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Introduction to Cold Flow – an understanding of wax and hydrate deposition in cooling systems.

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Abstract

Empig AS is creating a Cold Flow system for subsea. This thesis is looking at the cooling system. Wax and hydrate deposition appear in the cooling system that in the worst case can lead to clogged pipes. To prevent that from happening I have taken the Systems Engineering approach to create a Concept of Operations to get the understanding of the system. A section about intellectual property has also been derived because of the sensitivity of this product. Furthermore, Chapter 2 is research about Cold Flow, existing sensors for deposition, ultrasound and publication on leak detections for the petroleum industry. Chapter 3 is the modeling of the pressure loss, approximation of temperature, reflection coefficient in ultrasound to find wax deposition and Computational fluid dynamic model of a pipeline with wax in the middle of the pipeline. Moreover, Chapter 4 includes result and discussion of chapters 2 and 3. Where existing sensors and ultrasound had to be discarded because of the result and properties of the sensors. Chapter 5 is the conclusion and include the next steps from this thesis to the master thesis.

Acknowledgment

I would first like to thank my thesis supervisor Professor Jan Tommy Gravdahl of the Department of Engineering Cybernetics at Norwegian University of Science and Technology. His knowledge and experience has made this process fun.

I would also like to thank the company who were involved in this project Empig AS and CTO Fredrik Lund. Their passionate participation, input, and sharing of the details of the system such that my understanding is clear.

I would also like to thank Professor Ole Morten Aamo of the Department of Engineering Cybernetics at Norwegian University of Science and Technology for information about his publications.

In the end I would like to thank Associate Professor Alfonso Rodriguez-Molares of the Department of Circulation and Medical Imaging at Norwegian University of Science and Technology. His advice during TTK13 Ultrasound instrumentation about industrial use of ultrasound helped a lot for this thesis.

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Chapter 1

Introduction

Empig AS has developed ha new system for extracting oil and gas. The cooling system will decrease the temperature of the fluids. When the oil and gas reach a specific temperature inside the pipes of the cooling system, some of it will become wax and hydrates. Finding locations for wax and hydrates will be an advantage for the production. The worst-case scenario of not finding wax deposition and hydrates will result to clogged pipes. The production will stop, and maintenance must be done before production can start again. The economic consequences will be large and not optimal for oil and gas production.

1.1 Approach

The core of this thesis will be Systems Engineering. This is used in Subsea Engineering, Embedded Systems, Business and Management, Industrial Domain and Product Development. Systems engineering is an approach used by many companies, such as Kongsberg, Aker Solutions, Siemens and Borregaard to mention a few, (University of South-Eastern Norway, 2018). Dr. Alberto Sols made an improved Stevens model, see appendix C, this is a block diagram where you have a structural approach or framework for covering the important parts for product development or product improvement (Sols, 2014, p. 118). The contents of the next five blocks will be derived in the next sections.

1.1.1 Identification of need or opportunity

Empig AS wants an approach for finding where wax deposition and hydrates appear for the Cold flow system, see section 2.1. Wax and hydrates becomes thicker inside the pipeline of the cooling system, see fig. 1.1. They have made a robot arm with a heater that can heat up the pipeline where it is necessary. The robot arm and the attached heater will consume energy, to reduce the economic cost they want to minimize the heating operation.

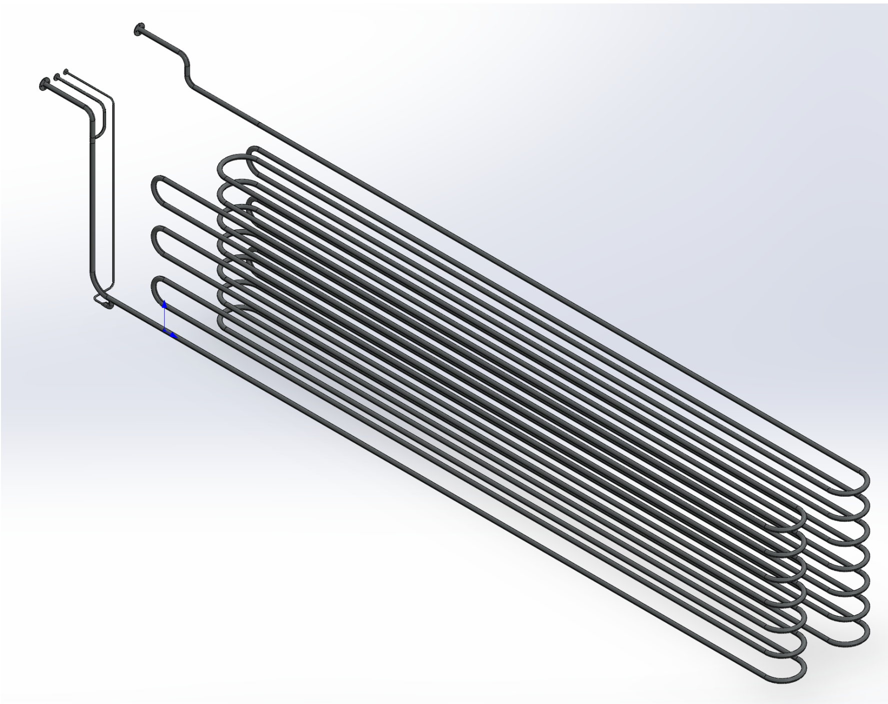


Figure 1.1: The CAD of the pipeline cooler. Contributed by Empig AS.

1.1.2 Problem formulation

The problem formulation for this thesis are as following:

> *Get an understanding of the concept of Cold flow, looking at some sensors that has been used to determine wax deposition before. See if ultrasound is a good method to find wax deposition in the cooling system. Make a simplified model and result of pressure loss, temperature loss and ultrasound to see how that can be used in the cooling system. Finally make Computational fluid dynamic model to see how pressure changes with wax inside a straight pipeline.*

1.1.3 Identification of stakeholders

The stakeholders are an important part of development. The stakeholders set the wanted requirements for a project. There are two types of stakeholders, active and passive. The active are the individuals or organizations which have direct effect on the project. There are two active stakeholders for this thesis. The stakeholders are Empig AS and the supervisor for this thesis, Professor Jan Tommy Gravdahl from the Department of Engineering Cybernetics at Norwegian University of Science and Technology (NTNU). Passive stakeholders are the individuals or organizations without requirements, but are interested in the result (see Sols, 2014).

Table 1.1: Stakeholders for this thesis.

Stakeholders	Active or Passive
Empig AS	Active
NTNU	Active
Competitors to Empig AS	Passive
SINTEF	Passive
Environmental Groups	Passive

There are only three passive stakeholders mentioned in table 1.1. Competitors to Empig are all other companies that offers a Subsea solution, national and internationally. If a unique product development is known by the competitors they can patent the solution before Empig do, then the competitor will benefit from it. Moreover, in section 1.2, the discussion information flow will be clarified.

Empig are making a Subsea system based on Cold Flow principle, see section 2.1. SINTEF is a research organization which have researched on Cold flow. The research documents by SINTEF are being used in this thesis. SINTEF may not have a direct connection to this thesis, it is possible they want the information that has been discussed in this thesis.

Environmental groups are interested in new non-renewable energy technology. Since it is new technology is created, an environmental group will most likely have a positive or negative reaction to the technology. For example, is the solution energy effective? To answer the question documentation has to be published to verify that this technology is a better alternative.

1.1.4 Requirements

The requirements are defined by the active stakeholders. Defining the requirements will give the engineers developing a product the guideline on how it should work and look like. Furthermore, defining requirements are considered a challenge. A good requirement is measurable and has no room for interpretation. For example, if a company is making a new car. The company can set requirement for speed of the car, a poor requirement is, “The car has to be fast”. Fast is a subjective term which makes it interpretable by individuals, companies or nations. A better approach for speed requirements could be, “The car has maximum velocity of 200 km/h on the company test site”. When the car is produced it can be tested at that location. Technical data for the site are publicly known, which will give customers a chance to test it on the location or make a replica of the site and verify the requirement, (Sols, 2014).

The requirements set by Empig and NTNU are listed in table 1.2.

Table 1.2: Requirements by Empig and NTNU.

Requirement	Stakeholder
Finding wax/hydrate location and wax/hydrate rate inside the cooler	Empig
Find out if ultrasound technology can be used to locate wax/hydrate	Empig
Finding wax location using cybernetics	NTNU
Create a model for a pipeline and simulate with the cybernetics approach	NTNU

Requirements for this thesis is an introduction to the master thesis. Completing the requirements will give a good foundation for the spring of 2019. Where Empig have made their product, and where this research can be implemented to verify the results.

1.1.5 CONOPS

Concept of operations is a user orientated document that describes the project. Making such a document will give all the participants an overall view of the project. For example, making a black box that do not describe the technical data, only the functions. The stakeholders can verify that the engineers understood the concept. This document includes the statement of the goals and objectives of the project, like in section 1.1.1.

Boundaries of the system can also be called requirements see section 1.1.4. The list of stakeholders and what their role in the project are, in section 1.1.3. Policies that affect the system, conceptual view of the system and processes to system are not included for this thesis, (Sols, 2014, p.127-128). Since only five first blocks are discussed in the Alberto Sols improved Stevens model.

1.2 Intellectual Property

The solution Empig share is a part of their Intellectual Property (IP). IP is a term used for inventions, patents, trademarks, names of companies etc. It is an importance of innovation, Norwegian Industrial Property Office (Norwegian Industrial Property Office, 2016) and World Intellectual Property Organization (WIPO) are the organizations with a purpose to publish patented items so that the creators get recognition for their work. Furthermore, having legal protections of patents will encourage to more innovation (World Intellectual Property Organization, 2004).

Technical data of every test, and sample are unique for Empig. Passive stakeholders such as competitors are an economical threat for the company (World Intellectual Property Organization, 2004). Leakage of information about a product in development can be a great loss. For example, if a product is in development and a competitor gets knowledge of the technology. The competitor can rush a similar product and patent it before the first company. This is unfortunate, and in worst-case scenario can bankrupt the company that first developed the product.

Chapter 2

Former research

There have been a numerous different approaches and studies on wax deposition. This chapter is going to show some of the approaches, patents, and technology that has been developed specific for wax deposition. Furthermore, approaches that has been used for solving a different problem, and with a modification can be used to find the location of the wax deposition.

2.1 Saturn Cold Flow

Saturn Cold Flow was a project by SINTEF, and the purpose was to make a groundbreaking technology that makes oil extraction much more environmental friendly (SINTEF, 2010).

SINTEF defined Cold Flow (CF) as (Larsen, 2008, slide 5):

- No use of chemicals to prevent deposition, neither for hydrates or wax, and no "emulsifikatorer"
- No warm up of pipelines or components
- No isolation of the pipelines

The way CF works is when extracted oil and gas goes through the pipeline. When seawater cools down the oil to 40°C wax will appear and 20°C for hydrates (Lund, 2018, personal communication, 15. August). Going through a novel recirculation scheme for seed particles of gas hydrates and wax (SINTEF, 2010). The seeds are going in a feedback loop to the hot stream well. Furthermore, in the hot stream well the seeds contribute such that wax, and hydrates does not clog the pipeline. A simple figure of the CF concept is shown in fig. 2.1.

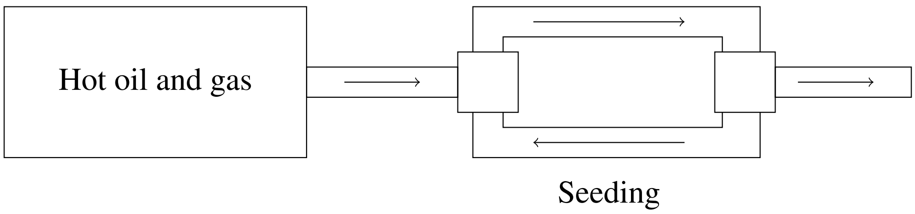
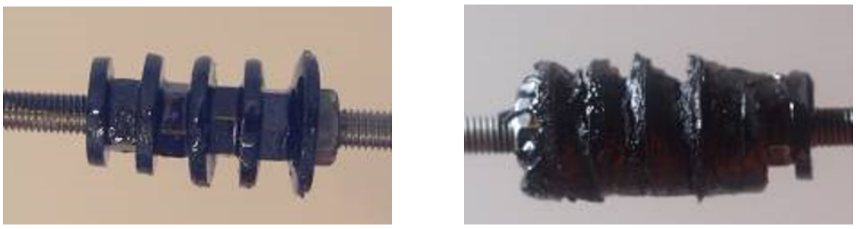


Figure 2.1: A simple set up for the concept of Cold Flow.

SINTEF tested the CF process with a focus on hydrates. The result showed a clear difference with use of CF process. Figure 2.2 shows the result after pigging. The CF process has a clean brush and the other process consist of hydrates.

SINTEF proved that the CF is a solution that does not need chemicals, heating or isolation of pipelines. The seeds of wax and hydrates will prevent clogging of hydrates in the pipeline. This will reduce the maintenance cost, and it is better for the environment (SINTEF, 2010).



(a) Pigging of the test pipe using CF.

(b) Pigging of the test pipe not using CF.

Figure 2.2: SINTEF test of CF process (Larsen, 2008, slide 9).

2.2 Empig

Empig is constructing a full-scale CF device for offshore usage, it is the discipline of Flow assurance. The CF device is based on Saturn Cold Flow by SINTEF and their own research. The oil and gas are extracted like before, but a cooler with a length of 280 m, from fig 1.1, is inside a container. The seeds are still in a feedback loop before cooled oil is transported to a separator. The illustration shown in fig 2.3 show their concept.

Making a CF process on a big scale had a challenge. Wax was not flowing freely with seeding. The pipes still got clogged, and Empig had to make some modifications to prevent clogging. A mechanical arm was made to heat up the areas of the cooler where the wax is. In a meeting there was also a discussion for isolate the bends in the cooler if necessary (Lund, 2018, personal communication, 25. September). This means that only one of SINTEF definitions in section 2.1 is still present to the solution Empig has today.

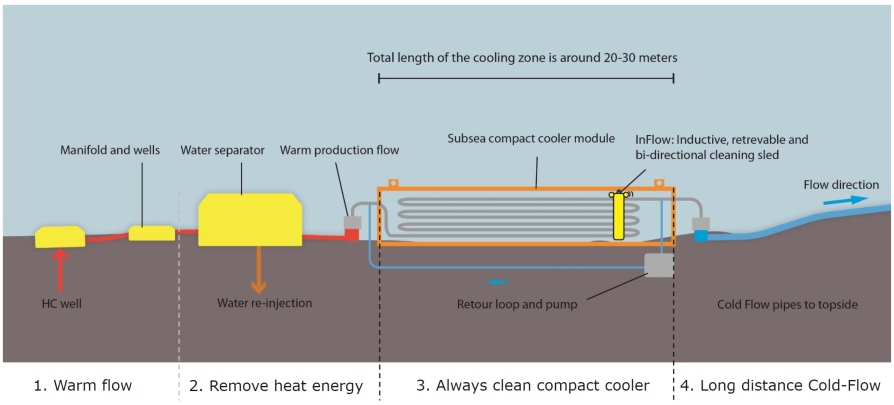
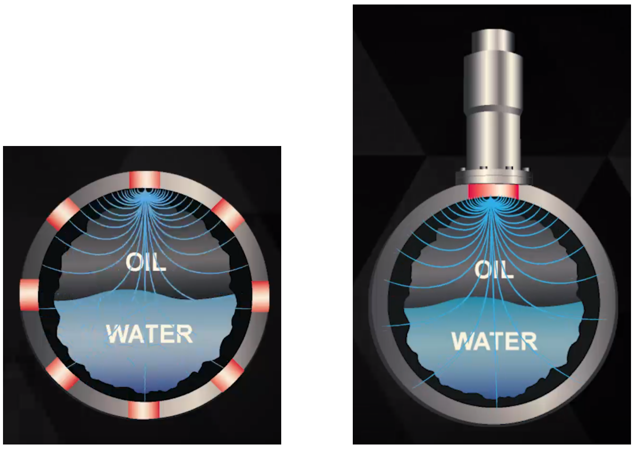


Figure 2.3: Empig CF device (Empig, 2016, slide 11).

2.3 Rocsole – Deposition sensors

Rocsole are making applications for oil and gas industry with pipeline monitoring products such as deposition watch, flow watch and sand watch. Using tomography (imaging by sections or sectioning) technology for measuring depositions in pipelines. The company has offices in Houston, USA and Kuopio, Finland (Rocsole, 2018a).

The deposition measuring can be used by two types of sensors, pipe and plug. The pipe sensor in fig. 2.4a is using a voltage injecting cycle. The eight red areas represent electrodes. One electrode sends a voltage injection and the seven other are measuring the response. This is repeated until all the electrodes have done a voltage injection. Measurements form the electrodes give an image of deposition and liquids, the pipe sensor is connected to a small part of the pipeline. The plug sensor fig. 2.4b is similar to the pipe sensor. This sensor has all the electrodes on the top of the pipe. One electrode is injecting voltage and the other electrodes are measuring. The measured cross section of the pipeline measures deposition and liquids (Rocsole, 2018b).



(a) Pipe sensor (b) Plug sensor

Figure 2.4: Rocsole sensors (Rocsole, 2018b)

2.4 Statoil Pertroleum AS

Statoil Petroleum sent an application for a patent in 2013, and in 2014 WIPO published the patent (Statoil Petroleum AS and World Intellectual Property Organization, 2014). The patent is for estimating the thickness of deposited material on a surface. The main purpose is to use it for Subsea, located on the Topside of a facility (Statoil Petroleum AS and World Intellectual Property Organization, 2014, p. 6). Furthermore, the patent is illustrated in fig. 2.5, where (1) is a pipeline that has a fluid containing pumped oil and gas. Seawater is pumped up by (8) to pipe (7). Adjusting the flow rate of the seawater makes the same thermal conditions. Inside (7) a heat pulse is sent through the pipe to measure the response.

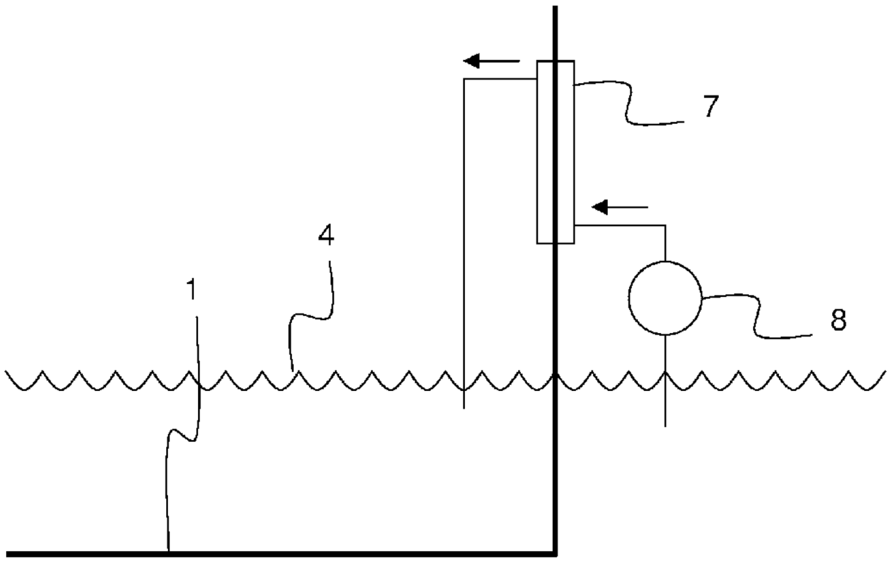
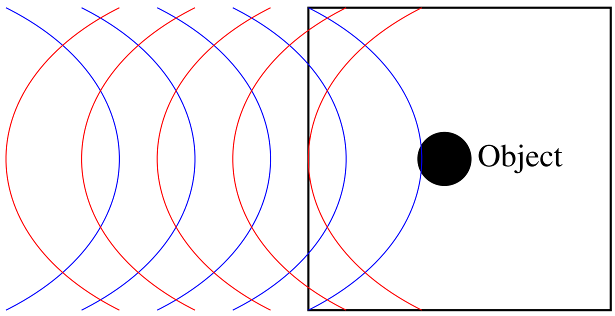


Figure 2.5: Illustrates schematically a sea-water filled annulus disposed around an insulated pipeline (Statoil Petroleum AS and World Intellectual Property Organization, 2014, p. 1)

The response with some computation of the temperature, with a logarithmic curve to a linear curve and then determine a time constant. Moreover, correlation with the time constant should give an estimate of the thickness (Statoil Petroleum AS and World Intellectual Property Organization, 2014, p. 25).

2.5 Ultrasound

Ultrasound can be used for industrial purposes. Ultrasound is most known for being used in medicine and health services. Ultrasound has a transducer that sends sound waves. To receive the sound wave it is possible to have the same transducer or have a separate receiver. The received analog signal get turned into a digital signal and an ultrasound image is produced for the user (radiologyinfo.org, 2018). The received sound-wave is in short, the time used for the signal hitting an object and return, see fig 2.6 for illustration. Time of flight is given by the equation $TOF = \frac{2r}{c_0}$, where $2r$ is the distance back and forth and c_0 is sound of speed of the tissue (Szabo, 2014, p. 5).



Ultrasound transfer and receive

Figure 2.6: Transducer transmitting (red) sound and hit an object and gets received (blue) back.

The principle for ultrasound can be used to see objects, but acoustic impedance as to be accounted for. Acoustic impedance is the conductivity of sound (Brekke, 2018) and how conductivity responds to neighbor material. This will be closer looked at in section 3.3. Cavitation can be produced by ultrasound. Cavitation occurs when low pressure creates bubbles and the bubbles implodes. This is causing a shock wave with destructive properties (Hoskins and Thrush, 2010, p. 161). It is a known problem in hydropower for “eating” the turbine blades. Orange Ultrasonics are using this ultrasound technology to their advantage, creating cavitation to clean heat exchangers and having a tank where cavitation is used for cleaning objects (Orange Ultrasonics, 2018).

2.6 Leak Detection, Size Estimation and Localization in Pipe Flows

Leakage in the petroleum industry can cause environment damage and economical loss (Aamo, 2016). Professor Ole Morten Aamo at NTNU has developed a method for finding leakage, size detection and localization. The approach is software-based which means that using pressure and flow measurements for estimating the leakage. Additional instrumentation is not necessary and will reduce the cost of purchasing equipment and the cost of installation.

The underlying model is a linearized, discretized pipe flow model on a grid of N nodes (Aamo, 2016, p. 426). Fig. 2.7 is an example for such a model.

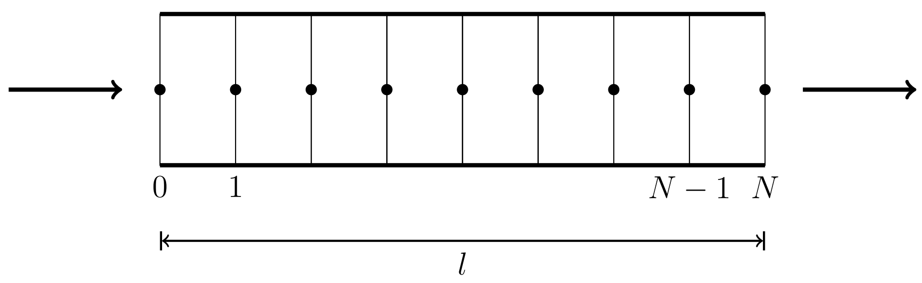


Figure 2.7: The model grid.

Furthermore, the mechanism for detecting a leak is to have observers and which one of the N observers that does not react to the leak depends on the location of the leak (Aamo, 2016, p. 426). The pipeline model is a 1-dimensional equations of mass conservation and momentum conservation for single phase fluid flow in a pipe of length l (Aamo, 2016, p. 426).

In fig. 2.8, the simulation on the left show that the estimated leakage size converge fast to the actual leakage size. The right plot is the simulated location of the leak and it is simulated very well if it is only one leakage.

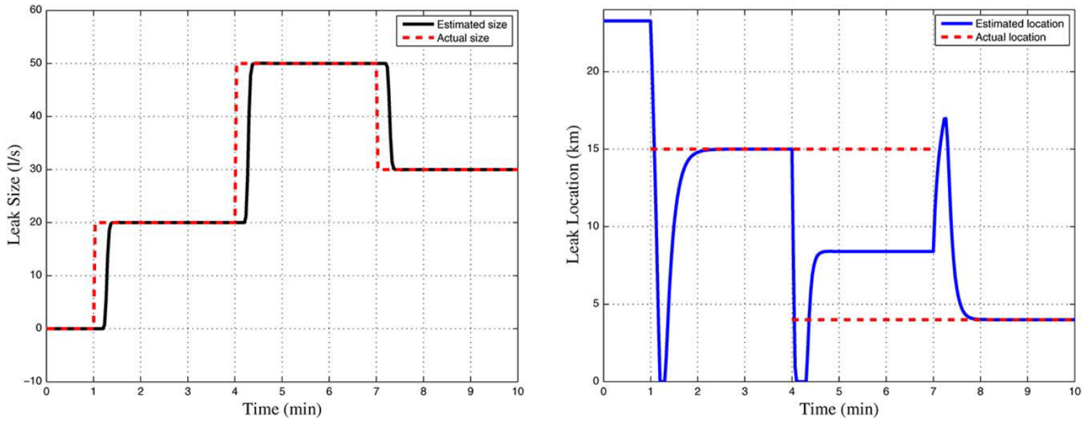


Figure 2.8: Plots of the simulation (Aamo, 2016, p. 250)

Chapter 3

Modeling

The importance of having a mathematical understanding on where the wax deposition in cooler of the Cold Flow system can be found by modeling. Setting up models of the system with various approaches in engineering such as pressure loss, heat transfer, ultrasound and Computational fluid dynamics. The various approaches will individually or combined give a result of wax deposition in the cooler.

3.1 Pressure differential

Pressure differential for a pipeline are calculated in three parts, laminar or turbulent flow for straight pipeline system, pressure loss in bends, and for mediums going upward.

The expressions will be derived for the next four subsections.

3.1.1 Straight pipeline

Figure 3.1 shows a model of a straight pipeline and the flow equation can be written as:

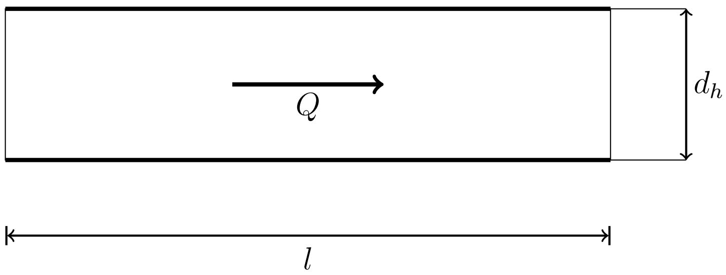


Figure 3.1: Model of a straight pipeline

$$Q = A \cdot c \tag{3.1a}$$
$$\frac{Q}{A} = c \tag{3.1b}$$

Where Q is the flow of the fluid, A is the cross-section areal for the fluid, and c is the velocity of the fluid (Fossmark, 2006, p. 4.5).

In pipelines the Reynolds number needs to be calculated. The Reynolds number is a dimensionless value that determines if the flow is turbulent or laminar. The equation for solving Reynolds is given by:

$$Re = \frac{c \cdot d_h}{\nu} = \frac{c \cdot d_h \cdot \rho}{\mu} \tag{3.2}$$
$$d_h = \frac{4A}{O} = \frac{4 \cdot d^2\pi}{4 \cdot d\pi} = d \tag{3.3}$$

Where ρ is density, d_h is the characteristic linear dimension which for circular pipe is the diameter d, ν is the kinematic viscosity and μ is the dynamic viscosity (Fossmark, 2006, p. 4.1).

The critical Reynolds number is set to be $Re = 2300$. Values below the critical Reynolds number is considered laminar, but there are disagreements in engineering community when flow is fully turbulent. To keep this simple every given value $Re \geq 3000$ is considered turbulent (Fossmark, 2006, p. 4.2).

Two expressions are made depending either the flow is turbulent or laminar. λ is the friction coefficient to be used for pressure differential for the straight pipeline (Fossmark, 2006, p. 4.11).

$$\lambda_{laminar} = \frac{64}{Re} \tag{3.4}$$

$$\lambda_{turbulent} = \frac{0.316}{\sqrt[4]{Re}} \tag{3.5}$$

Differential pressure for a straight pipeline is given by Darcy-Weisbach's equation $\Delta p = \frac{\lambda \cdot l\rho c^2}{2d_h}$, and substituting λ from (3.4) and (3.5) gives the final value (Fossmark, 2006, p. 4.10).

$$\Delta p_{laminar} = \frac{\lambda_{laminar} \cdot l\rho c^2}{2d_h} = \frac{64 \cdot l\rho c^2}{2 \cdot Re \cdot d_h} \tag{3.6}$$

$$\Delta p_{turbulent} = \frac{\lambda_{turbulent} \cdot l\rho c^2}{2d_h} = \frac{0.316 \cdot l\rho c^2}{2 \cdot \sqrt[4]{Re} \cdot d_h} \tag{3.7}$$

Where c is the velocity, ρ is density, d_h is the characteristic linear dimension and l is the length of the pipeline.

3.1.2 180° bend

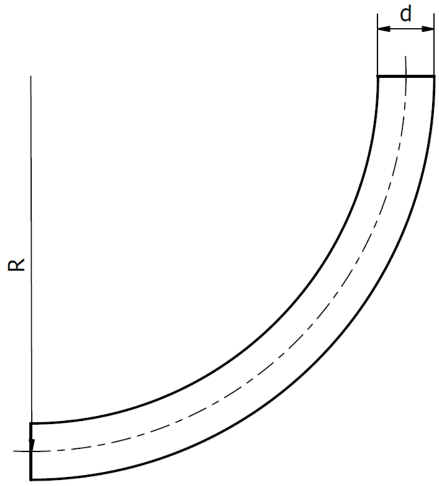
Additional pressure differential occur in the pipe, and the following expression is used (Fossmark, 2006, p. 4.13).

$$\Delta p_{90^\circ} = \frac{n\zeta\rho c^2}{2} \tag{3.8}$$

$$\Delta p_{180^\circ} = \frac{2n\zeta\rho c^2}{2} = n\zeta\rho c^2 \tag{3.9}$$

Where n is the number of bends, c is the velocity and ρ is density. ζ is called the singular loss coefficient, and it is the sum of every 90° bends and valves. Since the cooler in fig.1.1 has no valves the expression is derived to sum of singular loss coefficient value of $180°$ bends. Furthermore, the ζ value for $90°$ bends are found using table 3.1, where diameter d is compared much gain fits to the bend radius R of the pipeline, see appendix E.

Table 3.1: Table for singular loss coefficient.



R	d	2d	3d	4d	6d	10d
ζ	0.30	0.16	0.14	0.12	0.10	0.09

The pressure for bends will be added to the total pressure differential.

3.1.3 Pressure upward

Pressure for the height difference has is the last component that has to be added for the total pressure differential. Setting up a simple model of a tank width height h, and liquid width density ρ.

The force balance can be derived as:

$$\rho g\, dh\, dA + p\, dA = (p + dp)dA \tag{3.10a}$$
$$\rho g\, dh + p = p + dp \tag{3.10b}$$
$$dp = \rho g\, dh \tag{3.10c}$$

Where $p + dp$ is the pressure difference width the length of dh and p is pressure, dA is the differential area setting with dp and dh it is possible to integrate.

$$\int_{p_0}^{p} dp = \int_{0}^{h} \rho g\, dh \tag{3.10d}$$
$$p - p_0 = \rho g h \tag{3.10e}$$
$$p = p_0 + \rho g h \tag{3.10f}$$

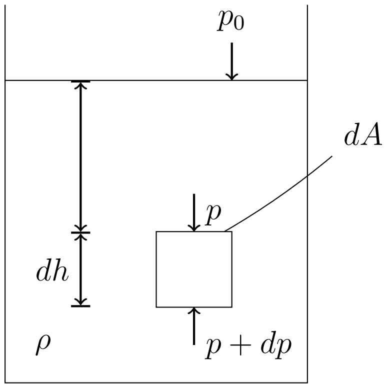


Figure 3.2: Physical model of liquid in a tank.

The same equation can be used in a upward pipeline to solve the pressure differential when the liquid is moving upward.

$$\Delta p_{upward} = p_0 + \rho g h \tag{3.11}$$

3.1.4 Total Pressure loss

The total pressure loss is just adding the three derived equations from subsections 3.1.1 - 3.1.3.

Depending if the flow is laminar or turbulent these two expressions can be used:

$$\Delta p_{Total} = \Delta p_{laminar/turbulent} + \Delta p_{180^\circ} + \Delta p_{upward} \tag{3.12}$$

$$\Delta p_{TotalLaminar} = \rho \left(\frac{64 \cdot lc^2}{2 \cdot Re \cdot d_h} + n\zeta c^2 + gh \right) \tag{3.13}$$

$$\Delta p_{TotalTurbulent} = \rho \left(\frac{0.316 \cdot lc^2}{2 \cdot \sqrt[4]{Re} \cdot d_h} + n\zeta c^2 + gh \right) \tag{3.14}$$

The result of the pressure differential will be calculated in chapter 4.

3.2 Heat transfer

To find an approximation on the time for the fluid to reach the temperature for wax deposition, the Newton cooling law will be used (Khan Academy, 2014). Given the temperature rate is equal a negative constant k times the difference between the fluid temperature T and ambient temperature T_a.

$$\dot{T} = -k(T - T_a) \tag{3.15a}$$

$$\int \frac{dT}{(T - T_a)} = \int -kdt \tag{3.15b}$$

$$\ln |T - T_a| = -kt + C_1, \qquad T = T(t) \tag{3.15c}$$

$$T(t) = Ce^{-kt} + T_a \tag{3.15d}$$

From this model, boundary conditions given by Empig can be used for calculating the cooling rate.

3.3 Ultrasound – Reflection coefficient

Empig wanted to see how ultrasound would work for detecting wax and hydrates in the cooler. For solving this problem using ultrasound, the acoustic impedance must be accounted for. Acoustic impedance, mentioned in section 2.5, is the conductivity of sound (Brekke, 2018). The expression for acoustic impedance is $Z = \rho c$, where Z is the acoustic impedance, ρ is the density and c is the speed of sound to the specific material.

The illustration in fig 3.3 shows the steel pipe and wax on the inside.

The two materials next to each other should have different acoustic impedance. If the difference is to great, will create a reflection between the two materials. This imply that it is not possible to get a clear image of the second material. To find out how much the reflection coefficient RF is between to materials the following expression can be used (Szabo, 2014, p. 5):

$$RF = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{3.16a}$$

$$|RF| = \left| \frac{Z_2 - Z_1}{Z_2 + Z_1} \right| \tag{3.16b}$$

It is a dimensionless value where Z_1 is the acoustic impedance of the first material and Z_2 is for the second. Adding the absolute value is to get a positive number.

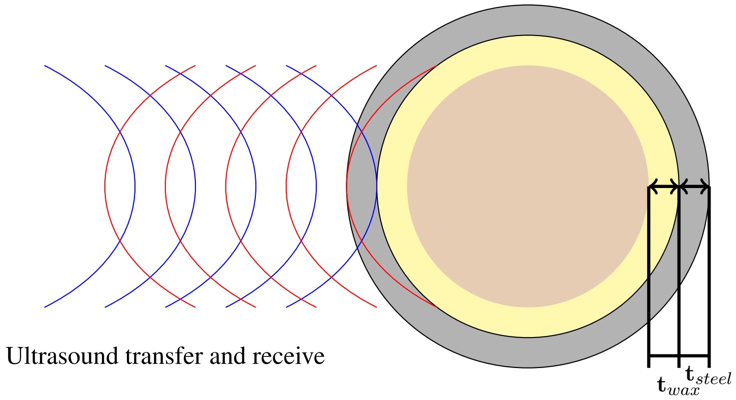


Figure 3.3: Transducer transmitting (red) sound waves and hitting the pipe, and sound waves (blue) returns to the receiver.

3.4 Computational fluid dynamics

Using CFD for the Master thesis, a model of a single pipeline has been modeled. This is to see what happens with pressure when wax is on the inside. When a pipeline is clean the pressure loss will look like the model from section 3.1.4. The model is a 7000 mm pipeline with a wax deposition located at 3500 mm. The inner diameter is 50,8 mm and outer diameter is 60,8 mm.

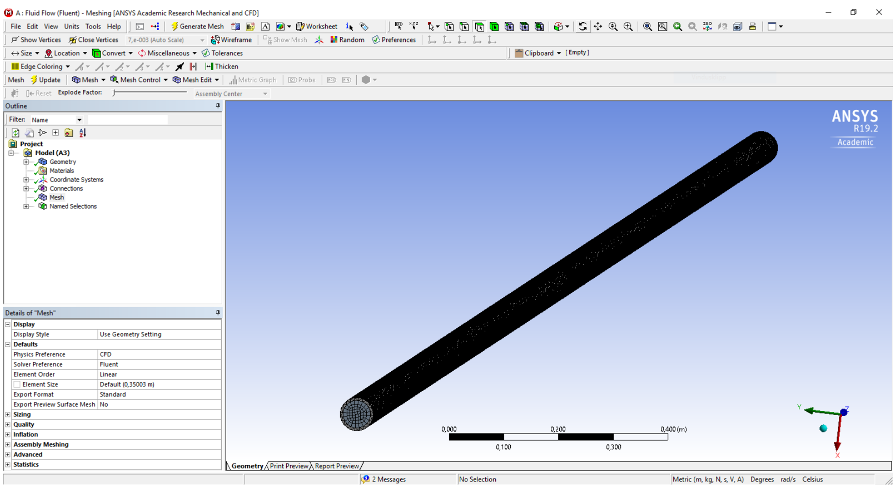


Figure 3.4: Meshing of the pipeline in ANSYS.

Using the setup function to include boundary conditions and run the iterations to see how pressure changes where the wax deposition is located.

Chapter 4

Result and Discussion

After the research and modeling, the result with a discussion on how different approaches and sensors can be used or discarded to solve Empig's problem on wax deposition. This chapter will contain a discussion of some the technology in former work in Chapter 2. Calculated results from Chapter 3 will be discussed.

4.1 Existing technology

For measure and remove wax deposition, there were already technology for that purpose.

Rocsole works for measuring wax deposition at a constant location. The solution will not solve Empig's problem due the fact that Empig need an approach that finds wax and hydrates along the cooler. Which can vary depending on temperature.

Statoil Petroleum solutions uses the thermal conditions to compare the thickness. This has the same problem as Rocsole, it is a device that only measure one area.

4.2 Results of the models

The results are given by looking at fig. 1.1 and using SolidWorks to measure CAD file dimensions given by Empig, and additional values. The missing values are documented by source.

4.2.1 Pressure loss

Having the expression from section 3.1.4 that is given by eq. 4.2.

$$Re = \frac{c \cdot d_h}{\nu} = \frac{c \cdot d_h \cdot \rho}{\mu} \tag{4.1}$$

$$\Delta p_{TotalTurbulent} = \rho \left(\frac{0.316 \cdot lc^2}{2 \cdot \sqrt[4]{Re} \cdot d_h} + n\zeta c^2 + gh \right) \tag{4.2}$$

Empig gave the following data.

The technical data for the fluid is found in the table for crude oil in the North Sea (Lundberg, 2018).

First the Reynolds number must be computed, knowing that $d_h = d$.

$$Re = \frac{c \cdot d_h}{\nu} = \frac{2 * 0.0508}{4.5 \cdot 10^{-6}} = 2.2578 \cdot 10^4 \tag{4.3}$$

Since the Re is clearly over 3000, it is safe to say it is turbulent. Finding the ζ values for R_h and R_v is done by finding the ratio with d_b, respectively. The ratio for $R_h/d_b \approx 5$ and gives $\zeta_h = 0.11$ using interpolation in table 3.1, and same way with $\zeta_v = 0.13$. The rest can be filled in from the technical data.

Table 4.1: Technical data from Empig (Lund, 2018, personal communication, 25. September)

What	Value
Length pipeline l	280m
Velocity c	2m/s
Diameter Pipeline d	0.0508m
Number of Horizontal bends n_h	21
Number of Vertical bends n_v	7
Radius of Horizontal bends R_h	262mm
Radius of Vertical bends R_v	181mm
Diameter bends d_{bend}	49.22mm
Height h	1.856m

Table 4.2: Technical data from SNL (Lundberg, 2018)

What	Value
Density ρ	842kg/m^3
Kinematic Viscosity ν	$4.5 \cdot 10^{-6}\text{m}^2/\text{s}$

$$\begin{aligned}\Delta p_{TotalTurbulent} &= \rho\left(\frac{0.316 \cdot lc^2}{2 \cdot \sqrt[4]{Re} \cdot d_h} + n\zeta c^2 + gh\right) \\ &= 842\left(\frac{0.316 \cdot 280 \cdot 2^2}{2 \cdot \sqrt[4]{2.2578 \cdot 10^4} \cdot 0.0508} + (21 * 0.11 + 7 \cdot 0.13)2^2 + 9.811.856\right) \\ &= 2.6545e + 05\text{Pa} \approx \underline{\underline{2.7\text{bar}}} \end{aligned} \tag{4.4}$$

Using this fluid, the pressure loss will change with 2.7 bar. The properties of the fluid will make the pressure loss change. If the pressure loss increases more than 2.7 bar for this case, you can imply there is some wax or hydrates created inside the pipeline, but only using this approach it is not possible to say where the deposition is.

4.2.2 Temperature

For finding an approximated value of the temperature a differential equation was derived $T(t) = Ce^{-kt} + T_a$.

Table 4.3: Technical data from Empig (Lund, 2018, personal communication, 25. September)

What	Value
Ambient temperature T_a	4°C
Velocity c	$2\mathrm{m/s}$
Temperature at the end $T(140)$	10°C

The temperature $T(140) = 10°C$ is found by $time = 280\mathrm{m}/2\mathrm{m/s} = 140\mathrm{s}$ and initial temperature is set to $T(0) = 90°C$ (Verdensklasse, 2018, Section Dannelsen av olje og gass).

Solving the initial values for the differential equation will give the following.

$$T(t) = Ce^{-kt} + 4 \tag{4.5a}$$
$$T(0) = C + 4 = 90, \quad C = 86 \tag{4.5b}$$
$$T(140) = 86e^{-140k} + 4 = 10, \quad k = \frac{\ln\frac{6}{86}}{-140} \approx 0.02 \tag{4.5c}$$
$$T(t) = 86e^{-0.02t} + 4 \tag{4.5d}$$

Finding t when $T(t) = 40$.

$$T(t) = 86e^{-0.02t} + 4 = 40 \tag{4.6}$$
$$\ln\frac{36}{86} = -0.02t \tag{4.7}$$
$$t = \frac{\ln\frac{36}{86}}{-0.02} = 43.5\mathrm{s} \tag{4.8}$$

Using the time to find distance at $l_{40°\mathrm{C}} = 43.54\mathrm{s} \cdot 2\mathrm{m/s} \approx \underline{\underline{87.1\mathrm{m}}}$.

This is an approximation, and this can change depending on the fluid. The result shows that there will be no wax deposition before $87.1\mathrm{m}$. Combining the pressure loss with this result can give a clearer information on the wax location.

4.2.3 Ultrasound

The reflection coefficient RF is given by.

$$|RF| = \left| \frac{Z_2 - Z_1}{Z_2 + Z_1} \right| \tag{4.9}$$

Where $Z = \rho \cdot c_0$ is the acoustic impedance. The acoustic impedance for steel is given by $\rho_{steel} = 7830 \mathrm{kg/m^3}$ (Çengel and Boles, 2015, p. 903, appendix A-3) and $c_{steel} = 5000 \mathrm{m/s}$ (Gjestland, 2018), which gives $Z_{steel} = 39150000 \mathrm{kg/m^2 s}$.

For oil, values are $\rho_{steel} = 842 \mathrm{kg/m^3}$ (Lundberg, 2018) and $c_{oil} = 1298 \mathrm{m/s}$ (The engineering toolbox, 2018, Benzene), which gives $Z_{oil} = 1092916 \mathrm{kg/m^2 s}$.

$$|RF| = \left| \frac{Z_{steel} - Z_{oil}}{Z_{steel} + Z_{oil}} \right| = \left| \frac{39150000 - 1092916}{39150000 + 1092916} \right| \approx \underline{\underline{0.946}} \tag{4.10}$$

The solution shows that using ultrasound as a device to see the wax deposition works poorly. The reflection coefficient value is too high. This means that when the transducer sends a soundwave, it will reflect almost immediately on the inside of the steel pipe and give no clear image of the oil when the signal is received. Furthermore, if the oil turns into wax along the pipe wall, it will become a change in RF. When using the amplitude of the sound can determine a difference. It must be stated that it is not an efficient method.

4.2.4 Computational fluid dynamics

After setting up the mesh, setup and boundary conditions. The simulation was set to 1000 iterations. Physical properties were set by the values from the previous sections.

The simulation, fig. 4.1, show a small change in the middle with a pressure decrease. This is expected, and with extracting the values, hopefully, this can be used for solving the wax location and the wax rate.

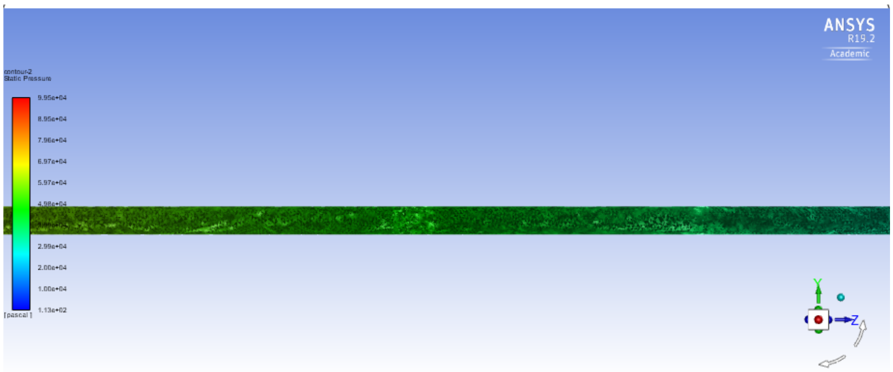


Figure 4.1: The pressure loss on the middle with "Wax". The light area show a small difference.

Chapter 5

Conclusion

5.1 The Conclusion

Empig are developing a Cold Flow system. The system encounter wax and hydrate deposition that in worst case can clog the pipes in the cooler system. The System Engineering approach is a structured method to find problem formulation, stakeholders and the Concept of Operations for this system.

The research on Cold Flow from SINTEF and Empig gave an understanding on how the system work and where improvements can be made. Rocsole and Statoil Petroleum had made products to estimate the wax deposition. These solutions are not going to work for Empig because of the products locked placement.

Professor Morten Aamo approach to find location and size for leaks is a potential method that can be used for Cold Flow systems, this has not been verified.

Setting up models for pressure loss in the cooler system has been derived. The solution was 2.7 bar. This solution only show pressure loss for a specific type of fluid and this result will change depending on the fluid.

With the initial conditions given by Empig, the Newton cooling law was used to find where the fluid reaches wax temperature, $40°\mathrm{C}$. The length was approximated to $87\mathrm{m}$. With different fluid and initial conditions this will change, but for this oil fluid that wax deposition in the cooling system before $87\mathrm{m}$ in cooling system will not occur.

Ultrasound to detect wax deposition in the cooling system is not a good solution due to the acoustic impedance of steel and oil. The reflection coefficient was 0.94 which means that sound wave will get reflected where steel and oil meet.

A CFD model in ANSYS was created to see how the pipeline reacted to wax deposition on the inside. As expected, the pressure decreased when flow went through wax deposition area.

5.2 The Next Steps

The next steps for the Master thesis is to extract the CFD result and make an observer based on Professor Aamo's work. Finding where wax is located, the wax deposition rate and what type of sensors are needed for the cooling system.

Empig is setting up their Cold Flow system at the Multiphase lab at SINTEF. This will give more accurate information.

Furthermore, ultrasound instrumentation for localization of wax and hydrates, Rocsole products and Statoil Petroleum product will discarded because of the results in this thesis.

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Appendix A

Nomenclature

ζ	Singular loss coefficient
$\lambda_{laminar}$	Friction coefficient
$\lambda_{turbulent}$	Friction coefficient
μ	Dynamic viscosity, $\mathrm{kg/ms}$
ν	Kinematic viscosity $\mathrm{m^2/s}$
ρ	Density material, $\mathrm{kg/m^3}$
A	Cross-section area, $\mathrm{m^2}$
c	Velocity, $\mathrm{m/s}$
C	Constant
C_1	Constant
d	Diameter, m
d_h	Character linear dimension, m
g	Gravitational acceleration, $9,81\mathrm{m/s^2}$
h	Height, m
k	Constant
l	Length, m
n	Number
p	Pressure, Pa
p_0	Initial pressure, Pa
δp	Differential pressure, Pa
Q	Flow, $\mathrm{m^3/s}$
Re	Reynolds number
RF	Reflection coefficient
t	Time, s
t_{steel}	Thickness steel, m
t_{wax}	Thickness wax, m
T	Temperature, $^\circ\mathrm{C}$
$T(t)$	Temperature function of time, $^\circ\mathrm{C}$
Z	Acoustic impedance, $\mathrm{kg/m^2s}$

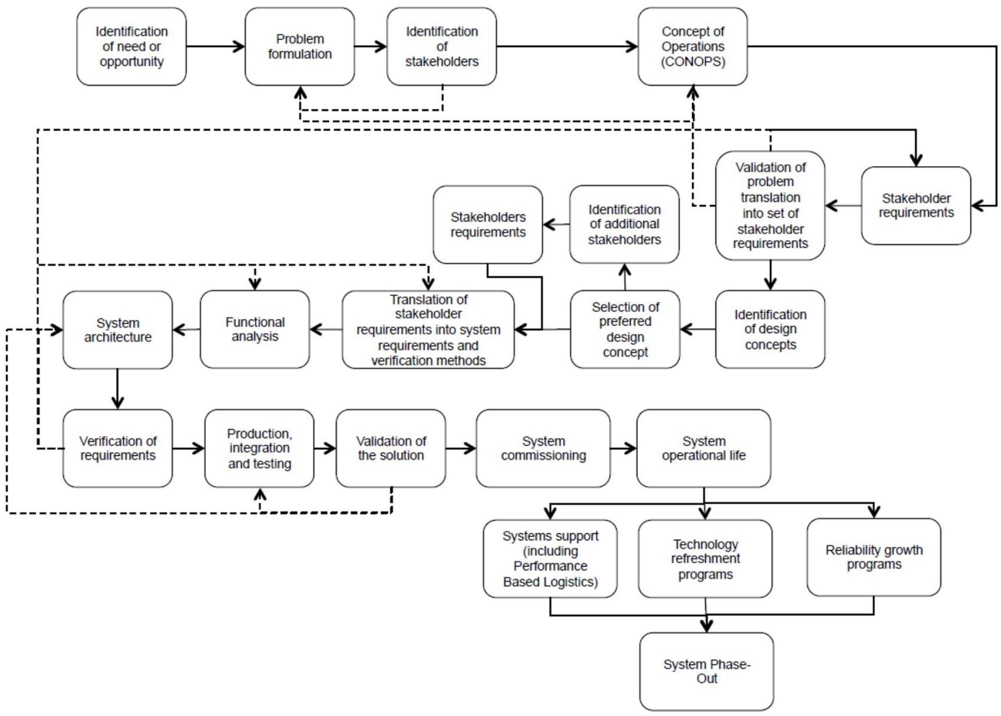
Appendix B

Acronym

CAD	Computed Assited Design
CF	Cold Flow
CFD	Computational Fluid Dynamics
CONOPS	Concept of Operation
IP	Intellectual Property

Appendix C

Alberto Sols improved Stevens model



Appendix D

CONOPS

Identification of need or opportunity

Empig AS has developed ha new system for extracting oil and gas. The cooling system will decrease the temperature of the mediums. When the oil and gas reach a specific temperature inside the pipes of the cooling system, some of it will become wax and hydrates. Finding locations for wax and hydrocarbons will be an advantage for the production. The worst-case scenario of not finding wax deposition and hydrocarbons will result to clogged pipes. The production will stop, and maintenance must be done before production can start again. The economic consequences will be large and not optimal for oil and gas production.

Boundaries

Get an understanding of the concept of Cold flow, looking at some sensors that has been used to determine wax deposition before. See if ultrasound is a good method to find wax deposition in the cooling system. Make a simplified model and result of pressure loss, temperature loss and ultrasound to see how that can be used in the cooling system. Finally make Computational fluid dynamic model to see how pressure changes with wax inside a straight pipeline.

Stakeholders

Table D.1: Stakeholders for this project.

Stakeholders	Active or Passive	Function
Empig AS	Active	Main stakeholder with the product
NTNU	Active	Main stakeholder with academic consultations
Competitors to Empig AS	Passive	Knowing of the product and make similar product before it is pattended
SINTEF	Passive	Researched Cold Flow for the first time in Norway
Environmental Groups	Passive	Promote the product if it is a better solutions then previous

Appendix E

Singular loss coefficient – Handout

Trykktap i rørsystemer

Alle bend, ventiler, skovler, tverrsnittsendringer etc i et rørsystem vil forårsake strømningstap.
Det er vanlig å beregne disse som trykktap,og de betegnes som singulærtap. Alle komponenter har en tapskoeffisient, ζ,
Som man finner i tabeller og som er funnet ved målinger.

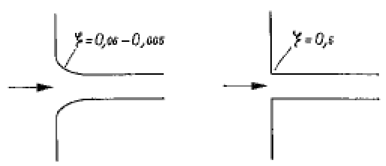
$$\Delta p = \xi \cdot \frac{\rho \cdot v^2}{2}$$

Totalt trykktap i et anlegg blir :

$$\Delta p_{Tot} = \Delta p_{Rør} + \Delta p_{Komponent1} + \Delta p_{Komponent2} + ... + \Delta p_{Komponent\,n}$$

Trykktap i rørsystemer

Innløp

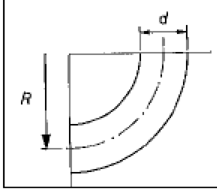


Tverrsnittsforandring

$\frac{d}{D}$	0,3	0,4	0,5	0,6	0,7	0,8	0,9
ζ_2	5,5	2,5	1,3	0,9	0,5	0,3	0,1
ζ_1	0,5	0,4	0,3	0,2	0,1	0,06	0,03

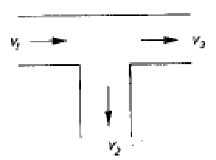
ζ regnes på hastigheten *før* tverrsnittsforandringen.

90° Rørbend

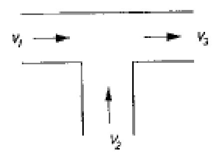


R	d	2d	3d	4d	6d	10d
ζ	0,30	0,16	0,14	0,12	0,10	0,09

Forgreininger



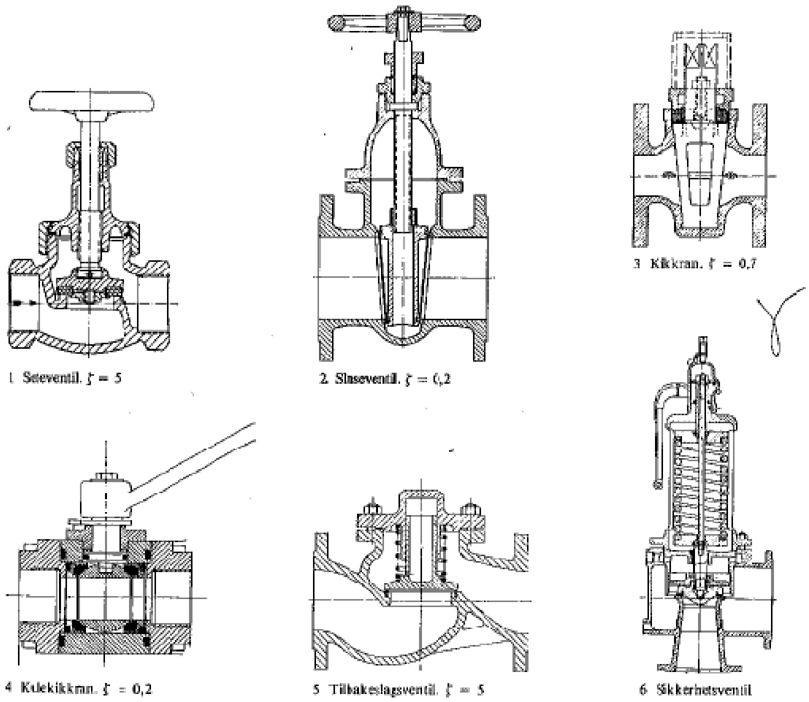
ζ = 1,0 (regnes på v_3)



$\frac{q_2}{q_1}$	ζ_2	ζ_3
0,4	0,1	0,3
0,6	0,5	0,4
0,8	0,7	0,5
1,0	0,9	0,6

ζ_2 regnes på v_2
ζ_3 regnes på v_3

Trykktap i ventiler



HØGSKOLEN I OSLO OG AKERSHUS