Douglas (2000) states that fluid will continue to flow as long as the force is applied to it. This also implies that fluid cannot recover its original form once the force is removed.

The value of shear stress can be calculated using the following expression (also known as Newton law of viscosity):

$$\tau = \mu \frac{du}{dy} \quad (eq. 3.1.)$$

This formula and its parameters are analyzed in more detail in chapter 3.2.4.1

Properties of a fluid are completely dependent on its molecular structure. Because of the immense number of molecules and the negligible separation between the molecules, fluids are considered to be a continuum (Douglas, 2000).

### 3.2.2. Density

The density of a substance represents the ratio of the mass of a given amount of substance to the volume it occupies (Massey, 2006). Since most liquids are incompressible, this statement is considered to be true. Unfortunately, the same cannot be applied to gases. The density value varies with the temperature and pressure variations (Tropea, Yarin, 2007). The term relative density is defined as the ratio of density of a substance to some standard density. Standard density of water is taken from a sample at 4°C and at this temperature water has the highest density value, 999.9720 kg/m$^3$.

### 3.2.3. Pressure

As stated in ¨Mechanics of Fluids¨ by Massey 2006, all fluids possess pressure as a result of countless molecular collisions within them. General definition of pressure states that pressure (P) is a force (F) that is applied over surface area (A) as a measure of force per unit area Lin (2007).

$$P = \frac{F}{A} \quad (eq. 3.2)$$

The value of pressure cannot be measured directly. Instruments for pressure measurement cannot detect the actual value of pressure and can only record the differences in pressure (Massey, 2006). Mostly this difference is between the pressure of the fluid and the pressure of the surrounding atmosphere. For this reason, in most cases atmospheric pressure is considered to be the datum pressure. In other words, reference or datum pressure represents the starting point for scale measurement (Massey, 2006).

The difference between a given pressure value and the local atmospheric pressure is known as gage pressure (Yuan, 1970). Absolute pressure is the pressure that is expressed as a difference between its value and the absolute zero pressure (Yuan, 1970). The value of absolute pressure can be determined using the expression:

$$P_{abs} = p_{gauge} + p_{atm} \quad (eq.3.3)$$

Atmospheric pressure is not a constant value.
It is known that force possesses direction, but the same cannot be said for pressure. Pressure is a scalar quantity and therefore it does not have direction (Massey, 2006). This can be confirmed through the following equation:

$$\overrightarrow{\text{Force}} = \text{Pressure} \times \text{Area } \overrightarrow{\text{of plane}} \text{ surface}$$

From where:

$$\text{Pressure} = \overrightarrow{\text{Force}} \,/\, \overrightarrow{\text{Area of plane}}\ \text{surface}$$

In Mechanics of Fluids, pressure is defined as a property of the fluid at the point in question. The unit for pressure is $Nm^{-2}$ or pascal (Pa). For larger magnitudes of pressure, the commonly used unit is the *atmosphere* (atm) (Massey, 2006). In order to have a clearer picture, 1 atm is $1.01325 \times 10^5$ Pa. The value of $10^5$ Pa is known as 1 *bar*. A thousandth part of a bar is known as a *millibar* and is commonly used in meteorology. In the SI system neither the bar nor the atmosphere are accepted as valid units of measurement.

### 3.2.4. Viscosity

The resistance, which occurs when one layer is forced to move over another layer is known as viscosity (Massey, 2006). Viscosity describes the resistance to the laminar movement of two neighboring fluid layers against each other (Rabie, 2009). In other words, viscosity represents the fluid's internal resistance to flow.

A fluid with the viscosity value of zero would be considered an ideal fluid (Franzini, 1977). This type of fluid does not exist in reality. Real fluid is always exposed to the tangential or shear forces whenever fluid motion takes place. The presence of these forces increases the value of fluid friction due to the fact that they oppose the movement of particles (Franzini, 1977).

Franzini (1977) defines viscosity as a measure of fluid resistance to shear or angular deformation.

This is an important property for analyzing liquid behavior and fluid motion near a solid boundary such as the pipe wall (Yuan, 1970). In ¨Foundations of Fluid Mechanics¨ from 1970 by Yuan, it is stated that viscosity is a result of the intermolecular forces, which automatically occur with contact between two sliding layers. The presence of shearing forces due to the relative motion between layers is unavoidable. These forces are applied in parallel to the surface over which they are acting (Franzini, 1977; Yuan, 1970). Consequently, a resisting force will occur parallel to the surface but only in the opposite direction.

Resistance to flow varies with particle conditions and certain fluids have greater resistance to flow than others (Massey, 2006).

The viscosity of liquids, for the purpose of better understanding, is divided into two groups:

1. Thick liquids, such as tar and glycerin - are characterized as liquids which do not have smooth movement and this type of liquid cannot be easily stirred;
2. Thin liquids, such as water and petrol - unlike thick liquids, are characterized by smooth, easy flow.

Molecular interchange and cohesive forces between the molecules in fluids contribute to the viscous shear stress in liquids. The value of cohesive forces is reduced with an increase in temperature. Simultaneously with the increase in temperature comes the increase in the molecular interchange rate. The result of this impact demonstrates that liquids will show a reduction in viscosity with increasing temperature (Douglas, 2000).

$$\mu_T = \frac{\mu_0}{1 + A_1 T + B_1 T^2} \quad (eq. 3.4)$$

Where:
$\mu_T$ – viscosity value at the given temperature
$\mu_0$ – viscosity at 0 °C (the value for water is 0.0179P)
$A_1$ and $B_1$ – constants depending on the type of liquid (water $A_1 = 0.034$; $B_1 = 0.0002$)

Pressure also affects the viscosity of liquids. With the increase in pressure comes an increase in energy, which is necessary for relative movement of molecules. This confirms the fact that the increase in pressure simultaneously results in increased viscosity (Douglas, 2000). Here the nature of liquid plays an important role due to the fact that it influences the value of the relationship between pressure and viscosity.
The impact of temperature on viscosity in both liquids and gases is significant. A change of temperature affects the value of viscosity. Increased temperature decreases viscosity in liquids. However, unlike liquids, viscosity of gases increases together with increases in temperature. In the case of liquids, this effect can be explained by the presence of cohesion forces, which diminish with increasing temperature (Franzini, 1977).

In the case of gases, the effects of increased temperature proportionally increase gas viscosity. This process impacts the velocity of particles in the layers. Shifting of rapidly moving molecules from a faster moving layer to a slower moving layer tends to change the characteristics of the layer. In this case the faster moving molecules tend to increase the speed of the slower moving layer (Franzini, 1977).

#### 3.2.4.1. Quantitative definition of viscosity

Movement of fluid particles occurs in the same direction, but the velocity of fluid is not constant among layers. Fluid within different layers is characterized by different velocities (Massey, 2006). Fluid velocity at the solid boundary/pipe wall is zero. The value of fluid velocity increases with the increase of distance from the solid boundary. In the case of circular pipes, the highest velocity is reached in the central section/centerline of the pipe.

The curve used to describe the change in velocity within a profile is known as the velocity profile curve. The following figure 1 shows the change of the fluid velocity through cross section profile of the pipe.

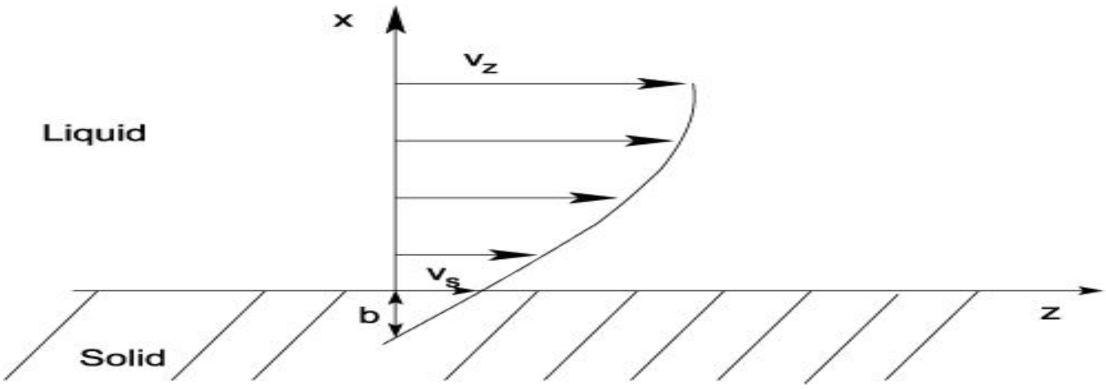


**Figure 3.1: No slip condition (Journal of Statistical Mechanics, N.K Ahmed)**

Assume that two adjoining fluid layers have different velocities. Imagine that the upper layer has higher fluid velocity than the lower layer. The force of the higher velocity layer will have an impact on the velocity of the lower layer.

At the same time, the lower velocity layer will tend to decrease the velocity of the higher velocity layer. The forces acting between these two layers are equal but opposite (Massey, 2006; Rabie, 2009).

Sir Isaac Newton postulated that for straight and parallel motion of a given fluid, the tangential stress between two adjoining layers is proportional to the velocity gradient in a direction perpendicular to the layers (Massey 2006):

$$\tau = \mu \frac{du}{dx}$$

The Greek letter $\mu$ represents a proportional constant and is also known as dynamic viscosity. According to the ¨Springer Handbook of Experimental Fluid Mechanics¨ from 2007 by Tropea, the dynamic viscosity of fluid represents a measure of its tendency to dissipate energy when it is disturbed from equilibrium by a velocity field. The actual value of this coefficient can be obtained from the previous equation:

$$\mu = \tau/(\frac{du}{dy})$$

The du/dy represents the velocity gradient. Dynamic viscosity is most commonly expressed in $Ns/m^2$ (in the SI system) and $lbs/ft^2$ (in the Gravitational System). Beside these units, dynamic viscosity can be expressed through poise and centipoise units, which represent the Centimeter-Gram-Second (CGS) system.
The dynamic viscosity value of Newtonian fluids is independent of the velocity gradient value of (du/dy) (Rabie, 2009). The value itself changes with the change of pressure and temperature values.

The ratio between dynamic viscosity $\mu$ and density $\rho$ is known as kinematic viscosity $\upsilon$ (Tullis, 1989). The commonly used units for kinematic viscosity are stokes (St). According to Richel (2002), kinematic viscosity is the value used mainly for the purposes of water pumping. The units for kinematic viscosity are $ft^2/s$ or $cm^2/s$.
Viscosity depends on the thermodynamic state of the fluid (Tropea 2007). Viscosity values vary with temperature and can only be determined experimentally. Viscosity values are given in the following table:

**Table 3.1: Physical properties of water - SI units (Lin, 2007)**

| Temperature T, °C | Specific gravity | Specific weight N/m$^3$ | Absolute viscosity N*s/m$^2$ | Kinematic viscosity m$^2$/s | Surface tension N/m$^2$ | Vapor pressure N/m$^2$ |
|---|---|---|---|---|---|---|
| 0 | 0.9999 | 9805 | 0.00179 | 1.795 x 10^-6 | 0.0756 | 608 |
| 4 | 1.0 | 9806 | 0.00157 | 1.568 x 10^-6 | 0.0750 | 809 |
| 10 | 0.9997 | 9804 | 0.00131 | 1.310 x 10^-6 | 0.0743 | 1226 |
| 15 | 0.9990 | 9798 | 0.00113 | 1.131 x 10^-6 | 0.0735 | 1762 |
| 21 | 0.9980 | 9787 | 0.00098 | 0.984 x 10^-6 | 0.0727 | 2504 |
| 27 | 0.9966 | 9774 | 0.00086 | 0.864 x 10^-6 | 0.0718 | 3495 |
| 38 | 0.9931 | 9739 | 0.00068 | 0.687 x 10^-6 | 0.07 | 6512 |
| 93 | 0.9630 | 9444 | 0.00030 | 0.371 x 10^-6 | 0.0601 | 79,002 |

The best examples of the importance of viscosity can be found in fluid flow problems, which are related to the Reynolds number (Re). Re represents the ratio of inertia forces to viscous forces (Tullis, 1989). A lower Re value means that viscosity has a higher impact on fluid flow.

# 4. Flow of fluid

## 4.1. Reynolds number

Geometry, surface roughness, type of fluid, flow velocity and surface temperature are factors that determine whether the flow is laminar or turbulent. Osborne Reynolds was the first to discover that the flow regime depends on the ratio of inertial forces and viscous forces in the fluid (Douglas, 2000). The ratio is called Reynolds number and it defines internal flow in a pipe. The Reynolds number (Re) is a dimensionless unit and it can be expressed by the equation:

$$\mathrm{Re} = \frac{\rho V L}{\mu} \qquad (eq. 4.1)$$

Where:
V- Characteristic velocity
L- Characteristic length
μ- Dynamic viscosity
$\rho$- Density of the fluid

Value of the Re number depends on both V and L values (Douglas, 2000). Thus the Reynolds number can be presented as the ratio of dynamic pressure and shear stress (Yuan, 1970). Also, according to Yuan (1970), the Reynolds number can be defined as a parameter of viscosity.

While studying flows, Osborne Reynolds discovered that a flow will behave orderly/regulated until critical speed is reached. If flow velocity exceeds the critical value, the flow automatically becomes turbulent (March 2002). The value of the Reynolds number does not necessarily determine the flow regime.

## 4.2. Laminar and turbulent regimes

In laminar flow, fluid is seen as an assembly of thin laminae/flow lines of uniform thickness (March, 2002). Individual particles within the laminar fluid flow do not cross paths with the neighboring particles (Massey, 2006). Highly viscous liquids or flows with lower velocities are the main characteristics of a laminar flow (Tullis, 1989). Tullis (1989) claims that viscosity of the liquid is the dominant factor for laminar flow.

Presence of a velocity gradient across the flow conditions the presence of a laminar flow. Due to the velocity gradient, laminar flow mostly forms in areas close to the solid boundary. The general conclusion states that laminar flow only occurs in situations where the velocity value is sufficiently low. Low velocity secures the conditions for the viscosity force to prevail over inertia forces. Thanks to the dominance of viscosity forces, movement of particles across different paths/layers is prevented (Massey, 2006).

Laminar regime is characterized by smooth, calm streamlines. In order to achieve this level, the fluid must have low velocity. Laminar regime can be presented as a series of parallel layers moving at different velocities.

March (2002) states that the characteristic feature of turbulence is its randomness and irregularity. Diffusivity is also considered a characteristic of turbulence. Diffusivity is responsible for high mixing and high rates of mass, heat or momentum transfer. Diffusivity is the most important property of turbulent flows (March, 2002). Unlike the laminar flow, in a turbulent flow the value of inertia forces increases at the expense of the kinetic energy of turbulence (March, 2002). In 1970, S.W. Yuan, p.358 (cited in Hinze Turbulence, 1959) defines that, "Turbulent fluid motion is an irregular condition of flow in which the various quantities show random variations with time and space coordinates, so that statistically distinct average values can be discerned". Taylor and von Kàrmàn (1937) state that turbulence can be generated by fluid flowing against a solid surface or by the flow of layers of fluids at different velocities against or over one another. Yuan (1970) claims that there are two different types of turbulences:

1. Wall turbulence, which is generated by the viscous effect;
2. Free turbulence, which is generated as a result of movement of layers at different velocities.

Movement of fluid through a conduit is an example of wall turbulence.
Most flows in pipes represent a turbulent regime, most of the time. According to March (2002) turbulence is a three-dimensional, time-dependent motion. Vortex stretching is considered to be the main cause of velocity fluctuations. The pressure drop that occurs in pipes with a turbulent regime is over hundred times greater than the value of the pressure drop in laminar flow (Yuan, 1970).
As stated in the ¨Introduction to Liquid State Physics¨ from 2002, by N.H. March, development of turbulence within a flow is mostly triggered by factors that destabilize the flow state. The essential element for turbulence is a continuous supply of energy that makes up for viscous losses, which occur during the flow.
Turbulence represents a state of instability. Involvement of force in the flow does not necessarily indicate the existence of a turbulence regime in the flow. What counts is the ratio of forces, both viscous and inertial.
March (2002) states that a laminar flow regime in a pipe transforms to a turbulent one when the primary eddies get out of control before viscosity can quench them, and start generating strings of further eddies. Experiments have shown that if the Re value is above critical, the pressure gradient increases faster than the linear rate of flow. The pressure gradient is essential for movement of fluid within a pipe.

## 4.3. Laminar and turbulent flow in circular pipes

As mentioned earlier, the nature of the flow is mostly determined by the magnitude of Re (Massey, 2006). The Re value for circular pipes is determined using the equation:

$$Re = \rho u d/\mu \quad \text{(eq.4.2)}$$

u - Represents mean velocity

As mentioned earlier, viscosity forces dominate in the laminar pipe flow, while inertia forces are predominant in the turbulent flow.
With an increase in velocity, laminar flow becomes unstable due to a sudden presence of eddies. If the flow is considered unstable, even a slight disturbance may cause the transformation of the flow from laminar to turbulent (figure 4.1). Therefore it is considered that eddies are responsible for disturbance of the flow (Massey, 2006).

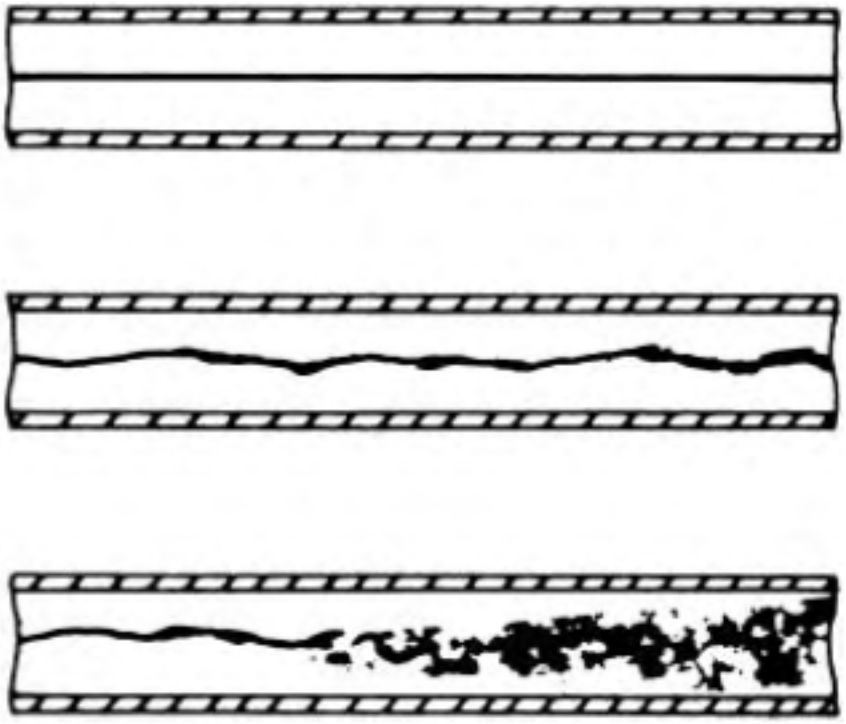

**Figure 4.1: Laminar, critical and turbulent flow in pipe (Massey, 2006)**

As shown by Massey (2006), the lower critical value is of greater importance because above this point laminar flow becomes unstable. The lower critical value varies are depending on factors such as pipe roughness and shape. For instance, the value of critical Re for smooth, straight uniform circular pipes is 2300. For pipes that do not have smooth walls, the usual Re value is 2000 (Massey, 2006).

There are cases where the upper limit for laminar flow in pipes is far beyond this defined value (Massey, 2006). In ¨Fluid Mechanics¨ from 2000 by Douglas, it is stated that there have been cases where laminar flow would be maintained up to Re of 50 000. The conditions of this flow are unstable and any disturbance of the flow will automatically transform it from a laminar to a normal turbulent flow (Douglas, 2000). Therefore it is allowed to conclude that there is no upper limit value for Re, but that there is a definite lower limit value. Yuan (1970) suggested that the upper limit of critical Re strongly depends on the initial disturbance.

When Re is lower than the critical value, any disturbance that may occur in the flow will be dampened by the dominant viscous forces (Massey, 2006).

In a turbulent flow the velocity fluctuates in terms of magnitude and direction and eddies are created as a result of the viscous shear between the adjacent particles (Douglas, 2000). That means that the cycle of eddies consists of forming, growing and disappearing phase. Fading and complete disappearance of eddies in a flow is a result of particles merging with adjacent eddies (Douglas, 2000). One of the main characteristics of a turbulent flow is definitely the continuous mixing of particles with a consequent transfer of momentum.
In a turbulent flow molecules are replaced every second. The value of eddy viscosity is not constant for the given fluid at the given temperature. The value depends on the level of turbulence in the flow. The physical concept of eddy viscosity is of the greater importance than its numerical value (Douglas, 2000).

### 4.4. Motion of fluid particles

All particles in a fluid will obey the laws of mechanics. When force is applied, the behavior of particles can be predicted using Newton's laws. The laws state that:

- A body will remain at rest or in a state of uniform motion in a straight line until acted upon by external force
- The rate of change of momentum of a body is proportional to the force applied and takes place in the direction of action of that force
- Action and reaction are equal and opposite.

For an element with fixed mass, Newton's second law applies. The law correlates and explains the change of velocity over a given time to the applied force (Douglas, 2000). Newton's second law states:

$$Force = Mass * \frac{change\ of\ Velocity}{Time}$$

$$Force = Mass * Acceleration$$

The relationship and changes between initial velocity $v_1$, final velocity $v_2$, acceleration and distance moved in time are given in the following equations:

$$v_2 = v_1 + at \quad (eq. 4.3a)$$

$$s = v_1 t + \frac{at^2}{2} \quad (eq. 4.3b)$$

$$v_2^2 = v_1^2 + 2as \quad (eq. 4.3c)$$

The value of velocity in general varies from point to point. If the flow is considered to be unsteady, the value of velocity at each point may vary with time as well (Douglas, 2000).

## 5. Fluid friction

Accurate estimation of energy losses within the pipeline of the system must be obtained when using energy equations such as the Bernoulli principle. Energy losses are generated as a result of shear stress between the fluid and the solid boundary, in this case the pipe wall (Tullis, 1989).

$$\tau = \mu du/dy \quad \text{(eq. 3.1)}$$

It is easy to conclude that shear stress is a function of the viscosity and the velocity gradient near the solid boundary (Tullis, 1989). Boundary roughness, velocity, thickness of the boundary and viscosity of the fluid are all factors, which impact the value of the velocity gradient.

In the book Hydraulics of Pipelines from 1989, Tullis, analyses the behavior of turbulent flow in the entry region of a rough pipe. Tullis (1989) also claims that if flow is provided from a large chamber, the velocity distribution at the entrance to the pipe will be uniform except for a thin boundary layer.

Values of shear stress and velocity gradient are considered to be at maximum level at the adjoining boundary. The values of velocity gradient and shear stress reduce with the increase of the boundary layer thickness.

Tullis (1989) also have analyzed the variations of relative wall shear stress in pipes. The relative wall shear stress is represented by the ratio $\tau/\tau_0$. The value of local shear stress is approximately 2.5 times the value of the fully developed value $\tau_0$. Value of relative wall shear stress reduces with the distance.

Because of the previously mentioned characteristics, it takes longer to develop the velocity profile.

The changes within the flow will occur as a result of presence of valves, fittings, elbows or changes in the pipe diameter. The flow itself cannot be considered to be uniform in these situations. Tullis (1989) considers that the impact of nonuniform flow on wall shear stress is negligible. The length of the pipeline is the only factor that determines whether the impact of nonuniform flow should be included or omitted. In the systems with a sufficient pipeline length, the impact of shear stress is

considered to be insignificant. Otherwise, this impact needs to be included (Tullis, 1989).
Probably the biggest challenge faced by the engineer in dealing with pipelines is to obtain reliable shear stress or pipe friction values for a fully developed flow.

## 5.1. Head loss due to friction

As stated in the Mechanics of Fluids from 2006 by Massey difference of pressure is of great importance for engineers. Pressure differences in the pipe are a crucial element because they induce the fluid to flow at a stable rate. Henry Darcy was one of the first engineers to conduct experiments related to the flow of water under turbulent conditions. In his experiments he concluded that the fall of the piezometric head in the direction of flow is caused by the dissipation of energy by fluid friction (Massey,2006). The decrease of piezometric head will be constant only if the conditions of flow through the pipe are held constant, i.e. if the flow passes through a pipe with a constant diameter, cross section and roughness.

The measure of pressure drop in a given length of pipe depends on the flow regime and the value is different for laminar and turbulent flow and in the transition zone between the two regimes (Tullis, 1989). The value of pressure drop for turbulent flow varies with the length of pipe, the square of velocity, size of pipe diameter, roughness of the pipe and the viscosity and density of the fluid.

The friction coefficient $f$ is commonly used to quantify the roughness of the pipe (Tullis, 1989). Friction coefficient $f$ is a function of the pipe roughness and the Reynolds number. As the value of the Reynolds number increases, the friction coefficient $f$ becomes independent of it and only depends from the pipe roughness. According to Tullis (1989) this as a fully turbulent flow. The range between laminar and fully turbulent flow is known as the transition zone.
Fluid flow is classified as:

- Uniform and nonuniform,
- Steady or unsteady.

Uniform flow represents a flow within a straight pipe of constant diameter. Unlike uniform flow, nonuniform flow occurs in situations when there is a change of flow characteristics, regardless of whether this is a change in the direction of the flow or the cross section of the pipe (Tullis, 1989).
Steady flow represents a flow where the average flow conditions do not change with time, while unsteady flow is characterized by oscillations of both pressure and velocity. Therefore, unsteady flow is subdivided:

- Surge, if changes in flow occur slowly
- Hydraulic transient or waterhammer, if changes occur rapidly

### 5.2. Head loss in pipes

Friction that forms along the pipe walls along with viscous shear stresses within the liquid creates resistance to flow within the pipe. The consequence of this process reflects on certain parameters, such as pressure drop or loss of head.

Both the Darcy-Weisbach and the Colebrook formula are accepted methods for calculating the value of friction loss in full flowing pipes. Both formulas depend on the values of fluid viscosity, flow velocity and pipe surface characteristics.

The Darcy-Weisbach equation

$$h_f = f\frac{L}{d}\frac{V^2}{2g} \qquad (eq. 5.1)$$

$h_f$– friction head loss of liquid
L – length of pipeline (m)
V - flow velocity (m/s)
d'- inside pipe diameter (mm)
f – friction factor (depends on the Reynolds number and surface roughness)
g – gravitational acceleration 9.81 m/s$^2$

The flow velocity V can also be computed using the expression

$$V = \frac{0.4085\ Q}{D_1^2} \quad (eq. 5.2)$$

Q - flow rate (usually in $m^3/s$)

$D_1$- Inside diameter of the pipe (mm)

As mentioned earlier, the flow regime of liquids can take laminar, transition or turbulent form.

The flow of incompressible liquids in most cases is in the turbulent flow.

Flows where the Re value exceeds 4000 are considered to be turbulent. In this case, the friction factor f is conditioned by two factors:

- Reynolds number (Re)
- Pipe surface roughness

The value of the friction factor can also be determined using the Moody diagram. This diagram can be used for different kinds and sizes of PE pipes. The value of friction factor can be determined with acceptable accuracy through the Moody diagram. The Moody diagram also determines the value of relative roughness, which represents the ratio of absolute roughness e, and inside pipe diameter d.

Absolute roughness is defined as the measure of pipe wall irregularity (Engineering Design Encyclopedia, s.a)

The nature of the flow depends on density, viscosity, velocity and the pipe diameter. The value of these parameters predicts the nature of the flow.

The value of friction factor can also be obtained from the Colebrook formula (eq.5.3).

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{e}{3.7\ d'} + \frac{2.51}{Re\sqrt{f}}\right) \quad (eq.5.3)$$

e– absolute roughness (determined from the table), usually expressed in mm

If the value of friction loss for one size of the pipe is known, it is possible to calculate friction loss for a pipe of different size. Of course there are certain conditions that have to be fulfilled, such as: same surface roughness of the pipe, same viscosity and same flow rate.

$$h_{f2} = h_{f1} \left( \frac{d_1'}{d_2'} \right)^5 \quad \text{(eq. 5.4)}$$

### 5.3. Head loss due to change in elevation

The change in elevation impacts the pressure in the pipe system. The pressure value for elevation change of liquid can be calculated using the equation

$$h_e = h_2 - h_1 \quad \text{(eq.5.5)}$$

$h_e$– elevation of head
$h_1$– Pipeline elevation at first point
$h_2$–Pipeline elevation at second point

Some pipelines may have several different elevation changes as they go over different types of terrain. Pressure will always be present in the pipe due to elevation differences. The calculation for this system of pipelines is based on finding two representative points where the slope of the pipeline changes and then adding the individual elevation heads for an overall pipeline elevation head. In general, at any low point on the pipeline, internal pressure will be equal to the height of the liquid above that point multiplied by the specific weight of the liquid. When liquid is flowing through the pipeline, the values of head loss and elevation head are added together in order to determine the value of pressure in the pipe at the given point (Plastic Pipe Institute, s.a).

### 5.4. Pressure flow of water – the Hazen-Williams Equation

The Darcy-Weisbach equation can be applied for calculations of flow resistance for both liquid and gases. The Hazen-Williams empirical formula has different forms, which are applied in different scenarios. Certain parameters such as temperature also have an impact on the form of the equation. For instance, the Hazen-Williams formula (eq. 5.6) for water flow in pipes at 60°F (16°C) applies to liquids with the same kinematic viscosity of 1.130 centistokes, which is equivalent of 1.1148 x $10^{-6}$ $m^2/s$. The value of fluid viscosity changes with temperature, so an error will occur if the temperature is higher than 60°F (Plastic Pipe Institute, s.a)

$$h_f = \frac{0.002083\, L}{D_I^{4.8655}} \left(\frac{100\, Q}{C}\right)^{1.85} \quad \text{(eq.5.6a)}$$

Friction head loss in feet of water

$$h_f = \frac{0.0009015\, L}{D_I^{4.8655}} \left(\frac{100\, Q}{C}\right)^{1.85} \quad \text{(eq.5.6b)}$$

Friction head loss in psi

$D_I$ - pipe inside diameter

C – the Hazen-Williams friction factor for PE pipes C = 150-155

The value of C factor for PE pipes was determined in the hydraulic laboratory

**Table 5.1: Properties of Water (Plastic Pipe Institute, s.a)**

| Temperature F/C° | Specific weight N/$m^3$ | Kinematic Viscosity Pa*s |
|---|---|---|
| 32/0 | 9,8061 | 0,00179 |
| 60/15.6 | 9,7983 | 0,00113 |
| 75/23.9 | 9,7826 | 0,0009 |
| 100/37.8 | 9,7402 | 0,00069 |
| 120/48.9 | 9,6946 | 0,00057 |
| 140/60 | 9,6427 | 0,00047 |

Turbulent flow prevents the process of sedimentation of any particles in the liquid. In turbulent flow the particles remain in suspended form. In situations where pipe flow velocity is low and unable to maintain turbulent regime, the solids accumulate at the bottom of the pipe forming a sediment layer. Turbulent flow also avoids excessive pipeline wear and possible clogging (Plastic Pipe Institute, s.a).

The type of fluid also affects the wear of certain elements of the pipeline. In the case of PE fittings, due to the softness of the material the wear is noticeable. In general, this type of material should not be the first choice for slurry applications. According to the PE Pipeline Guide the reason why PE fittings should be avoided is because the change of flow direction causes direct impingement of PE fittings. This is why it is recommended to use stronger materials when dealing with slurry fluids. Harder materials have longer resistivity to slurry fluids than PE.

Note that flow formulas for PE pipes usually assume the pipes to be round in shape. Buried PE pipes, due to their flexibility, will slightly deform under load and become elliptically shaped. This indicates a slight increase in the lateral and a proportional reduction in the vertical diameter of PE pipe. The new elliptical form affects the value of flow, which is in this case due to the deformity slightly reduced. This phenomenon relates to the pipe flow capacity and it can be neglected. According to the PE Piping Guidelines, the elliptical deformation decreases the vertical diameter of the pipe by 7% and causes flow reduction of 1% (Plastic Pipe Institute, s.a).

### 5.5. Gravity flow of liquids

In a pressure sewer pipeline, the pump is the key element as it provides the energy required to move the fluid through the pipeline. Gravity flow lines completely rely on gravity for the purposes of water distribution, to the energy resulting from the difference in elevation between the pipe inlet and discharge points. In gravity distribution systems, the value of friction loss depends on the viscous shear stresses of the liquid (Plastic Pipe Institute, s.a). The complexity of the gravity system depends on the pipeline grade variations, also affecting the value of friction loss in the pipeline. Certain sections of the pipeline may form internal pressure or a vacuum, which also affects the flow within the system (Plastic Pipe Institute, s.a)

# 6. Sewer systems and processes

## 6.1. Introduction: Purpose of sewer systems

Wastewater generated by the community and surface runoff from precipitation are typically collected and conveyed for treatment and disposal. The system used for this purpose is known as a sewer network or collection system. The system consists of individual pipes (also known as sewer lines) and a number of different installations such as inlet structures and pumps. The main purpose of these elements is to facilitate the collection and transport of wastewater (Jacobsen, 2002). Today, the main criteria observed for collection and transport of wastewater are:

1. Efficiency
2. Safety (refers only to public health)
3. Cost-effectiveness of the system

In the book titled Sewer Processes (2002), Jacobsen states that sewer networks are exposed to great variations in operating conditions. For instance, in dry weather seasons all of the wastewater that flows through the sewer system consists of municipal/community waste, but during wet seasons sewer systems receive community wastewater together with stormwater runoff.

With increasing population density in certain urban centers, the capacity of wastewater treatment plants and sewage systems tends to become overloaded. This presents a real challenge and over the last 20-30 years major efforts have been devoted to finding an adequate solution for this problem.

Hydraulics and transport of sewer solids are the most important elements in a sewage network. During the wet season, for example, these two factors are of major importance, unlike microbiological and chemical processes, which play a minor role. Chemical and biological processes have a larger impact on sewage during dry seasons, with possible implications for the subsequent treatment process and therefore must be taken into account (Jacobsen, 2002). One of the bigger problems, which might occur in sewage as a result of anaerobic conditions, is the presence of sulfides and their impact on the sewage network. The presence of sulfides negatively affects human health but, in addition to this, it also causes serious corrosion problems within the sewer network.

The sewer should be regarded as a process reactor. Overall criteria for a sewer network must observe the following:

1. Safe and cost-effective collection and transport of wastewater
2. Efficiency
3. Integration with the environment

### 6.2. Sewer development through history

It is believed that the first implementation of sewer systems occurred in the Roman Empire. As stated in Jacobsen (2002, Chapter1), these systems were constructed to transport storm runoff from urban areas and prevent possible flooding. Similar systems were used in Europe and America by the $16^{th}$ and $17^{th}$ century. In all these systems the discharge of household wastewater into storm drains was prohibited (Jacobsen, 2002).

Underground wastewater collection systems were first installed in the middle of the $19^{th}$ century and this was a revolutionary approach. The first cities to apply these systems were London and Paris but it did not take long before other cities started to follow their lead. The trigger for switching from open transportation of household wastewater to underground sewer systems were the unpleasant odors emanating from open sewers and demand for more space on the streets in densely populated cities (Jacobsen, 2002).

The approach of not mixing storm water and household wastewater changed with the introduction of these systems, which combined both wastewater streams. Unfortunately, unsanitary conditions in the sewer systems and water drinking reservoirs lead to serious health issues in the local populations in the $19^{th}$ century. After the outbreak of cholera it became clear that in order to reduce the incidence of epidemic disease sewers must become a sanitary and technical hygienic system.

At that time ($19^{th}$ century), sewage water did not receive any form of treatment and was discharged directly into the nearby water recipient, usually a river or sea. This resulted in serious environmental problems such as fish kills, bacterial contamination and dissolved oxygen depletion. Unfortunately this problem still exists and is the cause of serious environmental problems, such as eutrophication and toxicity of heavy metals and organic micropollutants. Installation and development of wastewater treatment plants represents a step forward in overcoming this pollution problem.

Over the last 50 years separate sanitary and storm sewer systems were prevalent over combined sewer systems and the old, combined sewer systems have been technologically improved and updated (Jacobsen, 2002).

## 6.3. Types and performance of sewer networks

According to Jacobsen (2002) "knowledge of sewer processes can be actively considered in the design and operation of a sewer network". The general definition states that the sewer represents an underground conduit, which transports wastewater and storm-water, usually to a treatment plant or point of disposal (Lin, 2007).

Sewer design and operation and sewage processes are interlinked and therefore cannot be considered independently of each other. For instance, the sewer type determines whether aerobic or anaerobic conditions will occur (Jacobsen, 2002). The Water and Wastewater Calculations Manual from 2007 by Lin describes three categories of sewers: sanitary, storm and combined.

There are three main sewer networks:

1. Sanitary sewer network
   Also known as separate sewers, these were developed to collect and transport wastewater from households, industries and commercial areas (Jacobsen, 2002). In this system the sanitary sewer is separated from the stormwater sewer network (Lin, 2007). The concentration of organic biodegradable matter in these sewers is relatively high and therefore these systems are considered to be biologically active. It can be said that wastewater in these sewers is a mixture of biomass and substrate for this biomass (Jacobsen, 2002).
   Flow within sanitary sewers can be controlled through

- Gravity - gravity sewer systems. As Jacobsen (2002, p.5) stated: "In a partially filled gravity sewer, transfer of oxygen across the air-water interface (reaeration) is possible, and aerobic heterotrophic processes may proceed".
- Pressure – pressurized systems develop full flow and there is no space for reaeration, unlike in gravity systems. Therefore, anaerobic processes are dominant in these systems (Jacobsen, 2002).

Conventional and pressure systems will be analyzed in more detail in a later section.

For sanitary sewer networks, residential time plays an important part because it affects the degree of transformation, which might occur (Jacobsen, 2002). The residence time depends from:

- Size of the catchment
- Specific characteristics of the sewer (slope and length)

Residence time is not the same in gravitational systems and pressurized systems. For pressurized systems it is generally said that these systems have a relatively high residence time, especially during the nighttime hours compared to the gravity systems (Jacobsen, 2002). These systems also do not allow reaeration therefore anaerobic processes will dominate.

2. Storm sewer network

These types of systems are constructed for collection and transport of stormwater originating from impervious and semipervious surfaces such as paved streets, parking lots, roofs, etc. This system also consists of buried pipes that transport storm drainage (Lin, 2007). Surface water enters these systems through inlets located in the street gutters. These systems function only in wet weather periods and stormwater from these systems usually receives limited treatment before being discharged. The reason for limited treatment of these waters lies in the fact that chemical and microbiological processes do not have a substantial impact on the water quality (Jacobsen, 2002).

3. Combined sewer network

   In these systems, both municipal wastewater and surface runoff are collected, mixed and transported together (Lin, 2007). Because of the ability to collect additional surface water, these systems are designed differently. They possess extra elements such as overflow structures and detention basins, which store additional water, not present in other systems (Jacobsen, 2002). These systems can function as gravitational, pressurized or combined systems.

   This type of system is quite common in old European and US urban communities (Lin, 2007). In situations where combined wastewater and stormwater exceed the capacity of the treatment plant, the overflow is bypassed directly to the receiving water body without treatment (Lin, 2007). Another alternative in this case might be to store the overflow water until it can receive treatment. The variations of flow and sediment transport rate are highest in combined sewage systems (Czarnota, s.a).

Regarding industrial wastewater, as the name indicates, is wastewater of industrial origin. This type of wastewater usually contains higher concentrations of metals, chemicals, oils and greases than the household wastewater (Environment One Corporation, 1997).

## 6.4. Chemical and physicochemical processes in sewers

Chemical and biological reactions are mutually linked. A chemical basis characterizes microbiological changes of wastewater during its transport through the sewer (Jacobsen, 2002). Fundamental chemical and physiochemical impacts on sewer systems and in-sewer processes are discussed below.

### 6.4.1. Redox reactions

Biochemical process can be defined as a microbial transformation of organic matter in wastewater under the influence of chemical components of sewage (Jacobsen, 2002). The presence of biomass, sediments and biofilms in wastewater is considered to be of main importance for biochemical processes that occur in sewage. Organic matter from wastewater provides for:

- microbial growth due to presence of carbon (anabolic processes-growth of new biomass);
- source of energy that maintains life (catabolic processes - providing energy for biomass/cells).

Jacobsen (2002) states that the energy stored in organic matter is available for microorganisms through the catabolic process in which degradation of organic matter occurs. The process of degradation is applicable through oxidation of organic matter.

### 6.4.2. Oxidation-reduction processes

As Jacobsen (2002) claims, the microbial catabolic process occurs in two steps:

1. Oxidation of organic matter, and
2. Reduction of an electron acceptor

The entire redox process consists of transfers of electrons from the electron donor to the relevant electron acceptor. The following figure shows schematically the redox process:

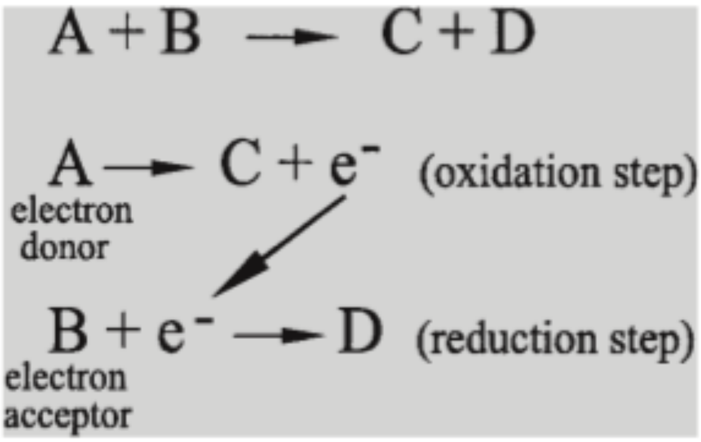


**Figure 6.1: Oxidation and reduction steps (Jacobsen, 2002)**

Where: A - represents the oxidation component (electron donor)

B - electron acceptor

C, D – components

### 6.4.3. Redox reactions in wastewater systems

Heterotrophic microorganisms may use different electron acceptors in the reduction step of a redox reaction (Jacobsen, 2002). Depending on the availability of oxygen, there are two scenarios:

1. In situations where oxygen is available, the electron acceptor is terminal (molecule of oxygen) and the process occurs in aerobic conditions.
2. In situations where oxygen is not available, nitrates become the electron acceptor and the process occurs in anoxic conditions.
3. If there is neither oxygen nor nitrates available, then sulfites and carbon dioxide act as potential electron acceptors and the reaction is strictly anaerobic.

### 6.4.4. Influence of temperature on microbial and chemical processes

Generally, temperature values within the sewer depend on different conditions such as the climate, source of wastewater and system characteristics. Development of microorganisms in the sewer is subject to temperature variations and to some extent their daily variability (Jacobsen, 2002). Under different temperature conditions different microorganism may develop and at different process rates. Jacobsen (2002) defines the differences and effects that long term and short term temperature variations have on microbial populations: long-term variations affect the types of microorganisms that will develop in the sewer, while short-term variations affect the microbial processes within cells and the diffusion rate of organic matter (substrate). Generally, presence and increased number of microorganisms in sewage pipelines is unwanted in any type of wastewater distribution pipes.

**Part 3: Methodology**

## 7. Wastewater collection facilities

In order to make the right choices and determine the most appropriate design for any wastewater collection facility, it is mandatory to define the service area in geographical, topographical, geological, climatological and economic terms (Technical Advisory Committee , 1981).

The first step in planning wastewater collection facilities is to define the service area. When defining the service area, the following factors needs to be taken into account:

1. Development and growth of the area
2. Natural and physical characteristics
3. Characteristics of the existing wastewater system (if any)
4. Regulations and institutions

Knowing the characteristics of any existing wastewater systems is very important and all relevant information must be included in the analysis when designing a pressurized system. The capacity and condition of the existing system needs to be considered before designing a pressurized system (Technical Advisory Committee , 1981). For instance, if the existing sewer has excess capacity, the engineer may use this system as a discharge receptor for the pressurized system. If the existing system does not have the capacity to receive additional sewage, an alternative solution must be applied (such as infiltration, inflow reduction).

Local regulations and institutions also play an important role in pressure sewer designs (Technical Advisory Committee , 1981).

### 7.1. Conventional systems

Also known as centralized systems, these collection systems transport wastewater from households or other sources by gravity flow through a buried piping system (United States Environmental Protection Agency, s.a). This system conveys wastewater from the source to the treatment plant/facility or discharge point. Conventional systems are considered reliable and when they run on gravity they do not consume any power. The essential requirement for conventional systems is the presence of slope, which unfortunately, in some situations may increase the cost of installation. Excavation in hilly and flat terrains is required to ensure an adequate slope and that is considered as the main disadvantage of these systems. Conventional systems may occasionally require installation of pumping stations in order to overcome terrain obstacles. This step significantly increases the cost of conventional systems (United States Environmental Protection Agency, s.a).

The presence of slope is of great importance for these systems because slope provides the necessary velocity to secure wastewater movement through the conduits and prevents sedimentation and clogging of the system. Pipes are placed on the slope with a minimum inclination of approximately 1%. Required self-cleansing velocity within conduits is 0.7 m/s or 2 ft/s (Strandberg, 2010). Although according to the results of Guzman (2007) the deposition of sediments in gravity sewer pipes may also occur even at velocities of 0.86 m/s.

Gravity sewers are economically beneficial in densely populated areas. The system is suitable for larger flows and it requires less mechanization (Strandberg, 2010).

Alternative collection systems are mostly used in situations where the conventional system is not applied due to high installation costs (EPA, Wastewater Technology Fact Sheet). According to the Texas Agricultural Extension Service there are many alternatives to centralized sewer systems, such as:

- Conventional septic tanks
- Advanced on site systems (sand filters, aerobic treatment units, pressure distribution systems)
- Cluster systems (for distribution from small collection networks to a common treatment plant)

For instance, pressure sewer systems are used in not so densely populated areas where the cost of installation of a conventional system would be too high (United States Environmental Protection Agency, s.a).

Application of alternative collection systems in rural areas provides (Texas Agricultural Extension Service, s.a):

- Protection for the environment
- Flexibility for communities to expand in the future
- Lower installation costs

Most commonly used systems in rural areas are septic tanks, installed individually for each home. This method is practical for areas where population is low and where the environment accommodates the amount of generated waste (Texas Agricultural Extension Service, s.a). With increasing populations, this particular solution might not be a suitable step.

The most convenient solution for wastewater management in rural areas is application of decentralized systems. Decentralized systems provide the following functions:

- Protection of public health and the environment
- Applicable in low density communities
- Applicable in different site conditions
- Environmentally beneficial
- Economically profitable

## 7.2. Introduction: Pressure sewers

These systems were initially developed in the 1960´s. In the early 1970´s pressurized sewer systems were becoming increasingly popular, especially in the rural areas. The worldwide breakthrough for these systems came in the 1980´s with the development (application) of submersible centrifugal and positive displacement pumps with grinders (Strandberg, 2010).

Due to their lower cost, pressurized sewer systems became more and more popular.

Since the 1980´s, according to the Flygt report, more than 150 000 grinder pumps were installed just in Holland, and Germany has installed around 40 000 grinder pumps (Strandberg, 2010).

A pressure sewer is a system that consists of completely sealed plastic pipes, usually with a smaller size diameter, that operate under moderate internal pressure

(Environment One Corporation, 1997). The value of pressure ranges from 137.9 to 413.68 kPa (or from 20 to 60 psi).

These systems are generally used for rural and semi-rural communities. Pressure sewers are most cost-effective in situations where:

- Housing density is low
- The terrain undulates (relatively high relief)
- The system outfall must be at the same or higher elevation

This does not mean that this type of system is not applicable for densely populated areas.

The main engine in this system is the existence of pressure, which delivers sewage to a desired treatment or distribution system. Pressurized sewage systems are watertight if they are properly designed, which means that the systems are impervious to infiltration (Environment One Corporation, 1997; EPA, Wastewater Technology Fact Sheet).

In other words, pipes are completely sealed preventing stormwater from entering the system. The pressurized system delivers only the intended/designed/planned sanitary waste, without additional stormwater. This system also prevents additional inflows of solids from hydraulic overloads. Therefore, wastewater within pressurized systems is more homogeneous in both quality and strength and the system generally delivers higher quality effluent to the treatment plant (Environment One Corporation, 1997). Therefore, the pressurized system also affects the treatment plant and its performance.

### 7.2.1. Pressure sewer systems

Pressurized sewer systems are based on small pump stations located near the households from which wastewater is received (Strandberg, 2010). Size of the system depends on the number of households that are connected to the system. A pump is installed for each household or for a group of households. A typical household will generate wastewater in the volume of 400-800 l/day.

The pressurized sewer system was designed to transport domestic wastewater produced in dwellings and commercial properties (Norsk Standard, 1997).

Grinder pumps are mostly used in this system, due to their ability to reduce the size of solids in wastewater, which decreases the chance of clogging the system (Strandberg, 2010).

Wastewater from the pressurized system is later released into:

- The main sewer
- Larger receiving pump station

Wastewater distribution through the pressurized system is divided into the following applications:

- Residential
- Commercial
- Municipal

Residential application refers to usage of small pumps. The focus of these systems is on maintenance-free equipment.

Commercial application refers to pumps located inside buildings. The pumps have to handle higher flows and are usually operating for longer periods. These pumps are bigger in size than the pumps used for residential applications. Operators that monitor and control the performance of these pumps are also responsible for their maintenance.

Municipal application of pressurized systems implies systems that possess lift stations on the wastewater distribution net. The system consists of large pumps that are telemetrically monitored. This system is operated by professional personnel.

Equipment used to generate pressure is located at the upstream end of the pressure pipe. The downstream boundary of the system represents a discharge point from the pressurized pipe into the recipient at atmospheric pressure (Norsk Standard, 1997).

The pressurized sewer system consists of the following elements:

- Collection chamber
- Pressure generation equipment
- Pump unit
- Pipework
- Pipe joints
- Valves

#### 7.2.1.1. Collection chamber

The capacity of the collection chamber determines the maximum number of buildings that may be connected to one chamber. Therefore, the collection chamber may serve one or more buildings.

The collection chamber consists of the following elements:

1. Ventilation
2. Suitable electrical supply
3. Alarm and control equipment
4. Level control sensors (for automatic control of the pump)
5. Non return valves and isolation valves

Both working volume (in the sump) and residual volume (remaining at the end of the pumping sequence) should be designed to be as low as possible without negatively affecting pump performance and operation (Norsk Standard, 1997).

The bottom of the collecting chamber is designed with the purpose of self-cleansing. This decreases the likelihood of sedimentation within the chamber. Small volume of the tank also reduces retention time, which further contributes to prevention of sedimentation (Norsk Standard, 1997).

Collection chambers also possess equipment for monitoring water levels and the pump activates automatically as soon as the preset level is reached.

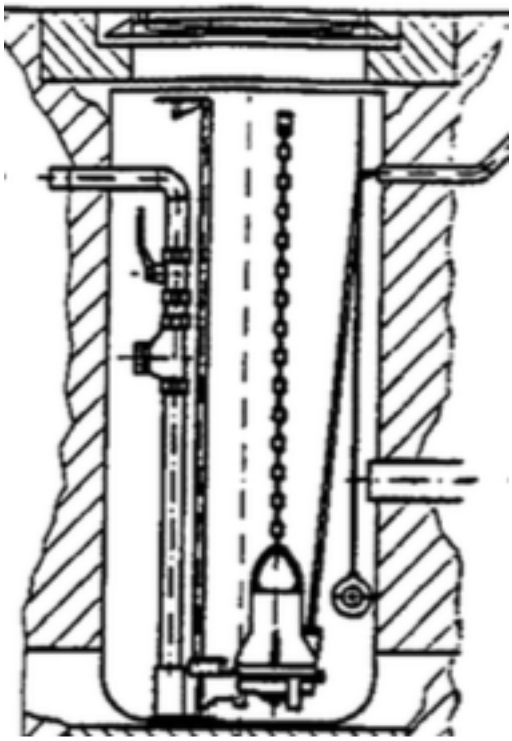

**Figure 7.1: Bottom of the collection sump (Norsk Standard, 1997)**

The collection chamber is designed to resist external forces, it is watertight and it does not allow any infiltration.

#### 7.2.1.2. Pressure operating equipment

The following pumps can be used for the purposes of pressurized sewer system:

1. Semi positive displacement pumps with grinder (Chapter 8)
2. Single vane non-clogging centrifugal pumps
3. Vortex pumps
4. Multi-vane open impeller pumps with grinder

#### 7.2.1.3. Pipework

Pipelines are laid so as to follow the ground contour. They are mostly constructed from corrosion free materials such as polyethylene (PE) or polyvinyl chloride (PVC), which are unaffected by permanent contact with wastewater, gases from wastewater and surrounding environmental conditions.

According to the Norsk Standard from 1997, pipelines in the collection chamber and the pipe system should be constructed from materials that can handle minimum pressure rating of 6 bar.

Most of these pipelines are placed in the ground but there are certain situations where pipelines are placed on the ground. In situations where the pipeline is on the ground it is necessary to evaluate the possible effects of loss of strength of the pipe material. Loss of strength of the pipe material is likely to occur with longer exposure at higher temperatures (Norsk Standard, 1997).

#### 7.2.1.4. Pipe joints

The fittings used to connect pipelines should be as smooth as possible, in order to avoid possible sedimentation and blockages of the pipeline.

#### 7.2.1.5. Valves

Valves play an important role in the operation and maintenance of the pumping station. Valves are used to control pressure as well as speed.

**Figure 7.2: Ending controlling valve (Source: the author)**

## 7.3. Design requirements

The pressurized sewer system needs to fulfill the following requirements:

- Operate without blockages
- Operation of the system will not cause flooding (it is important to properly analyze the amount of wastewater)
- The system will not endanger adjacent structures
- Pipes have to be resistant to pressure
- Prevent the formation of odor
- Easy access for maintenance

In order to ensure that the pressure sewage system operates constantly and safely without any unwanted problems, the following hydraulic requirements need to be met:

- Sufficient liquid velocity in pipes to prevent sedimentation inside the pipe
- Sufficient velocity removes air pockets in pipes
- Reduced retention time and reduced generation of hydrogen sulfide

### 7.3.1. Maximum retention time

In order to limit and prevent formation of wastewater gases within the system, it is strongly recommended to prevent wastewater retention longer than 8 hours (Norsk Standard, 1997). The allowed retention time varies with the location and temperature conditions.

### 7.3.2. Minimum velocities

The same criterion for self-cleansing velocities of the pipes applies to both pressure sewage systems and previously mentioned gravitational systems. The minimum required velocity to prevent possible sedimentation of solids is 0.7 m/s.
The Norsk Standard report from 1997, (p.16), states that: ”self-cleansing velocity refers to the flow velocity required to convey solids along with the water carrier”.

Therefore, adequate system performance depends on maintaining an unobstructed pipeline. The same source (p.16) indicates that: "flow velocity should be sufficient to transport grit and solids that may be present in the wastewater, to prevent grease depositing on the crown of the pipe, and to scour and resuspend previously settled material".

When a grinder pump is used in the pressurized system, the normal self-cleansing velocity is in the range from 0.6 to 0.9 m/s and it should occur once per day (Norsk Standard, 1997). It was thought that with velocities higher than 0.9 the system would perform better in terms of scouring/self-cleansing of the pipes, but higher velocity actually produced only higher flow rates and higher head losses (Norsk Standard, 1997)

The author´s experiment conducted at NMBU showed/indicated that an E/One grinder pump can be self-cleansing even at velocities lower than 0.6 m/s. This is more thoroughly analyzed in the chapter 14.

### 7.3.3. Power supply

Adequate power supply is necessary for functioning of the system. Most of these systems are running on electricity, which means that adequate power supply needs to be provided.

### 7.3.4. Emergency conditions

In case of power failure, emergency storage volume is secured through the collection chamber. According to the Norsk Standard (1997) emergency storage volume can store approximately 25% of the total daily inflow. In the event that the emergency storage is insufficient additional safety measures can be developed.

### 7.3.5. Pipe requirements

The pipe needs to resist pressure without bursting. Pipe size depends on flow design and distance (Norsk Standard, 1997). With proper design of the pressure sewage system, it is possible to prevent operating problems. For instance formation of $H_2S$ in pipes and the collection chamber can be prevented by minimizing retention time (Norsk Standard, 1997).

## 7.4. System calculation

For determining fixed flow velocity within the pipe, it is necessary to follow pressure differences in the given section (between entrance and discharge points of the pipe). Therefore the following equations (eq. 7.1a, 7.1b, 7.1c) are useful:

$$H_{tot} = h_{st} + h_l \quad \text{(eq. 7.1a)}$$

Where $h_{st}$ represents static pressure

$h_l$ is head loss that consists of two parts, head loss due to friction ($h_{fl}$) and head loss due to point losses ($h_{pl}$)

$$h_l = h_{fl} + h_{pl} \quad \text{(eq. 7.1b)}$$

$$h_l = \frac{f\ x\ l}{d}\ x\ \frac{v^2}{2g} + \xi \frac{v^2}{2g} \quad \text{(eq. 7.1c)}$$

Where:

f - friction value calculated using the Colebrook White formula. This value depends on the Reynolds number and pipe roughness.

d –internal diameter of pipe (m)

g – gravitational acceleration ($m/s^2$)

l – length of pipeline (m)

v – velocity of water (m/s)

$\xi$ – minor loss factor in the pipeline (the value varies as defined)

With measuring the pressure head at the pump's discharging point, it is possible to determine flow from the H-Q graph and thereby it is also possible to determine flow velocity in pipes (Norsk Standard, 1997). For calculation of velocity in pressurized pipes it is important to include the SDR (Standard Dimensional Ratio, Chapter 12) value of the pipe in determining the pipe diameter.

## 7.5. Application of pressure sewage systems

In less densely populated areas, gravity sewer systems are considered uneconomical due to their high construction costs.

Pressure sewer systems are an alternative to both gravity and vacuum sewage systems (Norsk Standard, 1997).

The main difference between pressure systems and gravitational systems is in their construction:

- Pipes in the pressurized system are closed, without entry facilities, unlike in the gravitational system
- The crucial element for the gravitational system is slope
- The pressurized system does not need gravity and pipes follow the contour lines

Pressurized systems are considered applicable in the following situations:

- High ground water level
- Insufficient terrain gradient
- Suburban areas, where population is not too dense
- Areas which are growing at a slow rate
- In critical environmental conditions

The Norsk Standard report from 1997 (p.15) states that a ”pressurized sewer system allows maximum freedom in overall design regardless of topographic conditions”.

## 8. Pumping system

The pumping system consists of pipes and one or more pumps depending on the size of the system. Pipes are elements/medium that transports liquid through the system. The action of the pump is to assist and control the process of distribution through the given system. During transportation the liquid is subject to several resistance factors, such as:

- Friction, which reduces flow as the fluid goes through the pipes.
  Friction loss is pressure loss or force that is required to push water to the discharge point. Total amount of friction is given as sum of all losses that occurs through pipeline, valves, elbows, fittings etc. The value of friction loss can be calculated once the system is designed.
- Pressure, in situations where the discharge point is at a higher elevation

Different water systems have different requirements and it is necessary to carefully evaluate the needs of the system. In order for the system to operate properly it is necessary that all components must be sized and selected properly (Beverly, 2009).
Factors that are used to size a pump are:

1. Flow
2. Pressure
3. Motor horsepower

### 8.1.Pumps

A distribution pump is a machine used to deliver a specified rate of flow through a particular system (Karassik, 2001). Total head and capacity of the pump are the key parameters that have to be taken into consideration in designing the distribution system. Total head ratings for centrifugal pumps are mostly measured in meters, while pressure ratings for positive displacement pumps are measured in bar or kilopascals (Rishel, 2002).

The function of a pump can be defined as the difference in energy levels between the discharge and entrance points (Jones, 2008). Performance of the pump is described in terms of static head H produced at the given flow capability Q.

The two main factors that determine the pump head rating are system pressure and resistance to flow. If the system is not properly designed, for instance if the requirement for total head is not met, the discharge performance of the pump will be reduced below the desired level. In case of positive displacement pumps, power consumption would increase, causing an increase of the designed pressure.

Most pumps are driven by electric motors. The pump can also be driven by gasoline (diesel, petrol) and the motors can be variable speed or constant speed motors.

There are many different classifications of pumps, but the main classification of pumps according to Jones (2008) divides pumps into two groups, as shown in Figure 8.1:

- Kinetic pumps
- Positive displacement pumps

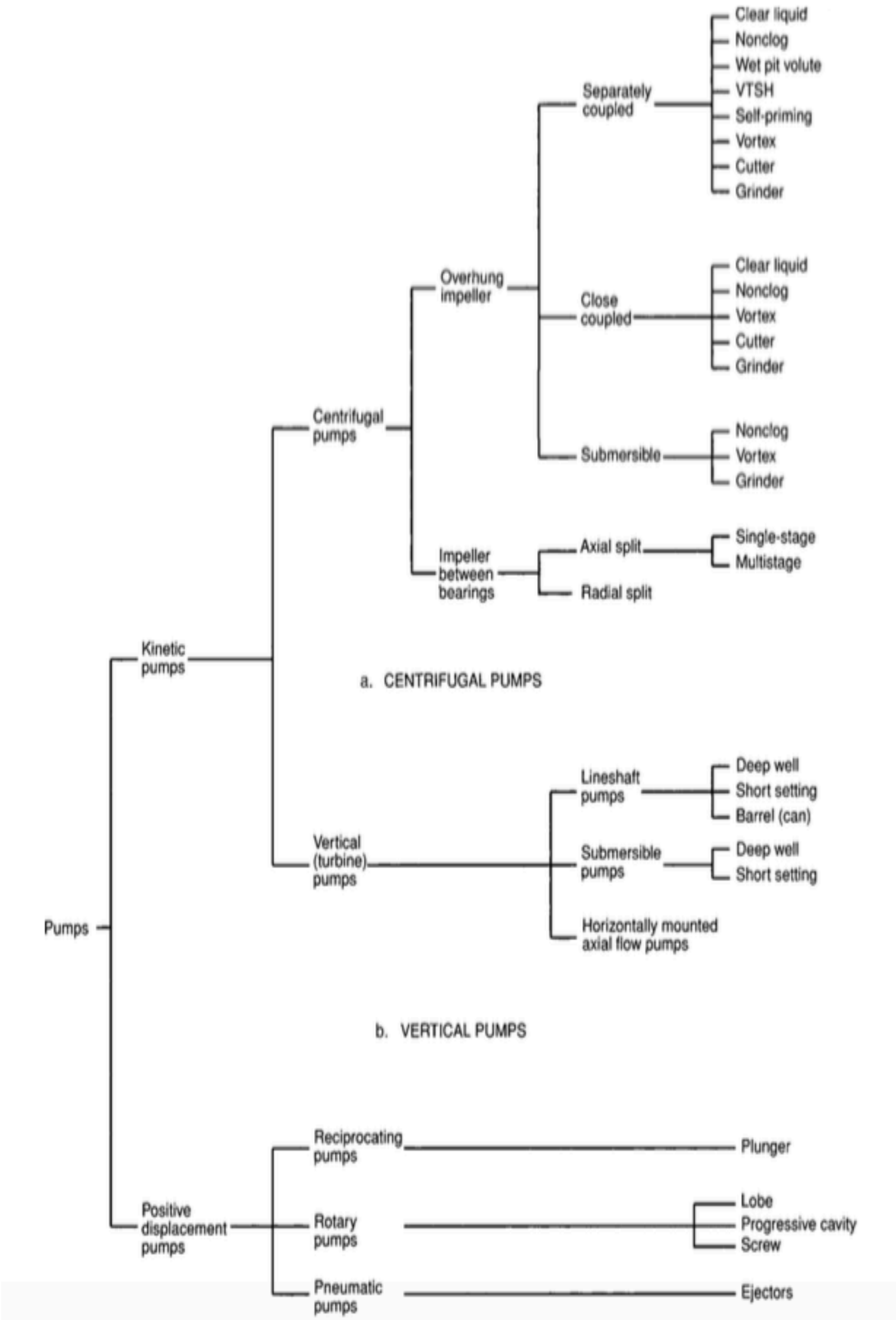


**Figure 8.1: Classification of pumps by Hydraulic Institute Standards (Jones, 2008)**

### 8.1.1. Kinetic pumps

The main characteristic of kinetic pumps is that they impart velocity and pressure on the fluid as it moves through the pump impeller. In this process a portion of velocity is converted into additional pressure (Jones, 2008). As shown in Figure 8.1, these pumps are divided into 2 groups:

#### 8.1.1.1. Centrifugal pumps:

This type of pump is defined as a rotating machine where flow and pressure are generated dynamically. The main pumping mechanism is the delivery of useful energy to the fluid mainly through velocity changes. The change in velocity occurs with the movement of fluid through the impeller.

The flow pattern of centrifugal pumps is considered three-dimensional and unsteady in varying degrees (Karassik, 2001).

When the pump starts working for the first time, all passageways within the pump are filled with air. Centrifugal pumps can pump air only when the pressure is equivalent to the rated head of the pump (because of the specific weight of air).

Main centrifugal pump characteristics are as follows:

- The generated dynamic head is a function of pump capacity and system requirements.
- For efficient operation, flow has to be kept within the optimal performance range.
- There are no acceleration heads that impose on the net positive suction head (NPSHA). NPSHA represents the required head value that prevents fluid from cavitation within the pump. NPSHA also determines the maximum speed at which the pump should operate (Karassik, 2001).

#### 8.1.1.2. Vertical pumps

Vertical pumps are pumps that are equipped with an axial diffuser.

### 8.1.2. Positive displacement pumps

Positive displacement pumps play vital role for distribution of water with solids (Rishel, 2002). Positive displacement pumps displace the liquid from the pumping station by the action of their moving elements: piston, rotor, and plunger. This type of pumps does not generate any pressure themselves unlike centrifugal pumps (Rishel, 2002). The flow rate within a positive displacement pump is proportional to the displacement rate and more or less independent of pressure levels (Karassik, 2001). The average capacity of positive displacement pumps within a certain range of pressure variations is practically constant, which offers a big advantage over centrifugal pumps (Karassik, 2001; Rushel, 2002). Positive displacement pumps usually operate at lower speeds compared to other types of pumps. As shown in Figure 8.1, there are 3 major groups of positive displacement pumps:

- Reciprocating pumps

  The moving element in this pump is a piston or plunger. This type of pump can develop very high pressures.
- Rotary pumps

  The pump rotor displaces liquid from the pump casing. This is usually a slowly rotating helical screw.
- Pneumatic pumps

  In this type of pump the main driver for movement of liquid is compressed air.

For the purposes of this project focus is placed on positive displacement pumps, particularly positive displacement grinder pumps.

## 8.2. Grinder pumps and hydraulic characteristics for centrifugal and progressive cavity grinder pumps

One of the newly developed procedures for collecting residential sewage uses a grinder pump. This type of pump is considered effective for handling raw sewage and it generates sufficient pump head to push/move the sewage through the system. This pump has cutters (grinder) that assist in the process of handling raw sewage in the pump.

### 8.2.1. Centrifugal grinder pumps

Centrifugal grinder pumps do not have constant flow and the flow value varies with the fluctuations in pressure. The flow usually ranges from 1.5 to 1.9 l/s or 20-25 gpm, which is relatively high compared to other types of pumps. This type of pump is wear resistant and the high discharge value can also achieve a self-cleansing effect. In situations where the value of static head is high, larger pumps and larger motors are required to handle the load.

These pumps are also used for sewage distribution (Strandberg, 2010). The centrifugal grinder pump consists of:

- Electrical motor
- Double mechanical seals (that separate the motor from the wet part)
- Cutting device
- Impeller

Design has a major influence on the performance of the pump. The typical shut-off head for centrifugal grinder pumps is from 33 m (110ft) up to 60 m (200ft) (Strandberg, 2010). This type of grinder pump used for residential purposes may have maximum flow of 3 l/s or 40 gallons per minute.

This pump requires 2-3 HP for achieving 33m (110ft) of head, which is slightly higher in comparison to progressive cavity pumps.

With centrifugal pumps, the increase of total dynamic head is accompanied by a decrease in power consumption. Centrifugal pumps do not have problems with high pressure, provided that the system that is built from pipes with a larger diameter.

This type of pump is the most common type in PSS (Strandberg, 2010).

They are also quite suitable and are used in relatively flat profiles (Rishel, 2002).

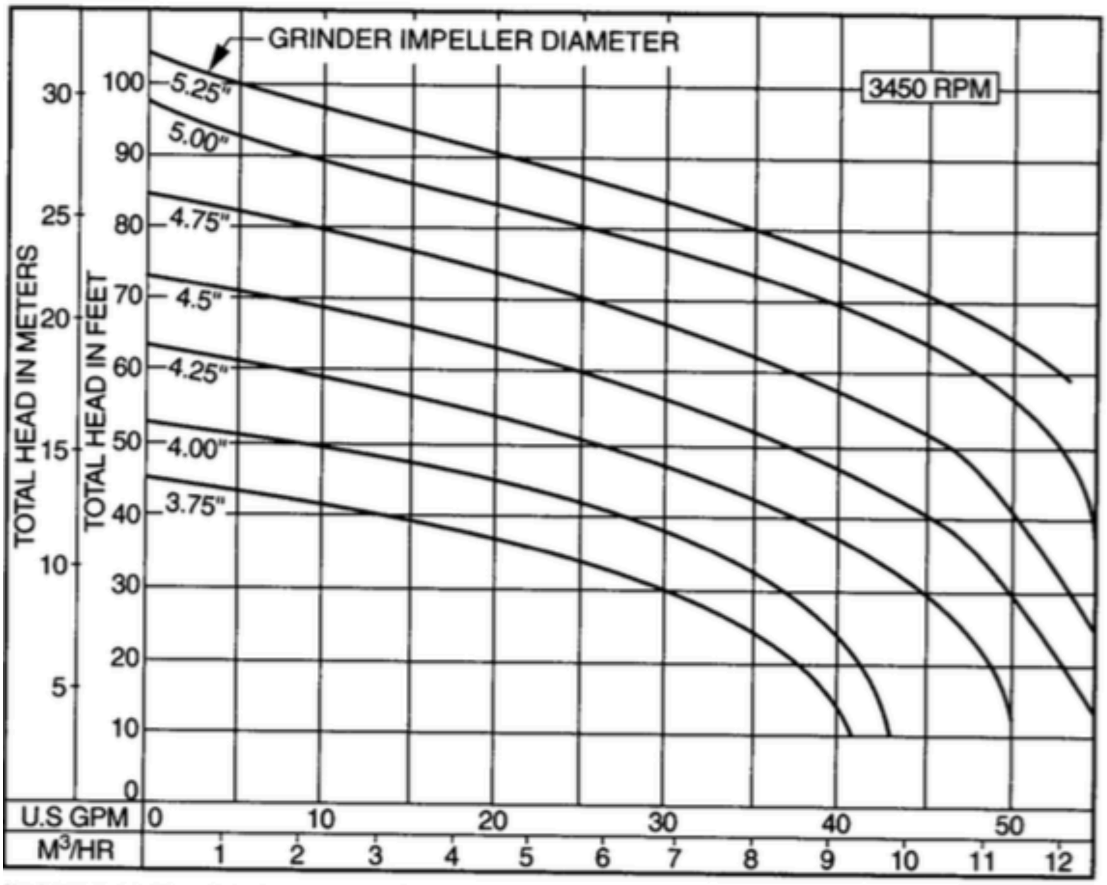


**Figure 8.2: Grinder pump performance, centrifugal type (Rishel, 2002)**

### 8.2.2. Progressive cavity grinder pumps

Progressive cavity pumps are mostly used in situations where the system requires smooth and steady discharge. This type of grinder pumps belongs to the category of positive displacement pumps. The pump moves fluid by trapping it and forcing it into the discharge pipe (Strandberg, 2010).

These pumps are most commonly used for distribution of materials that contain large particles. With the rotation of the rotor, fluid is forced to move through the rubber sleeve and this generates low and stable flow at both low and high heads (Strandberg, 2010; Environment One Corporation, 1997).

With each rotation of the corkscrew shaped rotor that turns within a rubber stator, pumping action occurs.

This type of pump is more sensitive to wear than a centrifugal pump if the pump runs at snoring, i.e. air suction at low liquid level.

The progressive cavity grinder pump generates relatively constant flow at various discharge pressures. This means that regardless of the pressure value the flow will vary within the range of 0.7 to 1.1 l/s or 9-15 gallons per minute (Strandberg, 2010). Flow capability is a function of helix pitch, rotor speed and rotor diameter (Jones, 2008). The pressure capability of these pumps is a function of the number of rotor stages. Performance of the pump is characterized by an almost vertical performance curve, as shown in Figure 8.4 (H-Q curve). The pump does not shut down when pressure reaches high values, however the flow reduces as the pressure increases. Flow is considered constant for almost all duty points. The typical maximum pump head is around 60 m or 200 ft.

Normal duty points in pressurized sewage systems for this type of pump rarely exceed total head value of 160 ft or 50 m. Therefore these pumps are suitable for hilly areas with high peaks and static heads.

These pumps are used for pumping difficult materials such as sewage waste. The main elements of the pump are:

- The helical rotor
- The rubber sleeve stator that is fixed to the side wall of the pump chamber and is helical shape

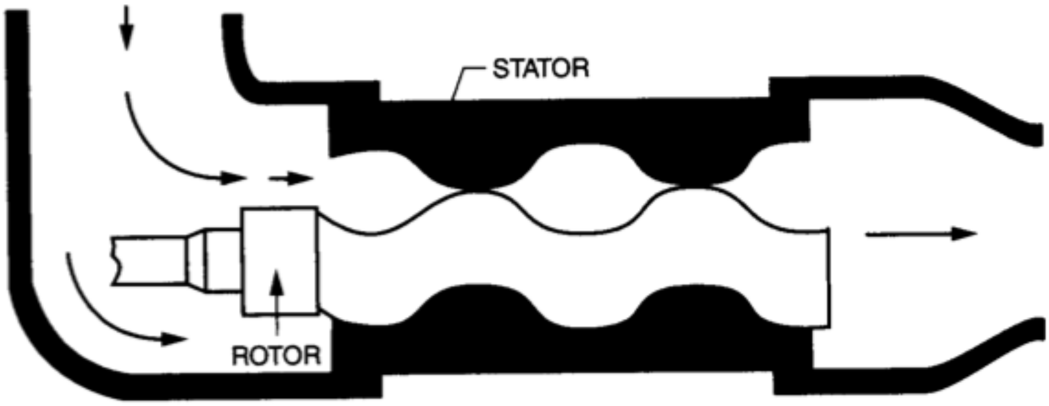


**Figure 8.3: Rubber sleeve stator of progressive cavity grinder pump (Rishel, 2002)**

Rotation of the rotor secures movement of the fluid through the rubber sleeve.

The typical power rating of this pump is 1.7 HP.

Power consumption increases with increased pressure; under normal conditions the pump consumes 8 amps but under strain consumption can reach up to 20 amps

(Strandberg, 2010). Very high pressure may cause increased thermal restrictions within the motor itself, leading to a complete stop of pump operation. This is why it is strongly recommended to control and monitor pressure values within this system.

These systems are applicable for collection and distribution of sewage in high terrain and high static lift conditions (Rishel, 2002). The size of solids that can be distributed through this pump is limited to 45 mm in diameter (Jones, 2008).

This type of pumps is not suitable for transportation of abrasive materials that may cause deterioration of the pump operation (Beverly, 2009).

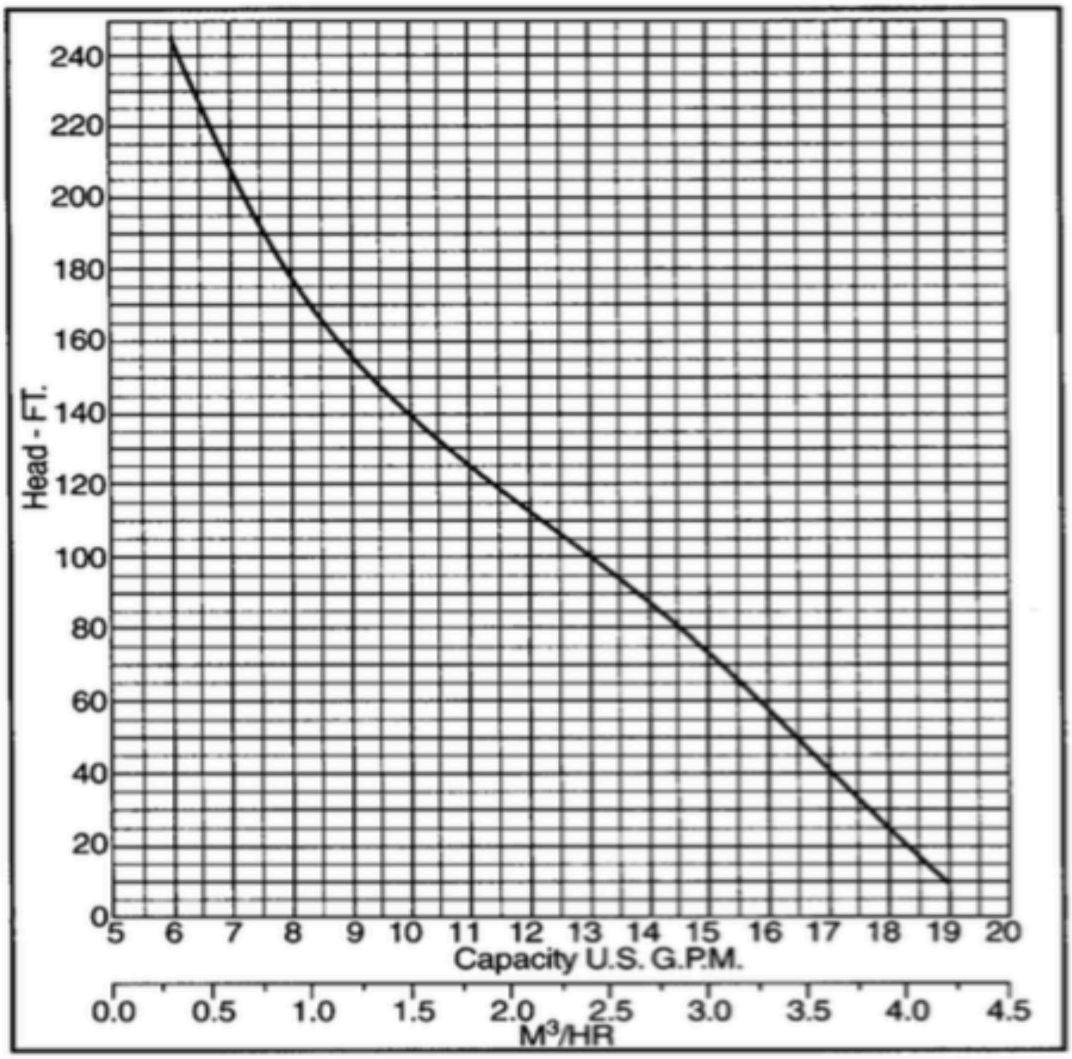


**Figure 8.4: Grinder pump performance, progressive cavity type (Rishel, 2002)**

## 8.3. Environment One grinder pump

The E/One grinder pump is a semi-positive displacement pump that was created over 40 years ago. The flow in this pump is nearly constant, regardless of the pressure. The E/One grinder pump has capability to exceed the steady state of normal rating pressure by up to 50% without causing harm to both pump and pipes (Environment One Corporation, 1997). This pump can only be applied for the purpose of wastewater distribution. E/One grinder pumps are mostly applied for distribution of wastewater generated from the household or households (depending on the size of the pump) to the main sewage pipeline. All of the above-mentioned characteristics of progressive cavity grinder pumps are implied to this pump as well.
At more or less constant flow this pump discharges fine slurry material that was previously grinded in pump.

Key characteristics of E/One grinder pump are:

- High heads, which secure reliable operation of the pump
- Constant flow regardless the pressure variation.
- High grinding torque, 1 horsepower motor that turns at 1725 rpm
- Energy efficient, the pump automatically activates and runs by itself (once the amount of wastewater reaches certain level in pump).
- Low operating cost
- Corrosion resistance, the pump is made of stainless steel ball type discharge valve.
- Low impact on environment; does not require big construction work to install these systems.
- Low maintenance

All sanitary waste that goes through this pump is reduced to slurry non-clogging material. This slurry material is later distributed through small diameter pipes to the desired location, which in most cases is gravitational sewage system (Environment One Corporation, s.a).

## 9. Pipe materials

Materials used for pressure pipes are:

1. Cast iron
2. Steel
3. Ductile iron
4. Plastic
5. Fiber glass
6. Reinforced concrete

Factors such as hydraulic roughness, pressure requirements, pipe size, resistance to corrosion (both internal and external), ease of handling and installation, and economics have an impact on the choice of material to be used for the system (Plastic Pipe Institute, s.a).

It is important to know that the planned pipe material must withstand maximum internal pressure. Besides the positive pressure rating of the pipe, another important factor that needs to be determined is whether the pipe will be exposed to any negative pressures. If the pipe is exposed to negative pressure for a short period this won't cause the pipe to collapse (Plastic Pipe Institute, s.a). If exposure is not just brief and temporary, negative pressure would destroy the pipe.

Selection of wall thickness also depends on the size of the pipe. Wall thickness for larger pipes depends on collapse pressure and handling loads more than on burst pressure. For instance, larger pipes with thin walls are adequate for resisting relatively high internal pressure but they may collapse under the influence of negative internal pressure. The problem proportionally increases with the increase of the pipe diameter and affects thin-wall steel and plastic pipes. On the other hand, certain pipes are capable of handling internal vacuum (for example, concrete is highly resistant to collapse).

Awareness that different materials have different resistance to the impact of load and forces caused by poor bedding conditions are essential for making the right decision. Steel, cast iron and ductile iron are resistant to impacts of load caused by external forces.

Pipes made of these materials are known to need less care in handling. On the other hand, plastic, concrete and corrugated metal pipes are more vulnerable during shipping, installation and handling. For these of materials it is very important to provide proper bedding conditions and proper backfill in order to avoid damage caused by external loads. The amount of plastic pipes used in global infrastructure increases each year. Plastic is resistant to corrosion and this gives it great advantage over iron pipes (Plastic Pipe Institute, s.a). Metallic pipes frequently need interior linings and exterior coverings, which can also lead to higher costs. The range of applications for plastic pipes is very wide. For example, plastic pipes are predominant in gas transportation pipelines, as well as drinking water and wastewater transportation pipelines. Plastic pipes are easy to install, connect and transport, which gives them a certain advantage over other materials.

Depending on the pipe material different methods are used for coupling pipe sections. For metallic pipes there are many types of different connectors available, such as welding, flange and mechanical fasteners. For plastic pipes we use flanges, mechanical fasteners, glue joints and bell and spigot joints.

## 9.1. Pipe pressure class

A major step in convenient pipe design is the selection of the pressure class. Certain organisations such as the American Water Works Association (AWWA), American Society for Testing and Materials (ASTM) and the Plastic Pipe Institute (PPI) have created guidelines with the objective to assist in making the right decision. Specifications are provided for all common types of pipe materials. The process of selecting appropriate pressure class for different pipe materials is complex. It is important while designing the pipeline to check the characteristics of the material that the designer intends to use.

Main considerations in selecting the pipe pressure class are:

1. Maximum internal operating pressure
2. Transient pressure
3. Variations of pipe properties (in combination with temperature/long term loading effects – for plastic pipes)
4. Possible damage during handling, shipping, installation, aging or chemical effects
5. External loads (both earth and live loads)

Most pipes are tested for quality control purposes. The hydrostatic pressure test varies depending on the pipe material. Testing is done at the manufacturing plant, on new pipes, under ideal conditions and without the effects of external loads. During pressure testing, pressure increases slowly and evenly up to the limit/highest point or until the pipe bursts. For non-destructive tests, the value of applied pressure is constant only for a short time and is then relieved. Maximum operating pressure cannot be the only factor for estimating pipe safety. The value of maximum operating pressure varies between gravity flow systems and pumped systems. In the gravity flow system the maximum operating pressure is the reservoir shutoff head, while in the pump system the maximum operating pressure is the pump shutoff head (Plastic Pipe Institute, s.a; AWWA).

The value of transient pressure or surge is difficult to anticipate. It depends on specific design and operation procedures relevant to each pipe system.

Strength of the plastic pipe is notably affected by temperature. For instance, an increase in temperature from 21.1 to 43.3 ˚C (70-110 ˚F) decreases the pressure capacity of PVC pipe to about half of its original strength (Plastic Pipe Institute, s.a). Besides temperature, there are other factors which can impact the value of operating pressure, such as chemical attack, handling, aging and shipping. The impacts of these factors are generally very difficult and sometimes even impossible to predict. These factors are often combined into the term “internal hydrostatic design pressure”. This can be expressed by the following equation (eq.9.1):

$$\text{Internal design pressure} = (P_o+P_s)SF \qquad \text{(eq. 9.1)}$$

$P_o$ defines the maximum steady state operating pressure, $P_s$ refers to waterhammer pressure (surge), SF represents the safety factor (usuall recommendation is 2 or 3). For this reason the designer should always take the safety factor into account.

The effect of external loads also plays an important role and it is important to test pipes for resistance to external forces as well. If the pipe does not break, split or crack the test is considered successfully passed.

Internal pressure is not applied for this type of test. External load tolerance of the pipe depends from:

1. Pipe diameter
2. Pipe material
3. Depth of the cover
4. Specific weight of the soil
5. Type of backfill material

### 9.2. Polyethylene (PE)

PE was synthesized in 1898 by the German chemist Hans von Pechmann. The first practical industrial polyethylene synthesis was discovered in 1933 by E. Fawcett and R. Gibson. PE gradually became one of the world's most widely used thermoplastic materials. The variety of applications started during World War II, where PE was used as a substitute for ruber in electrical insulation. Today PE is mostly used in pressure-rated gas and water pipes but it can also be used for automotive fuel tanks, landfill membranes and many other applications.

The first use of PE as a piping material occured in mid-1950's in the USA. It was used in the oil industry for applications that required a flexible, lightweight and tough piping product. Good performance of PE pipe systems subsequently led to wider use of this material, for example in distribution of potable water and wastewater. The advantages of it being a coilable, leak- and corrosion-free material opened the door for new possible applications. There are estimates that show that nearly 95% of all new gas distribution pipe installations in North America are made of PE (Plastic Pipe Institute, s.a). One of the main reason for rapid growth of PE pipe usage lies in cost savings in installation, labor and equipment compared to traditional piping materials.

Lower maintenance costs and increased service life made PE pipes a very competitive product.

From the designer's perspective, when selecting material certain requirements have to be met, such as reliability, long-term service durability and cost-effectiveness. The solid PE pipe wall provides a cost-effective solution for a wide range of piping applications such as:

1. Natural gas distribution
2. Municipal sewers and potable water
3. Industrial
4. Mining
5. Landfills
6. Electronics

PE pipes can be effective in buried and above ground conditions. This type of pipe has been used for purposes of distributing potable water for almost 50 years. PE pipe is approved by AWWA, ASTM and NSF standards.
Benefits of PE pipe are:

1. Life cycle cost savings - for municipal applications, PE pipe has a significantly lower life cycle cost than any other material. Along with inside smoothness of the PE pipe, which maintains flow characteristics, anoter important quality is that proper fusion joining eliminates leakages (Plastic Pipe Institute, s.a). These characteristics successfully reduce the total system operation cost.

2. Fully restrained joints - with PE heat fusion, newly formed joints are as strong as the pipe itself. Compared to other piping products, allowable water leakage for PE pipe is zero, which represents great advantage over other, competing products.

3. Corrosion and chemical resistance - this type of pipe is resistant to rust, pit and corrosion, it does not support biological growth and is highly resistant to chemicals. Pipes will need adequate protection in case of contact with organic solvents (Plastic Pipe Institute, s.a). Security measures assure that the quality of the fluid remains the same during transportation through the pipeline.

4. Fatigue resistance and flexibility - flexibility is one of the important assets of PE pipes. Depending on wall thickness, this type of pipe has a bending radius of 30 times the pipe's nominal outside diameter (Plastic

Pipe Institute, s.a). Durability of PE pipes has been well researched and tests have shown that PE pipe has excellent fatigue resistance. Analyses have confirmed that, while operating at maximum operating pressure, the pipe can withstand multiple surge pressure events up to 100% above its MOP without negative effects (Plastic Pipe Institute, s.a).

5. Seismic resistance - due to its toughness, flexibility, ductility and leak-free qualities, PE pipes are proved to be a good solution in tectonically active areas.

6. Construction advantage - simple installation, better impact resistance than certain other commonly used materials (like PVC pipe) and easy transportation are just some of the advantages that give PE pipes a great advantage over other materials (Plastic Pipe Institute, s.a). PE pipes are fabricated in straight standard lengths of 15.24 m (50 ft) or more. Pipes can be easily joined into long runs, laid above ground or in trenches.

7. Temperature resistance - the typical operating temperature for PE pressure service pipes is from -17 to 60°C (0-140°F) (Plastic Pipe Institute, s.a). For example, PE pipes for non-pressure purposes can handle an even wider temperature range. The conducted tests demonstrated that this type of pipe material can be applied in a very wide temperature range.

8. Durability - PE pipe manufacturers estimate the useful PE pipe service life to be approximately 50-100 years, provided that the system is properly designed, installed and operated. Maintenance is required in order to secure long life of the system.

9. Hydraulic efficiency - internal surface of PE pipes is smooth, with lowest resistance to fluid flow. For the purposes of water distribution

(both potable and sewage water) PE pipe's Hazen Williams C factor is 150. The value of C factor is constant and it does not change with time (Plastic Pipe Institute, s.a). In other type of pipes the C factor decreases with time due to biological build-ups and corrosion. PE pipe maintains a smooth interior.

There are two important physical properties, which have to be taken into consideration in dealing with PE pipes:

### 9.2.1. Ductility

By definition, ductility is the ability of a material to deform as a result of pressure exposure without breaking. Ductility can also be said to represent increased strain capacity. It therefore represents an important factor for PE piping. Ductility of the PE pipe enables safe handling of stress, while non-ductile materials do not handle localized high stress conditions as well as the polyethylene pipe. Placement of the PE pipe also has to be taken into consideration as it can influence the value of ductility of the pipe. Ductility has always been one of the representative and inherent properties of PE pipe materials. (Plastic Pipe Institute, s.a)

### 9.2.2. Viscoelasticity

PE pipe is also a viscoelastic material. Polyethylene is a combination of fluid-like and elastic-like elements. When we are talking about the viscoelastic nature of PE pipe, it is necessary to define two characteristics: creep-time dependent viscous flow component of the deformation and stress relaxation.

## 10. Sedimentation in sewer systems

Sediment transport rate varies greatly with the flow rate. Currently all sewage systems are designed to achieve uninterrupted transport of sewage solids through the system (Czarnota, s.a). Low velocity is considered to be one of the major disadvantages of gravity sewer systems. Low velocity is also suitable for deposition of solids and accumulation of gas pockets, and both of these factors have a negative impact on the performance of the sewage system (Bo Copeland, 2013). Accumulation of sediments in pipes negatively affects sewer systems by reducing their hydraulic capacity and it also may cause pollution of the environment due to the high concentration of high pollutants (Bong, 2014). Main parameters that affect the mode of transportation are properties of solids (density, shape, size, cohesive properties), conduit properties (size, shape, surface roughness, slope) and flow conditions (level of turbulence, velocity and depth) (Czarnota, s.a). The combination of these parameters affects the mode of sewage transport. Figure 10.1 shows the sedimentation process that takes place in pipe.

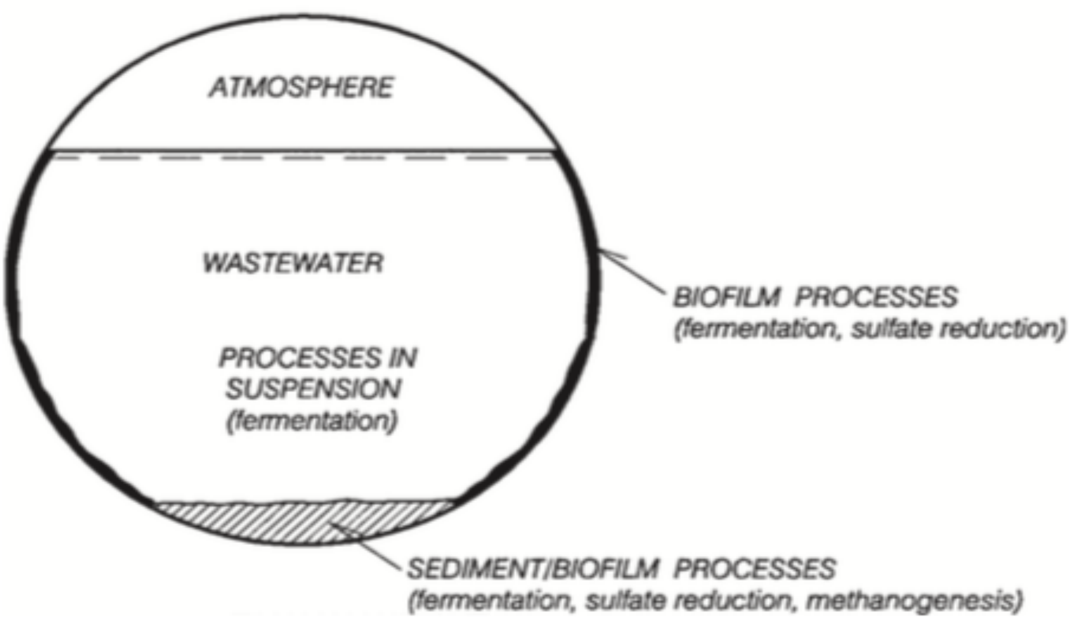


**Figure 10.1: Cross section profile of pipe (Jacobsen, 2002)**

Homogeneous suspensions flow occurs in situations where velocity is high enough for turbulent flow, which keeps the solid particles uniformly suspended and moving along with the fluid. The following figure 10.2 shows a homogeneous flow:

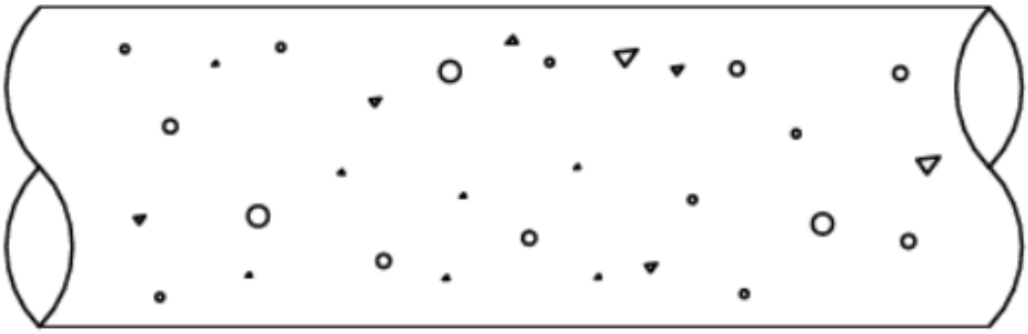

**Figure 10.2: Homogeneous suspension (Copeland, 2013)**

At lower velocities a heterogeneous suspension develops, in which heavier particles slow down and begin to settle/accumulate in pipes (Bo Copeland, 2013). This is shown in figure 10.3.

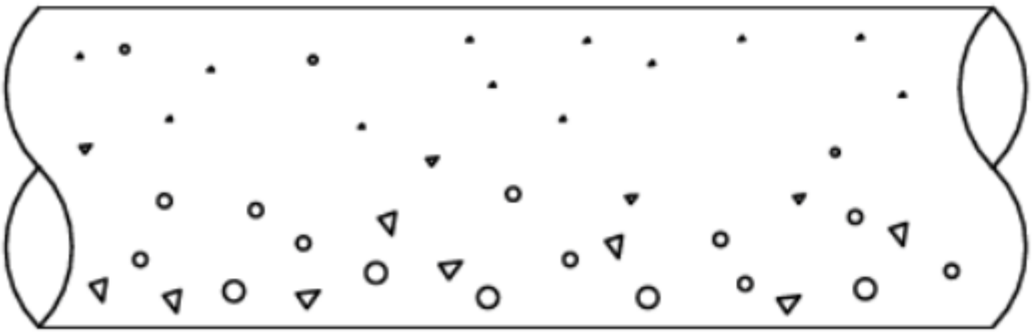

**Figure 10.3: Heterogeneous suspension (Copeland, 2013)**

Sliding bed conditions represent situations where the particles settle to the bottom of the pipe. Movement of particles is reduced and discontinuous due to slow velocity (Bo Copeland, 2013). The figure 10.4 shows scheme of sliding bed condition in pipes. This condition may cause abrasion of the pipe, as shown in Figure 10.5. Solids from the wastewater as light materials can move through the pipe in rolling way or as suspended material (Czarnota, s.a).

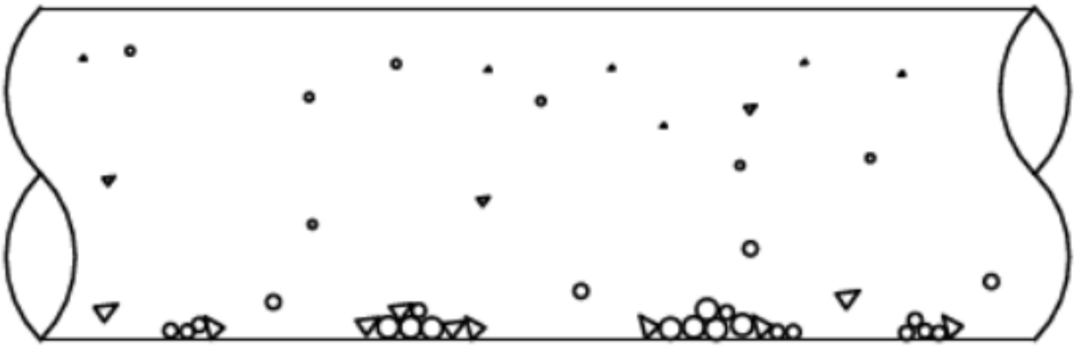

**Figure 10.4: Sliding bed conditions (Copeland, 2013)**

**Figure 10.5: Erosion of the pipe due to sliding bed conditions (Copeland, 2013)**

Stationary bed conditions occur in situations where large particles remain deposited in the lower parts of the pipe (figure 10.6). However not all particles are immobile, lighter particles will continue to move along the surface (Bo Copeland, 2013). Stationary bed conditions reduce the cross section of the pipe as a result of sediments deposited in the pipe.

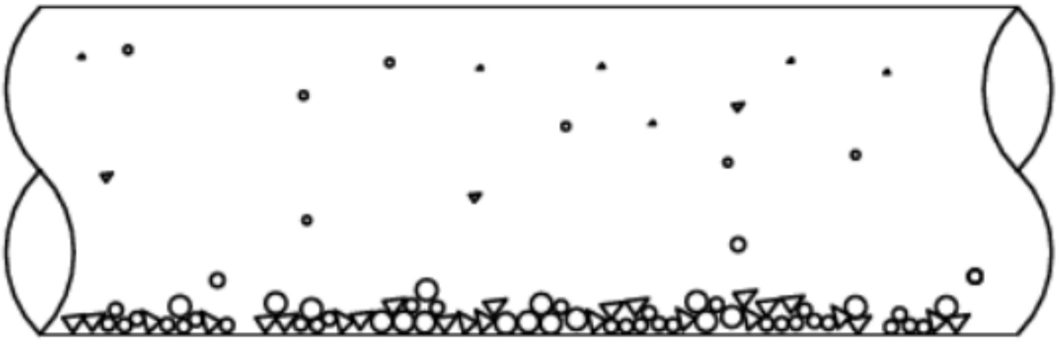

**Figure 10.6: Stationary bed conditions (Copeland, 2013)**

Deposition velocity, also known as re-suspension velocity, represents the transition point from heterogeneous flow to sliding bed flow (Bo Copeland, 2013).

So in order to avoid reduction of the cross section area of the pipe, it is desirable to operate the flow at a velocity that will maintain turbulent flow inside the pipe, thus maintaining a heterogeneous suspension of solids and preventing the deposition of solids.

For gravitational systems it is strongly recommended to periodically achieve scouring velocities in order to avoid possible erosion and decrease of cross section of pipes (Bo Copeland, 2013)

There are numerous publications such as the “Ten States Standards” (The Great Lake – Upper Mississippi River Board of State and Provincial Public Health and Environment Managers, 2004) and “Pumping Station Design” (Jones, 2008), which recommend that wastewater pumping facilities should be designed to maintain minimum velocity of 0.61 m/s (2.0 ft/s) in order to prevent possible depositing of solids. For gravitational sewer systems, it is suggested to periodically achieve higher flushing velocities of 1.07 m/s (3.5 ft/s) (Norsk Standard, 1997; Copeland, 2013).

When velocity is higher than 1.07 m/s, re-suspension of settled solids occurs within gravitational sewage pipes.

Gravitational sewer systems may require additional adjustable velocity pumps in order to maintain flow velocity of 0.61 to 1.07 m/s. Installation of these pumps only increases the cost of this system.

Copeland (2013) states that, for gravitational systems, if the velocity of 0.61 is not reachable the deposition and settlement of solids will occur within pipes. Side effects of this process are:

- Reduction of hydraulic capacity
- Odor
- Accumulation of gas pockets

Low velocity allows for build-up of biological slime and grease on the pipe wall, which decreases its hydraulic capacity and in some conditions may accelerate internal pipe corrosion. The build-up of sediments on the pipe wall also changes the roughness value of the pipe.

In addition to this, microbial activity in the sewer may generate dangerous gases such as $H_2S$ (hydrogen sulphide/sulfide gas).

The effect of low velocity causes a domino effect, which reflects on the overall performance of the sewer system (Bo Copeland, 2013). The consequences are:

- Increased dynamic system head loss
- Increased operating pressure (also refers to pumps)
- Reduced pumping capacity
- Increased odor
- Increased operation and maintenance cost
- Reduced asset life

### 10.1. Distribution of coarse sand

The change of velocity in pipes also changes both transportation mode and retention time. A very high level of turbulence is required to achieve and maintain homogeneous suspension for coarse sand (Admiraal, 2003). This is usually considered an impractical step due to high head losses and is not a common phenomenon.
In heterogeneous distribution of coarse sand, sediments are still suspended but the concentration of sediments is higher in the lower parts of the pipe (near the bed) (Admiraal, 2003). This type of suspension is more practical/convenient then the homogeneous one. As the velocity decreases, the mode of transportation changes. With the decrease of velocity it is quite common to see the bouncing effect of the sediments off the bed and back into the flow.
A lower velocity increases the concentration of sediments (coarse material in this case) near the bed. This creates a situation where particles may slide along the bed.
If flow velocity in the pipe drops significantly, stationary bed will develop, i.e. the sediments will start to settle. The movement of these sediments is known as the bedload (Admiraal, 2003). The presence and build-up of bedload with time also decreases the cross section of the pipe. The thickness of the bedload will gradually increase until the velocity is high enough to transport the settled sediments.
Changes that occur within the pipeline, such as the change of pipe diameter, may influence and form within the system a combination of two or more transport modes.
Heterogeneous suspension is considered as the best mode of transportation within pipe for sand and other coarse material.
In general, it would be desirable to have a heterogeneous suspension all the time, but unfortunately in particular situations that mode is not feasible.
The distribution of solid sediments such as slurry and sand is optimal when they are fully heterogeneously suspended in the flow (Admiraal, 2003).

Specific systems are designed to handle specific sediment loads and head drops (Admiraal, 2003). Therefore, performance of the distribution system may oscillate with types of sediments and time. Engineers generally believe that transportation of sediments should become more efficient in terms of energy losses. Admiraal states in his report that transportation of sediments (for example sand) through the bedload results in lower energy losses than its transportation in the form of a suspended load.

The key characteristic of a properly designed system is minimal head loss. The design of the system affects the value of head loss.

For instance, the same amount of fluid in different systems may have a different head loss value, depending on the system design. Therefore, minimization of head loss in the system is considered to be the designer's main goal.

Distribution systems are not necessarily always placed horizontally. For instance, pipelines in a pressurized sewer system follow contour lines, which may involve uphill and downhill sections. Slopes have significant impact on the system and they have to be taken into consideration. The presence of slope affects the head loss value through the pipeline and it also impacts the sedimentation process. With the increase of slope, head loss within the system also increases. This was demonstrated in the experiment by Shih (1964) where he used a mixture of water and wooden balls to prove the correlation dependence/relationship between head loss and slope (Admiraal, 2003).

The concentration of suspended solids may also impact the value of head loss in the system, and this was also confirmed by Shih´s experiment in 1964. Shih confirmed that relationship between head loss and pipe slope was more noticeable for mixtures with higher concentrations of suspended solids. General rule says that presence of steeper slope is followed with the increase of head loss (Admiraal, 2003).

Admiraal (2003, p.123) stated: "If pipe flow is optimized such that the sediment is carried as a heterogeneous suspension on the verge of settling, a slight change in pipe angle could cause a catastrophic increase in head losses".

## 11. Self- cleansing

### 11.1. Self-cleansing of wastewater pipes

It is desirable to design sewer systems with flows that achieve self-cleansing speeds. Self-cleansing of sewage pipes is one of the main characteristics that engineers want to achieve in a sewer system. This factor determines the design of the sewer pipes as well (Lysne, s.a).
Without self-cleansing, sediments will accumulate in the pipes and this will eventually cause problems with distribution. The process of sedimentation reduces pipe capacity and causes the system to become clogged. There are numerous guidelines for designing sewers that can achieve self-cleansing, and these guidelines/standards are based on minimum flow velocity, which is most commonly used criterion, or a minimum shear stress (Czarnota, s.a).

In order to avoid such problems, according to the Norwegian standard the design of the sewer pipes should secure a minimum flow velocity of 0.6 to 0.75 m/s (Lysne, s.a). However, this standard is not accepted in all countries and some countries have a standard requirement for achieving self-cleansing of 0.9 m/s.
Installation of sewer pipelines requires the presence of the slope in order to achieve this velocity. In most Norwegian communities, pipes are placed with the slope of 1/100 to 1/200 (0.01 to 0.02 %) (Lysne, s.a).

The two crucial factors in self-cleansing and dimensioning of sewer pipes are:

1. Estimate of the minimum water flow

   The recommendation is to determine the minimum flow rate at least daily, for both separate and combined sewage wastewater systems. In Norway, this estimate of household water flow is done using 3 methods:

   a) Using daily flow data; variations of wastewater through time (daily); the value depends on water usage per household
   b) Using relatively simple calculations
   c) Using flow values that are received from EDB analysis programs (Lindholm)

The following equation 11.1 can be used to determine minimum flow:

$$q_{dim} = \alpha\, q_{mid} \qquad (eq. 11.1)$$

Where:

$q_{dim}$– dimensioned flow

$q_{mid}$ – flow for minimum days

P – people equivalents

α – is determined through equation:

- if P < 3000 people $\alpha = 1 + \frac{23}{\sqrt{P}}$
- if P>3000 people or α= 1.43 for

Figure 11.1 shows the variation of coefficient α for dimensioning of flow

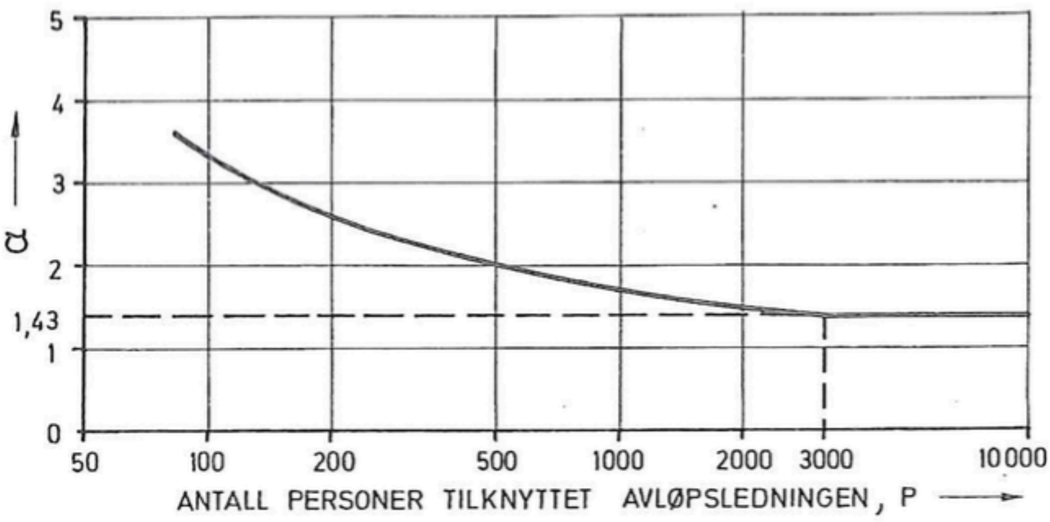


**Figure 11.1: Variation of coefficient α (Lysne, s.a)**

Determination of minimum flow through water pipes has to be done separately. The following two conditions also need to be evaluated when dealing with water pipeline projects.

i. Measurements have shown that in areas under construction the concentration of sand and silt in water pipes can be very high.

ii. The impact of climate change is an important factor and needs to be taken into consideration while dealing with the project. The influence of moderate runoffs can also cause accumulation of sediments and clogging of the pipe systems.

Generally, the composition of wastewater affects the friction factor of pipes.

2. Friction force (shear stress) between water and the bottom of the pipe. The lower bottom of the pipe is the part/section of the pipe where accumulation of sediments will occur in the case of low velocities in the pipe.

The following general conclusions can be made that the most common issues faced by people in the communities are related to self-cleansing of wastewater pipes. This involves the minimum required velocity, inclination and shear stress that will achieve the self-cleansing effect.
The values of these parameters are conditioned by the pipe diameter and the function of the pipeline, regardless of whether this is a combined or separate wastewater system.

For the proper functioning of the system it is always good to know the variability of wastewater flow or the number of people connected to the sewage system. It is also useful to obtain information about the absolute minimum wastewater flow, as well as the maximum and minimum usage time per day.
If the value of velocity is determined from graphs, it is important to know whether flow in the pipe is full or not.

### 11.2. Requirement for shear stress

Shear stress can be defined as a force per unit area, where water flow in the pipe/canal has to be in equilibrium.
In pipes, the value of shear stress varies over sections (Lysne, s.a). The following figure 11.2 will show the shear stress curve along the bottom of the pipe.

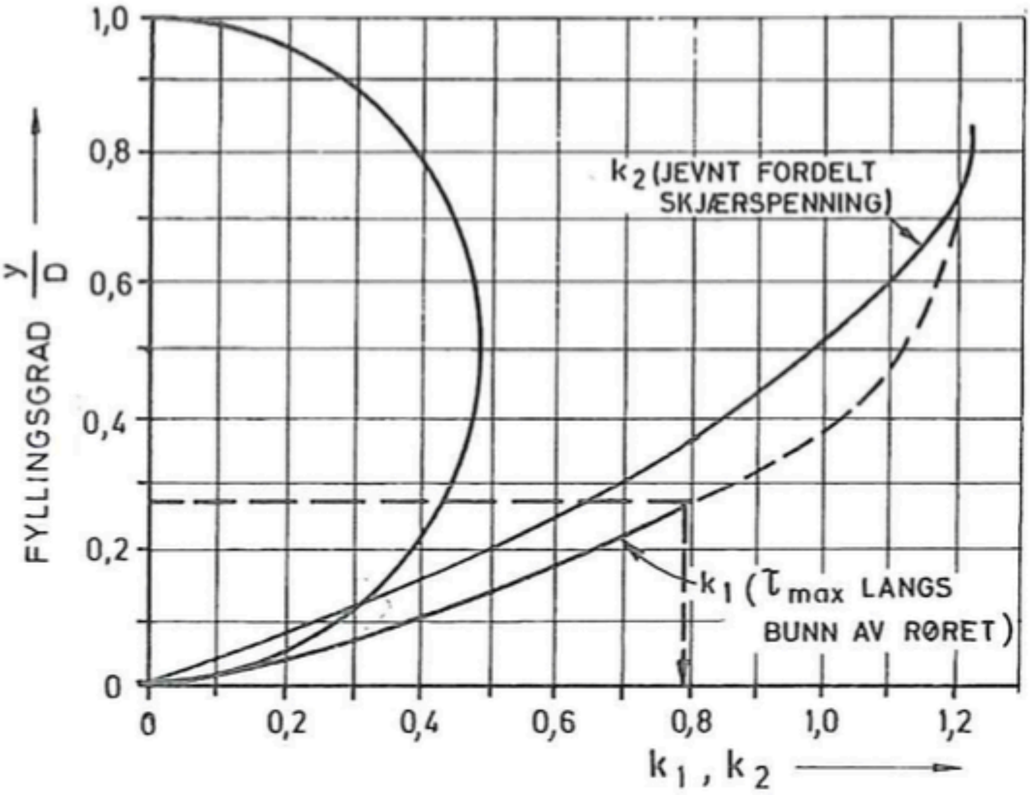


**Figure 11.2: Shear stress curve (Lysne, s.a)**

The value of the hydraulic radius R is expressed through equations 11.2a, 11.2b and 11.2c:

$$R = k_1 \frac{D}{4} \qquad (11.2a)$$

$$\tau_{max} = \gamma\, k_1 \frac{D}{4}\, I \qquad (11.2b)$$

$$\tau = \gamma\, R\, I \qquad (11.2c)$$

Where:

τ- shear stress (Pa)

I- energy gradient (m/m)

R- hydraulic radius (m)

γ- water density ($N/m^3$)

Where 1 $N/m^2$ = 0.1 $kp/m^2$

The value of $k_1$ coefficient is taken from the curve in the previous figure.

For full flow, the hydraulic radius of the pipe is determined as: $R = \frac{D}{4}$

The shear stress value that secures self-cleansing varies with the type of pipe system:

- Combined system
- Separate system

The self-cleansing effect is also conditioned by the type of the pipe:

- Concrete pipe
- Plastic pipe

Experimental results that could provide exact shear stress values are not available. The value of shear stress varies from 1.0 to 4.0 $N/m^2$.

According to the Lysne data:

For combined sewer systems, shear stress value for concrete pipes is 4 $N/m^2$ (or 0.4 $kp/m^2$), while for plastic pipes the shear stress value ranges from 2-3 $N/m^2$ (or 0.2-0.3 $kp/m^2$). The value of shear stress in separate sewer systems is considered to be 2 $N/m^2$ (0.2 $kp/m^2$) regardless of the pipe material.

### 11.3. Dimensioning from nomograms

While talking about water flow, we must also take into consideration the size of the pipe. The principle of determining maximum flow from nomograms is based on the Darcy-Weisbach equation (eq.5.1 and eq.11.3):

$$h_f = f\,\frac{L}{D}\frac{V^2}{2g} \qquad (eq.\,5.1)$$

or, for partly filled pipe:

$$\frac{h_f}{L} = I = f\,\frac{1}{k_2 D}\frac{V^2}{2g} \qquad (eq.\,11.3)$$

The coefficient $k_2$ is determined from the above figure (figure 11.2). Parameters such as water depth and velocity are determined based on even distribution of shear stress along the wet section.

The friction coefficient f can also be determined through the Prandtls´equation

$$\text{Prandtls´ equation}=\frac{1}{\sqrt{f}} = 2\log\left(3{,}72\ \frac{D}{k}\right) \quad \text{(eq.11.4)}$$

Where the k factor is:

- for concrete: k=1mm
- for plastic pipes:
  1. k=0.01mm for pipes where D<200 mm
  2. k=0.05mm for pipe where D≥200mm

**Table 11.1: Self-cleansing and velocity characteristics (Lysne, s.a)**

| pipe type $\tau(N/m^2)$ | f | V (m/s) | Recommended Vmin |
|---|---|---|---|
| Concrete 2 | 0.026-0.021 | 0.79-0.87 | ≈ 0.8 |
| Concrete 4 | 0.026-0.021 | 1.1- 1.23 | ≈ 1.15 |
| Plastic 2 | 0.017-0.014 | 0.97-1.06 | ≈ 1.0 |

The following nomograms (figure 11.3 and 11.4) rely on principles based on the previously mentioned equations 11.1, 11.2b and 11.3.

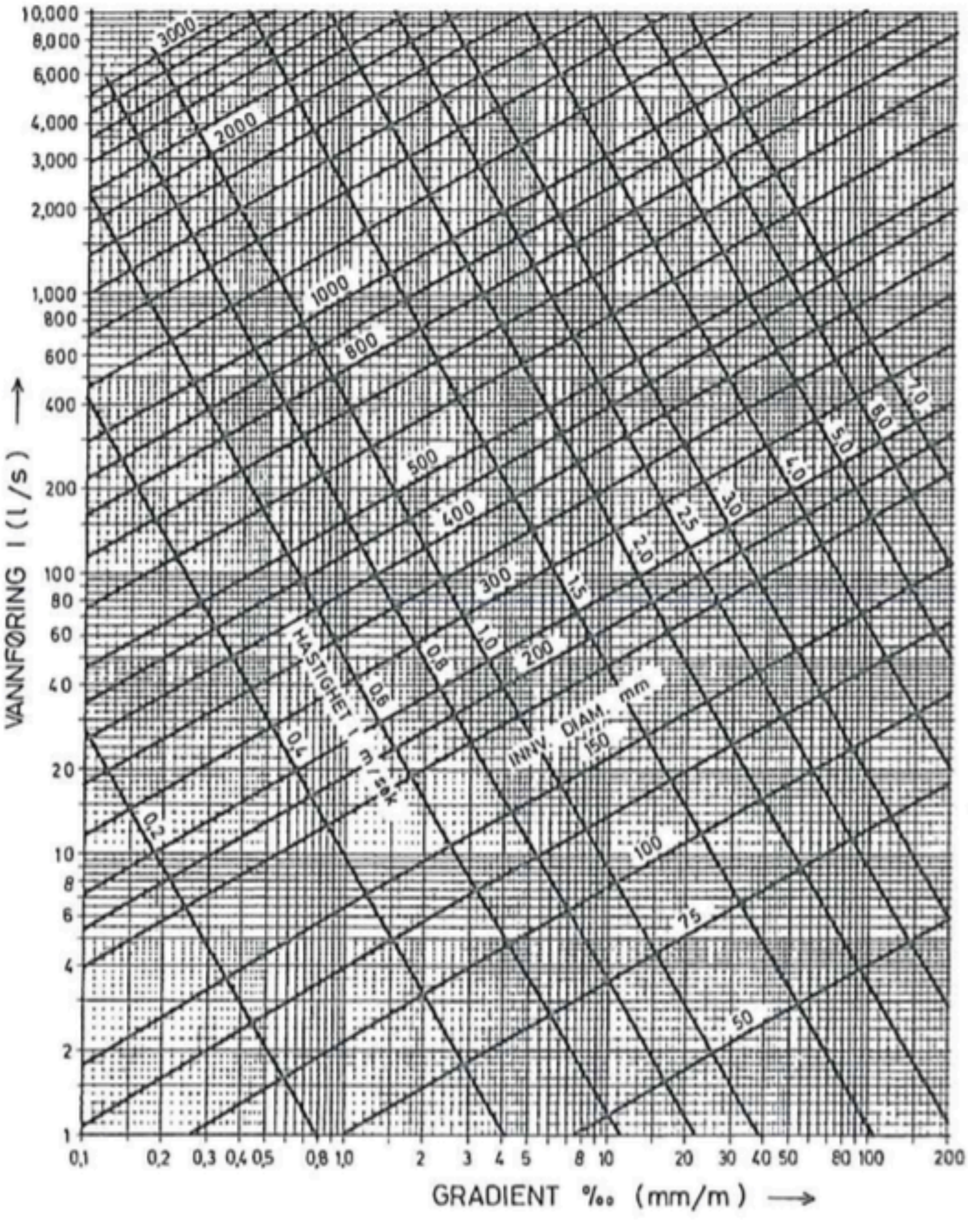


**Figure 11.3: Nomogram for filled pipe k=1 (Lysne, s.a)**

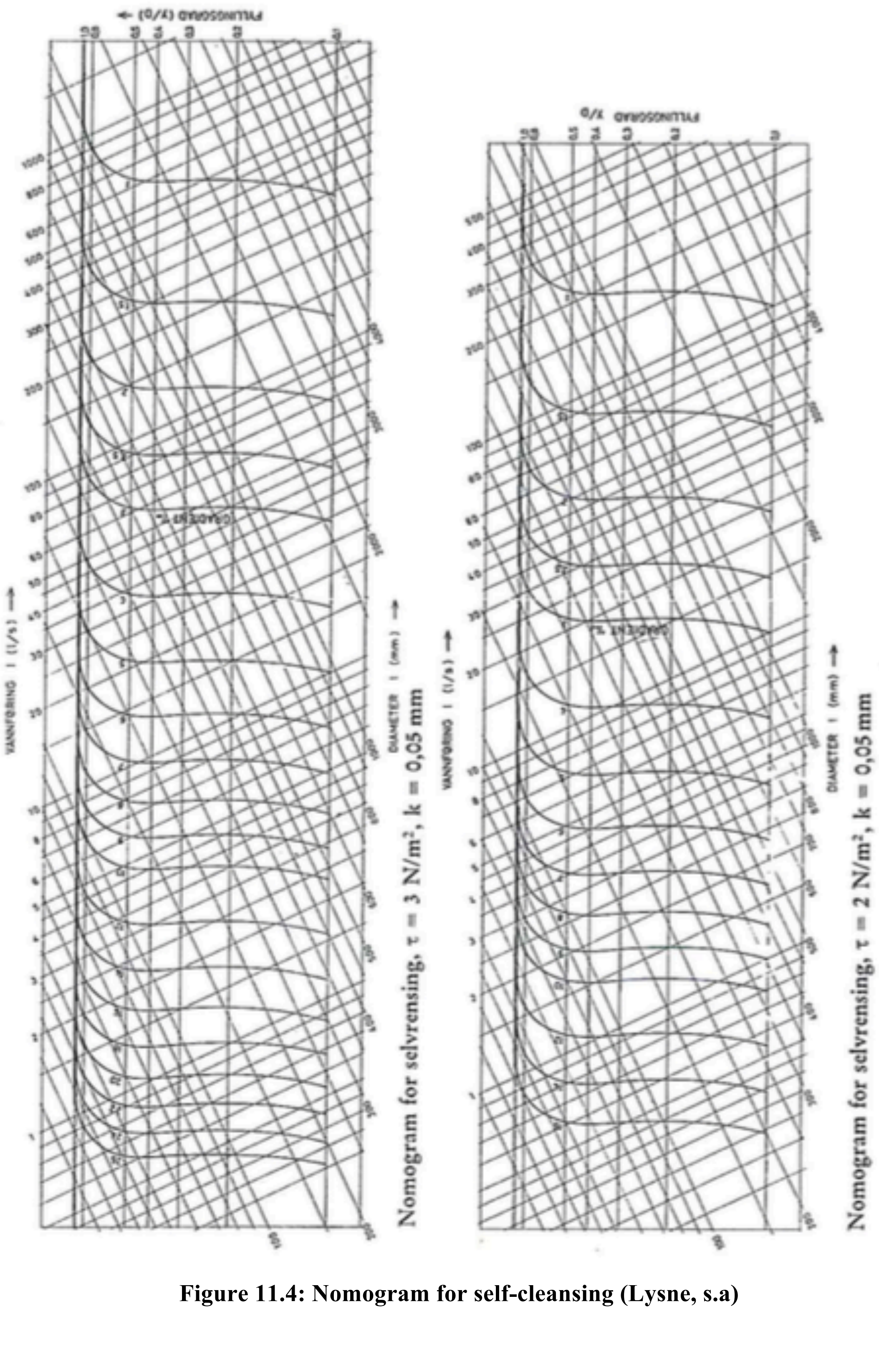


**Figure 11.4: Nomogram for self-cleansing (Lysne, s.a)**

### 11.4. Results from the Norwegian survey

The importance of shear stress on the self-cleansing effect in gravitational sewer pipelines was shown in a test conducted in 35 Norwegian municipalities. This test has confirmed the importance of shear stress, flow velocity and flow coverage of the pipe for self-cleansing performance. The following table (11.2) shows the results of these analyses of distribution in concrete and plastic pipes, along with the impact of shear stress.

All communities in this case have suffered from clogging of the system at some point. The common reason for clogging of the system lies in too little shear stress in pipes (Lysne, s.a).

Other reasons for accumulation of sediments in the pipes lies in bad pipe fittings and joints, foreign objects (particles) and partially damaged (crushed) pipes.

**Table 11.2: Analysis of pipe self-cleansing performance for gravitational systems (Lysne, s.a)**

| | **self-cleansing ($N/m^2$)** | **Non self-cleansing ($N/m^2$)** |
|---|---|---|
| For 15% pipe capacity | 1,31 | 1,26 |
| For 25% pipe capacity | 2,03 | 1,96 |
| For 35% pipe capacity | 2,68 | 2,59 |
| Total standard deviation for 25% | 1,1 | 1,2 |
| For concrete pipes with 25% filling | 2,17 | 2,04 |
| For plastic pipes with 25% filling | 1,3 | 1,27 |
| For combined pipe systems with 25% filing | 2,11 | 2,17 |
| For separate pipe systems with 25% filling | 1,86 | 1,59 |
| Number of pipes used for research | 28 | 28 |

The results of this analysis have shown that accumulation of sediments in pipes and failure to achieve the self-cleansing effect are existing problems, quite often present in sewer systems.

### 11.4.1. Current dimensioning for self-cleansing of wastewater pipes

If the main objective is to achieve self-cleansing of the pipes, certain rules have to be followed. In practice, it is difficult to apply a universal approach (solution) for all cases. Different circumstances affect the systems in different ways and therefore variations in dimensioning of flow are necessary.

For instance, the Oslo community is using a system with bigger diameter pipes, operating under higher shear stress value of $\tau = 4\ N/m^2$. For PE pipes shear stress can be $2\ N/m^2$.

## 11.5. Dimensioning of flow with regard to self-cleansing

In past there were a lot of discussions about dimensioning of the flow and self-cleansing of the pipes. The common requirement states that wastewater flow through the pipe has to occur once per day and it has to be large enough to prevent the accumulation of sediments.

The French scientist Million developed theoretical and experimental research that determined water flow variations in sewage pipes for users that are connected to the system.

The relationship between medium wastewater flow during the day at a given point on the pipeline and the maximum wastewater flow at the same point can be expressed by the equation 11.1:

$$q = \alpha\, q_{mid} \qquad (eq. 11.1)$$

Where:

α represents a factor related to the duration of the wastewater flow

$$\alpha = 1 + \beta \sqrt{\frac{q}{q_{mid}}} \qquad (eq. 11.5a)$$

Where:

q- average consumption of wastewater

β- duration factor; the value of this factor is reduced with the increase of wastewater effluent.

Or it can be obtained through this equation:

$$\alpha = 1 + \beta \sqrt{\frac{T}{t}} \sqrt{\frac{1}{N}} \qquad (eq. 11.5b)$$

Where:

T- base period of 24 hours

t- effective flushing time during 24 hours

N- the number of connected users

### 11.6. Criteria for self-cleansing in wastewater pipelines

To analyze the process of self-cleansing in wastewater pipes entails evaluation of certain parameters. The most important parameters are the pipe diameter, flow variations, inclination, velocity, friction and shear stress. The distribution of shear stress and adequate shear stress are necessary for self-cleansing process.

While dimensioning wastewater pipelines, it is not considered practical to calculate and evaluate all the parameters individually.

An efficient way to determine all these factors (parameters) is to use the appropriate nomograms. With the application of adequate calculation techniques it is possible to determine more than one just one parameter just by looking at the nomogram. This procedure does not involve complex calculations or dimensioning work.

In the past, the usual method for determination of sewer network design was based on an assumption that flows in pipes was full or partially full flow (also using graph curves for determination).

The only condition that was required for successful self-cleansing was to secure minimum velocity in pipes of 0.6-0.75 m/s.

In this project the flow value was obtained from a nomogram. Just from obtaining the pressure value it was possible to determine the pump discharge flow (read from the graph), and later using those values it was also possible to obtain velocity values in the pipes as well. Filling of the tubes is not a necessary parameter in this case. Normally, wastewater flow through the sewer lines is partially full.

### 11.7. Friction, velocity distribution and shear stress

Friction, velocity and shear stress are parameters that are expressed as physical parameters. When evaluating the distribution of sediments and erosion, it becomes clear that a close connection exists between these two processes.
All these parameters are expressed as a force that is generated when the flow of fluid passes over a certain surface boundary (such as the bottom of the pipe).
Organic material or sand tends to accumulate along the bottom of the pipe and it is precisely these parameters that determine the future of the accumulated material – whether these sediments are going to stay there or whether they will gradually erode and be transported further with the flow.

When liquid (fluid) is moving through the pipe, or along any surface, the resistance to flow (i.e. friction resistance) will occur and counteract the movement.
Internal forces occur in fluid flow and boundary layer, between the liquid flow and the solid interface (boundary). As a result of this movement, energy is irreversibly lost. In reality the friction forces are the ones that are controlling and regulating liquid flow and under certain conditions they also can determine fluid velocity.
Friction loss can be determined using the Darcy-Weisbach equation and from there we can later determine the necessary pipe dimensions and inclination.
Because the flow in pipe is turbulent, the Darcy-Weisbach equation (equation 11.3) is:

$$h_f = f \, \frac{L}{D}\frac{v^2}{2g}$$

Where:
D – diameter
$h_f$ – friction loss
L – pipe length
v – velocity
g – gravitational acceleration
f – friction coefficient

When friction, flow and cross section are known, it is possible to determine the average velocity. It is important to remember that velocity across the flow area is not constant.

At the pipe wall, velocity is considered to be equal to 0. As the distance from the wall increases, so does the velocity value.

The following figure 11.5 shows the velocity profile for full flow, with different values of the Reynolds number.

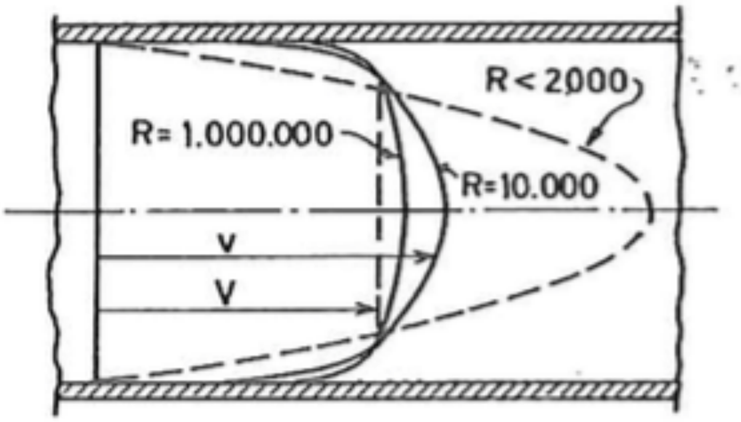


**Figure 11.5: Velcocity profile for different Re values (Lysne, s.a)**

The Re number does affect the value of average velocity in the pipe. The flow in wastewater pipes is always turbulent (Chapter 4).

The presence of turbulence has an effect on the velocity profile in the pipe and leads to equalization of the velocity profile.

Velocity distribution near the bottom of the pipe is especially interesting and closely related to erosion processes. The process itself varies with the shape of the tube (cross section). In practice it is difficult to accurately determine the velocity distribution near the bottom of the pipe but that section of the pipe is considered suitable for analyzing the process of erosion.

## 12. Test description

As mentioned earlier, the objective of this thesis was to evaluate the performance of pressurized sewage systems utilizing an E/One grinder pump and its effect on self-cleansing of the pipes. The specific objectives of this project were to analyze self-cleansing processes of pipes and to trace and describe potential sedimentation on pipe walls. The experiment was designed with help from my supervisor Jon Arve Engan, and personnel from Skandinavisk Kommunalteknikk Jens Beckman and Trym Sætre.

### 12.1 Installation

Skandinavisk Kommunalteknikk AS provided one E/One grinder pump and PE pipes of different diameters (40 mm, 50 mm and 63 mm) to the experiment. The same company also provided a 63 mm discharge valve and the appropriate fittings. The pipes used for this experiment/test were type SDR11. SDR stands for "Standard Dimensional Ratio" and refers to the geometry of the pipe. It indicates the ratio between the pipe diameter and the thickness of the pipe wall, which can be expressed by the following expression:

$$SDR = \frac{D}{s} \qquad (eq. 12.1)$$

Where

D – pipe outside diameter (mm)

S – pipe wall thickness (mm)

In an SDR11 pipe, the outside diameter (D) is eleven times greater than the thickness of the pipe walls. For the purposes of this experiment, all three SDR11 PE pipes have successfully handled the interior pressure.

The test assembly consisted of the following elements:

- ***E/One*** grinder pump. This is a pump station that pumps sewage into a pressurized pipe system. The pump ensures movement of wastewater through the pipes. For the purposes of this test, one E/One grinder pump was used. Figure 12.1 shows the E/One grinder pump in operation.

**Figure 12.1: E/One grinder pump (Source: the author)**

- ***PE pipes***: SDR11 type: 40 mm, 50 mm and 63 mm diameter (50 m length). (see Figure 12.3)
- ***Pipe fittings***: 2 x 40mm, 1 fitting 40 to 50 mm, 1 fitting 50 to 50 mm, 1 fitting 50 to 63 mm and one fitting 63 to 63 mm.
- ***Discharge Valve***: installed at the end of the 63 mm pipe, with the main function of controlling pressure and velocity in the pipes and preventing any pests from entering the pipes and clogging the pipeline system.
- ***Distribution pump:*** used to distribute greywater from the greywater tank to the mixing reservoir, and later from the mixing reservoir to the E/One grinder pump.
- ***Discharge point:*** the discharge point for wastewater used in the test was one of the nearby manholes.
- **Mixing reservoir**: 115 wide x 155 cm long.
- **Insulation material**: Vintermatt – for protection against direct exposure to sunlight, in order to prevent unwanted warming of PE pipes. Increased temperature could result in a change of viscosity, as well as increased microbial activity. Material thickness was 1 cm and it was placed on pipes in layers. Figure 12.2 shows the Vintermatt insulation material used to cover the

pipes and prevent the increase of temperature of the pipes.

- **Bucket with scale**: used for manual distribution of blackwater from its source to the mixing reservoir.
- **Manometers:** 3 manometers, which recorded the pressure value in each pipe

**Figure 12.2: Insulation material (Source: the author)**

Figure 12.3, shows the uncoiling of the 50 m long SDR11 63 mm pipe and preparations for installation.

**Figure 12.3: SDR11 PE 63 mm pipe (Source: the author)**

## 12.2. Test design

The pump station was located at the university campus, inside the wastewater laboratory. The location of wastewater laboratory along with its surrounding area and wastewater facilities were convenient for the purposes of this test. The pipes were placed on the ground and for the most of their length they follow the contour line/relief. Pipes were installed in sequence, from the E/One pump and starting with the 40 mm pipe, followed by the 50 mm pipe. The pipe with the largest diameter (63 mm) came last, building on the 50 mm pipe. All pipes were connected by appropriate fittings. The fittings were made of the same material as pipes and it was important that pipes are properly fitted and secured (locked) in order to avoid unwanted leakages.

At the beginning, the length of each pipe had length of 50 m and this resulted in the total pipe system length of 150m. For the purposes of this test the total length of all 3 pipes from E/One pump to the discharge manhole was more than sufficient, and it was decided to shorten the 40 mm and 50 mm pipes. The 40 mm pipe was shortened by approximately 12.1 m, and the 50 mm pipe by approximately 6.1 m. The length of the 63 mm pipe was not modified due to higher importance of this pipe for self-cleansing analyses.

Each pipe was placed on the ground. The pipes were not buried, which means that the cross section of the pipe did not change and it remained circular. This is important to remember for subsequent calculations. As already mentioned, each pipe follows the contour line/relief for most of its length. Slopes were created with the idea to test/challenge possible sedimentation inside the pipes. The height of the slopes installed for 40 mm and 63 mm pipes is approximately 1.76 m. The height of these slopes is the same because both pipes are going over the same hurdle. Another slope was installed approximately 12 m away from the first one, with almost the same height as the first one.

Figures 12.4 and 12.5 show the slopes installed for the sedimentation test.

**Figure 12.4: Slope for 40 mm and 63 mm SDR 11 PE pipes (Source: the author)**

**Figure 12.5: Slope for 40 mm and 50 mm SDR11 PE pipes (Source: the author)**

### 12.3. Test procedure

For the first couple of days, as a precautionary measure, the pump was tested with fresh water.

The trial test was performed continuously for 4 days using approximately 250-300 liters of fresh water every day. Fresh water is suitable for detecting possible leakages. Additionally, fresh water would prevent contamination of the environment and unpleasant odor that wastewater would cause in case of leakage. Pipefittings were carefully observed, as these points were considered to have the highest probability of presenting leakages.  The trial test confirmed that the pipeline was functioning properly, without any leakages, thus allowing the wastewater to begin.

Initially the test was performed with the discharge valve completely opened but after a week long test run the valve was partly closed in order to observe pressure in pipes. This change was recorded on the manometer as well (Table A1, Table A2, Table A3). The existing pressure in the pipes affects the value of fluid velocity in the pipeline.

The test started on Monday 4th of August 2014 and remained continuously until Wednesday17th of September 2014. In the first couple of weeks this test was mostly daily running from Monday to Friday, where in the last two weeks of testing the pump was continuously running without a day of pause.

As mentioned in Chapter 8 (see positive displacement pumps), the change in the “operating pressure” did not result in significant changes in the terms of E/One grinder pump discharge. Due to the desire to follow as much as possible realistic conditions the operating pressure of the pump for the purposes of this test never exceeded 5 bars. Usually the low pressure sewage systems operate under the pressure of 2-3.5 bar. The operating discharge pressure remained below 5 bar, with an average pressure value of the pump of 2.76 bar (Table A1), which represents normal (most common) operating conditions. . During the pumping operation, the measurements of the pressure were recorded on the manometers that were installed on pipes. During the pump operation once the discharge pressure is stabilized, I would go, check and record the values of the other two manometers. With the movement of fluid through the pipeline was followed with the reduction of pressure in pipes, as the fluid was approaching the discharge point and atmospheric pressure. Therefore the pressure value in other two manometers was gradually decreasing

Variations in the pump discharge due to small pressure oscillations were considered negligible. Thus the discharge value of the pump was approximately always 0.8 l/s.

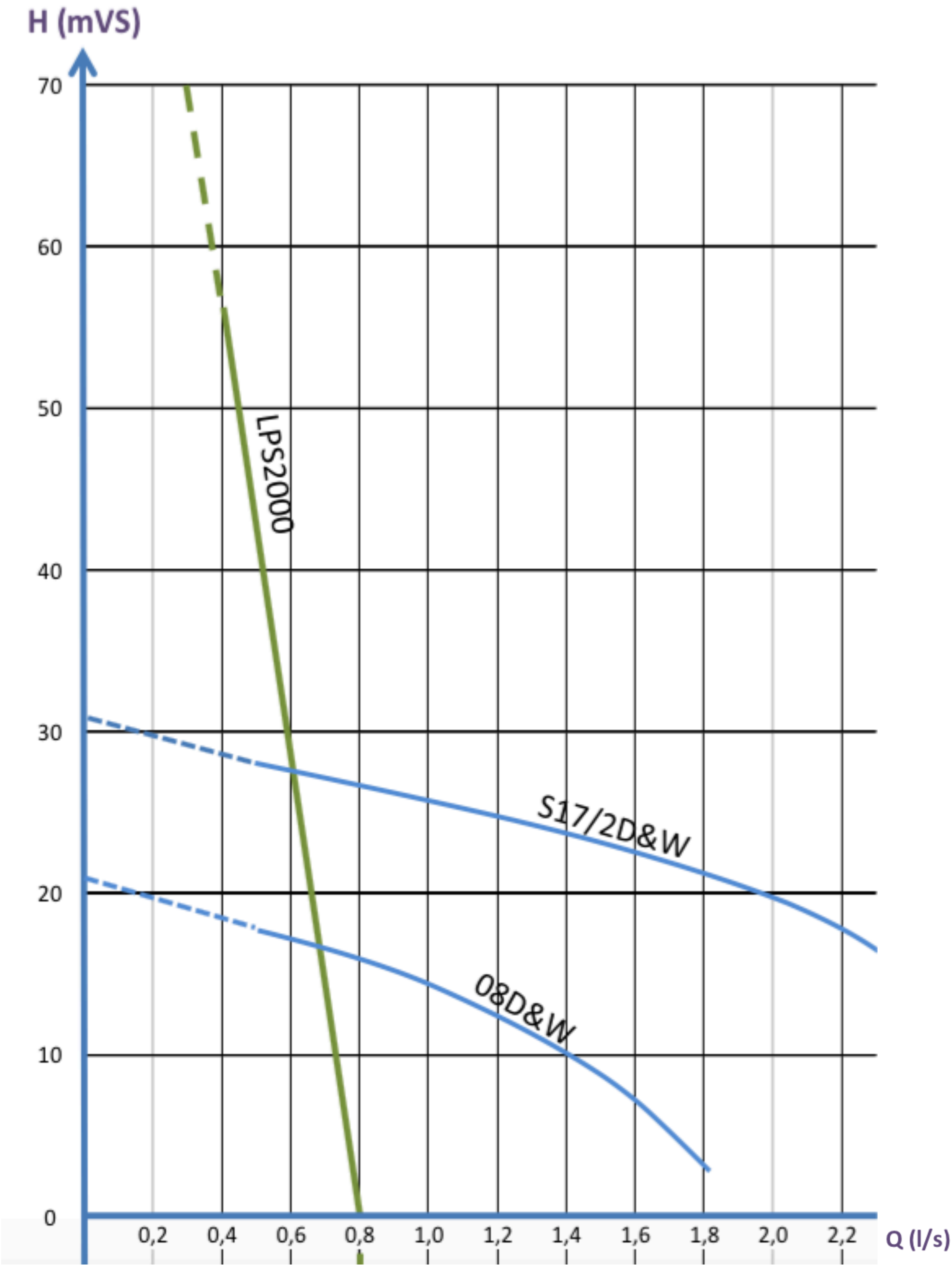


**Figure 12.6: H-Q pump curve (Skandinavisk Kommunalteknikk, 2014)**

Before every pump operation, the discharge valve was closed. With this step the process of building up pressure in pipes was secured. The pump discharge pressure would not exceed 10 bar in this early phase of test. Once the operating pressure in the pipes reached 10 bar (or close to it), the discharge valve was slightly opened. With the opening of the discharge valve, the pressure in pipes was slowly reduced. The main purpose of this process was to calibrate and adjust the discharge valve so when the E/One pump is active and fully operational the pressure in the pipes does not exceed 5 bar. Operating pressure values are shown in Additional tables A1, A2 and A3.

Reliability of the model:
The experiment, as a model of a real scenario, did not reflect precisely all real conditions. The wastewater used for the purpose of this project did not come from one household, but it was generated as a result of separately collecting and afterwards mixing of black and greywater. Therefore, one of the main objectives of this thesis was to prepare a wastewater sample that would reflect real conditions.

Discharge point:
The fresh wastewater that was generated each day had to be disposed in a proper way. For the purposes of the test it was important to use fresh wastewater, which meant that once the test is done the water had to be disposed of. The discharge point in this case had also influenced the design of the pipe system. The manhole that was used for discharge purposes is placed/located on the backside of the wastewater laboratory and it was used to distribute wastewater from surrounding houses to the main sewage line by gravity. The 63 mm pipe was used from the pipe fitting (50 to 63 mm) to the discharge valve, which had the same diameter as the 63 mm pipe. For safety reasons, after every test run it was mandatory to close the manhole and the discharge wall for safety reasons. The Figure 12.7 and Figure12.8 shows discharge segment and closing valve.

**Figure 12.7: Discharge segment (Source: the author)**


**Figure 12.8: Closing valve (Source: the author)**

### 12.4. Blackwater

As mentioned earlier, wastewater contained blackwater and greywater. All wastewater used for the purposes of this test was collected from the NMBU facilities. The amount of available blackwater and greywater was limited in the period before approximately 15th of August. Wastewater was collected from the university complex. It is important to mention that black and grey wastewater were collected separately.
The simplest definition of blackwater is that it represents wastewater from toilets. Blackwater contains urine and feces that are combined with flush water and toilet paper. It is estimated that one person discharges 1.5 liters of waste per day but the total amount of wastewater per person increases to 25-50 l/d, depending on the quantity of flushing and the flushing system. That is why the amount of blackwater varies from household to household. Blackwater used for this project contained only wastewater from toilets.
In general, blackwater largely consists of organic matter. It contains high concentrations of phosphates and nitrogen and as such it is rich in nutrients. Both these elements are recyclable and can be utilized for agricultural purposes, as fertilizer.

The first set of blackwater was taken from Sørhellinga building at NMBU campus and was distributed through normal sewer pipes to the VaskehallenFløy (wastewater laboratory) building, where the test took place. The procedure consisted in opening a valve at the first manhole close to Sørhellinga, to distribute blackwater to the second manhole located next to VaskehallenFløy and subsequently to the test site. After collecting the required daily amount of blackwater, the valve was again closed manually.
There is an important rule that needs to be followed while dealing with pipelines and valves. The order of opening and closing has to be done in proper sequence. First the previously closed (inactive) valve must be opened and subsequently the active valve can be closed. If the procedure is done the other way around, there is a possibility that the pipes might burst.
It is important to mention that the toilet systems used at Sørheilinga were vacuum type. This means that the amount of flushing water used per flush was very small. In

other words, blackwater from that facility contained less water than the normal representative samples. Later additional mixing of black and greywater samples (together) would dilute the blackwater samples, which automatically secured the necessary quality of final sample.

After blackwater arrived to the manhole, distribution from the manhole to the lab was done with a regular pump installed in the collection tank. Then the blackwater would get collected in a scaled bucket with maximum carrying volume of 25 liters and transported to the mixing tank manually. This procedure of collecting blackwater from Sørheilinga took place for almost 2 weeks. Due to the fact that not many students were present in the campus at the beginning of August, on certain days it was difficult to obtain the desired amount of blackwater. In that period the amount of available blackwater varied around 35-45 l/d. The samples collected from this facility were not well sorted. For the purposes of successful distribution and functioning of this test, it was necessary to balance/regulate the size of particles within the sample. Mixing of blackwater and greywater was done manually, using mixing spatula. .

After the 15th of August, upon suggestion from Professor Arve Heistad, the source of blackwater got changed. From that day onwards the blackwater was collected from the Kaya student housing complex. The same complex supplied the laboratory with greywater. The amount of blackwater provided from this facility was enough to carry out the E/One pump test properly, without oscillations. This sample of black water, unlike the previous one, was very well sorted and mixed. Additional fragmentation of particles was not required in this case. The amount of blackwater was stabilized, and for the purposes of testing 50 liters per day were used. Figure 12.9 shows the daily amount of blackwater used for the test in period from 4th to 27th of August.

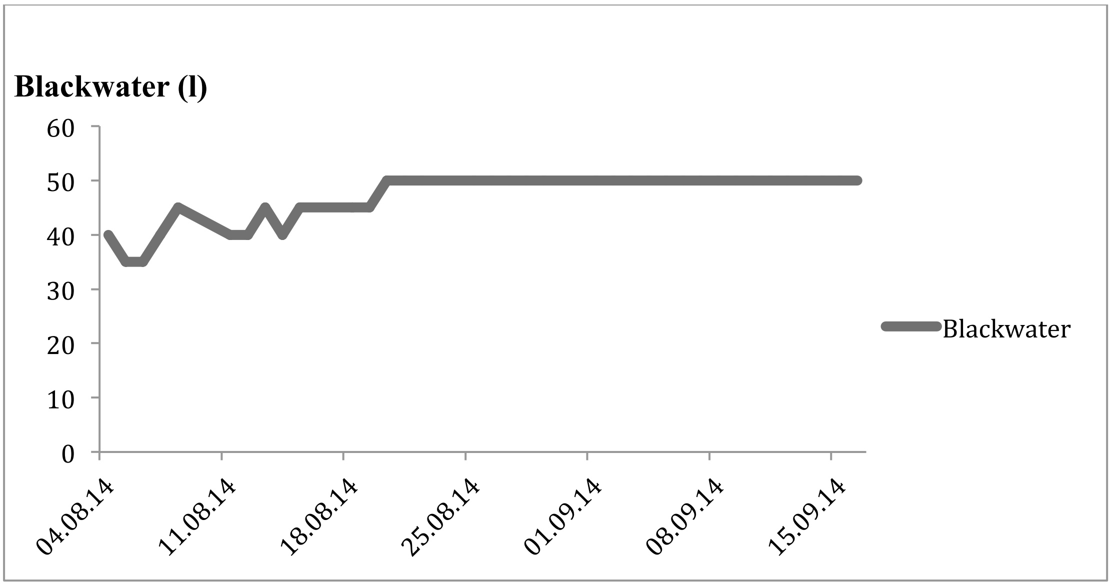


**Figure 12.9: Daily blackwater consumption**

The following picture (Figure 12.10) shows the procedure of filing the 25 l scaled bucket with well-mixed blackwater.


**Figure 12.10: Fine mixed blackwater (Source: the author)**

## 12.5. Greywater

Greywater is defined as wash water, i.e. water that comes from kitchen and bathroom sinks, washing machines and showers. It is important to remember that this water does not come into contact with toilet water and its feces and urine contents. It contains dirt, food, oil, grease and household cleaning products. Wastewater mostly consists of greywater, which represents more than 80% of the total volume.
Usually the smell of greywater is not as unpleasant and strong as the smell of blackwater. Moreover, it also contains far less nitrogen (N) and pathogens than blackwater.

For the purposes of this test greywater was obtained from the neighboring households, mainly occupied by students. These households have two active periods: from September to December, and from February to June. During the holidays most students go home, especially in the summer period, between June and August/September. Thus, the amount of generated greywater in this student complex was significantly reduced in this period.
Particularly, in the period from the 4$^{th}$ to the 15$^{th}$ of August the amount of greywater generated from Kaia student housing was limited. After August 15$^{th}$ the available amount of generated greywater was higher due to the arrival of students, and desirable amount of greywater was secured for the purposes of this test (450 liters per test).
Greywater was collected in the tank (Figure 12.12) from where it was distributed to the two projects taking place at the time being this project one of these two.

As mentioned earlier, the amount of available greywater was limited and unstable/variable at the beginning of this test. These conditions are evidenced in Figure 12.11, which shows the daily amount of greywater used for the test. As shown on the figure, at the beginning of the test procedure the available amount of greywater was varying due to insufficient amount of greywater in the collection tank.

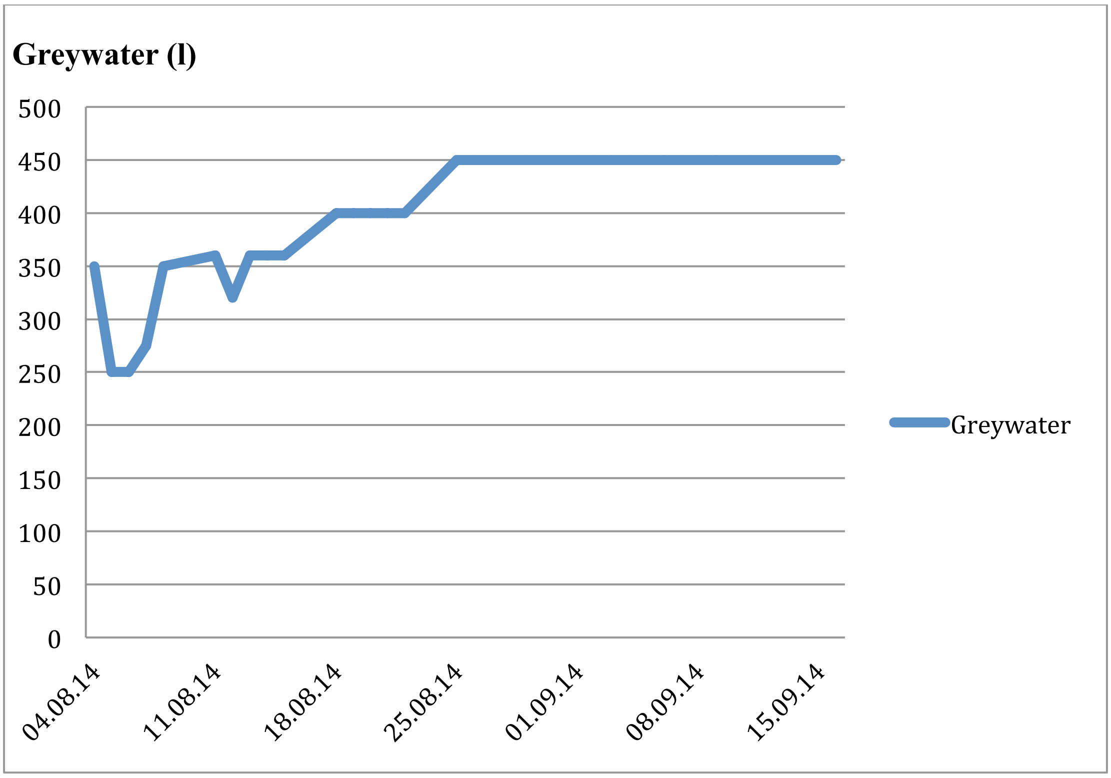


**Figure 12.11: Daily greywater consumption**

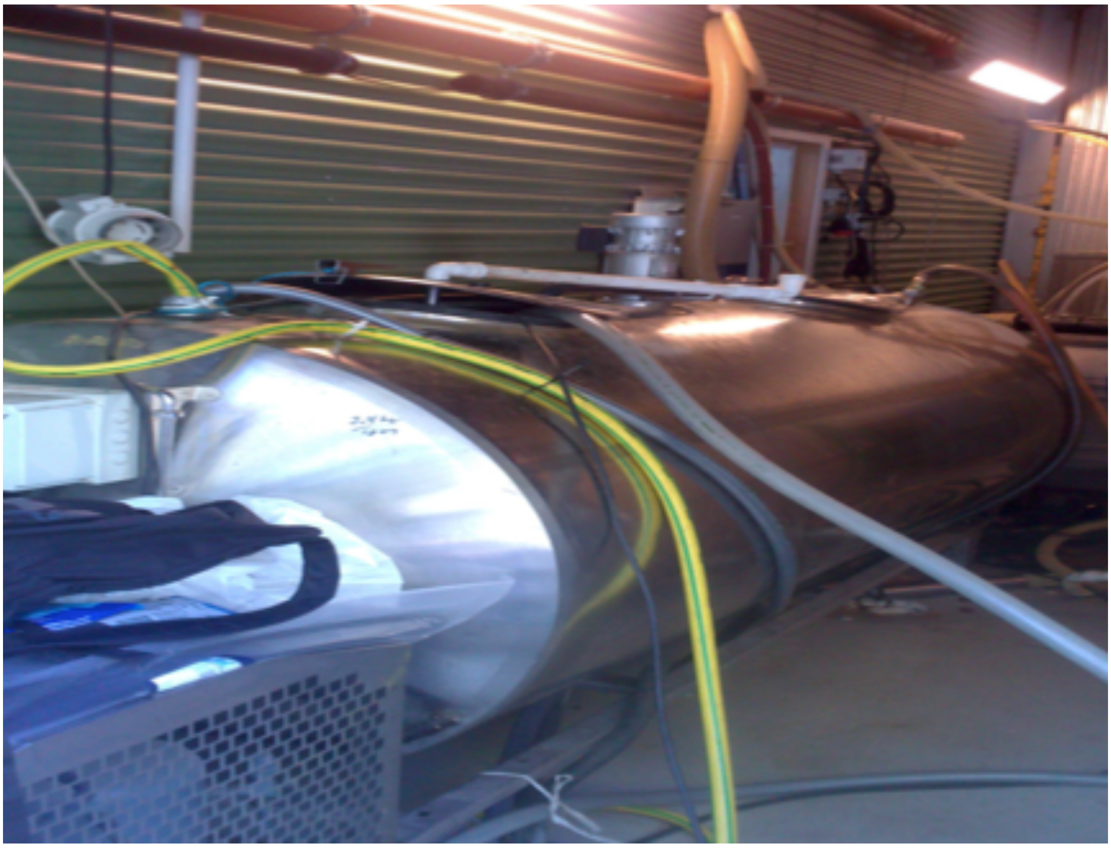

**Figure 12.12: Greywater tank (Source: the author)**

### 12.6. Mixing and pumping process

In order to use a wastewater sample that was as realistic as possible, it was necessary to ensure a proper ratio mixture of black and grey water. The aim was to maintain the normal ratio of blackwater to greywater, which varies from 1:9 to 1:10. Hereafter, this ratio is referred to as wastewater ratio.

The first step of the test was collection of blackwater, as described in Chapter 12.5. For precise measurement of the amount of used blackwater a bucket with a measuring scale was used.

First step in wastewater sample preparation was the addition of blackwater, which was manually transported from the blackwater discharge source to the mixing reservoir. The second step in sample preparation was the addition of greywater. Additional pump was used for this purpose. The wastewater ratio used for the purposes of this experiment was from 1:9 to 1:10.
Despite the lack of availability of greywater during the first two weeks of August, the wastewater ratio was kept as 1:9, thus lying within normal values.

In the initial period, for the sake of precision, greywater was added manually using a scaled bucket. Afterwards the process of adding greywater was improved and became less time consuming. Greywater was pumped directly from its reservoir into the mixing tank, which also automatically mixed the wastewater sample.
It was necessary to continue mixing the new sample of wastewater everyday, in order to secure the transport of all the solids in the wastewater through the distribution pump to the E/One pumping station and also to make the sample more representative.

From the 25$^{th}$ of August onwards, the amount of greywater used for the pump test increased to 450 liters and remained at this level until the end of the experiment. From that moment the wastewater ratio changed to 1:10 and was kept at this level until the end of the test.
Of the total 450 liters of greywater, 425 l were pumped directly from the greywater reservoir into the mixing tank, while the remaining 25 l were added separately using

the scaled bucket. The greywater from the bucket was added at the very end to facilitate pumping from the mixing reservoir to the E/One pump station.

As the newly generated wastewater was pumped from the reservoir to the E/One pump, the concentration of heavier particles at the bottom of the tank was increasing. It was necessary to mix the wastewater sample during the process.

While observing the operation of the distribution pump, it was obvious that a certain amount of sediment (usually the larger and heavier particles) was not distributed to the E/One pump. The small pump was not able to distribute it to the E/One station due to insufficient "liquid". This is why 25 l of greywater was poured in from the bucket at the very end, in order to distribute the remaining sediment and collect/transport as much sediment as possible to the E/One grinder pump.

**Figure 12.13: Mixing tank (Source: the author)**

Distribution of wastewater from the mixing reservoir to E/One grinder pump was done using the DP 250W distribution pump. This pump has the capacity of delivering 8 $m^3$ per hour. In order to avoid overflow of wastewater out of the E/One pump station caused by excessive inflow of wastewater from the distribution pump, it was necessary to control the working time of the distribution pump. Figure 12.14 shows the distribution pump.

**Figure 12.14: Distribution pump (Source: the author)**

Movement of wastewater through the pressurized pipeline was provided by the E/One grinder pump. This pumping station provided the energy necessary to generate and sustain movement of water within the pipeline.

In order to avoid possible sedimentation inside the pipes, Norsk Standard recommends minimal fluid velocity in the pipe of 0.7 m/s. This standard was questioned and challenged with this test - and was proved wrong.

Other research studies have conducted experiments and challenged this standard as well, for example Xylem Water Solutions. They have done a test that also proved that self-cleansing of pipes can be achieved at velocities lower than the 0.7 m/s.

**Part 4: Discussion**

## 13. Testing segment

The sections lying between the sloped sections (see Figure 13.1 and 13.2) were of special interest in this research project. These sections were suitable for sedimentation, because of the existence of hurdles surrounding these sections, which impeded the movement of wastewater through them (as they were followed by upward slopes). In other words, wastewater was forced to settle in these three sections.

For that reason, section between two slopes (canyon shape profile, also known as a V profile) had a higher chance of forming sedimentation inside the pipes. For that reason these sections were placed horizontally, following field configuration/relief.

Testing segments were designed to be 2 meters long. All 3 pipes had checking sections of the same length, defined by adequately spaced pipefittings. Figure 13.1 shows the checking section for 40 mm and 63 mm pipes.

**Figure 13.1: Checking sections on the 40 mm and 63 mm pipes (Source: the author)**

Potential accumulation of sediments in pipes is conditioned by factors such as:

- Velocity
- Pipe material (PE), which in this case is smooth and suitable for self-cleansing
- Shear stress
- Slope
- Size of sediments

Adequate conditions must be present for possible accumulation of sediments to occur inside the pipe. Sedimentation starts to occur once the velocity value is not high enough to move sediments within flow. Therefore velocity of the fluid is one of the most important factors, which affects the results of possible sedimentation. Velocity of the fluid in the pipe is inversely proportional to the size of the pipe diameter. Higher fluid velocities will occur in pipes with smaller diameters. Higher fluid velocity prevents the accumulation of sediments and erodes the formed layers of sediment, with its high energy which fluid possess.

The diameter of the pipe affects the sedimentation process but it also influences the shear stress value within sewers. The value of actual shear stress $\tau$ in relation towards critical shear stress value $\tau_{critical}$ (for both for erosion and sedimentation) will determine which process will occur inside of the pipe. If the value of $\tau$ (actual shear stress) is between critical shear stress value for deposition and erosion, than neither erosion nor sedimentation will take place inside of the pipe. If the value of the $\tau$ (actual shear stress) exceeds critical shear stress value for erosion, then the process of erosion of sediments will occur in pipe. Therefore it is also correct to say that critical shear stress value is a main criterion for self-cleansing of the pipe.

The concentration of sediments impacts the rhythm of sediment transport but it does not play the crucial role for process of sedimentation inside of the pipe. For instance, the increase of sediment concentration may occur during the flush wave as a result of re-suspension of particles that got eroded from previously accumulated material.

The size of the sediment particles also plays important part for predicting the formation of sediment bed. General rule is that bigger size particles lead to faster sedimentation of suspended particles and faster formation of suspended bed.

The presence of slope in wastewater distribution system and its impact on shear stress value play important part on sediment removal and re-suspension. The impact of slope on sedimentation is enormous, and it is well defined by Shirazi (s.a.), who confirmed that big difference in the slope leads to a clear difference in sediment bed evolutions and shapes.

The following figure 13.2 shows the opening of testing segments of SDR11 40 and 63mm pipes.

**Figure 13.2: Testing segment check for 40 mm and 63 mm pipes (Source: the author)**

### 13.1. Sedimentation check

As mentioned in previous chapter testing segments, for possible sediments within the pipes were installed in areas close to the installed slopes. Testing segments were designed for easy access and analysis of possible accumulations of sediments. These areas were constructed for all three pipes (40, 50 and 63 mm).

Possible accumulation of sediments was especially relevant for the 63 mm pipe, which had the highest likelihood of accumulating sediments due to its velocity characteristics, which will be analyzed later in this chapter.

It was considered that possible sedimentation might also occur in the 50 mm pipe. Therefore the second slope was designed approximately in the same way as the slope for 40 mm and 63 mm pipes. Possible sedimentation in the 40 mm pipe was considered unrealistic due to high flow velocity. The velocity and self-cleansing effect will be discussed and analyzed later in this chapter.

Even if the sedimentation process occurs in smaller diameter pipes, the chances that the sedimentation will stay untouched by erosion process are kept to a minimum. As the diameter of the pipe increases, the velocity of the fluid decreases. With decreased velocity, the chances for possible accumulation of sediments increase. Figure 13 .3 shows the preparation for the sedimentation tests on 40 mm and 63 mm pipes.

The process of possible sedimentation in pipes was observed through daily testing of the pump.

**Figure 13.3: Finished check for 40 mm and 63 mm (Source: the author)**

The procedure for the sedimentation test was based on opening the pipes in the checking section. After opening 40mm pipe, the first step was a routine observation and inspection of the pipe, where it was searched for possible accumulation of sediments. Figure 13.4 shows the open pipe in the first checking section for 40mm pipe.

**Figure 13.4: Opening of SDR11 PE 40 mm pipe (Source: the author)**

The same procedure was repeated for 50 mm and 63mm SDR11 PE pipes. During this pump test, pipes were opened 4 times. Every time after opening the pipe, a part of the pipe in each section would be cut off in order to monitor possible sedimentation in each section and compare it with further cuts. The cut pieces were approximately 10 cm long. After each pipe was cut off at the checking section, the edges of the pipe were left rough and uneven and to successfully reattach them to the pipeline (to avoid possible leakages due to pressure differences) it was necessary to make the edges on both sides of the pipe smooth again. The process of smoothing the cut edges was performed with the regular scalpel. As you can see from Figure 13.5 the sediments move together with the wastewater. The movement of particles in wastewater occurs at the bottom of the pipe but, due to turbulent flow in the pipes, homogeneous suspension (refer to Chapter 10) prevents the sedimentation of particles.

**Figure 13.5: Distribution of sediments in SDR11 PE 63 mm pipe (Source: the author)**

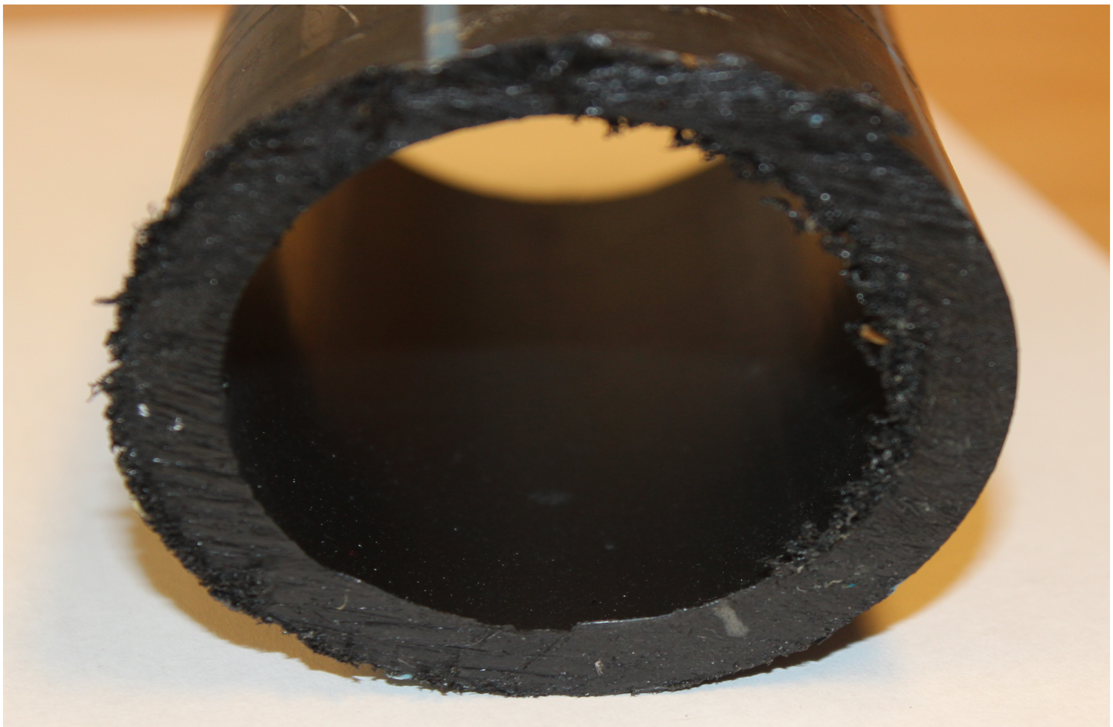

**Figure 13.6: Cut off section of the SDR11 PE 50 mm pipe (Source: the author)**

Figure 13.6 shows the cut part of the 50 mm pipe after 4 weeks of testing, proving that the sedimentation process did not occur in this pipe. All cuts that were made during this test confirmed that the process of self-cleansing in was successful for all 3 pipes.

## 14. Velocity in pipes

### 14.1. Velocity in the 40 mm pipe

The discharge value of the pump, as mentioned earlier, is considered more or less constant, regardless of the head value. From the H-Q graph (Figure 12.6) the value of discharge Q is 0.8 l/s due to the pressure generated by the pump. In order to calculate the velocity value for the 40 mm PE pipe, one additional factor needs to be included and that is the SDR value of the pipe. SDR 11 pipes were used for this experiment. As already mentioned, the SDR value can be calculated through expression 12.1:

$$SDR = D/s \qquad \text{(eq.12.1)}$$

Where: D = outside diameter of the pipe; for the first pipe it is 40 mm

s = pipe wall thickness; which in this case is 3.7mm

SDR= 40mm/3.7mm

SDR=10.81 to 11

**Table 14.1: PE dimensions (Polyethylene Pipe Systems, 2008)**

| Nominal O/D | Max O/D | Average O/D | Max. Straight pipe | SDR 9 | | SDR 11 | | SDR 11 Average pipe bore |
|---|---|---|---|---|---|---|---|---|
| | | | | Min | Max | Min | Max | |
| 16 | 16,3 | 16,15 | 1,2 | 2 | 2,3 | 0 | 0 | 0 |
| 20 | 20,3 | 20,15 | 1,2 | 2,3 | 2,7 | 2 | 2,3 | 15,85 |
| 25 | 25,3 | 25,15 | 1,2 | 3 | 3,4 | 2,3 | 2,7 | 20,15 |
| 32 | 32,3 | 32,15 | 1,3 | 3,6 | 4,1 | 3 | 3,4 | 25,75 |
| 40 | 40,4 | 40,2 | 1,4 | 4,5 | 5,1 | 3,7 | 4,2 | **32,6** |
| 50 | 50,4 | 40,2 | 1,4 | 5,6 | 6,3 | 4,6 | 5,2 | **40,4** |
| 63 | 63,4 | 63,2 | 1,5 | 7,1 | 8 | 5,8 | 6,5 | **50,4** |
| 75 | 75,5 | 75,25 | 1,6 | 8,4 | 9,4 | 6,8 | 7,6 | 60,85 |

It is important to include the SDR value in the calculation, due to the fact that it decreases the actual cross section of the pipe. The actual diameter of the 40 mm SDR11 PE pipe decreases for the thickness of the pipe wall, which is usually 3.7 – 4.2 mm.

The actual diameter D’ of the 40 mm SDR11 pipe can be calculated using the following expression:

$D' = D - 2 * 3.7$ (eq.14.1)

$D' = 40 - 7.4$

$D' = 32.6$ mm

From this value, it is easy to determine the pipe radius:

$r = D'/2$ (eq. 14.2)

Where the value of radius for the 40 mm SDR 11 pipe is $r_1 = 16.3$mm.

The value of pipe cross section for the same pipe can be calculated through the equation:

$A = (D'/2)^2 \pi$ (eq.14.3)

$A_1 = (32.6mm)^2 / 4 * 3{,}14$

$A_1 = 834.27mm^2$

$A_1 = 0.00083m^2 = 8.34*10^{-6}m^2$

After computing the cross section value A, the velocity of fluid within the pipe is computed with a simple equation. Note that for the purposes of this project the velocity value will be expressed in m/s.

$Q = VA$ (eq.14.4)

$V = Q/A$

$V_1 = 0.8l/s / 0.00083\ m^2$

$V_1 = 0.0008\ m^3/s / 0.00083\ m^2$

$V_1 = 0.959 = 0.96$ m/s

$Q = 0.8$ l/s

$r_1 = 16.3$mm

$A_1 = 0.00083m^2$

$V_1 = 0.96$ m/s

The value of fluid velocity within this pipe is too high for possible sedimentation, which was confirmed by examination of the checking section. Velocity values are recorded on the following figure 14.1.

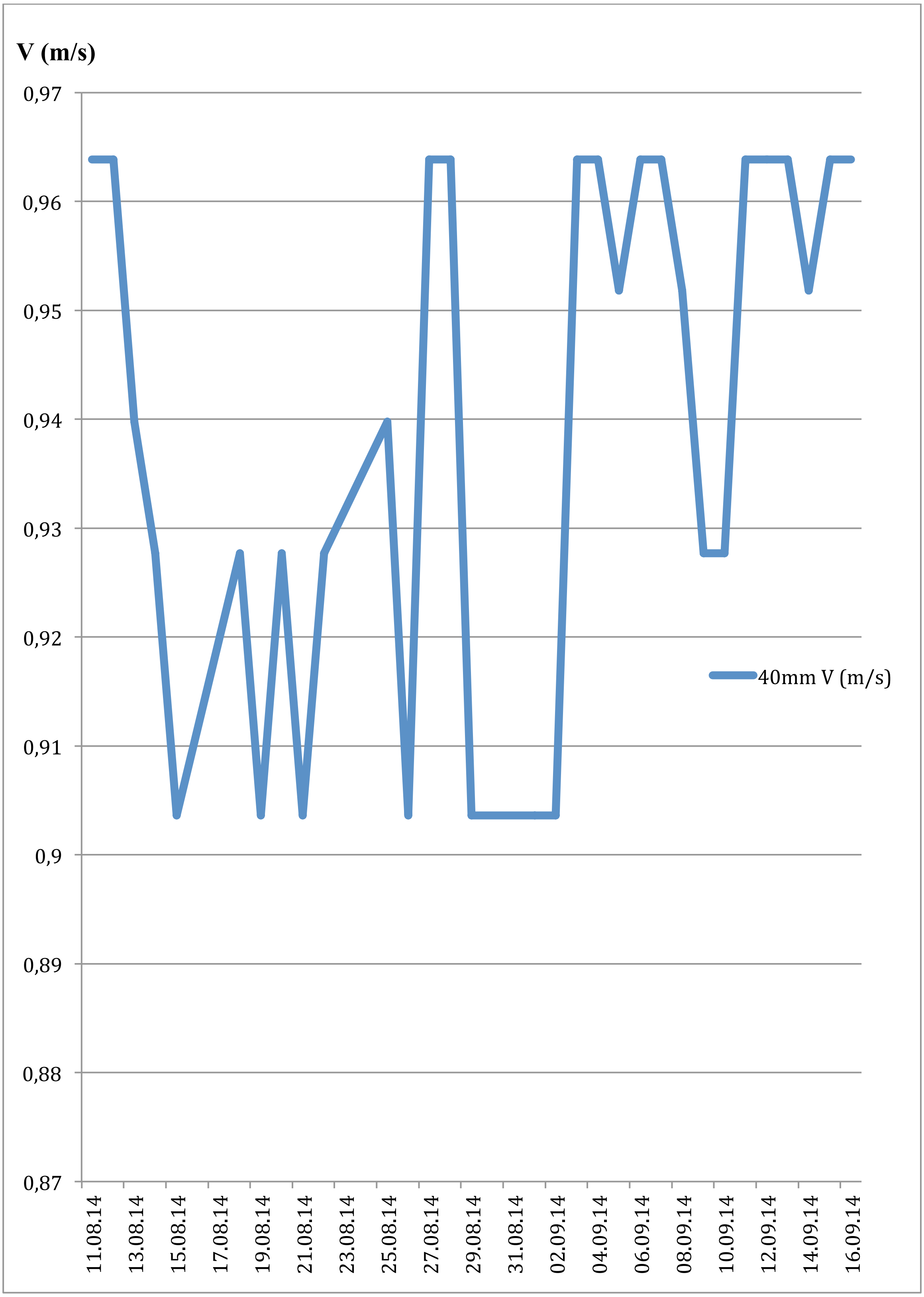


**Figure 14.1: Velocity in SDR11 PE 40mm pipe**

### 14.2.Velocity in the 50 mm pipe

Exactly the same calculation procedure needs to be repeated for the 50 mm and 63 mm pipes. The SDR must be included in determining the value of fluid velocity inside the pipe. The SDR value for the 50 mm PE pipe is 4.6 - 5.2.
The actual diameter D' of the 50 mm SDR11 pipe can be calculated using the following equation:

$D' = D - 2*4.8$

$D' = 50 – 9.6$

$D' = 40.4$ mm

From this value, it is easy to determine the pipe radius:
$r = D'/2$;
Where the radius for the 50 mm SDR11 pipe is $r_2 = 20.2$mm.

The value of pipe cross section for the 50 mm pipe is:

$A = (D'/2)^2\pi$

$A_2 = 1281.24\ mm^2$

$A_2 = 0.001281\ m^2$

The fluid velocity in the 50 mm pipe is:

$Q = VA$

$V = Q/A$

$V_2 = 0.8l/s / 0.001281\ m^2$

$V_2 = 0.0008\ m^3/s / 0.001281\ m^2$

$V_2 = 0.624 = 0.62$ m/s

$Q = 0.8$ l/s

$r_2 = 20.2$mm

$A_2 = 0.001306\ m^2$

$V_2 = 0.62$ m/s

The figure 14.2 displays velocity values for 50mm pipe.

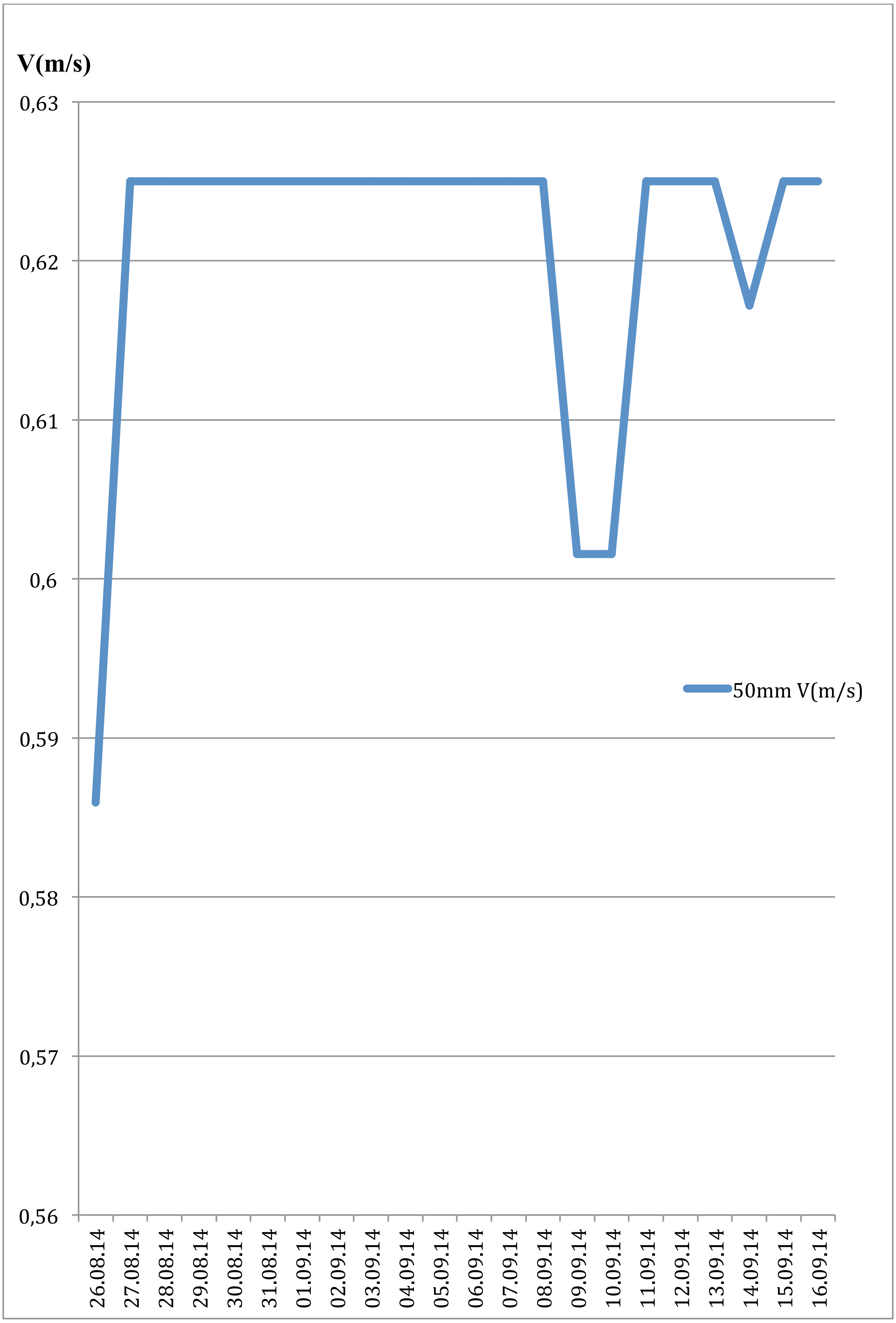


**Figure 14.2: Velocity in SDR11 PE 50mm pipe**

### 14.3. Velocity in the 63 mm pipe

Actual diameter D’ of the 63 mm SDR11 pipe can be calculated using the following equation:

$D' = D - 2*6.3$

$D' = 63 - 12.6$

$D' = 50.4$ mm

radius for the 63 mm pipe is

$r = D'/2$

$r_3 = 25.2$ mm.

The value of pipe cross section $A_3$ for 63 mm pipe is:

$A = (D'/2)^2\pi$

$A_3 = 1994.02\ mm^2$

$A_3 = 0.001994\ m^2$

The fluid velocity within the 63 mm pipe is:

$Q = VA$

$V = Q/A$

$V_3 = 0.8 l/s / 0.001994\ m^2$

$V_3 = 0.0008\ m^3/s / 0.001994\ m^2$

**$V_3 = 0.40$ m/s**

$Q = 0.8$ l/s

$r_3 = 25.2$

$A_3 = 0.001994\ m^2$

$V_3 = 0.40$ m/s

**As you may see from the previous calculations, the fluid velocity value proportionally decreases with the increase of pipe diameter.**

The following figure 14.3 displays the velocity in 63mm pipe.

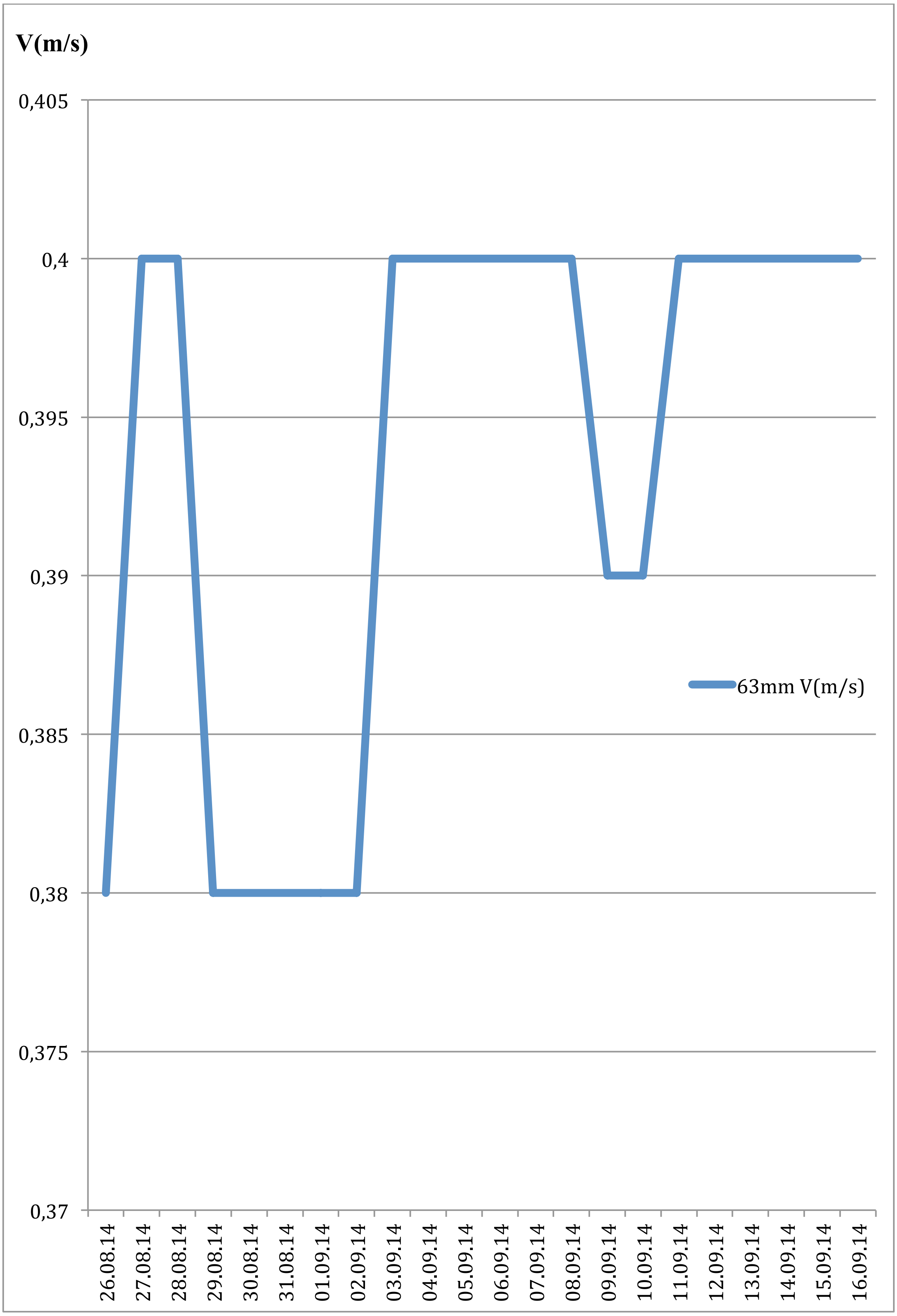


**Figure 14.3: Velocity in SDR11 PE 63mm pipe**

In the period of 40 days of testing, cut samples of the pipe for the sedimentation test were taken 4 times, approximately every tenth day.

The fact that wastewater remained in pipes after the test run, automatically meant that with opening of the pipeline water will flow out of the pipe.

Once the pipe was opened, the amount of water that came out of the pipes was the result of atmospheric pressure and installed slopes. In order to prevent possible ponding of wastewater, upon suggestion from Jon Arve Engan a small hole was dug. With the opening of the pipe wastewater would get discharged and later infiltrated through soil naturally. This procedure prevented possible formation of unpleasant odor. The effect of additional nutrients from wastewater, which were infiltrated through the soil, and affected the nearby vegetation. The growth of a different type of mushroom was recorded in the area where the discharges took place.

The following tables in appendix (A1, A2 and A3) are shown with the daily pressure, flow and velocity values in all three pipes for the period of testing.

**Part 5: Conclusion**

## 15. Result Analysis

As shown in the previous chapter, with the use of E/One grinder pump 5 times per week, accumulation of sediments did not take place in the 40 mm, 50 mm and 63 mm SDR11 PE pipes.
This test proved that the self-cleansing of SDR11 PE 40, 50 and 63mm pipes in pressurized sewer systems exists, and that this process occurs throughout the entire length of the pipes even at velocities lower than the required 0,7m/s, which is previously defined/required by the Norwegian Standard for pressurized sewage systems from 1997.

Considering that the velocity in the 40 mm SDR11 PE pipe was 0.9 m/s, it was more than obvious that self-cleansing process would take place inside of this pipe.
With the 50 mm SDR11 PE pipe, the assumption was the same as for the 40 mm pipe. The velocity in this pipe was 0.6 m/s, which was less than in the 40 mm pipe but was still sufficient to achieve the self-cleansing effect.
However, the biggest concern of this test was related to the 63 mm diameter SDR11 PE pipe. The increase of pipe diameter automatically meant that the velocity in the 63mm pipe would be the lowest compared to the other two pipes. The decrease of velocity from 0.6 m/s to 0.4 m/s posed the main question of this test, namely whether this newly formed velocity would be high enough to move the sediments (heavier particles) from the bottom of the pipe during the testing period. The results of test were very satisfying and it confirmed that process of self-cleansing occurs in 63mm pipe as well.
The values of flow energy and shear stress in SDR11 PE 40,50 and 63mm pipes were high enough to prevent sedimentation process of taking place inside of the pipe.

The results suggested that the generally successful performance of this system lies in components compatibility and functioning. Therefore characteristics of the PE pipes also contributed to achieving the self-cleansing effect as well. PE pipes that were used for the purpose of this project handled the pressure perfectly and did not have any leakages. The inner smoothness of pipes (friction coefficient of the pipe) played an important part in maintaining the self-cleansing process in this pipelines.

Consistency of E/One pump flow during this test was at a high level and it also contributed on the final results along with the good design of the system.

Regardless of the pressure value, this pump has delivered more or less the same amount of wastewater, which confirmed the reliability and quality of this pump and the system in general.

**16. Conclusion**

This thesis analyzed the self-cleansing performance of a pressurized sewer system. Along with the analysis, the thesis also compared between conventional systems and pressurized sewer systems.

The general performance of E/One pressurized sewage system during this test was highly satisfactory and suggested that it can safely distribute wastewater from households to gravitational system.

Main source of energy that secures the movement of fluid through pipelines of both gravity and pressurized sewage system is not the same. The movement of fluid through pressurized sewage system is secured through semi-positive displacement pump, while for gravity system the existence of pipe inclination secures the movement of fluid in pipes. As long as the energy of the flow in pipes secures movement of the solids in suspended mode, the chances of accumulation of material in pipes are reduced to a minimum. Sudden reduction in velocity and shear stress of both systems lead to sedimentation in pipes. Due to the fact that these two systems function under different mechanisms, different pace of flow transportation occurs in their pipes. The flow in pressurized sewage system only occurs when the pump is active unlike the gravity system where flow is constantly moving.

In addition to this, because of the main difference in pipe sizes of the systems, defined velocity requirements for self-cleansing of pipe should not be the same for all sewage systems.

The main weakness of defined velocity standards for self-cleansing are arbitrary and the fact that the type and quantity of sediments and their impacts were not taken into consideration when this velocity standard was designed.
Based on a daily usage, the performance of E/One grinder pump was on very high level throughout entire pump test, and its contribution to self-cleansing of the pipes was very satisfying.
E/One grinder pump has proved that in pressurized sewage system the process of self-cleansing can occur even at velocities that are significantly lower than 0,7m/s, which is defined by the Norwegian Standard for pressurized sewers.
Therefore, Norwegian Standard criterion regarding velocities for self-cleansing of pressurized sewage systems is too high and it should get reevaluated and redefined.

After completing this project, I have concluded that there is no doubt as to the importance of self-cleansing of pipes for the purposes of wastewater distribution. The new technology, materials and knowledge can help us in designing systems that might significantly reduce sedimentation in pipes. Therefore, velocity criterion for self-cleansing of pipes should always follow and adapt to latest knowledge and new technologies.

Hopefully this thesis provides a milestone for further research with more thorough analysis of the distribution of heavier particles, such as sand, within a pressurized system. In addition, the movement of the particles could also be analyzed, by installing a camera inside the pipe. The system can be also tested at different flow velocities in order to monitor changes in the behavior of various types of sediments. Furthermore, the testing of E/One grinder pump and pressurized sewage system would be conducted for longer period on pipelines with larger pipe diameters. The further research can give a clearer picture of the movement, distribution and accumulation of sediment within the system. I also hope that this study on the pipe will contribute to develop the technology and knowledge, which can help in designing even safer and more efficient wastewater distributing systems.

Appendix:

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**Additional tables:**

**Table A1: SDR11 PE 40mm pipe measurements**

| Date | Temperature | Pressure for 40mm | Flow for Q 40 l/s | Q $m^3/s$ | A 40mm ($m^2$) | V (m/s) |
|---|---|---|---|---|---|---|
| 11.08.14 | 18 ° C | 2,3 | 0,8 | $8*10^{-4}$ | $8.3*10^{-4}$ | 0,96 |
| 12.08.14 | 15 ° C | 2 | 0,8 | $8*10^{-4}$ | $8.3*10^{-4}$ | 0,96 |
| 13.08.14 | 14 ° C | 3 | 0,78 | $7.8*10^{-4}$ | $8.3*10^{-4}$ | 0,94 |
| 14.08.14 | 16 ° C | 3,5 | 0,77 | $7.7*10^{-4}$ | $8.3*10^{-4}$ | 0,93 |
| 15.08.14 | 16 ° C | 4 | 0,75 | $7.5*10^{-4}$ | $8.3*10^{-4}$ | 0,9 |
| 18.08.14 | 15 ° C | 3,5 | 0,77 | $7.7*10^{-4}$ | $8.3*10^{-4}$ | 0,93 |
| 19.08.14 | 14 °C | 4 | 0,75 | $7.5*10^{-4}$ | $8.3*10^{-4}$ | 0,9 |
| 20.08.14 | 13 °C | 3,5 | 0,77 | $7.7*10^{-4}$ | $8.3*10^{-4}$ | 0,93 |
| 21.08.14 | 11 °C | 4 | 0,75 | $7.5*10^{-4}$ | $8.3*10^{-4}$ | 0,9 |
| 22.08.14 | 16 ° C | 3,6 | 0,77 | $7.7*10^{-4}$ | $8.3*10^{-4}$ | 0,93 |
| 25.08.14 | 14 °C | 3 | 0,78 | $7.8*10^{-4}$ | $8.3*10^{-4}$ | 0,94 |
| 26.08.14 | 16 ° C | 4,1 | 0,75 | $7.5*10^{-4}$ | $8.3*10^{-4}$ | 0,9 |
| 27.08.14 | 19° C | 2 | 0,8 | $8*10^{-4}$ | $8.3*10^{-4}$ | 0,96 |
| 28.08.14 | 19° C | 1,9 | 0,8 | $8*10^{-4}$ | $8.3*10^{-4}$ | 0,96 |
| 29.08.14 | 21° C | 4,2 | 0,75 | $7.5*10^{-4}$ | $8.3*10^{-4}$ | 0,9 |
| 01.09.14 | 19° C | 4,1 | 0,75 | $7.5*10^{-4}$ | $8.3*10^{-4}$ | 0,9 |
| 02.09.14 | 19° C | 4,2 | 0,75 | $7.5*10^{-4}$ | $8.3*10^{-4}$ | 0,9 |
| 03.09.14 | 16 ° C | 2,4 | 0,8 | $8*10^{-4}$ | $8.3*10^{-4}$ | 0,96 |
| 04.09.14 | 16 ° C | 0 | 0,8 | $8*10^{-4}$ | $8.3*10^{-4}$ | 0,96 |
| 05.09.14 | 15° C | 2,5 | 0,79 | $7.9*10^{-4}$ | $8.3*10^{-4}$ | 0,95 |
| 06.09.14 | 17° C | 1,8 | 0,8 | $8*10^{-4}$ | $8.3*10^{-4}$ | 0,96 |
| 07.09.14 | 19° C | 2 | 0,8 | $8*10^{-4}$ | $8.3*10^{-4}$ | 0,96 |
| 08.09.14 | 16 ° C | 2,5 | 0,79 | $7.9*10^{-4}$ | $8.3*10^{-4}$ | 0,95 |
| 09.09.14 | 15 ° C | 3,5 | 0,77 | $7.7*10^{-4}$ | $8.3*10^{-4}$ | 0,93 |
| 10.09.14 | 16 ° C | 3,3 | 0,77 | $7.7*10^{-4}$ | $8.3*10^{-4}$ | 0,93 |
| 11.09.14 | 14 °C | 2,1 | 0,8 | $8*10^{-4}$ | $8.3*10^{-4}$ | 0,96 |
| 12.09.14 | 15 ° C | 1,8 | 0,8 | $8*10^{-4}$ | $8.3*10^{-4}$ | 0,96 |
| 13.09.14 | 14 ° C | 1,2 | 0,8 | $8*10^{-4}$ | $8.3*10^{-4}$ | 0,96 |
| 14.09.14 | 14 ° C | 2,6 | 0,79 | $7.9*10^{-4}$ | $8.3*10^{-4}$ | 0,95 |
| 15.09.14 | 15 ° C | 1,9 | 0,8 | $8*10^{-4}$ | $8.3*10^{-4}$ | 0,96 |
| 16.09.14 | 14 ° C | 1,2 | 0,8 | $8*10^{-4}$ | $8.3*10^{-4}$ | 0,96 |
| | | 2,76 p avg | 0,78 Q avg | $7.8*10^{-4}$ Q avg | | 0,94 Vavg |

**Table A2: SDR11 PE 50mm measurements**

| Date | Temperature | Pressure for 50mm | Flow for Q 50 l/s | Q $m^3/s$ | A 50mm (m^2) | V (m/s) |
|---|---|---|---|---|---|---|
| 26.08.14 | 16 ° C | 3 | 0,75 | $7.5*10^{-4}$ | $1.28*10^{-3}$ | 0,59 |
| 27.08.14 | 19° C | 1,7 | 0,8 | $8*10^{-4}$ | $1.28*10^{-3}$ | 0,62 |
| 28.08.14 | 19° C | 1,7 | 0,8 | $8*10^{-4}$ | $1.28*10^{-3}$ | 0,62 |
| 03.09.14 | 16 ° C | 2,1 | 0,8 | $8*10^{-4}$ | $1.28*10^{-3}$ | 0,63 |
| 04.09.14 | 16 ° C | 2 | 0,8 | $8*10^{-4}$ | $1.28*10^{-3}$ | 0,63 |
| 05.09.14 | 15° C | 2,2 | 0,79 | $7.9*10^{-4}$ | $1.28*10^{-3}$ | 0,63 |
| 06.09.14 | 17° C | 1,6 | 0,8 | $8*10^{-4}$ | $1.28*10^{-3}$ | 0,63 |
| 07.09.14 | 19° C | 1,9 | 0,8 | $8*10^{-4}$ | $1.28*10^{-3}$ | 0,63 |
| 08.09.14 | 16 ° C | 2,3 | 0,79 | $8*10^{-4}$ | $1.28*10^{-3}$ | 0,63 |
| 09.09.14 | 15 ° C | 3,2 | 0,77 | $7.7*10^{-4}$ | $1.28*10^{-3}$ | 0,6 |
| 10.09.14 | 16 ° C | 3 | 0,77 | $7.7*10^{-4}$ | $1.28*10^{-3}$ | 0,6 |
| 11.09.14 | 14 °C | 2 | 0,8 | $8*10^{-4}$ | $1.28*10^{-3}$ | 0,63 |
| 12.09.14 | 15 ° C | 1,6 | 0,8 | $8*10^{-4}$ | $1.28*10^{-3}$ | 0,63 |
| 13.09.14 | 14 ° C | 1 | 0,8 | $8*10^{-4}$ | $1.28*10^{-3}$ | 0,63 |
| 14.09.14 | 14 ° C | 2,5 | 0,79 | $7.9*10^{-4}$ | $1.28*10^{-3}$ | 0,62 |
| 15.09.14 | 15 ° C | 1,8 | 0,8 | $8*10^{-4}$ | $1.28*10^{-3}$ | 0,63 |
| 16.09.14 | 14 ° C | 1,1 | 0,8 | $8*10^{-4}$ | $1.28*10^{-3}$ | 0,63 |
| | | 1,92 p avg | 0,795 Q avg | $7.9*10^{-4}$ Q avg | | 0,62 V avg |

**Table A3: SDR11 PE 63mm pipe measurements**

| Date | Temperature | Pressure for 63mm | Flow Q63 l/s | Q63 $m^3/s$ | A 63mm ($m^2$) | V (m/s) |
|---|---|---|---|---|---|---|
| 26.08.14 | 16 ° C | 2,7 | 0,75 | $7.5*10^{-4}$ | $1.99 * 10^{-3}$ | 0,38 |
| 27.08.14 | 19° C | 1,5 | 0,8 | $8*10^{-4}$ | $1.99 * 10^{-3}$ | 0,40 |
| 28.08.14 | 19° C | 1,4 | 0,8 | $8*10^{-4}$ | $1.99 * 10^{-3}$ | 0,40 |
| 29.08.14 | 21° C | 4 | 0,75 | $7.5*10^{-4}$ | $1.99 * 10^{-3}$ | 0,38 |
| 01.09.14 | 19° C | 3,9 | 0,75 | $7.5*10^{-4}$ | $1.99 * 10^{-3}$ | 0,38 |
| 02.09.14 | 19° C | 3,6 | 0,75 | $7.5*10^{-4}$ | $1.99 * 10^{-3}$ | 0,38 |
| 03.09.14 | 16 ° C | 2 | 0,8 | $8*10^{-4}$ | $1.99 * 10^{-3}$ | 0,40 |
| 04.09.14 | 16 ° C | 0 | 0,8 | $8*10^{-4}$ | $1.99 * 10^{-3}$ | 0,40 |
| 05.09.14 | 15° C | 2,1 | 0,79 | $7.9*10^{-4}$ | $1.99 * 10^{-3}$ | 0,40 |
| 06.09.14 | 17° C | 1,4 | 0,8 | $8*10^{-4}$ | $1.99 * 10^{-3}$ | 0,40 |
| 07.09.14 | 19° C | 1,8 | 0,8 | $8*10^{-4}$ | $1.99 * 10^{-3}$ | 0,40 |
| 08.09.14 | 16 ° C | 2,2 | 0,79 | $7.9*10^{-4}$ | $1.99 * 10^{-3}$ | 0,40 |
| 09.09.14 | 15 ° C | 3,1 | 0,77 | $7.7*10^{-4}$ | $1.99 * 10^{-3}$ | 0,39 |
| 10.09.14 | 16 ° C | 2,9 | 0,77 | $7.7*10^{-4}$ | $1.99 * 10^{-3}$ | 0,39 |
| 11.09.14 | 14 °C | 1,9 | 0,8 | $8*10^{-4}$ | $1.99 * 10^{-3}$ | 0,40 |
| 12.09.14 | 15 ° C | 1,5 | 0,8 | $8*10^{-4}$ | $1.99 * 10^{-3}$ | 0,40 |
| 13.09.14 | 14 ° C | 0,9 | 0,8 | $8*10^{-4}$ | $1.99 * 10^{-3}$ | 0,40 |
| 14.09.14 | 14 ° C | 2,4 | 0,79 | $7.9*10^{-4}$ | $1.99 * 10^{-3}$ | 0,40 |
| 15.09.14 | 15 ° C | 1,7 | 0,8 | $8*10^{-4}$ | $1.99 * 10^{-3}$ | 0,40 |
| 16.09.14 | 14 ° C | 1 | 0,8 | $8*10^{-4}$ | $1.99 * 10^{-3}$ | 0,40 |
| | | 2,1<br>p avg | 0,79<br>Qavg | $7.9*10^{-4}$<br>Qavg ($m^3/s$) | | 0,40<br>Vavg (m/s) |

Note:
Measurements for certain dates were not recorded due to the difficulties in observing and running the pump at the exact same time.

Norwegian University
of Life Sciences

Postboks 5003
NO-1432 Ås, Norway
+47 67 23 00 00
www.nmbu.no