Master Thesis
TVVR 21/5014

Pipe Surface Roughness at Microscale and Discussion of Possible Relation to Flow Properties

Mahsa Kajbaf Nezhad
Yiting Qiao

Division of Water Resources Engineering
Department of Building and Environmental Technology
Lund University

Pipe Surface Roughness at Microscale and Discussion of Possible Relation to Flow Properties

By:
Mahsa Kajbaf Nezhad
Yiting Qiao

Master Thesis

Division of Water Resources Engineering
Department of Building & Environmental Technology
Lund University
Box 118
221 00 Lund, Sweden

Water Resources Engineering
TVVR-21/5014
ISSN 1101-9824

Lund 2021
www.tvrl.lth.se

Master Thesis
Division of Water Resources Engineering
Department of Building & Environmental Technology
Lund University

Swedish title:	<Råheten hos rör i mikroskala och diskussion av möjlig koppling till flödets egenskaper>
English title:	<Pipe Surface Roughness at Microscale and Discussion of Possible Relation to Flow Properties>
Author(s):	< Mahsa Kajbaf Nezhad> <Yiting Qiao>
Supervisor:	<Kenneth M Persson> <Magnus Larson>
Examiner:	<Hossein Hashemi>
Language	<English >
Year:	2021
Keywords:	<pipe flow; roughness; microscale; SEM>

Acknowledgement

This thesis was written as part of the Master program of Water Resources Engineering, the department of Technical Water Resources Science, Faculty of Enginnering (LTH) in Lund University. The project has been prepared and guided by Kenneth M Persson and Magnus Larson since November in 2020. We were fascinated about the idea of looking for the water movement mechanism at microscale and possibility to develop the certain mechanism into Darcy-Weisbach equation. In the process of reading relevant materials and writing, we soon noticed that this project could not fulfill the initial ambitious goal. This project is just a first step and we tried our best to make this step as big as possible in the limited and special covid-19 time period. It is not perfect and generates a lot more questions to deal with, but it is a symbol of our endings in this two-year program. We are both delightful to be involved in this special research project, although the whole process was also frustrating.

No matter how, the thesis work is finished and many thanks to our two supervisors who gave us guidance and encouragement all the way. Thanks for the detailed comments made by Hossein Hashemi, our examiner. And Crispin Hetherington, who helped us with the SEM experiments; Fainaz Inamdeen, who guided us to use the software. And very appreciate it that we got so much love and support from our friends and families to go through the frustrating period.

Abstract

Despite decades of intense research, the behavior of water molecule still warrants new research. Water flow through various pipe systems has become a pivotal corner stone of functioning human infrastructure. the energy consumed by the pumping system takes the proportion of around 22% of the supplied energy for electromotors around the world (Shankar et al. 2016). A large amount of annual budget in each country is spent on pumping water through pipes. Minimizing the energy loss in the pipe and pumping systems is of great importance and interest. One important variable is the energy loss due to the friction at the boundary level near the pipe wall, which could be strongly affected by the micro-structure of the interior wall of the pipe and specific patterns how different pipe materials deteriorate with age. This project is an attempt to minimize energy loss during water transportation through pipes. We characterized microscale surface texture of PVC and PE pipe inner surfaces and attempted to quantify energy loss due to roughness of the inner surface of the pipe. We used Scanning Electron Microscopy (SEM) to obtain high resolution images of pipe surface that we further analysed with MountainsSEM. In the pipes we studied on average three to four million water molecules can fit in the distance between highest ”peak to valley” of the surface topography. We studied $0.3mm^2$ of pipe surface for each sample. When this result is extrapolated across entire pipes surface total energy loos might be noticeable. However, this method has many flaws and further research program is necessary to give definitive answer.

In this study three different pipes (sample (a) PVC diameter of 110 mm, sample (b) PE Diameter of 110 mm, and sample (c) PE diameter of 16 mm) were observed and analyzed by SEM, the roughness height e were described by roughness parameter R_f, which were 142.2, 132.9 and 123.4 micrometers respectively. This result means around 3 to 4 million water molecules can fit in this height which can have hydrogen bonds within themselves, and solid wall. Dissociation bod energy for the H-O is about 20.8 KJ/mole, and for the H-C the value is almost 500 KJ/mole. Considering friction loss is from the bonds between water molecules and wall, only one of the peaks can cause 3.36·10L−15 KJ,2.84 ·10L−15 KJ, 2.61·10L−15 KJ extra energy lost in sample a, b and c respectively. This is the result of increase in the solid surface that water molecule can make H-C hydrogen bond with. With assumption of turbulent flow velocity of 1 m/s through a 100-meter-long pipe, the friction factor calculated by Darcy-Weisbach equation of the three pipe samples were 0.0210, 0.0206 and 0.0340 correspondingly.

To achieve a better resolution images of pipes interior we suggest that in future it is more fruitful to use Atomic Force Microscope (AFM). To fully address the research question, it is necessary in future to track movements of a singe water molecule to precisely quantify how it creates and breaks bonds with other molecules and move in the pipe. And finally one must remember that such studies in different ambient temperatures because temperature directly affects length of the water molecule bonds and through them the water flow energy. Darcy-Weisbach leans on simplified rough assumptions of temperature effects to calculate friction loss as kinematic viscosity. It is important to meticulously evaluate whether more detailed coefficients for these variables could help us to save energy to a meaningful level.

Contents

1 Introduction

1.1 Background

Transfer of water is an element of human infrastructure with utmost important role. Each country spends on a large amount of the budget to run electrical pumps that keep the water going through pipe systems (drinking water delivery, waste water disposal etc). Up till now all existing systems have been built based on rather old theoretical assumptions that have at a time used simplified coefficients that were not possible to measure precisely. One such potentially important variable is the energy loss due to the friction at the boundary level near the pipe wall. This may be strongly affected by the microstructure of the interior wall of the pipe and specific patterns how different pipe materials deteriorate with age. Even marginal improvement in these estimates may save a substantial amount of resources (electricity cost of the pumps, maintenance of pipe systems).

Boundary conditions are necessary and important to establish for solving problems in hydrodynamics. For describing fluid flows along a solid wall (e.g., pipes and channels), non-slip condition is mostly assumed between the flow and the boundary (Lauga and Squires 2005). In practice, this condition without any relative motion between the fluid and solid surfaces may not always hold true at molecular scale (Shu, Teo, and Chan 2016). It has already been demonstrated that discontinuity in velocity and slip may occur near a solid boundary wall for certain conditions when a certain critical shear stress is exceeded (Zhou, Gu, and Shao 2011). In these special cases, roughness of the channel and pipe walls play an important role for fluid movement. Subtle variations in roughness caused by different materials or shapes of the wall may result in large differences in the shear rate (Duttine and Tatsuoka 2009) near the boundaries. Therefore, if the attempt at looking into the solid boundary and the fluid layer near the boundary from a microscopic view such as the molecular level, some novel or undefined fluid behaviors may be noticed. At least there is a potential to find the relative movement between the boundary wall and the fluid which has not been included in the commonly used Darcy-Weisbach equation. When it comes to a molecular scale, take water flow in pipe as an example, movement and binding patterns of individual water molecules among themselves and the pipe wall, to our knowledge were not investigated before. To be more ambitious, if one single molecule can be marked and traced with the neutron scattering device, the motion trail of the molecule would be revealed to us. By characterizing how the molecule bounces at solid surfaces with different roughness heights and patterns without the assumption of non-slip condition, it is possible to synthesize a new equation to supplement of the Dary-Weisbach equation that can account for the fluid motion profile at microscale. There is a long way to go to achieve the objectives mentioned above, this project is an incipient step of it. We tried to start from the pipe water flow, looking for possible relations between pipe wall roughness and water molecules at a microscale.

In water pipe systems, the water movement behavior at the molecular level with regard to roughness conditions and how to apply this behavior at the macroscale for modelling, for example, frictional losses, are essential to clarify. The high demand of water utilization leads to the widely use of water pumping system. According to the report about pump energy efficiency from the European Commission, the energy consumed by the pumping system takes the proportion of around 22% of the supplied energy for electromotors around the world (Shankar et al. 2016.It is always a hot issue of reducing energy losses in the pumping system, because the energy loss always exists and its reduction will help optimization of the pumping efficiency. Frictional loss along the pipe in the water pumping system cannot be negligible and need to be overcome. Studying friction between the boundary layer and the pipe wall in a microscopic view may provide with some clues for a more accurate computation of boundary conditions, which gives more precise estimation of energy loss in pipe and pumping systems in macroscopic models (Hafizi et al. 2011).

1.2 Objectives

The long term aims of this study is to move the understanding of how the friction losses are generated in pipes on molecular level forward. Also how the surface roughness influence friction losses from a microscopic view. As this project is in the very beginning to go toward answering the questions we focused on the following objectives:

- Observing the pipe surface of three different by taking advantage of SEM (scanning electron microscope).
- Analysing the result from SEM to visualize the topography of the pipe surface and obtain roughness parameters.
- Calculate the approximate number of extra water molecule in the pipe due to the pipe topography in comparison with a complete flat pipe.
- Finally, calculate the energy of the hydrogen bonds between water molecules and the pipe in the peak heights. As this interaction of the water molecules and the surface that is hydrogen bond is the source of frictional loss.

Furthermore, if it is possible to access the neutron scattering system, we can get the opportunity to observe how water molecules or water layers adjacent to the pipe wall move. If the movement path of water molecules has certain patterns or rules to follow, how the bonding between water molecules and solid wall in pipes push water to move, transport energy and cause friction loss precisely could be able to investigate. In addition, the friction will bring forth temperature change which in turn affects fluid viscosity, Reynolds number and friction factor. This bidirectional effect could play an important role in pipe system in regions where extreme temperature variation exists. This report also tends to figure out what kind of mechanisms that temperature plays at both macro- and micro-scale.

1.3 Procedure

Three pieces of pipes were collected as samples for observing inner surface roughness. Sample (a) is a used polyvinyl chloride (PVC) wastewater pipe segment with diameter of 110 mm; sample (b) is polyethylene (PE) pressure pipe with diameter of 110 mm; sample (c) is PE pressure pipe with diameter od 16 mm. Both the polyethylene pipes were requested from Uponor Infrastructure company.

Two image-capturing instruments were used to obtain the pipe wall roughness. One is a digital microscope called Dino-Lite which is portable and able to magnify at most 200x. And also the scanning electron microscope (SEM) was applied to inquire into more analysis. Both

Dino-Lite and SEM can magnify and shot clear images of the pipe inner surface. However, Dino-Lite cannot give a clear view of the pipe wall above 50x maginification. In addition, there is no corresponding analytical application to measure details on pictures captured by Dino-Lite. In comparison, the magnification of 140x was done by SEM and the images are able to analyzed by many software, like GIS, ImageJ and other image processing applications. We chose two software to analyze the SEM images, which are QGIS (an application of the geographic information system) and MountainsSEM. Both software are capable of extracting profile patterns of the roughness. But GIS cannot acquire the numerical values of the roughness, in development, MountainsSEM is able to build stereoscopic model based one two SEM images shot from two different angels under the same magnification factor.

At the very beginning, hydraulic experiments for obtaining friction factor were also planned in the project. Unfortunately there was no laboratory accept external people to conduct any experiments due to the covid-19 situation. In the near future, if it is possible to do more empirical work or even get access to the neutron scattering facilities, it would be a potentially fruitful continuation of the project.

2 Pipe flow at macroscale

2.1 Darcy-Weisbach equation

The quantative equation of the fluid friction or head loss though a pipe is described according to the Bernoulli principle and expressed as the energy equation:

$$h_L = (\frac{V_1^2}{2g} + \frac{p_1}{\rho g} + z_1) - (\frac{V_2^2}{2g} + \frac{p_2}{\rho g} + z_2) \approx (\frac{p_1}{\rho g} + z_1) - (\frac{p_2}{\rho g} + z_2) \tag{1}$$

take water pipe flow as an example, where h_L is the water friction or head loss between the cross section 1 and 2 along the pipe, V is the average velocity of water, g is the acceleration of gravity, p is the water pressure, ρ is the water density and z is the elevation of pipe cross section. The right-hand-side of equation (1) is applied for the constant flow when water velocity dose not change.

The head loss h_L for incompressible flow in laminar condition through a cylindrical pipe was derived from experimental results by Jean Léonard Marie Poiseuille and Gotthilf Heinrich Ludwig Hagen, called Hagen–Poiseuille equation:

$$h_L = \frac{32\nu LV}{gD^2} \tag{2}$$

Equation (2) relates fluid friction directly to fluid kinematic viscosity ν and velocity V, pipe diameter D and pipe length L, which is convient and successfully applied for both air fow and water flow, but only limited in the laminar regime. A Germany engineer, Julius Weisbach proposed an equation to calculate head loss based on energy equation in 1845 applicable to both laminar and turbulent flow, which is also the one we use most commonly and called Darcy-Weisbach equation, valid for fully developed, steady state and incompressible flow:

$$h_L = \frac{fL}{D}\frac{V^2}{2g} \tag{3}$$

compared to Poiseuille equation, equation (3) also relates fluid friction to pipe material, which is represented by f, a non-dimensional parameter called friction factor. Weisbach presented the relationship for friction factor as:

$$f = \alpha + \frac{\beta}{\sqrt{V}} \tag{4}$$

where α and β are friction coefficients obtained from experiments. Equation (4) gives an empirical way to calculate f, which is a complex parameter related to properties of both pipe and fluid. The effects of pipe roughness, diameter and flow velocity, viscosity on the friction factor was inferred by Weisbach but not taken into too much importance at that time. During the next decade, the definition and quantification of f had been a tough topic to investigate.

At the same time in Franch, instead of Weisbach's equation, another relationship that was widely used to find head loss is the Prony equation:

$$h_L = \frac{L}{D}(aV + bV^2) \tag{5}$$

where a and b are empirical coefficients from Prony's experiments, which were believed as independency from pipe roughness. Without electronic calculators, equation (5) was more convenient with less computation process (Brown 2003).

2.2 Frictional loss based on Darcy-Weisbach equation

Friction factor for smooth pipes

Almost at the same period when equation (3) was publsihed, it showed in various hydraulic experiments that there is a distinction of flow between pipes with very small and large diameters. Osborne Reynolds described this two phenomena as "steady direct" and "sinuous or eddying" with a parameter **Re**:

$$Re = \frac{VD}{\nu} \tag{6}$$

Where ν is the kinematic viscosity of fluid and **Re** is what we use as Reynolds number (Reynolds 1883). This parameter is of great importance for experimenters later to establish the quantative relationship for friction factor f (Eckert 2021). From 1911 to 1914, researcher Heinrich Blasius presented the functional dependence of the frictional factor f on the **Re**, combined with Darcy-Wisbach equation (equation (3)) and equation (6), he quantified the friction factor f for laminar flow with equation:

$$f = \frac{64}{Re} \tag{7}$$

the exact information of who and when the equation (7) was proposed are not sure, around early years of the 20th century. And in 1904 Ludwig Prantdl put forward the concept of boundary layer or frictional layer (Prandtl 1904). He puzzled to explain why the flow separated from the wall when transferring between tubes with varying diameters. Prandtl spent 3 years to come up with a qualitative solution of velocity profiles that matches the situation. Even without the mathematical details of the concept, this Boundary layer theory still solved many engineering problems related to the question why a flow near a solid surface detaches in stead of flows along the wall, and was applied to investigate drag force of airship models in the wind tunnel (Eckert 2021). In the later investigation process, Prandtl found that the boundary layer is applicable to both laminar and turbulent flow and presented in 1914 (Bodenschatz and Eckert 2011).

With the emergence of boundary layer theory, the contemporary hydraulic scholars conducted a series experiments trying to find a function for the friction factor f that valid for a wide range of flow conditions. Blasius then proposed one for smooth pipes by combining Theodor von K$\acute{a}$rm$\acute{a}$n's similarity theory with Darcy-Weisbach equation:

$$f = \frac{0.3164}{Re^{1/4}} \tag{8}$$

for values of **Re** varying between 4000 and 80,000, equation (8) is commonly applied now and called Blasius formula. However, equation (8) is out of validity for Reynolds number that larger than 80,000 (Brown 2003). Johann Nirkuadse did exhaustive observations of flow in different types of pipes and proposed a ”universal” friction law:

$$\frac{1}{\sqrt{f}} = A + B * log(Re\sqrt{f}) \tag{9}$$

where *A* and *B* are empirical constants Equation, (Nikuradze 1932). Prandtl and von K$\acute{a}$rm$\acute{a}$n both engaged to summarize a more precise version of equation (9), Hunter Rouse summarized their achievements and published the elaborated equation, which is now called Prantdl-von-K$\acute{a}$rm$\acute{a}$n's equation:

$$\frac{1}{\sqrt{f}} = 2log(Re\sqrt{f}) - 0.08 \tag{10}$$

for the whole range of turbulent flow in smooth pipes, equation (10) gives better fitting and is commonly used (Brown 2003).

Friction factor for rough pipes

The difference between smooth and rough pipes and its effect on friction losses have not been exhausted until now. The investigation of relationship between surface roughness and boundary flow was of practical interest in 70s-80s of last century. Counehan and Cook used different shapes of blocks generating various roughness parameters to observe how this affects boundary flow layer in wind tunnel(Counehan 1971; N. Cook 1978). Perry et al. conducted experiments with two kinds of wall roughness to observe pipe flow behaviour (Perry, Schofield, and Joubert 1969).

When publishing equation (8) and confirming its validity for the turbulent flow in smooth pipes, Blasius also discussed the situation of rough pipes. He brought in the parameter ε, which he described as the height of the bumps attaching to the pipe inner surface. Blasius assumed the ratio of ε and pipe diameter *D* together with Reynolds number could be relevant to the friction factor in rough pipes. But he doubted the existence of the precise formula among these parameters (Blasius 1913). In 1914, Richard von Mises first came up with the term of relative roughness, which is the parameter ε/D Blasius referred (Mises 1914). With the concept of relative roughness, von K$\acute{a}$rm$\acute{a}$n developed that the friction factor is a function of relative roughness of rough pipes (Kárman 1930):

$$\frac{1}{\sqrt{f}} = 1.14 - 2\,log(\frac{\varepsilon}{D}) \tag{11}$$

Equation (11) was verified later by Nirkuradse's experiments (Nikuradse 1933). The observation of pipe flow carried out by Colebrook and Nikuradse, and from which the empirical pipe flow models they derived are of great importance for better understanding of transition region between the smooth and rough pipe laws. According to Nikuradse's results, friction factor is independent from roughness in both laminar and laminar-to-turbulent transition region (Nikuradse 1933).But Colebrook and White stated the complexity of that in the transition region where fluid viscosity and pipe roughness both effect the friction. They presented the rewritten equations and plotted curves for flow in pipes with uneven roughness, which shows a difference from the ones for smooth pipes, and the type of roughness plays an important role.(Cyril F Colebrook and White 1937). Colebrook presented an equation:

$$\frac{1}{\sqrt{f}} = 1.14 - 2\,log(\frac{\varepsilon}{D} + \frac{9.35}{Re\sqrt{f}}) \tag{12}$$

Equation (12) is specifically applied in the transition zone between laminar and turbulent flow for commercial pipes (Cyril Frank Colebrook et al. 1939).

Moody diagram and Rouse diagram

Hunter Rouse pointed that these equations are too complex for the practical application, He tended to summarize all the information including functions and their validity conditions into diagrams or tables (Rouse 1943). Rouse then plotted a diagram shown in figure 1 below, where equations (7), (10), (11) and (12) are collected into the same system, in which the primary horizontal axis and vertical axis show $\mathbf{Re}\sqrt{f}$ in logarithmic form, and $\frac{1}{\sqrt{f}}$ respectively. Lewis Moody then redrew and produced another diagram (figure 2) based on study results from Colebrook and Rouse for convenience of engineering application. It could give the value of friction factor f and head loss h_L with known of flowrate Q and pipe diameter D.

2.3 Boundary layer thickness in pipe flow

The friction force between water and pipe wall generates shear stress along the boundary, which is defined by the equation:

$$\tau_o = \frac{\rho g R_h h_L}{L} \tag{13}$$

where τ_o is the shear stress, R_h is the hydraulic radius of the pipe, L is the pipe length.

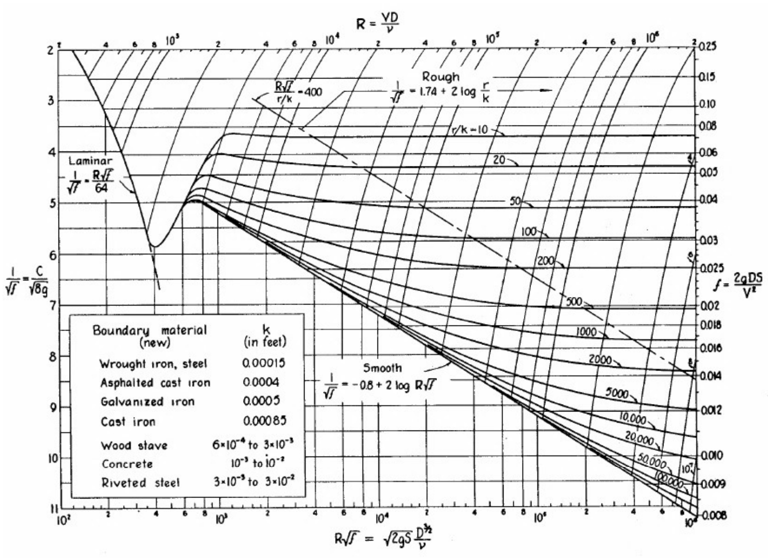


Figure 1: Rouse diagram (Rouse 1943; Ettema 2006)

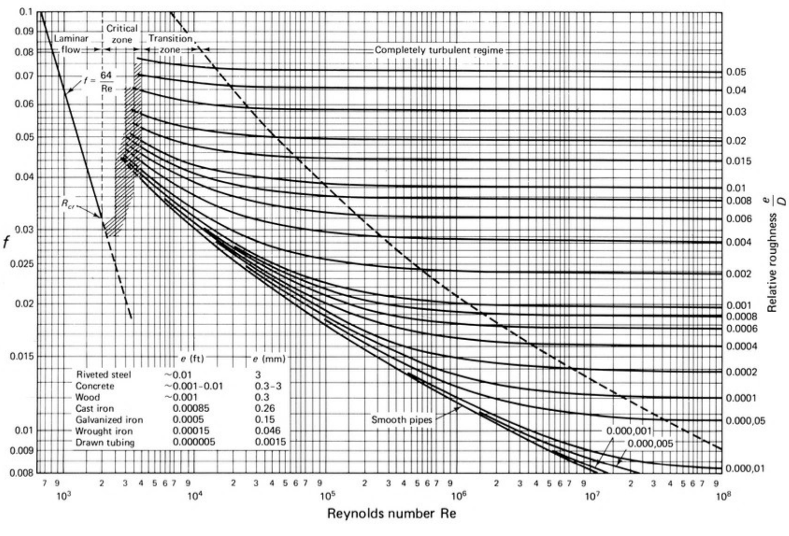


Figure 2: Moody's diagram (Moody 1944; Ferro 2012)

For the pressurized water flow in a circular pipe, R_h in equation (13) equals to $D/4$, where D is the pipe diameter. Combining the Darcy-Weisbach equation (equation (3)) with equation (13) above, the shear stress in a circular full pipe is expressed as:

$$\tau_o = \frac{f \rho V^2}{8} \quad (14)$$

where relates the shear stress τ_o and friction factor f together. And $\sqrt{\frac{\tau_o}{\rho}}$ generated from equation (14) is defined as shear velocity, ν_*, which is determined by the friction factor and the mean velocity:

$$\nu_* = \sqrt{\frac{\tau_o}{\rho}} = V\sqrt{\frac{f}{8}} \tag{15}$$

equation (15) is of practical use in terms of its adaption on flow regime and boundary condition.

Velocity profile

For laminar pipe flow, the velocity profile near the pipe wall could be assumed as a linear function and expressed in a dimensionless form:

$$\frac{\nu}{\nu_*} = \frac{\nu_* y}{R} \tag{16}$$

The velocity profile expression of turbulent flow was generated from Nikuradse's experiments in 1933, he characterized an equation applicable for either smooth or rough pipes:

$$\frac{\nu_c - \nu}{\nu_*} = -2.5ln(\frac{y}{R}) \tag{17}$$

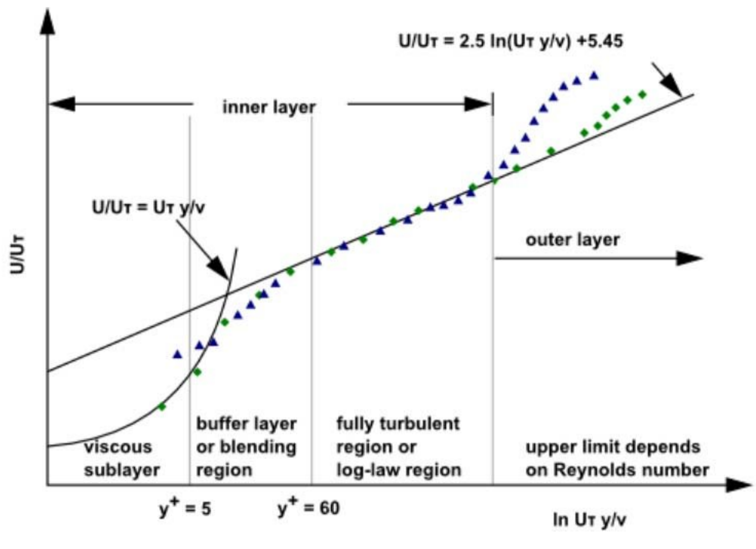


Figure 3: The velocity profile of near-wall region (Králik 2016)

In equation (16) and equation (17), ν is the water velocity along y direction, ν_* is the shear velocity and ν_c is the velocity at the centerline of the velocity profile. According to the velocity distribution along a smooth wall, see in figure 3 at the intersection point from the laminar to turbulent region, the boundary layer thickness is:

$$\delta_\nu = 11.6 \frac{\nu}{\nu_*} \tag{18}$$

3 Pipe flow at microscale

3.1 Micro-channel flow

The fluid flow in microscopic scale has brought into interests since late 80s. Several relevant experimental studies have been conducted to verify the validity of continuum theory and search for any possible existing but unidentified fluid-wall mechanisms from microscopic view. When it comes to the micro-scale, so far different studies showed different results. Early studies observed lower friction factor while later researchers observe friction factor higher in comparison with what has been predicted by conventional theory. Majority of the studies find friction factor in agreement with what the existing theories predict. However, despite all contradiction in results most of the researchers individually acknowledged that diameter of the micro-tubes plays an important role in micro-scale flow characteristics.

Mala and Li (1999) conducted investigation on the flow through micro-tubes with diameter between 50 to 254 μm. It has been done on Fused silica and stainless steel micro-tubes . Observation showed in bigger diameter the flow characteristic is in agreement with conventional theories. However, as the Reynolds number increases deviations occur and increase as the pipe diameter decrease. Friction factor obtained higher than calculated friction factor based on convectional theories, and early transition has been observed (Mala and D. Li 1999).

Brutin et al. (2003) measured friction in circular micro-tubes of Fused silica with a few hundred μm diameter and water as fluid. They performed the experiment at Reynolds number between 10 and 1000. Their result showed in laminar flow within the diameter they studied the microtube characteristics are in a good agreement with conventional theories (Brutin, Topin, and Tadrist 2003). Meanwhile, Li (2003) also invested on experimenting with micro-tubes with water fluid. Three different pipe materials glass, silicon, and stainless steel with respective diameter of 79.9-166.3, 100.25-205.3, and 128.76-179.8 μm had been tested in the study. Li found out the value of f*Re in glass and silicon that can be classified as smooth, is about 64 just like in macro-scale pipes, but when it comes to stainless steel with relative roughness of 3%-4%, the $f * Re$ value is noticeably higher than expected by the theory (Z. X. Li 2003).

The experimental result of Sharp and Adrian (2004), on flow behavior in glass microtubes with diameter between 50-247 μm was in a good agreement with macro-scale. No evidence for early transition has been recorded, and the value obtained for f*Re was 64 as for it was expected from convectional theory (Sharp and Adrian 2004). The similar result was also obtained by Hao et al. (2007), they also studied glass microtubes, and the diameter was 230micro meter using micro particle image velocimetry (micro-PIV), and the result from this method also confirmed the similarity in flow behavior in micro and macro scale (Hao et al. 2007).

At the same year result from Yang and Lin (2007), showed there is no evidence of significant tube diameter effect on flow characteristics in micro-tubes with diameter between 123 to 962 μm. However, their observation showed an increase between predicted value and test results as the diameter decrease (Yang and Lin 2007).

Investigation on Nitrogen flow in micro-tubes between 27 and 508 μm showed a good agreement between laminar regime and conventional theory for diameter bigger than 100 micrometers in both rough and smooth micro-tubes in terms of friction factor, and no evidence of early transition has been observed. However, when diameter goes under 100 micrometers with Reynolds number less than 1300 the deviation from conventional theories increases. It has also been observed that in turbulent regime friction factor depends less than expected on Reynolds number and more on relative roughness (Lorenzini, Morini, and Salvigni 2008).

Ghajar et al. (2010) studied flow characteristics on stainless-steel mini and microtubes with diameter from 2,083 to 337 micrometers. The outcome of the study with a high accuracy in the sense of uncertainties showed decrease in diameter and increase in relative roughness have noticeable impact on friction factor this statement has seen to be true even in laminar region. Furthermore, it has been observed increasing relative roughness and decreasing diameter result in early transition (Ghajar, C. C. Tang, and W. L. Cook 2010).

It is important to know how the flow characteristics get affected by the wall. This can be seen by studying the flow behavior in the micro-tubes. In micro-tubes the main flow is closer to the wall therefore the characteristics are affected by this fact, and as the diameter decrease the effect on the characteristics get stronger. One of the characteristics that is important for this study is friction coefficient that can also get effected by the diameter since decrease in diameter effect relative roughness. Relative roughness will directly affect friction coefficient. So, in the following there is a literature review on the studies that had been done on the relationship of flow characteristics specifically friction coefficient and diameter of micro-tubes.

In the current study micro-scale and macro-scale approaches about friction coefficient come together as the goal is to find the frictional loss due to the surface topography in macro-scale (pipes). The bulk in the pipes is free from the effects of the solid while in the micro-tubes the bulk is still under the wall influence. In a molecular approach the water molecule can move from the boundary layer and distances close to the wall to bulk. It means it is moving from the part of the flow that is effected a lot by the surface to the bulk that is free of the surface effects. Therefore, it is expected to have the similar flow characteristics with micro-tubes when the molecules are near to the surface while having different characteristics as they move to the bulk. So a water molecule can experience different characteristics similar to both flow in micro-tubes and pipes while moving from point A to point B along the pipe depends on the distance it has from the surface.

3.2 Microscopy imaging technique

To more accurately understanding surface roughness, micro-electronic devices are applied to study the multi-scale morphology of the surface roughness structure. The surface roughness meters are movable instruments specifically designed for examining the values of some roughness criteria. Hamlaoui et.al (2017) were using a roughness meter called Surftest 201 Mitutoyo to study the roughness of polyethylene pipe materials (Hamlaoui et al. 2017). Ghabeche et.al (2019) compared the inner surface roughness of polyethylene pipe before and after the exposure to toluene methanol mixture with application of scanning electronic microscope (SEM) (Ghabeche, Chaoui, and Zeghib 2019). Also the atomic force microscopy (AFM) and X-ray scattering are verified to be accurate and thorough techniques to measure the 3D spatial parameters of roughness (Arnault et al. 2001). According to experimental results from Arnault (2001), even very smooth surface with a roughness height smaller than 5 micrometers could be well described with AFM and X-ray diffuse scattering system.

3.3 Hydrogen-bonds between water molecules and surfaces

3.3.1 Hydrogen bond

The Hydrogen bond among water molecules can be defined as the electrostatic force of attraction between the oxygen atom from one water molecule and the hydrogen atom from another water molecule (Arunan et al. 2011). The spatial patterns and mechanism of breaking and forming of the hydrogen bonds in the liquid water determines the specific of water properties (Liu et al. 2018; Luzar and Chandler 1996). When it comes to micro-scale pipes with water as fluid, there should be a kind of mechanism of interaction between water molecules and pipe surface which results in the energy loss. It is possible that a type of hydrogen-bond structure exists like the form of O-H...S (S means pipe inner surface), of which the breaking and forming generates friction loss. In metal pipes, former studies observed that this form of hydrogen bonds are uncommon compared with bonding between oxygen atom of water molecules and metal atom of surfaces (Thiel and Madey 1987).

Previously it has been discussed in micro scale surfaces the attracting between fluid molecules and the pipe wall plays big roll in frictional loss. Surfaces can be considered as hydrophobic and hydrophilic, these surfaces simply act different when it comes to molecular attraction that leads to different energy loss. The different materials used for this study are all hydrophobic material. Therefore, here we review hydrophobic surfaces, and their characteristics.

3.3.2 Hydrophobic surfaces

Hydrophobic surfaces are inspired by natural structures like lotus leafs, and they are known for their low adhesion and friction. The effect they have on the slip velocity and drag reduction make them an interesting surface for many industrial purposes.

A hydrophobic surface can be obtained by creating two properties in the surface. Low surface energy and high roughness. Providing both of these characteristics is necessary in order to reach the maximum capacity of hydrophobicity (Miwa et al. 2000). Adhesion energy between liquid and the solid surface is a function of the area that liquid and solid are in contact. Analysing the force balance in a drop on a hydrophobic surface and the angle it starts to move result in adhesion energy having a constant value per unit area, and the volume of the liquid does not make a difference in that value (Y. H. Kim, K. Kim, and Jeong 2016).

Furthermore, a hydrophobic surface affect the number of hydrogen bond between water molecules in the vicinity of the surface in comparison to the bulk, and the number of hydrogen bonds between hydrophobic surfaces and water molecules is not big enough to be taken under consideration (Y. Tang et al. 2018).

3.3.3 Hydrophilic surfaces

Although the nature of the material we investigated in is hydrophobic, and the interactions between water molecules and the polymeric surface can be regarded as hydrophobic interaction, but due to formation of a thin layer of bio film by bacteria attached to the pipe wall after the system operates for several days it, the studied surfaces will get coated with a few microns thick polysaccharide. This also changes the interaction from a hydrophobic interaction into a hydrophilic interaction where hydrogen bonds are very important for the layering.

Therefore, the interaction of first water molecule layer with the pipe surface in the case of a pipe in use can be assumed as mainly hydrogen bond.

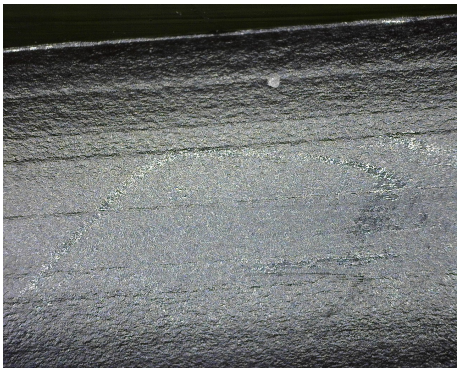
4 Dino-lite digital microscope——a failed trial

In order to capture the roughness topography we tried different methods. First attempted was with a microscope named Dino-lite, see in figure 4. It is a handheld USB microscope with magnification of 200x. There were two main reasons to choose this device. First, using this microscope was giving us possibility to scan all the surface and avoid cutting it into small pieces, therefore curves from the cutting process would not affect the result. Second, it was easy to scan a big surface fast and decide if the pipe wall structure is homogeneous enough to interpolate the result to the whole surface or not. Although the method failed in the end but the observations by around 50x magnification showed a surface that may assumed to be homogeneous.

Figure 4: Dino-Lite digital microscope

Although the perspective of the result looked good but in practice Dino-lite microscope was not useful for the purpose of the project. the highest magnification for these materials with a sharp and clear image was only about 50x, see in figure 5 (a). More attempts could only give a vague view, like what figure 5 (b) presents. It was also not feasible to capture the cross section of the pipe as it is a handheld microscope, and we did not have a stand set the microscope and sample on to avoid displacement. In addition, the instrument has a LED point light source equipped itself, which makes the edges of the images to show different pattern from the centering area, see in figure 5 (c). The light effect caused the image results confusing. Besides it was inconvenient to process the pictures, there is no relevant applications or software that can provide a reliable and measurable numerical analysis.

(a) PE pipe (D110 mm) 48x (b) PE pipe (D110 mm) 100x



(c) PE pipe (D16 mm) 50x

Figure 5: Images captured by Dino-lite

5 Scanning electron microscope (SEM)

Three pipe segments were collected and treated to be observed by the scanning electron microscope (SEM). Qgis and MountainsSEM® Premium were applied to analyze the microscopy images captured by SEM to get the pipe inner surface roughness surface profile and the 3D model of the roughness pattern.

5.1 SEM analysis

The model number of the SEM instrument (figure 3) for pipe inner surface observation is JSM-6700F, which is equipped with a cold Field Emission Gun (FEG) and was operated at accelerating voltages of 10 kV.

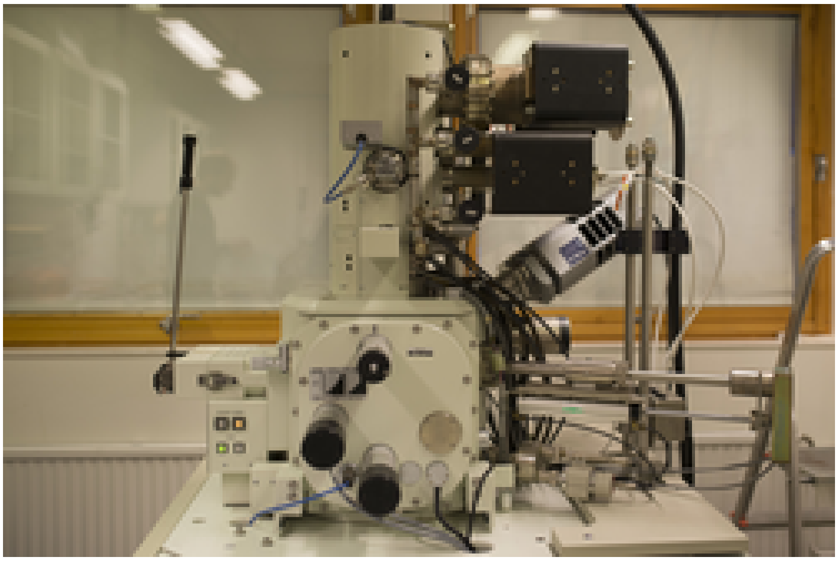


Figure 6: SEM instrument

Three pipe samples were collected and used for microscopic observation: (a) used wastewater polyvinyl chloride (PVC) pipe with diameter of 110 mm, (b) new polyethylene (PE) pipe with diameter of 110 mm, and (c) new polyethylene (PE) pipe with diameter of 16 mm. The pipe segments were cut into pieces with surface dimension of $8 * 8\ mm^2$ square to fit in the SEM instruments, see in figure 4.

The plan view on the surfaces could help figure out the patterns and profile of the roughness, but the exact values of the bumps are unclear, which is also a weakness point of the SEM analysis on surface roughness. In order to get better estimation of the pipe wall roughness, each sample was observed from two different angles (the ones give clearest and sharpest images) with the SEM instrument, see in table 1. The images captured from two angels could help build a 3D model of the roughness profile.

Table 1: The parameters of SEM instruments observation on samples

Sample No.	Material	Diameter	Magnification	Angle
(a)	PVC	110 mm	140x	0 deg/22 deg
(b)	PE	110 mm	25x	0 deg/45 deg
(c)	PE	16 mm	25x	0 deg/45 deg

5.2 3D reconstruction from SEM images by MountainsSEM

MountainsSEM® Premium was applied to build a measurable 3-Dimensional model from two scanning electron microscope images. The software is able to conduct the stereoscopic reconstruction from the loaded SEM images taken from two different angels under the same magnification. Once the tilted angle and direction is settled, MountainsSEM® Premium can automatically detect between the images to finish the reconstruction. The generated 3D models are available to be carried out measurements including distances, angles, volumes and step heights on the surface along each direction.

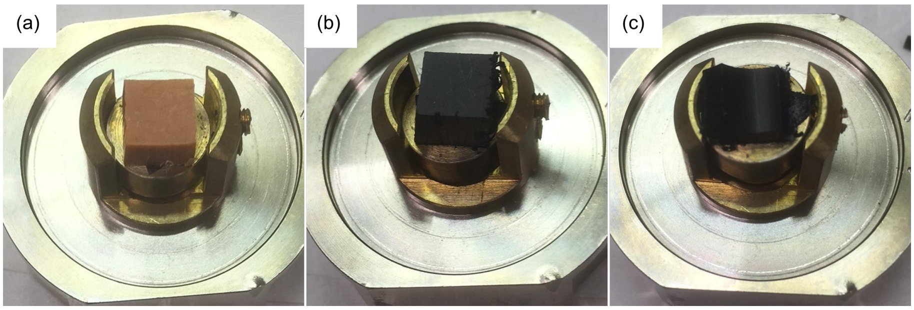
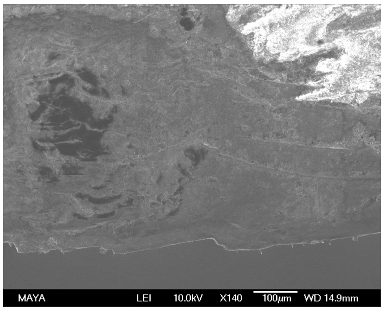


Figure 7: Pipe samples in the holder of SEM instrument

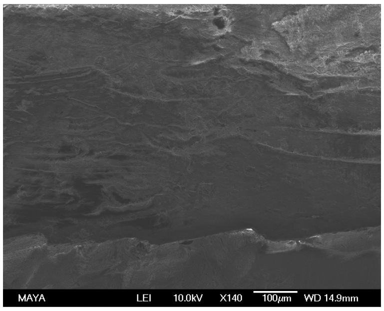
6 Results

6.1 Pipe wall roughness profile.

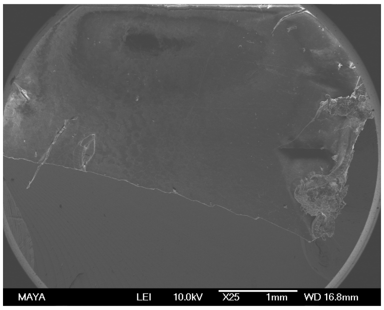
Images from SEM analysis and their dimensions are presented in figure 8. The PVC pipe sample images was captured under 140x magnification, involving the pipe surface area of $861.1 \times 688.8\ \mu m^2$. While PE pipe samples has a magnification of 25x and the size of around $4.8 \times 3.8\ mm^2$ of the sample surface.



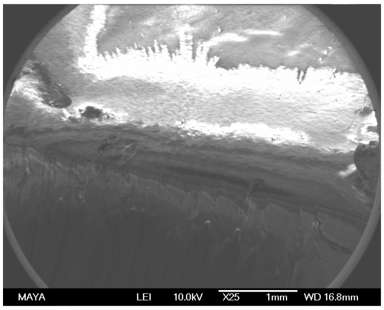
(a) PVC (D110 mm) 140x 0deg



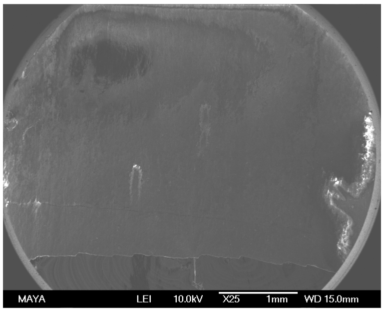
(b) PVC (D110 mm) 140x 22deg



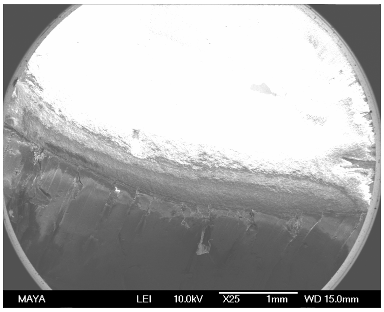
(c) PE (D110 mm) 25x 0deg



(d) PE (D110 mm) 25x 45deg



(e) PE (D16 mm) 25x 0deg



(f) PE (D16 mm) 25x 45deg

Figure 8: SEM Images

6.2 Qualitative roughness profile generated by Qgis

QGIS software was used to get an overview of the surface texture. First the SEM images in figure 8 were inserted in QGIS, then the symbology of layers were changed in layer properties from singleband gray to hilshade and Z factor was increased to 10 under band rendering. Afterwards by using a tool called ”terrain profile”, the elevation profile along the pipe would be created, see in figure 9. However, the vertical axis in figure 9 could not give any numerical meaning of the roughness height because they are just pixel values of the horizontal surface information. But still it indicates clearly that the used PVC pipe is much more rougher than the new pipes, which is an expected result. We were unable to find a solution for setting a correct size scale for the Y dimension.

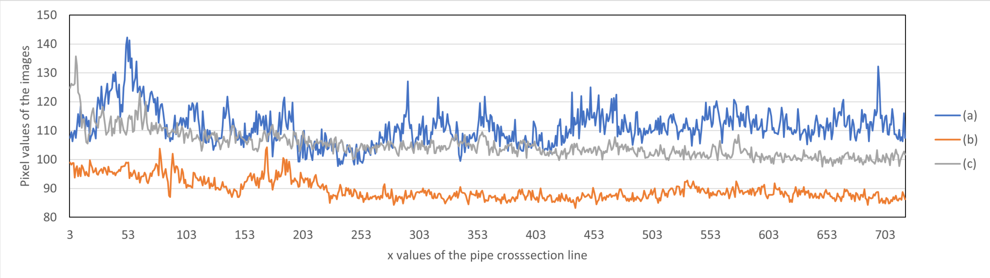


Figure 9: Pipe wall roughness profile analyzed by Qgis

6.3 3D profile models built by MountainsSEM

Loading the image pairs shown in figure 8 into MoiuntainsSEM gives results of the 3D roughness profile. In the original SEM images, due to the location variance of the sample edges when the observation angle changes,the valid surface area for 3D reconstruction is different from the image size. The image size used for stereoscopic reconstruction and the generated roughness 3D model are shown in figure 10 and figure 11 respectively.

The left-side images symbolize the area used for stereoscopic reconstruction, which are similar among the three samples. But as the magnification factor (25x) of sample (b) and (c) are much smaller than that (140x) of sample (a). The proportion of the 3D-building area of sample (b) and (c) are minuscule, which are also seen in table 2. The color scale of images on the left side in figure 10 takes the lowest elevation on the surface as the platform, marked their elevation as 0. So the highest roughness height e_max of the three pipe segment samples are 406.2 μm, 343 μm and 315.4 μm respectively, which are also presented in table 2. On the right side in figure 10 the corresponding roughness distribution histogram of each sample are indicated. Histograms are sensitive to the data limitation and occasionally occurs of the extreme values. The roughness height histogram of the PVC pipe sample demonstrates the right-skewed distribution, which is not symmetrical, because the data limits restrain the outcomes on the right side. This means that there is a large number of occurrences in the lower roughness values (deep scratches) and few in high values (peaks). Therefore the real mode of the roughness height should be higher than 140 μm that is shown in figure 10 (a) and table 2. Also the histograms in 10 (b) and (c) also have similar skewed distribution but not that typical, probably because of the very limited surface area used for stereoscopic model reconstruction.

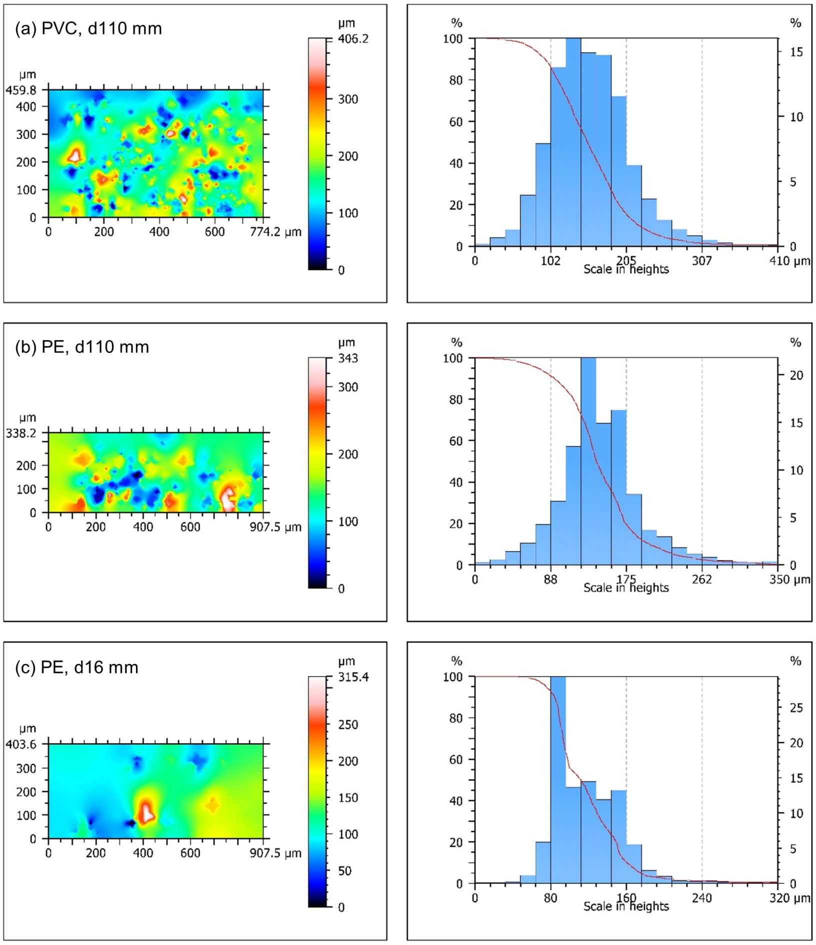


Figure 10: The plan view of the 3D roughness model (left) and the corresponding histogram of roughness distribution (right)

In figure 11 the color scale demonstrates the elevation values on the z-axis, which is the surface roughness. The mean roughness is defined as 0, shown as green color in the palette. The elevation profile that is lower than the mean roughness height are seen as valleys, the others are roughness peaks. It is clear that the roughness profile of the used PVC pipe in figure 11(a) is the most rugged with high appearance frequency of peaks and valleys. While the PE pipes are rather smoother with more green areas in the 3D model, because they are new without the scouring or corrosion made by water and other particles.

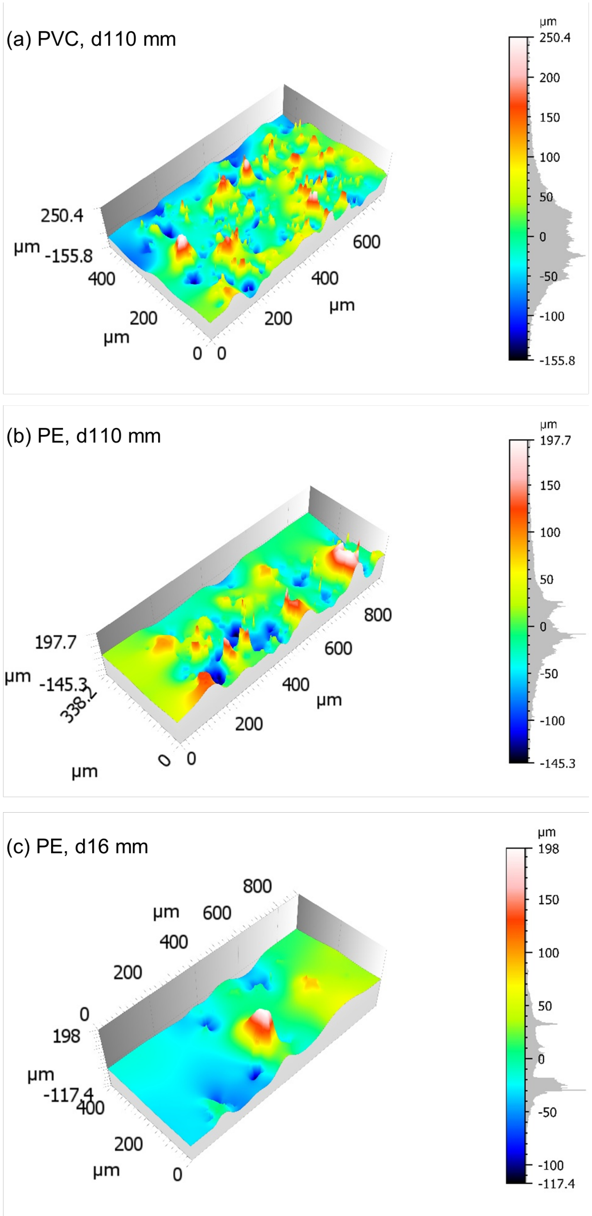


Figure 11: 3-Dimensional model of the pipe inner surface segments

Four roughness parameters were obtained from the stereoscopic profile model, which are

- R_p: maximum peak height above the mean profile;
- R_v: maximum valley depth below the mean profile;
- R_t: the distance between the highest and the lowest elevation on the surface;
- R_f: roughness height occurring with highest frequency.

These parameters are commonly used to estimate the surface roughness condition (Taylor, Carrano, and Kandlikar 2006; Gadelmawla et al. 2002). R_t is easily affected by the highest bump or the scratches, therefore this parameter loses validity on sample (a) which is a piece of used wastewater pipe with scratches made by the impurities such as screes in the rapid flow. R_f is sensitive to quantity of the roughness, the larger area of the observed surfaces will make the parameter more reliable.

Table 2: Projected area of the 3D model and roughness parameters

Sample No.	Projected area for 3D reconstruction		Roughness Parameters [μm]			
	area [mm^2]	proportion of the sample area	R_p	R_v	R_t	R_f
(a)	0.36	59.67%	250.4	155.8	406.2	142.2
(b)	0.31	1.68%	197.7	145.3	343.0	132.9
(c)	0.37	2.01%	198.0	117.4	315.4	123.4

It is shown in table 2 that the roughness parameters show similarities between two PE pipe samples, in comparison, the polyvinyl chloride material seems rougher. However this result is undependable because the PVC pipe was used and the projected area for the 3D profile model reconstruction of the PE pipes are extremely small with respect to the sample size. As the data limits and lack of the control group for comparison, the quantitative results from the MountainsSEM analysis for sample (b) and (c) are not convincing enough.

6.4 Friction factor

Assuming a normal pipe flow velocity of 1 m/s in turbulent condition, and R_f in table 2 as the roughness height e, the friction factor of the three pipe samples for laminar and turbulent flow condition were calculated by Darcy-Weisbach equation and Moody diagram, which are presented in table 3. The corresponding head loss h_L in 100-meter long pipe were also computed.

Table 3: Friction factor computation of the pipe samples

sample	D, m	e, mm	Re	turbulent flow		
				e/D	f	h_L, m
(a)	0.11	0.142	1.10E+05	0.00129	0.0210	0.974
(b)	0.11	0.132	1.10E+05	0.00120	0.0206	0.955
(c)	0.016	0.123	1.60E+04	0.00769	0.0340	10.842

The results in table 3 indicated that friction factor of sample (c) is larger than others. And for the same pipe material, pipe of smaller diameter means higher relative roughness e/D, which will affect the head loss dramatically, around 10 times larger in this case.

7 Discussion

7.1 Possible relations between pipe wall roughness and microscopic sub-layer flow

The maximum peak obtained from SEM pictures for sample a, b and c are 406.2, 343.0, and 315.4 μm respectively. Knowing a water molecule diameter is 1 Å=0.0001 μm the following information can be extract.

The result from analysing these pictures with MountainsSEM shows the highest peak in the roughness topography in sample a,b and c is what mentioned above this values should be higher as what the histograms of the roughness frequency analysis showed, and lacking of enough data because of the relatively too small pipe inner surface area and few amounts of pipe samples for SEM study.

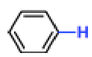
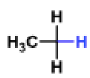
Based on these analysis we can calculate the number of the extra water molecules in the pipe in comparison with the perfectly smooth pipe without any peak or valley. These molecules can fit in the distance between peak to valley result in extra hydrogen bond therefore extra friction loss. The mean energy of hydrogen bond between two water molecule is estimated to be 20.8 KJ/mole (Wendler et al. 2010). The number of water molecules in the maximum height of each sample and the energy between their bond is presented in the table 4 below:

Table 4: The number of water layers fitting into the roughness and corresponding energy (Valdés, Rufino-Felipe, and Morales-Morales 2019)

Sample number	Number of water layer	Number of moles	Estimated hydrogen bond energy (kJ)
a	4,062,000	$6.75 * 10L - 18$	$1.4 * 10L - 16$
b	3,430,000	$5.69 * 10L - 18$	$1.18 * 10L - 16$
c	3,154,000	$5.24 * 10L - 18$	$1.089 * 10L - 16$

Another extra reason for hydrogen bond and following by that energy loss is the extra surface area available for the water molecule to be in contact with. Previously, it has been discussed the bonding of water molecules with the solid area can be assumed to be hydrogen bond from the type of C-O. Based on the maximum height of the peaks in the surface and the number of water molecules fit there is the same number as showed in table 4. But the C-H bond is much stronger than O-H. C-H dissociation bond energy differs between 410 and 550 KJ/mole based on the type of bond structure (Valdés, Rufino-Felipe, and Morales-Morales 2019). It means the energy between molecules and surface is around 24 times bigger than water molecules among themselves.

Figure 12: C-H bond structures and contained energy

Type of C–H	C(sp)	C(sp^2)	C(sp^3)
structure	≡C–H		
BDE (kJ/mol)	552.2	473.0	410.8
pKa	~25	43	~50

As the calculation shows almost 3 to 4 million extra water layers making both C-O and O-H hydrogen bond can be form in the area we studied. Based on Wendler's study, the energy of the H-O hydrogen bond is estimated 20.8 KJ/mole and the energy of C-H hydrogen bond is almost similar. however to calculate the average energy caused by hydrogen bond in the pipes per unit area it is needed to have an analyse of the volume between to neighbour peak to be able o calculate the number of water molecules in that volume. This number can be extrapolate to the whole pipe as the pipe surface considered to be homogeneous (Wendler et al. 2010).

This number is also a function of temperature as the energy between the bonds is depended on the distance between molecules and the average number of hydrogen bonds a single molecule can form. High temperature increases the length of the bond and reduce the number of the bonds. Hence, the values in the table might be less or more based on temperature. Therefore, in molecular approach discission about frictional energy loss climate factor must be taken under consideration.

7.2 Discussion for further study

The result from SEM showed the plastic material under the study can be count as smooth as the peaks height are in the rage of 300 to 400 μm . Considering a water molecule 1Å , 3,000,000 to 4,000,000 layer of water can be fit in this height.

As it has been discussed in the literature review the result from studying flow characteristics in micro tubes seems to be different in terms of friction coefficient. The reason for it can be the big impact of the walls on the bulk in micro tubes, still in macro-scale approach even when we are studying the surface in micro-scale we still have to keep in mind that Darcy-Weisbach works well in macro-scale.

Darcy-Weisbach equation is directly affected by kinematic viscosity, which varies with temperature. Kinematic viscosity itself represents the impact of temperature on interaction between fluid molecule. Therefore, Darcy-weisbach equation can be considered as a simplification of the complected bonding between water molecules and neighboring molecules in different temperature that contain hidden energy that can be converted to heat and affect the bonds again, which is a source of energy loss. However, using Dircy- weisbach equation consider as a good way for designing pipe systems so far because, it cover energy loss caused by molecules interaction by using kinematic viscosity, and it is true and trustable in practice.

It rises the question of the accuracy of this method. Darcy-weisbach might over estimate the energy loss in order to give us a trustful answer, or the movement of water molecules including rotation and vibration actually leads to that much energy loss. For assessing the accuracy of the available methods for designing, further study is needed to find the connection between kinematic viscosity from a micro scale point of view, and friction coefficient. If there is any relation then we can judge if we have been over estimating the energy loss or no. In case we were doing so then by knowing the behavior of water under different temperatures and its effects of friction coefficient then we can have a more accurate energy lost estimation. Through this it is possible to prevent pumping water with extra energy that may not be needed.

Since the behavior of the water in liquid form is still under study, the next potential step can be marking and observing water molecules, their movement and bonds they make when flowing in the pipe under different temperature, velocity and pressures to be able to judge better about the energy loss we can calculate with the commonly used methods.

7.3 Uncertainties

7.3.1 Technique Limitation

SEM:
Unfortunately SEM method in our study run in to several limitations. SEM generally looks at a surface, but is not very sensitive to roughness (height change) on that surface. So observations were done at 45 degrees tilt (within the tilt range of the holder) or 90 degrees tilt (by remounting the sample). There is also charging, leading to white patches or distortions. Other SEMs are now available that have thin atmospheres to eliminate charging but the instrument (JSM-6700F) used in this project is not capable to do that. The option of coating with a 5nm metal film is also not really possible on a three dimensional object. If trying to go to smaller voltage (1 kV instead of 10 kV), it will be hard for large objects as it needs a smaller working distance and the plastic pieces might hit the polepiece. Instead of SEM, atomic force microscopy (AFM) will be more suitable technique for roughness analysis, which scans sample surface with a probe without direct contact and has no strict limitation on sample size (the sample size requirement of 8*8 mm surface for SEM analysis is too small compared with the pipe in reality).

MoutainsSEM:
The stereoscopic construction from two SEM images of different tilting angels is an undisputed function of the Mountains software. However, there are also several restrictions existing. The 3D synthesis can only deal with images with vertical or horizontal tilting, other oblique angels are unprocurable, which requires higher accuracy of manual operation on the SEM instrument. The SEM images of sample (b) and (c) are not vertically tilted, with around 5-7 degrees variance, which would result in deviation error for certainty. In addition, although the generated 3D model is measurable and could produce images, profile charts, histograms and so on, there is not a eat to extract the data. In this study, all the elevation data of the profile was expected to be derived as text or excel for further mathematical analysis, but the software does not provide any function to achieve the expectation.

7.3.2 Reliability of the roughness height values

The uncertainties mentioned above also result in the unreliability of the roughness analysis results. In the results of Hamlaoui et al. (2017), the roughness peaks and valleys of PE pipe measured by roughness meter were between 4.33 and 11.21 μm. Another roughness measurements of high-density polyethylene (HDPE) pipe material also applied SEM analysis by Ghabeche et al. (2019), their results showed roughness peaks of the pipe inner surface from 6 to 10 μm. In comparison, the roughness values obtained in this project are around 10 times higher. The huge variance could be the results of technique defect, and also the pipe material provided by different manufacturer with different production process could also make a difference.

8 Conclusions

1. With the same pipe material, smaller diameter results in larger relative roughness of the pipe wall, which could affect the friction factor and head loss dramatically.

2. Further study is needed to track the movements of a single water molecules, the way it moves between two point, and it bonds with neighboring molecules. There is a possibility that a water molecule would not simply travel between two points, due to the attraction between molecules and their strength. If that would be the case it may go back and forth, and bond with more molecules therefore, needs to break more bonds to move forward. The water molecules may also move perpendicularly or diagonally so it can move from the layers in boundary layer to the bulk flow and that can affect the energy. To verify these different movements and bonding a water molecule can have it is needed to take advantage of techniques that provide the opportunity to study the flow in the pipe at microscale, neutron scattering devices, for example.

3. Since temperature affect the bondings which has big influence on frictional loss, further investigation is needed to study the effect of temperature on frictional loss, and study the accuracy of Darcy-Weisbach equation. The climate issue should be taken into account when it comes to local pipeline design or related work.

4. In a perfectly smooth wall, we can consider the space between two walls are filled with water molecules. These molecules are making hydrogen bonds within themselves. Hydrogen bond between water molecules and wall also will form since the wall will be covered by a thin layer of bio film. From SEM images we can see the distance between peak to valley can have 3,000,000 and 4,000,000 water layer in PE and PVC pipe respectively that result in bigger number of hydrogen bonds from one wall to another.

Considering the energy of hydrogen bond between water molecules almost 20.8 KJ/mole. extra energy that is laying in one column of water molecule in the highest peaks of sample can be calculated easily. Besides, due to the solid liquid contact surface increase, the number of hydrogen bond between biofilm and water molecules from the type C-H increase as well. The energy of the C-H bond is almost 500 KJ/mole, so the energy loss in the column in contact to surface is about 24 times bigger than the rest of the columns.

References

Arnault, JC et al. (2001). “Roughness fractal approach of oxidised surfaces by AFM and diffuse X-ray reflectometry measurements”. In: *Applied surface science* 171.3-4, pp. 189–196.

Arunan, Elangannan et al. (2011). “Definition of the hydrogen bond (IUPAC Recommendations 2011)”. In: *Pure and applied chemistry* 83.8, pp. 1637–1641.

Blasius, Heinrich (1913). “Das Aehnlichkeitsgesetz bei Reibungsvorgängen in Flüssigkeiten”. In: *Mitteilungen über Forschungsarbeiten auf dem Gebiete des Ingenieurwesens*. springer, pp. 1–41.

Bodenschatz, Eberhard and Michael Eckert (2011). “Prandtl and the Göttingen school”. In: *A Voyage Through Turbulence*. Ed. by Peter A. Davidson et al. Cambridge University Press, pp. 40–100. DOI: 10.1017/CBO9781139018241.003.

Brown, Glenn O (2003). “The history of the Darcy-Weisbach equation for pipe flow resistance”. In: *Environmental and water resources history*, pp. 34–43.

Brutin, D, F Topin, and L Tadrist (2003). “Transient method for the liquid laminar flow friction factor in microtubes”. In: *AIChE journal* 49.11, pp. 2759–2767.

Colebrook, Cyril F and Curt M White (1937). “Experiments with fluid friction in roughened pipes”. In: *Proceedings of the royal society of london. Series A-Mathematical and Physical Sciences* 161.906, pp. 367–381.

Colebrook, Cyril Frank et al. (1939). “Correspondence. turbulent flow in pipes, with particular reference to the transition region between the smooth and rough pipe laws.(includes plates).” In: *Journal of the Institution of Civil engineers* 12.8, pp. 393–422.

Cook, NJ (1978). “Wind-tunnel simulation of the adiabatic atmospheric boundary layer by roughness, barrier and mixing-device methods”. In: *Journal of Wind Engineering and Industrial Aerodynamics* 3.2-3, pp. 157–176.

Counehan, J (1971). “Wind tunnel determination of the roughness length as a function of the fetch and the roughness density of three-dimensional roughness elements”. In: *Atmospheric Environment (1967)* 5.8, pp. 637–642.

Duttine, Antoine and Fumio Tatsuoka (2009). “Viscous properties of granular materials having different particle shapes in direct shear”. In: *Soils and foundations* 49.5, pp. 777–796.

Eckert, Michael (2021). “Pipe flow: a gateway to turbulence”. In: *Archive for History of Exact Sciences* 75.3, pp. 249–282.

Ettema, Robert (2006). “Hunter Rouse—His work in retrospect”. In: *Journal of Hydraulic Engineering* 132.12, pp. 1248–1258.

Ferro, Marco (2012). *Experimental study on turbulent pipe flow*.

Gadelmawla, ES et al. (2002). “Roughness parameters”. In: *Journal of materials processing Technology* 123.1, pp. 133–145.

Ghabeche, Wafia, Kamel Chaoui, and Nassereddine Zeghib (2019). “Mechanical properties and surface roughness assessment of outer and inner HDPE pipe layers after exposure to toluene methanol mixture”. In: *The International Journal of Advanced Manufacturing Technology* 103.5, pp. 2207–2225.

Ghajar, Afshin J, Clement C Tang, and Wendell L Cook (2010). “Experimental investigation of friction factor in the transition region for water flow in minitubes and microtubes”. In: *Heat Transfer Engineering* 31.8, pp. 646–657.

Hafizi, ZM et al. (2011). “High Frequency Acoustic Signal Analysis for Internal Surface Pipe Roughness Classification”. In: *Applied Mechanics and Materials*. Vol. 83. Trans Tech Publ, pp. 249–254.

Hamlaoui, N et al. (2017). “Machining of tough polyethylene pipe material: surface roughness and cutting temperature optimization”. In: *The International Journal of Advanced Manufacturing Technology* 92.5, pp. 2231–2245.

Hao, Peng-Fei et al. (2007). “Transitional and turbulent flow in a circular microtube”. In: *Experimental thermal and fluid science* 32.2, pp. 423–431.

Kárman, Th. vón (1930). “of Mechanical Similitude and Turbulence. G ”o ttingen, Math”. In: *phys. Class*.

Kim, Yong Hwan, Kiwook Kim, and Ji Hwan Jeong (2016). “Determination of the adhesion energy of liquid droplets on a hydrophobic flat surface considering the contact area”. In: *International Journal of Heat and Mass Transfer* 102, pp. 826–832.

Králik, Juraj (2016). “CFD simulation of air flow over an object with gable roof, revised with Y+ approach”. In:

Lauga, Eric and Todd M Squires (2005). “Brownian motion near a partial-slip boundary: A local probe of the no-slip condition”. In: *Physics of Fluids* 17.10, p. 103102.

Li, Zhi Xin (2003). “Experimental study on flow characteristics of liquid in circular microtubes”. In: *Microscale thermophysical engineering* 7.3, pp. 253–265.

Liu, Jinfeng et al. (2018). “Hydrogen-bond structure dynamics in bulk water: insights from ab initio simulations with coupled cluster theory”. In: *Chemical science* 9.8, pp. 2065–2073.

Lorenzini, Marco, Gian Luca Morini, and Sandro Salvigni (2008). “Laminar, Transitional and Turbulent Friction Factors For Gas Flows in Smooth and Rough Microtubes”. In: *International Conference on Nanochannels, Microchannels, and Minichannels*. Vol. 48345, pp. 129–136.

Luzar, Alenka and David Chandler (1996). “Hydrogen-bond kinetics in liquid water”. In: *Nature* 379.6560, pp. 55–57.

Mala, Gh Mohiuddin and Dongqing Li (1999). “Flow characteristics of water in microtubes”. In: *International journal of heat and fluid flow* 20.2, pp. 142–148.

Mises, V (1914). *Elemente der Techn. Hydromechanik*.

Miwa, Masashi et al. (2000). “Effects of the surface roughness on sliding angles of water droplets on superhydrophobic surfaces”. In: *Langmuir* 16.13, pp. 5754–5760.

Moody, Lewis F (1944). “Friction factors for pipe flow”. In: *Trans. Asme* 66, pp. 671–684.

Nikuradse, Johann (1933). “Stromungsgesetze in rauhen Rohren”. In: *VDI-Forschungsheft* 361, p. 1.

Nikuradze, J (1932). “Laws of the turbulent flow in smooth pipes, research”. In: *work. Engineering beings* 356.

Perry, Anthony Edward, William H Schofield, and Peter N Joubert (1969). “Rough wall turbulent boundary layers”. In: *Journal of Fluid Mechanics* 37.2, pp. 383–413.

Prandtl, L (1904). “Beiträge zur Theorie der Dampfströmung durch Düsen”. In: *Z. VDI* 48, pp. 348–350.

Reynolds, Osborne (1883). “XXIX. An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, and of the law of resistance in parallel channels”. In: *Philosophical Transactions of the Royal society of London* 174, pp. 935–982.

Rouse, Hunter (1943). “Evaluation of boundary roughness”. In: *Proceedings Second Hydraulics Conference*.

Shankar, Vishnu Kalaiselvan Arun et al. (2016). “A comprehensive review on energy efficiency enhancement initiatives in centrifugal pumping system”. In: *Applied Energy* 181, pp. 495–513.

Sharp, Kendra V and Ronald J Adrian (2004). “Transition from laminar to turbulent flow in liquid filled microtubes”. In: *Experiments in fluids* 36.5, pp. 741–747.

Shu, Jian-Jun, Ji Bin Melvin Teo, and Weng Kong Chan (2016). “A new model for fluid velocity slip on a solid surface”. In: *Soft Matter* 12.40, pp. 8388–8397.

Tang, Yuechao et al. (2018). “Contributions of van der Waals interactions and hydrophobic attraction to molecular adhesions on a hydrophobic MoS2 surface in water”. In: *Langmuir* 34.47, pp. 14196–14203.

Taylor, James B, Andres L Carrano, and Satish G Kandlikar (2006). “Characterization of the effect of surface roughness and texture on fluid flow—past, present, and future”. In: *International journal of thermal sciences* 45.10, pp. 962–968.

Thiel, Patricia A and Theodore E Madey (1987). “The interaction of water with solid surfaces: Fundamental aspects”. In: *Surface Science Reports* 7.6-8, pp. 211–385.

Valdés, Hugo, Ernesto Rufino-Felipe, and David Morales-Morales (2019). “Pincer complexes, leading characters in C–H bond activation processes. Synthesis and catalytic applications”. In: *Journal of Organometallic Chemistry* 898, p. 120864.

Wendler, Katharina et al. (2010). “Estimating the hydrogen bond energy”. In: *The Journal of Physical Chemistry A* 114.35, pp. 9529–9536.

Yang, C-Y and T-Y Lin (2007). “Heat transfer characteristics of water flow in microtubes”. In: *Experimental Thermal and Fluid Science* 32.2, pp. 432–439.

Zhou, JianFeng, BoQin Gu, and ChunLei Shao (2011). “Boundary velocity slip of pressure driven liquid flow in a micron pipe”. In: *Chinese Science Bulletin* 56.15, pp. 1603–1610.