Emergency Rapid Drain System

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Sammanfattning

Metso Power är ett världsledande företag med spetskunskap inom konstruktion och service av sodapannor. Genom att återvinna kemikalier och generera elektricitet från restprodukter skapar sodapannan de nödvändiga förutsättningarna för pappersindustrin att möta de ständigt ökande miljökraven från dagens samhälle.

För att undvika en explosion måste pannorna vara utrustade med ett säkerhetssystem som kan tappa av vattnet ur tryckkärlet vid en eventuell olycka. Syftet med det här examensarbetet är att designa ett Matlab-program som beräknar tömningstiden och de resulterande krafterna som uppstår för ett sådant system. Det utvecklade programmet använder en homogen modell för att approximera tryckgradienter för tvåfasflöden. Andra modeller har undersökts och utvärderats i jämförelse med experimentellt uppmätta trycksänkningar men uppvisar inga förbättringar i noggrannhet.

Resultaten jämförs med beräkningar från ett tidigare använt program och uppvisar likheter i bland annat tömningstid för den första delen av processen. Krafterna på rörmynningarna beräknas till cirka 25% större än vad tidigare har antagits.

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Abstract

Metso Power possesses world leading competence in the design and service of recovery boilers; an important and widely used unit in the pulp and paper mills of today. By recovering chemicals and producing electricity from waste products the recovery boiler greatly improves the possibility for the paper industry to meet environmental demands. To avoid an explosion in case of an accident the boilers must be equipped with an emergency system that can drain a two phase water mixture from the pressure vessel.

This Master of Thesis deals with the designing of a Matlab computer program that calculates the draining time and the resulting forces for such a system. The program developed uses a homogenous model to approximate pressure gradients for two phase flows, the choice being based on research of existing correlations in combination with their proven accuracy. Results are compared to a program previously used, among other things predicting a similar time for the first half of the draining but a shorter time for the second part. The forces at the pipe outlets are estimated to be about 25% higher than those previously calculated. This paper provides information to gain a good understanding of how two phase flows can be treated and used to predict a number of factors important to design of draining systems.

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The aim of this Master Thesis Project is presented.

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Contains detailed information about the actual problem along with a discussion of what simplifications can be justified and special phenomenon that the solution must pay attention to.

Chapter 6, Strategy
Armed with the information from Chapter 5 an algorithm to solve the assignment is suggested.

Chapter 7, Execution
Contains discussions concerning what pressure models can be used and what information still needs to be provided. Subjects that need further investigation are presented with an analysis of how the calculations needed for the suggested algorithm will be addressed.

Chapter 8, Result
Results from the program parts developed are presented and combined to calculate the time for the whole draining process.

Chapter 9, Discussion
A discussion highlights points that may influence the validity of the program and results are compared to the formerly used program. By using existing facilities the differences between the programs are analysed.

Chapter 10, Conclusion
The most important conclusions are summarized.

1 Introduction

The pulping industry is one of largest in the world; an enormous quantity of wood is turned into paper each year. From an ecological and economic point of view it is of great importance to use all means possible to minimize the stress placed on the environment. By attaching a recovery boiler to the pulp mill one can reduce the amounts of chemicals used and at the same time utilize the heating value of the waste products. The constant improvement of units such as this provides the means necessary to combine the pulp industry with a society where energy supply and environmental issues are major concerns.

In the recovery boiler waste products are burned, producing steam of high temperature and pressure. Should there for some reason be a leakage of liquid from the water system into the furnace a rapid expansion due to water vaporising would occur. This would place the material of the furnace under great stress and avoiding this is a primary concern in the construction of recovery boilers. In order to prevent such an accident, the boilers are equipped with a safety system which drains the water. If it is drained too quickly the pressure vessel is placed under much thermal stress while a slow drainage is dangerous due to the issues earlier discussed. This paper deals with how the drainage time of a pressure vessel consisting of water and steam can be calculated and thus designed in order to meet the demands placed upon it.

2 Background

2.1 Employer

Metso Power builds, install and service recovery boilers that are to be a part of existing or planned paper mills. Boilers are sold separately or together with whole pulp mills in co-operation with Metso Paper.

Metso Power, with main operations in Finland, Sweden, USA and Brazil, employs 1500 people worldwide. The base for this Master of Science project has been in the office at Lindholmen, Gothenburg.

2.2 Assignment

The agreement between suppliers, users and insurance companies states that the system must be possible to drain in about twenty minutes. This is a compromise between reducing the risk of explosions due to uncontrollable vaporisation and the thermal stress placed on the pressure vessel. This reveals a need for a program that calculates the draining time for existing systems and that also can be used in the design of new ones. The program currently used has many flaws and was originally constructed for a HP calculator and later implemented in Matlab. It lacks references and relies on extensive research which is not well documented (the program designer is retired and can not be consulted with this problem). This makes the train of thought very difficult to follow and since the results obtained rely on that a program match can be found (further discussed in Chapter 9.2) their accuracy is limited. To remedy this, a new program must be developed which can better deal with the complicated nature of two phase flow and is adjusted to the technology and computer abilities of today.

3 Aim of the Master Thesis Project

This study focus on developing a new algorithm for handling the nature of two phase flow in pipe systems and predict the drainage time of the water inside the pressure vessel. The program developed will, in a user friendly way, illustrate how the pressure inside the recovery boiler varies with removed liquid and present the mass flow through each pipe as a function of time. The program must be able to handle either saturated or unsaturated water entering the pipes, its condition depending on where in the recovery boiler it is to be drained from.

4 Theory

4.1 The Recovery Boiler

In order to break the chemical bindings and extract cellulose fibres, the chipped biomass used in the pulp production is cooked in a boiler. To separate lignin and hemi-cellulose from cellulose, and also recover important chemicals, the pulp is passed through a washer. Afterwards the washing fluid contains chemicals and waste which, after it has been steam dried to 65-80% dry substance, is burned in the recovery boiler. Figure 1 shows a general flow sheet for a pulp mill and how the recovery boiler is integrated in the fibre line.

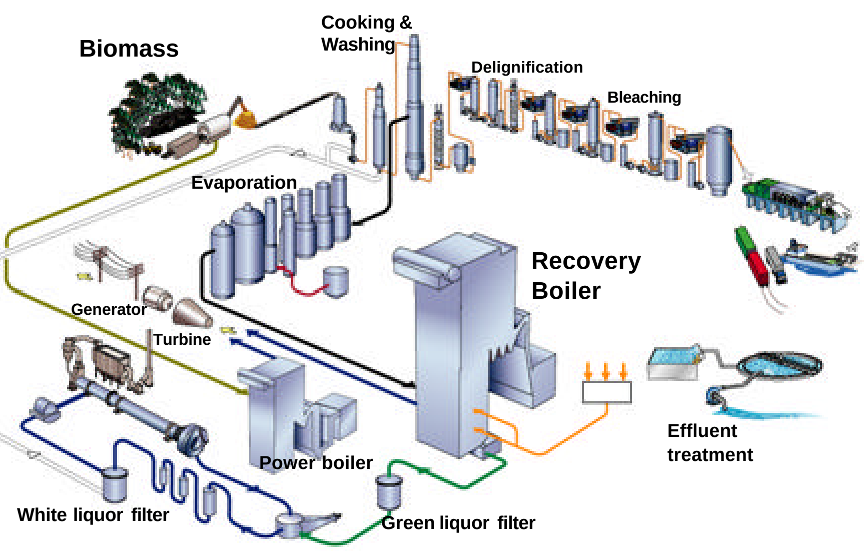

Figure 1: Flow sheet for a pulp mill (Metso slideshow).

By burning the organic waste and utilizing the heating value, steam for the drying process is provided. The excess steam is expanded in a turbine in order to produce electricity. During the combustion sodium carbonate (Na_2CO_3) and, due to less oxygen than needed for complete combustion, sodium sulphide (Na_2S) is formed. Because of the high temperature in the combustion chamber these compounds melts and are passed through the burning bed to the dissolving tank. The use of burned chalk (CaO) helps solving the sodium carbonate and both sodium hydroxide (NaOH) and calcium carbonate ($CaCO_3$) are formed, the later being a solid substance (commonly referred to as mesa) [1]. Left in the liquid are sodium sulphide and sodium hydroxide which are used in the digesting of the pulp. The adding of secondary air above the bed provides extra oxygen and ensures complete combustion (and thereby maximum steam production) of the organic compounds.

By using the procedure outlined above a minimum of chemicals is consumed, steam for drying is provided and electricity produced [1]. A simplified overview of the process is given by figure 2.

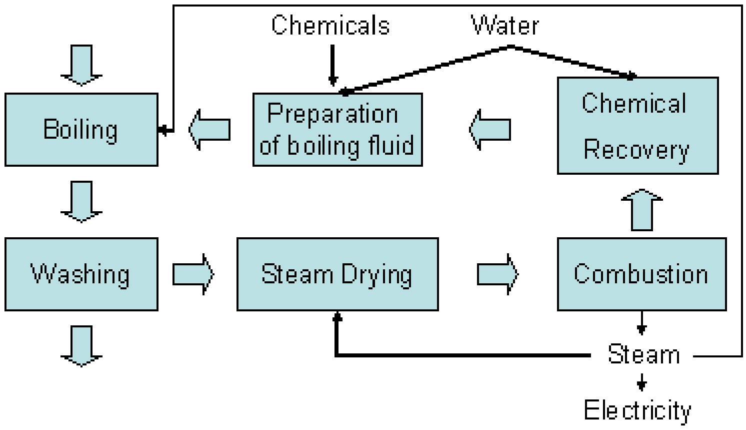

Figure 2: Overview of recovery part of the pulp process [1].

4.2 Flow Patterns

The phenomena of a liquid flowing together with a gas greatly complicate the analysis compared to the case of single phase flow. To accurately describe a certain flow one must know the momentary flow pattern and adjust it if pressure drops causes it to change further down streams. Flow patterns in horizontal pipes are divided into bubbly flow, plug flow, stratified flow, wavy flow, slug flow and annular flow [2]. Figure 3 illustrates what the gas and fluid profile for the different flow patters may look like. Each type calls for simplifications which causes different pressure drops, velocity distributions and heat transfer. To predict the correct behaviour of a certain flow it is therefore very important to choose an appropriate model.

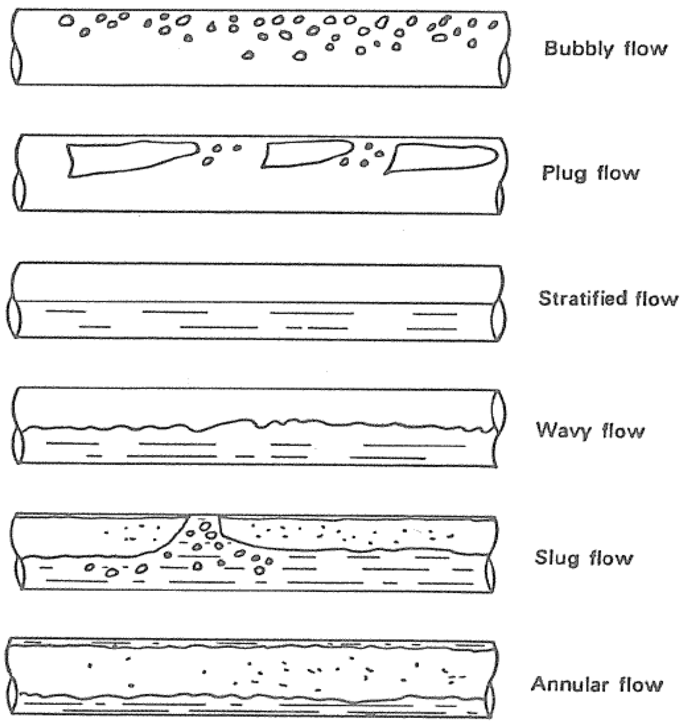

Figure 3: The different flow patterns for adiabatic flow in horizontal pipes [2].

In bubbly flow, the gas is moving as isolated bubbles in the liquid and as the fraction of gas increases the result is plug flow with large plugs of air. Stratified flow can only truly exist if the gas and liquid is moving with the same velocity since the forces between the surfaces then will equal each other. In all other cases the forces causes waves on the surface of the liquid, small waves in wavy flow and large ones that reach the ceiling in slug flow. When the fraction of gas is further increased and the flow velocity is high annular flow will dominate and the liquid only exist in a film along the wall [2].

To determine what type of flow that exists in a certain application one can use photographs or use one of the numerous flow regime charts that have been developed over the years. The chats predict the type of flow at a certain point depending on the density, viscosity and mass flux of gas and liquid. Figure 4 shows an example of what a flow regime chart may look like. A problem with using a chart is that the result is only true for the point being examined and the flow pattern will in many cases change as the pressure decreases down stream.

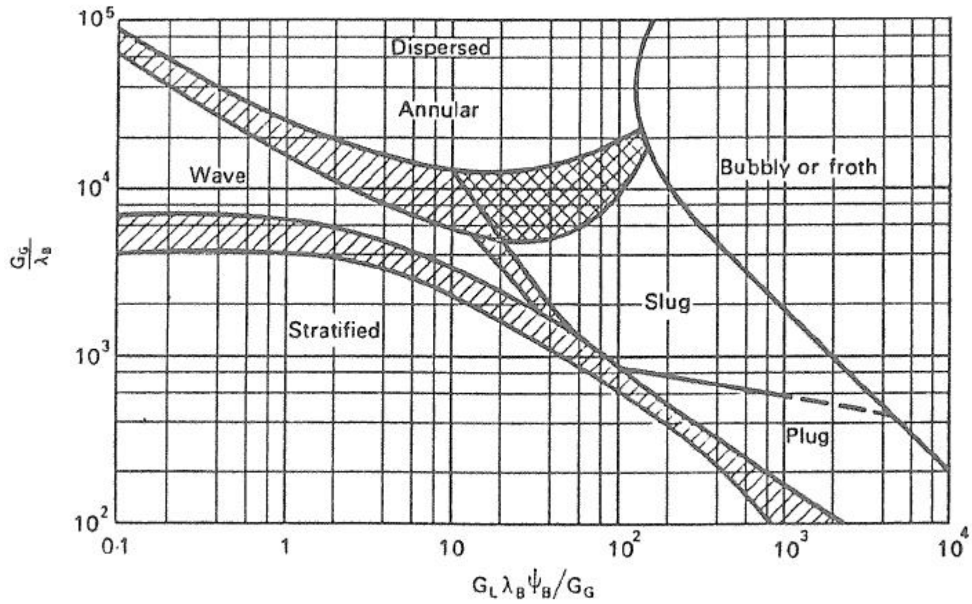

Figure 4: Flow regime chart by Scott 1963 [2].

4.3 Theoretical Deriving of the Pressure Drop in a Pipe

By deriving general expressions for the pressure gradient that are valid for all types of flows it is later possible to choose a flow model that fits the situation at hand. Different models calls for different simplifications which affect the expressions derived. The choice of model mainly depends on the need for accuracy, available data and computer power. Below the pressure gradient for flow in an inclined pipe is derived by using the law of momentum conversation. The type of flow does not affect the resulting equations and stratified flow is used as an example to illustrate the problem.

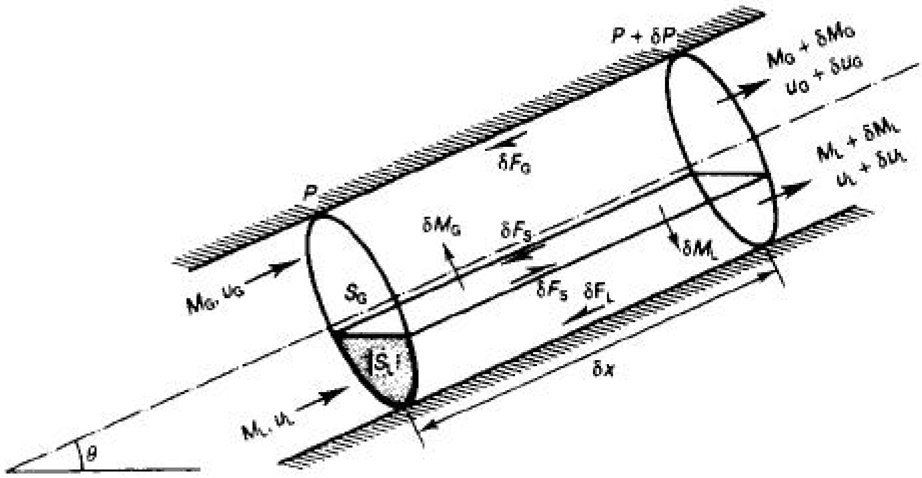

Figure 5: Momentum and forces for acting on a fluid flowing in an inclined pipe [2].

The change of momentum and the force acting on the fluid in the positive x direction can be expressed as

$$(M_G + dM_G)(u_G + du_G) + (M_L + dM_L)(u_L + du_L) - (M_G u_g + M_L u_L) \qquad \text{eq 1}$$

and

$$-SdP - dF_G - dF_L - (S_G r_G + S_L r_L) g \sin q dx \qquad \text{eq 2}$$

where index L represents liquid and index G gas [3].
Also:

S = cross sectional area	(m^2)
u = speed	(m/s)
M= mass	(kg)
F= force	(N)
P= pressure	(Pa)
g = gravitation constant	(m/s^2)
? = density	(kg/m^3)

In eq 1 the first two terms represents the momentum leaving the control volume and the last term the momentum entering it. The forces acting between the two phases have been left out in eq 2 since they cancel each other.

The net force acting on the fluid equals its change of momentum and the above equations can be set equal and rearranged to create an expression of the pressure drop along the x-axis. In equation 3 the second order derivatives have been neglected, which according to Holland is acceptable in almost all cases [4].

$$\frac{dP}{dx} = -\frac{1}{S}\frac{dF}{dx} - \frac{1}{S}\frac{d}{dx}(M_G u_G + M_L u_L) - \left(\frac{S_G r_G}{S} - \frac{S_L r_L}{S}\right) g \sin q \qquad \text{eq 3}$$

The three components of the right hand side of equation 3 will from here on be referred to as the pressure gradient due to friction, acceleration and static head.

$$\left(\frac{dP}{dx}\right)=\left(\frac{dP}{dx}\right)_f\left(\frac{dP}{dx}\right)_a\left(\frac{dP}{dx}\right)_{stat} \qquad \text{eq 4}$$

When calculating pressure drops along pipes it is more convenient to express the momentum and acceleration term with the help of the mass flux (G), void fraction (a) and the mass fraction (?) of gas. These are defined as:

$$a=\frac{S_G}{S} \qquad \text{eq 5}$$

$$1-a=\frac{S_L}{S} \qquad \text{eq 6}$$

$$w=\frac{M_G}{M} \qquad \text{eq 7}$$

$$1-w=\frac{M_L}{M} \qquad \text{eq 8}$$

$$G=\frac{M}{S} \qquad \text{eq 9}$$

These equations make it possible to express the velocity of the fluid in terms of its specific volume (V):

$$u_G=\frac{M_G V_G}{aS}=\frac{wGV_G}{a} \qquad \text{eq 10}$$

$$u_L=\frac{M_L V_L}{(1-a)S}=\frac{(1-w)GV_G}{1-a} \qquad \text{eq 11}$$

Finally the definitions used above and the expression for the velocity are substituted into the pressure equations which yields:

$$\left(\frac{dP}{dx}\right)_f=-\frac{1}{S}\frac{dF}{dx} \qquad \text{eq 12}$$

$$\left(\frac{dP}{dx}\right)_a=-G^2\frac{d}{dx}\left(\frac{w^2V_G}{a}+\frac{(1-w)^2V_L}{1-a}\right) \qquad \text{eq 13}$$

$$\left(\frac{dP}{dx}\right)_{stat}=-\left(\frac{a}{V_G}+\frac{1-a}{V_L}\right)g\sin q \qquad \text{eq 14}$$

4.4 Models for Pressure Drop

All the models discussed below are treating the flow with a uniform velocity profile, meaning that the velocities in the centre and at the boundary are the same. Since the fluid at the boundary is stationary this is not true but the averaging of speed over the cross section greatly simplifies the calculations and seems to produce acceptable errors [2].

4.4.1 Homogenous Model

Instead of treating the flow as two fluids a homogenous approach models the flow as one fluid with properties that are a mixture of the two flows. The properties are weighted in relation to the quality of the mixture. This approach has two major requirements; that the two fluids are in thermal and mechanical equilibrium and that they have the same velocity.

When these simplifications are made, a less complicated expression for the momentum can be derived. The mean specific volume and the product of cross section area and mean density can be expressed as:

$$\overline{V} = wV_G + (1-w)V_L \qquad \text{eq 15}$$

$$S\overline{r} = S_G r_G + S_L r_L \qquad \text{eq 16}$$

By using the above equations combined with the fact that the velocities are equal the pressure equation (eq 3) can be written as:

$$\frac{dP}{dx} = -\frac{1}{S}\frac{dF}{dx} - G\frac{du}{dx} - \overline{r}g\sin q \qquad \text{eq 17}$$

Before further analysis is made, the pressure gradient due to friction must be expressed in terms of known quantities. This is achieved by using the inner diameter (d_i) and the shear stress at the wall (eq 18). The later is a function of the density, speed and friction factor (f) according to eq 19.

$$\left(\frac{dP}{dx}\right)_f = -\frac{4t}{d_i} = -\frac{2f\overline{r}u^2}{d_i} \qquad \text{eq 18}$$

$$t = \frac{1}{2}\overline{r}u^2 f \qquad \text{eq 19}$$

In analogy with the previous derivation of the general pressure gradient eq 17 can now be divided into three components and written in terms of mass flux, mass fraction and void fraction.

$$\left(\frac{dP}{dx}\right)_f = -\frac{1}{S}\frac{dF}{dx} = -\frac{2f\overline{r}u^2}{d_i} = -\frac{2fG^2\overline{V}}{d_i} \qquad \text{eq 20}$$

$$\left(\frac{dP}{dx}\right)_a = -G\frac{du}{dx} = -G\frac{d}{dx}(G\overline{V}) = -G^2\frac{d\overline{V}}{dx} = -G^2\left[w\frac{dV_G}{dx} + (V_G - V_L)\frac{dw}{dx}\right] = -G^2\left[w\frac{dV_G}{dP}\frac{dP}{dx} + (V_G - V_L)\frac{dw}{dx}\right] \qquad \text{eq 21}$$

$$\left(\frac{dP}{dx}\right)_{stat} = -\bar{r} g \sin q = -\frac{g \sin q}{\bar{V}} \qquad \text{eq 22}$$

Since the mass fraction of gas and therefore mean specific volume will change along the pipe, the pressure drop due to acceleration is quite complicated. It is an implicit function and in the expression for the total pressure gradient it must be rearranged to arrive at an explicit expression.

$$\frac{dP}{dx} = -\frac{\left(\frac{2 f G^2 \bar{V}}{d_i} + G^2 (V_G - V_L)\frac{dw}{dx} + \frac{g \sin q}{\bar{V}}\right)}{1 + G^2 w \frac{dV_G}{dP}} \qquad \text{eq 23}$$

If the properties above are evaluated at a known pressure and considered constant for a short length, the pressure gradient for this section can be calculated. Multiplying the result with the length considered and subtracting it from the initial pressure will yield the starting pressure for the next section. However there are two major problems left to solve for this to be a usable method.

- The friction factor must be calculated.
- The rate of quality change over the section considered must be known.

There is no theoretical literature on how these matters should be treated and approximations for this paper are addressed in Chapter 7.2.2 and Chapter 7.2.3 respectively.

4.4.2 Drift Flux Model

The drift flux model, as the homogenous model, relies on calculating properties for a mixture and therefore also requires thermal and mechanical equilibrium. Interestingly it allows for the phases to travel at different velocities. This is done by introducing a drift velocity which models the relative speed of one phase compared to the other. So far this model has unfortunately only shown successful results for bubbly flow and plug flow [5]. It will not be further investigated in this report.

4.4.3 Separate Flow Model

In separated flow the gas and liquid are treated as two separate flows, which are not bound by the conditions of thermal equilibrium and equal speed. Fewer simplifications can be made and eq 12 – eq 14 well models the pressure gradient [6]. Unfortunately there are very few analytical models for calculating the frictional part of the pressure gradient (there are a few ones existing for bubbly flow but not for the annular flow that might be expected in this application). Therefore the calculations of the frictional pressure gradient in all separated models depend on empirical correlations and diagrams, most commonly by presenting values of the so called two phase multiplier. Using the whole mass flow as either gas or liquid, depending on the dominating, the multiplier is the estimated constant that the pressure gradient due to friction for one phase flow is to be multiplied by in order to give the pressure gradient for the two phase flow being examined [7].

$$\left(\frac{dP}{dx}\right)_f = \left(\frac{dP}{dx}\right)_{f,liquid} j^2 \qquad \text{eq 34}$$

f ^{2} = Two phase multiplier

The first thoughts concerning the evaluation of two phase multipliers were presented by Lockhart and Martinelli in 1949 and were based on the idea that each phase of the flow occupies a certain space. Standard pressure gradient equations were used separately on each flow and thus the interaction between the phases was ignored. The study yielded values of the two phase multiplier for four different flow regimes and were graphically presented. By only considering the turbulent flow regime Martinelli and Nelson further developed the correlations, making it valid for boiling and condensation applications as well [8].

One of the parameters that must be evaluated to use the two phase model is the integral of the two phase multiplier over the length of the pipe. Marinelli and Nelson chose to present this as a numerical value depending on the pressure and quality. Void fractions which also must be known to evaluate the pressure drop were estimated by interpolating pressure curves in a quite complicated way and were presented in a diagram as a function of pressure and quality [7]. In 1964 Thom concluded a study which compared the values of the two phase integral and void fractions estimated by Martinelli and Nelson to a large data bank in Cambridge, England. He suggested slightly different values of these factors and presented it in tabular form. They are not presented here but can be viewed in “Convective Boiling and Condensation” by Collier.

Another common way to evaluate the void fraction is by comparing the slip (Sl) and mass fraction. Also in this field extensive studies containing large quantities of data have been conducted. One of the most accurate is Chisholm’s study from 1973 (eq 25) which is a simple relationship that provides the least standard deviation of the studies compared. It should be noted that the standard deviation still is of the order 25%. Once the quality has been determined the void fraction is calculated by using eq 26 [7].

$$Sl = \left[w\left(\frac{r_L}{r_G}\right) + (1-w)\right]^{1/2} \qquad \text{eq 25}$$

$$Sl = \left(\frac{w}{1-w}\right)\left(\frac{r_G}{r_L}\right)\left(\frac{1-a}{a}\right) \qquad \text{eq 26}$$

5 Problem Description

A program to solve the problem at hand must have access to some general information about the pressure vessel. In all calculations the pressure vessel will be considered a tank with unspecified geometry and the parameters that may be used as input are:

-The total volume of the tank
-The volume of liquid before the draining
-The volume of liquid after the draining
-The initial pressure inside the tank

In the beginning of the draining process it is necessary to remove liquid more quickly than in the end. For this reason the draining should be split into two parts where each part can use a different number of draining pipes. To decrease the risk of uncontrollable vaporisation and avoid too much thermal stress on the pressure vessel it has been agreed that each part should take about ten minutes to complete.

In reality the liquid is drained from the downcommers which are subject to some static pressure. This means that the fluid may be slightly sub cooled instead of saturated at the pipe entrance but as the pressure will quickly decrease, this will be ignored.

Since a mix of vapour and liquid co-exist in the tank it will be assumed that they are in equilibrium and each phase is saturated. This makes it possible to use enthalpy, internal energy, specific volume, enthalpy of vaporisation and temperature corresponding to the saturation pressure. It must however be kept in mind that liquid will turn into steam as the pressure decreases (a phenomena referred to as flashing) and since the specific volume of vapour is greater than that of liquid the mixture must accelerate in order to not violate the law of mass conversation. According to physical laws the velocity can not exceed the speed of sound and when the flow is limited by this constraint it is commonly referred to as choked flow. Choking is definitely a limiting factor in this application and must be taken into account during the calculations.

When the calculations are finished the program must provide the following:

-The pressure inside the tank as a function of removed liquid
-The initial mass flow through each pipe used
-The time for each part the draining
-The force that the pipe outlet will be subject to

6 Strategy

The strategy for finding the time needed to empty the tank is to:

1. Calculate the pressure inside the tank as a function of how large volume that has been removed (either by vaporization, draining or change in density).

2. Calculate the pressure drop in the pipe system as a function of the flow. This step requires information regarding material and construction of the pipe system and must also pay respect to choked flow and flashing.

To avoid some of the problems associated with transient flow, the volume of fluid that needs to be removed will be split up into a number of volume elements. During the draining of one volume element the pressure inside the tank will be viewed as constant (being the mean of the initial and ending pressures for the current volume element). This makes it possible to treat the flow during the drainage of one volume element as constant.

3. The correct flow rate for one volume element can be calculated by comparing the pressure difference between the tank and the pipe exit to the pressure drop over the pipe system calculated in point 2. The correct mass flow is the flow that causes equal pressure differences. This flow can then be used to determine the time needed to drain a certain volume element.

4. By adding the time for each volume element the total time is calculated.

5. Since the number of pipes used during the first part of the draining may not be the same as in the second part, the program will be split in two (as mentioned in Chapter 5). Each will calculate the time needed to drain the volume specified as input data. Changes will have to be made to the pipe system if either one of them greatly differs from ten minutes.

7 Execution

7.1 Discharge of the Tank

When water is drained from the tank the pressure inside it will decrease. Since the water is saturated it will immediately start boiling and a certain amount is vaporized. This process requires energy and the temperature inside the system will therefore decrease. When equilibrium is reached and the system once again is saturated the boiling will stop but the pressure at this point will be lower than the initial one. In case of an accident the important thing is to empty the tank of liquid which means that the removed volume can be viewed as the sum of the liquid exiting the tank and the amount turned into steam.

The end pressure inside the tank can be calculated using a thermodynamical approach. For systems with unsteady flow rates, the energy balance over a control volume (in this case the tank) can be expressed as [9]:

$$E_{in} - E_{ut} = \Delta E_{system} \qquad \text{eq 27}$$

E_{in} = energy entering the system
E_{out} = energy leaving the system
?E = change in internal, kinetic and potential energy inside the system

Since energy can enter and leave a system by heat, work or mass flow eq 27 can be written as:

$$Q_{in} + W_{in} + \sum_{in} mq - Q_{out} - W_{out} - \sum_{out} mq = m_2 e_2 - m_1 e_1 \qquad \text{eq 28}$$

Q_{in} = Heat transfer to the control volume
Q_{out} = Heat transfer from the control volume
W_{in} = Work done on the system
W_{out} = Work done by the system
m_{in}= Mass entering the control volume
m_{out}= Mass leaving the control volume
?$_{in}$= The energy of a entering fluid stream per mass unit
?$_{out}$= The energy of a leaving fluid stream per mass unit
m_1 = Mass inside the control volume before
m_2 = Mass inside the control volume after
e_1 = Energy per mass unit of fluid inside system before
e_2 = Energy per mass unit of fluid inside system after

The energy of a flowing fluid per mass unit is the sum of its enthalpy (h), kinetic energy (Ke) and potential energy (Pot).

$$q = h + Ke + Pot \qquad \text{eq 29}$$

The system is stationary and thus its change in kinetic and potential energy is zero. The energy inside the system per mass unit (e) is then only the internal energy (u). Also no work is done on or by the system and no mass is entering the control volume. This reduces eq 28 to

$$Q_{in} - Q_{out} - m_{out}(h + Ke + Pot) = m_2 u_2 - m_1 u_1 \quad \text{eq 30}$$

u_1 = Internal energy before per unit mass
u_2 = Internal energy after per unit mass

In reality there is no input of heat to the system but the term will still serve a purpose in this calculation. The idea is that if the pressure after the removal of the liquid was known the heat supplied to reach this pressure could be calculated. This is possible since the internal energy and enthalpy for gas and liquid can be evaluated from steam tables under saturated conditions. One can be sure that in order to keep the pressure constant, heat must be added because of the energy needed to convert liquid to steam. By carefully decreasing the assumed final pressure, and repeatedly doing so until eq 30 shows that no heat needs to be transferred to the system, the correct pressure can be estimated. The calculations below show how the terms in eq 30 can be evaluated for an assumed end pressure.

The total mass inside the control volume is the sum of the gas and liquid masses. Since the total volume, initial and ending liquid volume, and the initial and final pressures are known or assumed, the masses before and after the draining can be calculated with eq 31 – eq 32. The pressures are used to determine specific volume, internal energy and enthalpy from steam tables.

$$V_{tot} = V_{gas} + V_{liq} \quad \text{eq 31}$$

$$m_{1,2} = m_l + m_g = \frac{V_{liq}}{V_l} + \frac{V_{gas}}{V_g} \quad \text{eq 32}$$

V_{liq} = Volume occupied by the fluid
V_l = Specific volume of the fluid
V_{gas} = Volume occupied by the gas
V_g = Specific volume of the gas

The enthalpy per mass unit for the liquid used in eq 30 will be the average enthalpy corresponding to the initial and final pressures. If a known fraction of steam would exit with the liquid it could easily be accounted for by adjusting the enthalpy according to thermodynamical relations. Examinations of test results show that this is seldom the case (Lufkin study).

The amount of mass leaving the system is equal to the total change of mass inside the system.

$$m_{out} = m_1 - m_2 \quad \text{eq 33}$$

The total internal energy of the system is the product of internal energy and mass, in this case calculated as the sum contributions done by the liquid and the gas.

$$m_{1,2}u_{1,2} = m_l u_l + m_g u_g \quad \text{eq 34}$$

The potential energy per unit mass of the exiting fluid is neglected and the kinetic energy is approximated by eq 35 using an exit velocity (c) of 6m/s. This value depends on the construction and diameter of the exit hole but tests show that the contributions of kinetic energy to the total exiting energy are as small as 0.1-0.2 percent and further analysis are not needed.

$$Ke = \frac{1}{2} c^2 \qquad \text{eq 35}$$

There is no really good way to approximate the heat transfer from the system. In reality the losses would depend on the size of the pressure vessel, the pressure inside it, the surface temperature and its material. Since some of these quantities will vary in time it would be a difficult transient problem to solve. Instead the following approximations have been made:

- The time (t) needed to drain each volume element belonging to the same part of the draining process is equal.
- The total time for one part is 600 seconds.
- A constant value (800kW for part one and 950kW for part two) is chosen for a tank volume of 126m^3. This ensures that the results match documented data of the final pressure and the losses noted during a draining test. The losses are weighted in relation to the total volume of the tank.

This yields eq 36 and eq 37 for the first and second part of the draining respectively.

$$Q_{out} = \frac{800kW}{126} V_{tot} \cdot t \qquad \text{eq 36}$$

$$Q_{out} = \frac{950kW}{126} V_{tot} \cdot t \qquad \text{eq 37}$$

This provides all properties necessary to evaluate eq 30. As previously discussed the process of assuming a final pressure is repeated until the calculation shows that no heat needs to be added to the system.

With the method above the final pressure in the tank could easily be calculated. That would, however, not be quite satisfactory. Using the average pressure to calculate the flow in the pipe system would cause considerable error. Instead the total volume is divided into smaller volume elements. For each element a final pressure is assumed and the heat calculation continued until the correct end pressure of this element is reached. This pressure serve as input data to the next volume element and the process is complete when the end pressures of all the volume elements have been determined. The mean pressure for each element is used as input to the program that calculates the flow through the pipe system.

7.2 Pressure Prop in a Pipe System

7.2.1 Choosing a Model

As the liquid flows along the pipe the pressure will decrease. The large pressure difference between the internal pressure in the tank and the outlet pressure combined with the fact that the liquid is close to saturated will quickly initiate intensive boiling and fast vaporisation.

These circumstances imply annular flow and validate the choice for a model fitting this flow [10]. Should the drainage be done from the economiser of the recovery boiler instead, the liquid will not be saturated and thus the regime where annular flow occur would be shorter. It must however still be considered relatively short due to the large total pressure drop and the same model could be used.

Since the homogenous model uses average quantities of the mixture and depend on thermal equilibrium between the phases, it requires that one phase is well dispersed into the other. The later ensures that the momentum and energy transfers are quick enough for equilibrium to be established. The model is most applicable if no great changes in flow pattern occur along the pipe and thermal non-equilibrium would not greatly influence the flow pattern [7].

Experiments with flows in high pressure steam tubes, by Whitcutt and Chojnowski in 1973, compared measured results to the results predicted by the homogenous model using a single phase friction factor. In 95% of the cases the error was lower than 8% which must be considered relatively low [8]. There is a good chance the error would have been even lower if a better method for determining the friction factor had been used.

Many different studies for providing values of two phase multipliers for separated flow have been conducted. Unfortunately it is difficult to be sure which correlations give the most accurate results. Also, all correlations for annular flow that have shown decent accuracy are missing algebraic expression and therefore solely rely on diagrams. These have to be converted to computer code if they are to be used in this application.

Bergles [7] expresses the opinion that the Martinelli-Nelson correlation seems to be better than the homogenous for low mass velocities ($G<1300kg/m^2s$) but in other cases the homogenous model might be a better option. One of the shortcomings of Martinelli-Nelson is that it does not account for the surface tension between the phases even though at high pressures it could prove to be very important.

Whalley [5] states “The homogenous model can give very satisfactory results for the void fraction and the overall pressure gradient. However at low pressures the results can be inaccurate”. More precisely he recommends the homogenous model as long as the density ratio between the liquid and the gas is lower than ten (which corresponds to a pressure above 120bar) and the mass flux is above $2000kg/m^2s$.

The correlations presented by Lockhart, Martinelli, Nelson and Thom does not account for the influence of mass flow. Experiments by Muscettola in 1963 indicate that all these correlations are mostly valid for mass fluxes of $500\text{-}1000kg/sm^2$. This shortcoming has been addressed by correlations suggested by Baroczy and Friedel [7]. The Baroczy correlations unfortunately have drawbacks that will later be discussed. The Friedel correlation is one of the most recent models developed and in fact much of the literature used in this study is too old to include this model. The prediction of pressure drop by the Friedel correlation seems to give quite good results when compared to experimental data [6].

A study by Idsinga (1977) used 3460 experimental steam-water pressure losses ranging from 17 to 103 bars with a steam quality from subcooled to superheated. It compared 18 existing correlations for determining the pressure drop in two phase flow. Overall the homogenous model delivered the most accurate results. For the special range of the quality being below 0.6 and the mass flow below 2700 kg/m^2s the Baroczy correlation best modelled the measured pressure drop [7]. Unfortunately this model relies on diagrams and only has data for the two phase multiplier based on a mass flux of 1356kg/m^{2}s. Therefore it needs extensive interpolation of existing diagrams in order to be of use for other mass flows. This is possible but would require time consuming work to be done. To account for the effect of mass flux Streeter [11] instead suggests the use of the Friedel correlation as earlier mentioned.

As a final note it is important to highlight the fact that even the best empirical methods for the calculation of two phase pressure gradients give errors of the order of 40% [5]. Because of the uncertainty of the methods for separated flow outlined above, this project will determine pressure gradients from the homogenous model. Should this not give reliable result the pressure drop part of the program can be redesigned.

7.2.2 Friction Factor

To be able to use the homogenous model the friction factor and the change of quality along the pipe must be known. First the problem with determining the friction factor will be addressed. This may represent the biggest uncertainties of this model (and other commercial programs too) and time invested in improving this step could be well spent. There are numerous ideas presented in this field by among others, Whalley, Streeter, Collier, Cengel and Bergles. Unfortunately few conclusions have been confirmed even though much focus has been paid to the subject. When comparing different models it is important to keep in mind that some authors use the Fanning definition of the friction factor while others use the Darcy definition. One is simply a multiple of the other but should the wrong one be used it obviously greatly affects the result. There are several ways to estimate the friction factor and three of them will be further discussed.

(1) Constant Value of the Friction Factor

This is the simplest and also the most incorrect way to treat the frictional pressure drop. It is best used for a first estimate and in that case a value 0.005 for the friction factor in high pressure boilers and annular flow may be used [12].

(2) Friction Factor Equal to One Phase Flow

The frictional pressure gradient can be evaluated using a friction factor corresponding to if the whole flow in the pipe was considered to be one phase. One must of course decide if it is appropriate to use liquid or gas as the reference flow, the choice most likely depending on the quality of the flow. If the whole flow is considered liquid the frictional pressure gradient can be expressed as

$$\left(\frac{dP}{dx}\right)_{LO} = \frac{2 f_{LO} G^2 V_L}{d_i} \qquad \text{eq 38}$$

where index LO denotes “Liquid overall” [11]. This equation is derived the same way as eq 20 but uses only the specific volume of the liquid instead of an average value.

The ratio of the actual pressure gradient to the “liquid overall” pressure gradient is

$$\left(\frac{dP}{dx}\right)_f \Bigg/ \left(\frac{dP}{dx}\right)_{LO} = \frac{2 f G^2 \overline{V}}{d_i} \Bigg/ \frac{2 f_{LO} G^2 V_L}{d_i} = \frac{f \overline{V}}{f_{LO} V_L} \qquad \text{eq 39}$$

By assuming that the friction factor for the two phase flow equals the friction factor for the liquid phase the frictional pressure drop can be written

$$\left(\frac{dP}{dx}\right)_f = \frac{\overline{V}}{V_L}\left(\frac{dP}{dx}\right)_{LO} \qquad \text{eq 40}$$

Using this approach the first term in eq 27 can be substituted by eq 40.

This leaves only the evaluation of the friction factor for “liquid overall” flow, which is normally done by using the Moody chart. This is a well known and widely used graphical correlation connecting Reynolds number (Re) to the friction factor for different pipes. Since the friction factor in the program must be evaluated many times over eq 41 presented by Colebrook (where e is the roughness of the pipe) will instead form the base of calculation.

$$\frac{1}{\sqrt{f_{Darcy}}} - 2\log\left(\frac{e/d_i}{3.7} + \frac{2.51}{\mathrm{Re}\sqrt{f_{Darcy}}}\right) \qquad \text{eq 41}$$

The value of the Fanning friction factor is a quarter of the Darcy factor and is used in all calculations in this project.

The Colebrook equation is implicit and instead of using an iterative process (which might prove more accurate) an approximate equation presented by Haaland in 1983 will be used.

$$\frac{1}{\sqrt{f_{darcy}}} - 1.8\log\left(\left(\frac{e/d_i}{3.7}\right)^{1.11} + \frac{6.9}{\mathrm{Re}}\right) \qquad \text{eq 42}$$

According to Cengel [3] the results obtained from eq 42 are within two percent of those given by the Colebrook equation. Carefully determining the friction factor from the Moody chart for each section would be slightly better but this is in this case not very practical.

As long as the steam quality is reasonably low this way of determining the frictional pressure drop seems quite good. Should the quality rise above fifty percent it would be better to use a “gas overall” model. The program developed will use the above model for estimating the friction factor.

To evaluate the Reynolds number one must know the viscosity of the liquid since

$$\mathrm{Re} = Gd_i / m \qquad \text{eq 43}$$

where µ is the viscosity.

The viscosity is mainly a function of temperature and therefore the temperature in the pipe has been assumed to equal the saturation temperature at the current pressure. A regression of tabular values for liquid water has been made and is presented in figure 6.

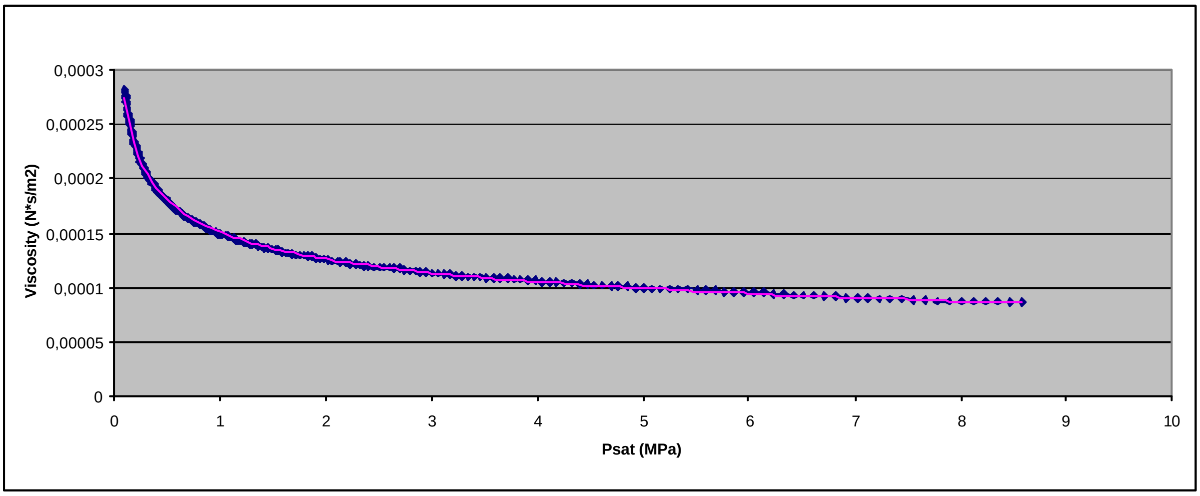

Figure 6: Regression of tabular values for viscosity of liquid water.

This concludes the task of calculating the parameters needed to evaluate the frictional pressure gradient. It is the approach that will be used in this study but in case of future changes an alternative way of approximating the viscosity is outlined below. This will affect the value of the friction factor and could prove more correct.

(3) Frictional Pressure Prop Using a Mean Viscosity

The mean viscosity can be used in evaluating Reynolds number and then the friction factor can be calculated as for one phase flow. One way to express the viscosity is eq 44 but many other suggestions have been made too.

$$\frac{1}{\overline{m}} = \frac{w}{m_g} + \frac{(1-w)}{m_l} \qquad \text{eq 44}$$

This may present a better method than the one outlined above as it predicts the correct viscosity when the quality is both zero and one. There is however no guarantee that the value of Reynolds number and friction factor will be correctly estimated, a fact that many reports have pointed out and caused Dukler to evaluate the mean viscosity in a different manner [7]. It is difficult to predict how much the choice of model will affect the result in this application but it might be worth more attention.

The Reynolds number calculated by the mean viscosity can be used in eq 42 as with model number two used in a connection with the Blasius equation (being valid only for smooth pipes). The later approach makes it possible to calculate the frictional pressure drop directly with eq 45 (which will not be derived here) and in that way avoid the error introduced by eq 41 and its simplification eq 42.

$$\left(\frac{dP}{dx}\right)_f = \left(\frac{dP}{dx}\right)_{LO}\left[1 + w\left(\frac{V_g - V_l}{V_L}\right)\right] * \left[1 + \left(\frac{|m_l - m_g|}{m_g}\right)\right]^{-1/4} \qquad \text{eq 45}$$

It should be pointed out that the old program used an expression of Churchill that originates from the Colebrook equation. This study has found no validation of this expression.

7.2.3 Determination of the Quality

By assuming that no vaporisation occurs along a pipe the pressure gradient at the entrance can be calculated (using eq 23). Since the water is saturated and the outlet pressure is lower than the inlet pressure a certain amount of steam will in fact form. Hence the pressure at the outlet will in fact be slightly higher than the pressure that was calculated using the pressure gradient above. An energy balance between the inlet and outlet is used to see what quality would satisfy the energy equation, eq 46 (which is evaluated with media data corresponding to the calculated outlet pressure). As long as this quality is not equal to the exit quality assumed when calculating the pressure the exit quality is increased and the calculation repeated.

$$h_{l1} - h_{l2} + w_1 h_{vap,1} - w_2 h_{vap,2} + \frac{c_1^2}{2} - \frac{c_2^2}{2} + 9.81(z_1 - z_2) = 0 \qquad \text{eq 46}$$

h_l = enthalpy of liquid per mass unit
h_{vap} = enthalpy of vaporization per mass unit
c = velocity of fluid
z = height above reference level
Index 1 = Inlet
Index 2 = Outlet

The output data from one pipe section is used as input to the next. Using this approach enough information is available to determine how the pressure varies with the length of a pipe.

Since the pipe system that is to be evaluated consists of many connected pipes the flow will also be subject to singular pressure drops at the entrance to a new pipe. The knowledge of these pressure drops for two phase flows is still limited and needs further investigation [7]. This study uses equation 47 which according to tests in Lufkin can be used with acceptable results [13].

$$\Delta P = \frac{G^2}{2} V_l z F \qquad \text{eq 47}$$

The value of z is dependent on how the pipes are connected and can be estimated from general guidelines of singularities. F is the two phase multiplier and defined as

$$F = 1 + w(V_g / V_l - 1) \qquad \text{eq 48}$$

This approach directly determines the pressure after a singularity but to continue the calculation the quality at this point must also be known. Eq 49 provides the necessary expression [3].

$$w = \frac{1}{h_{vap}}(h - h_l) \qquad \text{eq 49}$$

Since the pressure after the entrance drop is know, the enthalpy of the liquid and enthalpy of vaporization is easily evaluated from steam tables. The actual enthalpy of the fluid (h) is calculated by noting that since there are no heat losses from the pipe the decrease in enthalpy along the pipe is the result of increased velocity [13]. In equation 50 the actual enthalpy has been replaced by the initial enthalpy (the enthalpy of saturated water in the tank) minus the kinetic energy of the fluid at this point.

$$w = \frac{1}{h_{vap}}(h_0 - \frac{c^2}{2} - h_l) \qquad \text{eq 50}$$

In eq 51 the velocity of the fluid has been expressed in terms of quality, mass flux and specific volumes of the gas and the liquid. This gives an implicit expression for the quality which is recalculated with different values of quality until a satisfactory match is obtained.

$$w = \frac{1}{h_{vap}}(h_0 - \frac{G^2(wV_G + (1-w)V_L)^2}{2} - h_l) \qquad \text{eq 51}$$

7.2.4 Flow Determination and Pressure Drop

The output in terms of pressure and quality from one pipe is used as input to the next. This means that for a given mass flow, the pressure along the whole pipe system can be determined. If liquid is drained from the tank to the atmosphere, the resulting flow will be the flow that yield an outlet pressure equal the atmospheric pressure or the critical pressure for this flow. If very large pipes are used the critical pressure will be below the atmospheric pressure and the whole pressure potential of the tank can be used to maximize the flow. Often this is not very practical and the flow is instead restricted by the critical pressure.

The program developed uses a method of interval decreasing to determine the accurate flow. If the flow tried causes choking at some point, the program tries a mass flow equal to the mean of the last tried flow and the last flow that did not cause choking instead. This process is continued until the difference between the current flow and the flow used in the last successful calculation is satisfactory small. It should be noted that only when the resulting outlet pressure is exactly equal to the critical pressure or the back pressure (whichever is highest), the pressures along the pipe will be correct. This is further discussed in Chapter 9.1. Since the speed of the program is a primary concern it does not iterate until a precise match between outlet pressure and critical pressure is found but only until the mass flow has stabilized. Should the pressures along the pipe system be needed the default conditions concerning when to end the iteration must be changed.

7.2.5 Forces at the Pipe Outlets

The mass leaving the pipe system will cause forces on the pipe structure and from an engineering point of view these forces are important to know. Since force is a product of pressure and area, and pressure can be divided into a static and a dynamic part, the net force for one pipe can be calculated according to eq 52 [11].

$$F = P_{tot} * S = (P_{static} + P_{dynamic} - P_{back}) * S \qquad \text{eq 52}$$

P_{back} is the back pressure, meaning the pressure at the point where the fluid is being drained to (often atmospheric) and S is the cross section area of the pipe outlet. The static pressure is the pressure calculated by the program and a dimension analysis show that the dynamic pressure can be expressed as

$$P_{dynamic} = \frac{r v^2}{2} = \frac{r G^2 V^2}{2} = \frac{G^2 V}{2} \qquad \text{eq 53}$$

where V is the specific volume of the fluid.

8 Result

8.1 Result Tank

Table 1 show the initial and final pressures in the tank according to documented cases and this model for both part 1 and part 2 of the draining. The names represent real facilities containing recovery boilers where the tank pressure after the draining has been evaluated with the old program. As previously discussed the losses from the tank have been chosen to produce final pressures similar to documented data.

Table 1

		RB1	RB2	RB3	RB4	RB5	RB6	RB7
Part 1	Pstart (MPa)	4,02	5,5	5,1	8,28	4,52	4,2	7,5
	Pend new (MPa)	3,25	4,48	4,12	6,89	3,83	3,71	6,28
	Pend doc (MPa)	3,21	4,54	4,16	6,9	3,87	3,68	6,31
Part 2	Pstart (MPa)	3,21		4,12	7,05		3,71	6,28
	Pend new (MPa)	2,79		3,56	5,9		3,09	5,28
	Pend doc (MPa)	2,85		3,61	5,89		3,09	5,28

Comparison of ending pressure for the new program and documented cases. No documented data exist for the second part of RB2 and RB5..

If no losses are included in the calculations, the predicted end pressures will be slightly higher than those presented here. By approximating the losses as discussed in Chapter 7.1 the end pressures seem to well match documented cases.

The first part of draining the tank in RB7 will be used as an example of how the pressure in the tank varies, illustrated in figure 7. The input data used in the analysis are can be found in Appendix 1.

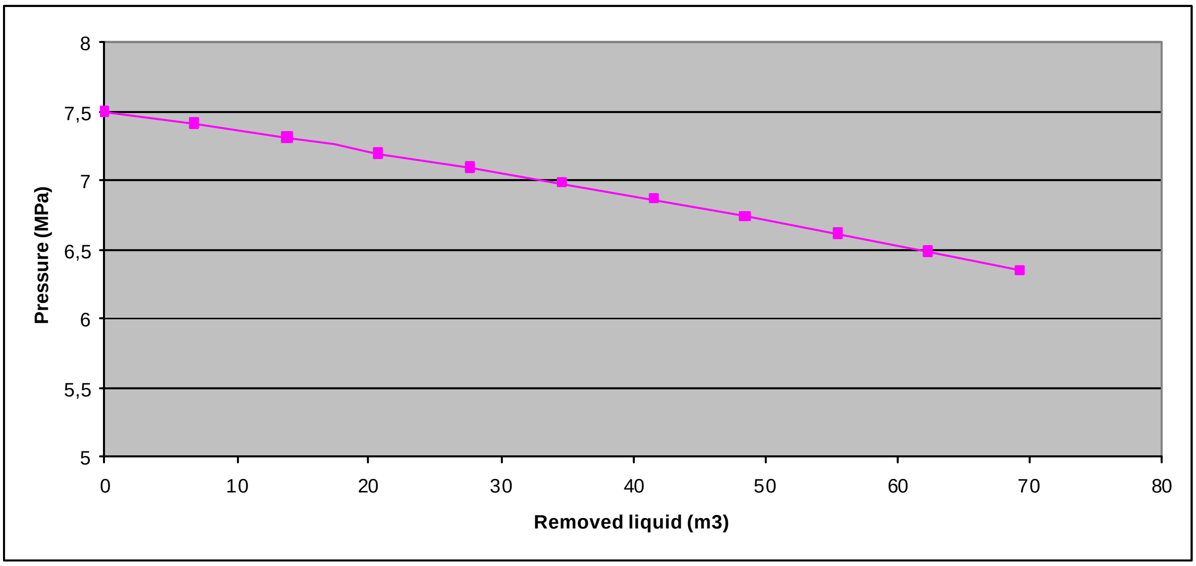

Figure 7: Pressure in the tank as a function of removed liquid.

The approach to determine the tank pressure described in Chapter 7.1 also generates data of how much liquid must actually be drained. This volume is not equal to the volume shown in figure 7 which rather illustrates the total volume that must be removed as viewed from the initial conditions. During the process of emptying the tank the density will change and liquid will evaporate, which means that all liquid that must be removed does not have to be drained. The mass that must in fact leave the tank through the pipes for each volume element is shown in figure 8.

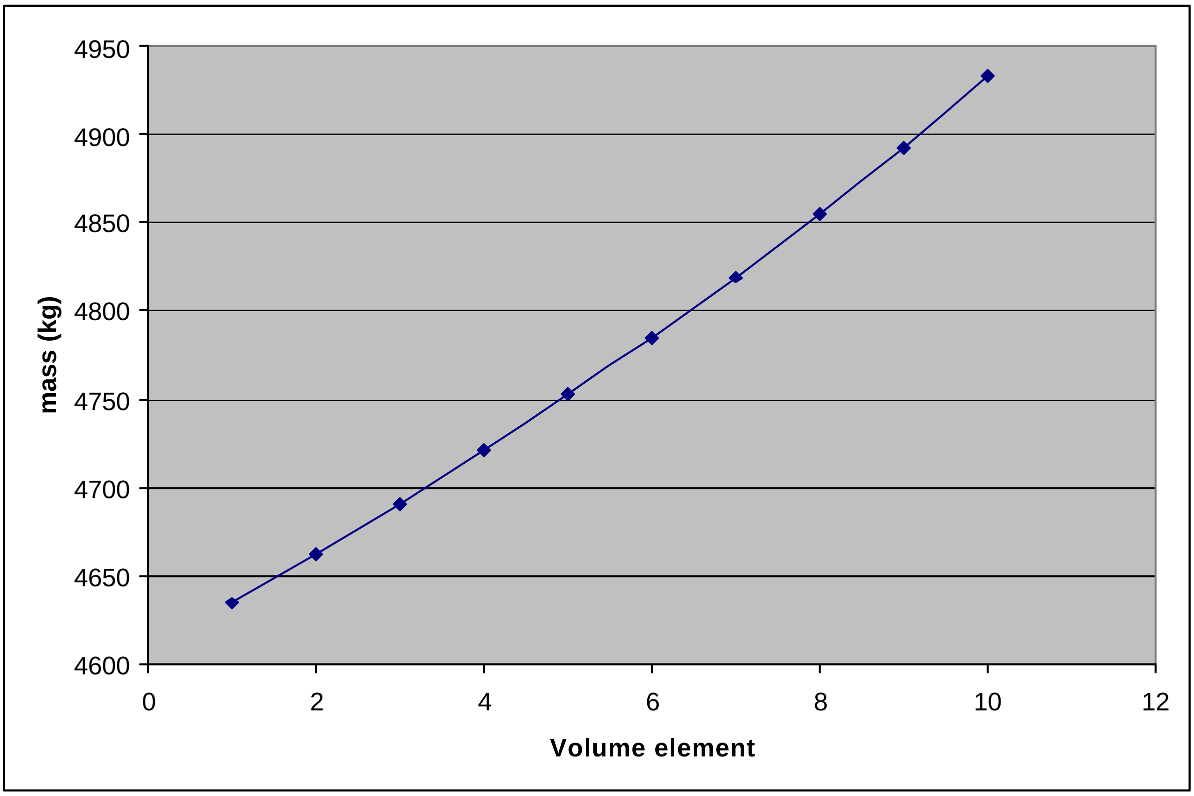

Figure 8: Mass that is to be passed through the draining pipes of RB7 for each volume element of part 1.

8.2 Result Pipe System

The result from the pipe pressure calculations will also be illustrated by the example of RB7 part 1. Figure 9 shows how the pressures varies along each pipe for the initial mass flows. A linear decrease in pressure over each pipe section has been assumed. The outlet pressure varies among the pipes due to the difference in mass flow and pipe diameter.

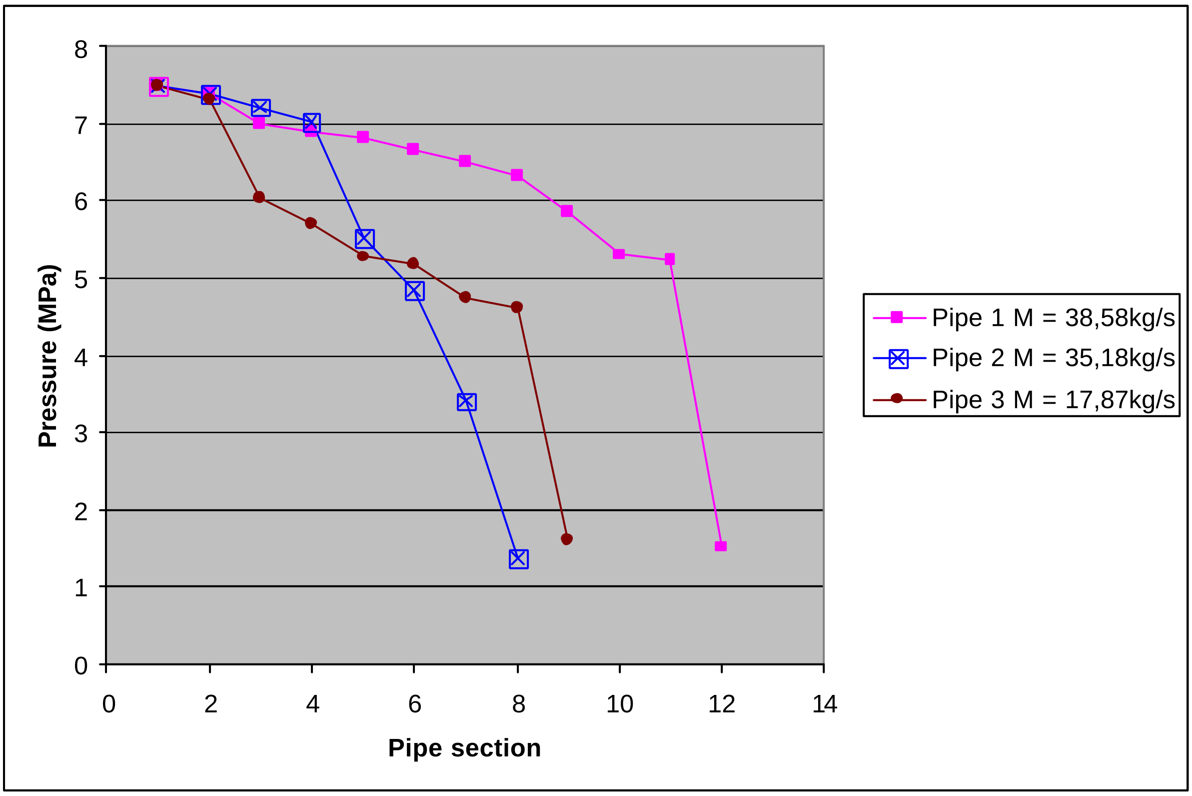

Figure 9: Pressures for initial mass flows along the pipe 1,2 and 3 for RB7 Part 1.

Appendix 3 contains more results of how the pressure varies with pipe length for the calculated mass flows. They are compared to the results generated by the old program to make sure that the calculations yield similar results.

8.3 Result Combination of Programs

By combining the two programs described it is possible to calculate the constantly changing mass flow during the whole process and the time needed to drain each volume element. The mean pressure for each volume element is sent to the pipe program which determines the flow rate through each pipe during the draining of this volume element. Figure 10 shows how the flows varies during the draining of RB7 Part 1.

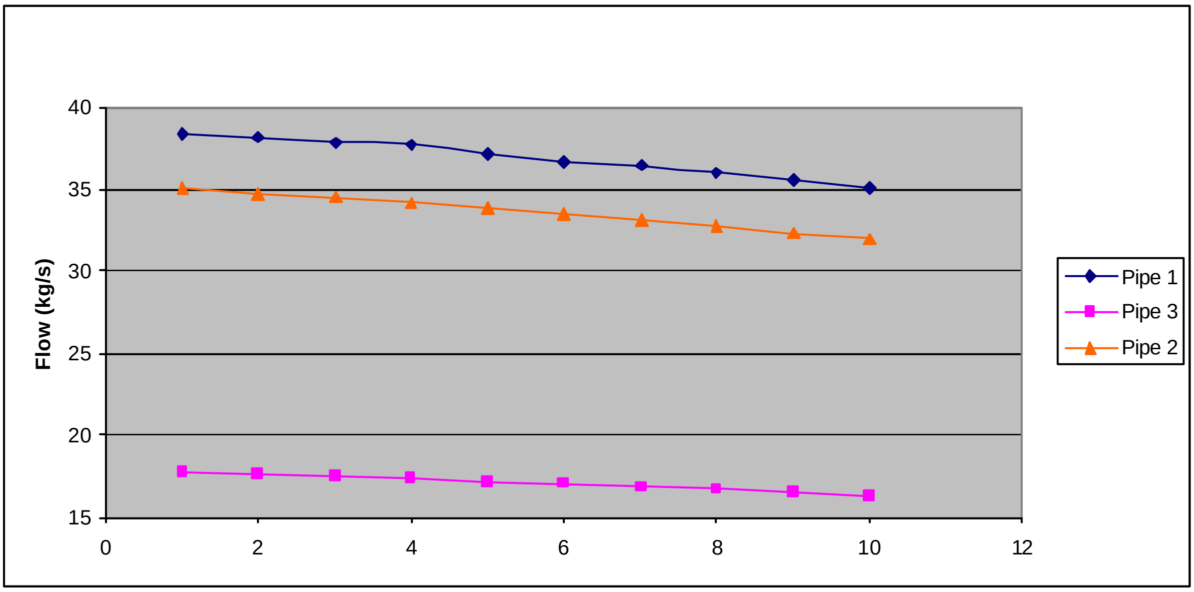

Figure 10: Flow rate for pipe 1, 2 and 3 during draining of RB7 Part 1

The mass that must leave the tank during the draining of one volume element, calculated in the tank program, is divided with the mass flow to calculate the time needed to empty a volume element. The draining times for RB7 part 1 are presented in figure 11. The total time for the whole process is the sum of the times for each volume element.

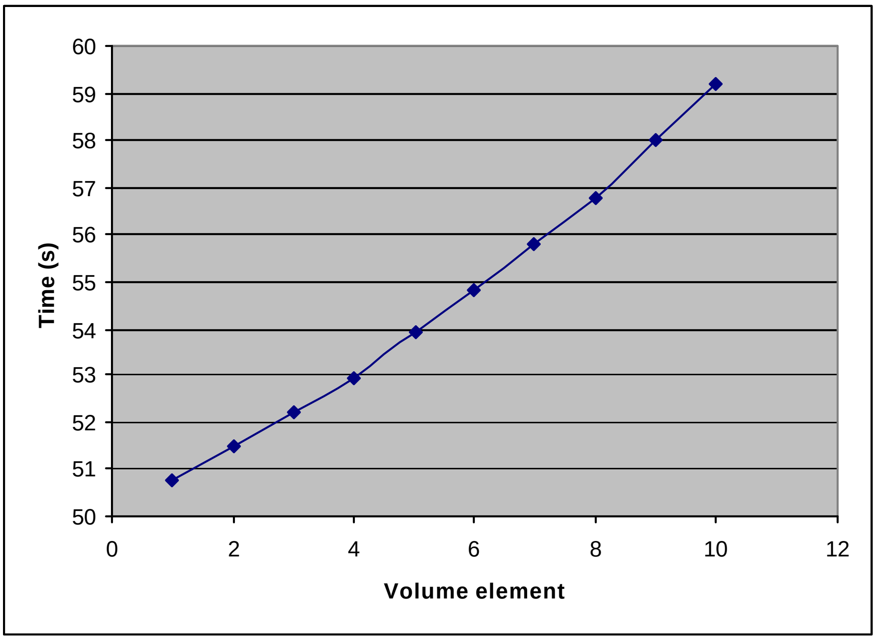

Figure 11: Time to drain each volume element.

The total time is calculated to 546 seconds. Simulations for the second part of the draining in RB7 (using only two pipes) estimate the time to 441 seconds. This corresponds to a total time of 16 minutes and 27 seconds which is several minutes faster than recommended.

The forces acting on the pipe outlets from RB7 at the maximum flow rates are 10.9kN, 10.1kN and 5.0kN respectively.

9 Discussion

9.1 Thoughts Concerning the Validity of the Program

The discussion in Chapter 7.2 clearly states that the choice of model can greatly affect the evaluation of the pressure gradient for pipe flows. Since this is a major part of the final program it is important to keep in mind when evaluating the results. Having pointed this out it should be noted that the pressures along the pipes and the corresponding mass flows very well match those obtained with the old program (see Appendix 2) which uses a different model. This suggests that the model used for the pressure gradient is reasonably well designed.

As earlier discussed the total volume liquid that must be removed is divided into a certain number of volume elements. For each element the end pressure is calculated by determining the heat that must be supplied to reach an assumed pressure. An error is associated with each calculation and the more volume elements used, the greater the error will be. Using small steps when assuming the end pressure will increase the accuracy but at the expense of calculation time. One must also keep in mind that the whole point of using a large number of volume elements was to be able to assume short periods of constant pressure inside the tank. The more elements used, the more valid this assumption will be, thus a large number of elements is preferred from this point of view. Because of the reasons stated it is important to carefully consider the number of volume elements and how the expression for the assumed pressure should be written. It will always be a compromise between time, accuracy of the tank pressure program and accuracy of the pipe system program. The default value of number of volume elements is ten for each part of the process and the method of pressure assumption can be viewed in Appendix 4 (file pipepressure).

The program does not allow flows that result in that the critical pressure is reached. If the flow is choked and hence constrained by an upper section there is no guarantee that the outlet pressure will equal the critical pressure. An example of this is illustrated in table 2 where the pressure along a fictional pipe and the critical pressure is compared.

Table 2

Ppipe (MPa)	7,24	7,21	7,18	3,59	3,24	3,18	1,62
Pcrit (MPa)	1,19	1,19	1,19	3,37	0,76	0,76	0,76

Pressure along a pipe with a sudden decrease in diameter in the fourth section. A mass flow low enough not to fall below the critical pressure in section four it will not reach the critical pressure at the outlet.

Since it is assumed that the outlet pressure is equal to the critical pressure (or P_{back} if it happens to be higher) when determining the force on the pipe this is important to keep in mind. Which section that places the constraint on the flow is indicated by the pressure matrix in the output file. **If this section is not the last one it is highly recommended to re-construct the design of the pipe system.** Pressure gradients in choked flow are a complicated matter and all calculations in this paper should be doubted when choking occurs. The output file for the example above would show the number four in the cell corresponding to the last not valid mass flow, indicating that the choking occurred in that section. If a larger diameter was chosen the critical pressure would instead occur in the end of the last section and all calculations would be much more reliable. While on the subject of critical pressure it is worth mentioning that Bergles [7] suggest the use of a homogenous model instead of the slip model developed by Moody (which for practical reasons both the new and old program uses) to predict the critical pressure. According to him the slip model tend to over predict the possible flow before choking occurs.

The pressure difference between the tank pressure and the pipe outlet will force a certain mass flow through the pipes. Since the calculations of pressure gradients are dependant on that the mass flow is known, one must assume a flow and check if the correct outlet pressure is reached. This means that the calculated pressures along the pipe will only be correct if in fact the mass flow assumed is exactly correct. If this is not the case the pressure gradient will not be correctly evaluated which will result in incorrect pressures along the pipe. Test runs show that these pressures seem to be extremely sensitive to which mass flow is used and only a mass flow very close to the correct value will yield pressures close to reality. Unfortunately calculation speed is a major concern and should the pipe pressures for some reason be needed the parameter flow_accurancy in the input file can be decreased. This will give better pressure accuracy but also further increase the calculation time.

Finally it should be noted that in order to estimate the heat losses from the tank an assumption was made that each volume element would take the same time to drain. Figure 11 shows that this is not entirely true but since the losses are small compared to the total energy content the assumption should still be acceptable.

The calculated forces on the pipe outlets is greatest at the beginning of the draining (when the flow is at its peak) and since the program uses the mean pressure of the first volume element to estimate the flow used in eq 53 one should expect slightly higher forces than those calculated. Tests show that this increase is of the order 0.5-1%.

9.2 Comparison of Model to Old Program

By comparing results to real cases it has been confirmed that the old Matlab program give acceptable results and it would be preferred if results of the new program did not greatly differ from the old ones. The draining of the recovery boilers in RB2 and RB7 will serve as examples when the results are compared. In RB2 the old program was used to calculate the draining time for an existing boiler with a pipe system in place. In RB7 it was instead used to simulate how the pipe system should be constructed in order to complete the first part of the draining in 600 seconds. When the old program is used these purposes call for widely different approaches. As time is an output from the new program it should be much easier to use and both facilities can be handled in the same way. In RB2 the time output is the final result. In RB7 a pipe system is chosen, the total time calculated and if this is not close to 600 seconds changes should made to the pipe design.

9.2.1 RB2

Test runs using the input data for RB2 specified in Appendix 2 predicts that the initial flow through the pipes will be 61.1kg/s, 55.1kg/s and 35.3kg/s respectively. The total time is estimated to 334 seconds but it should be kept in mind that the losses in the program are based on the fact that the draining will take 600 seconds. The error in the result will therefore be greater the more it deviates from this value.

The mean flow to empty the pressure vessel in 600 seconds with the use of the old program is calculated to 75kg/s. When the actual flows through the pipes are calculated and added it yields a total initial flow of 161kg/s, more than twice the recommended flow (see results in table 3).

Table 3

Old program	Actual flow (kg/s)	Calculated tank pressure (MPa)	Known tank pressure (MPa)
Pipe 1 initial	68	5,4898	5,5
Pipe 2 initial	57	5,4841	5,5
Pipe 3 initial	36	5,4917	5,5

Shows the initial mass flows through each pipe for RB2 part 1 as calculated by the old program. The good matches between the pressure used in the calculations and the known initial tank pressure indicate that the flows are quite accurate.

The documented calculations for this facility are summarized in table 4. They incorrectly assume that the mass that must be drained is the product of the change in liquid volume and the density at the initial pressure. The time needed for the draining is assumed to be equal to the quotient of the mass and initial flow.

Table 4

Pressure	5,5	Mpa
Density	768	kg/m3
Drained Volume	65	m3
Mass	49920	kg
Draining flow	161	kg/s
Time	310	s

Documented calculations of RB2 part 1.

This approach uses a number of simplifications:

- The mass calculated above is the total change in liquid mass. All of this mass must not be drained; a certain amount will vaporize and thus present no danger. Also neglected is the change in density for the liquid when the pressure is lowered. This means that the remaining mass after the draining does not quite occupy the whole space assumed. The later neglecting does not however have any significant impact on the result.

- The flow used to calculate the time is the initial flow and will decrease slightly during the draining.

In addition to the errors above there also seems to be an error in the flow rate calculation for pipe 1. According to Appendix 3 the pressure inside the pipe system will sink below the critical pressure for a flow of 68kg/s. This means choking will occur and to deliver this flow one of the pipe sections will have to be changed. The new program does not allow critical flow and therefore only an initial mass flow of 61kg/s. The total time according to the new program for part 1 was, as mentioned, calculated to 334 seconds, which can be compared to the 310 seconds predicted by the old program in combination with man made calculations (which as discussed above are not entirely correct).

A similar comparison is made for the second part of the process. The old program indicates that the flow through pipe 3 should be 32kg/s for the draining to be completed in 10 minutes. Based on the existing pipe system the initial flow through this pipe is calculated to 20kg/s. No other pipes are being used during this draining. By using the same method as outlined above the total time is calculated to 1004 seconds.

The time calculated by the new program is 754 seconds which is a lot shorter than what was previously assumed. The main reason for this is that the old program uses the stagnation enthalpy corresponding to the starting pressure of the first draining while the new program continuously evaluate it for each volume element. This fundamental difference exits throughout all the facilities compared and is the single greatest cause to that the programs does not deliver equal draining times.

9.2.2 RB7

This calculation is a much more complicated procedure using the old program. The basic idea is to first use the program to decide what the initial and ending flows should be in order to empty the pressure vessel in 600 seconds. Data for how the boiler is constructed is then used to calculate how the flow should be distributed among the three pipes. When this is established another part of the program is consulted to calculate the initial tank pressure using a specific mass flow. If either the resulting pressure does not match the initial tank pressure or the flow used does not match the desired flow the draining time will not equal 600 seconds. How long it will be is not estimated. The desired flows, tank pressure and pipe flows are summarized in table 5.

Table 5

Old program	Desired flow (kg/s)	Actual flow (kg/s)	Calculated tank pressure (MPa)	Known tank Pressure (MPa)
Pipe 1 initial	30,5	39	7,487	7,5
Pipe 2 initial	36,3	36,3	7,474	7,5
Pipe 3 initial	14,7	14,7	6,605	7,5

In reality the actual flow through a pipe will be the flow that causes the calculated tank pressure to equal the known tank pressure. As shown here this flow is often not the desired one.

It can easily be seen that pipe 1 has not been very well designed. Calculating from the outlet a flow of 39kg/s is necessary to reach the tank pressure at 7.5MPa. The desired flow is only 30.5kg/s, hence the pipe is oversized. In pipe 3 the flow used to calculate the pressure in the tank equals the desired flow but the calculated pressure is below the known tank pressure. This is clearly seen in figure 12 where the pressures along the pipes are shown for both the old and the new program. This means that the actual flow for pipe 3 in the old model should in fact be a bit higher than table 5 suggests.

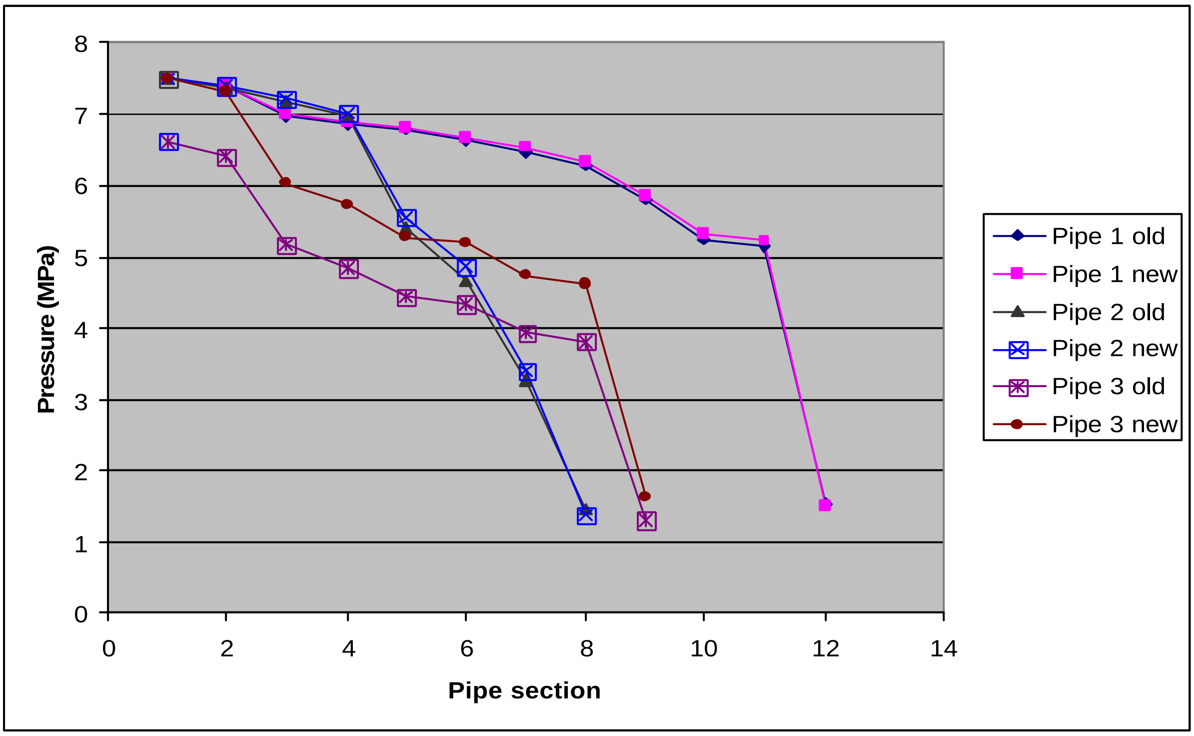

Figure 12: Pressure along the pipes for resulting flows in old and new program.

It deserves to once again be pointed out that in the determination of the actual flow through the pipes during part two of the draining the stagnation enthalpy corresponding to the initial pressure of part one is used. As an example this causes the initial flowrate of pipe 2 in RB7 to be merely 26.9 kg/s compared to the 31.4 kg/s predicted by the new program. If the stagnation enthalpy corresponding to the initial pressure of part two is used instead the old program predicts a flow of 32.5 kg/s which is much closer to the value of the new program.

The documents of this facility show that none of the flows above (that were calculated with the old program) were used when designing the pipe system. The tank pressure used in the calculation of the flow through pipe 2 was actually 5.0MPa instead of the known 6.27MPa. This mismatch will under predict the flow through the pipe and hence the total draining time in this case also will deviate from the preferred 600 seconds. As a reminder it can be pointed out that the time earlier calculated by the new program was 441 seconds. The main reason however is still the different use of stagnation enthalpy even if the under predicted flow in pipe 2 also contributes.

An overview of the forces present at the outlet from the pipes is shown in table 6. The values calculated in the old program seem to be about 80% of those predicted by the new. Both models have arrived at the same conclusion of how the force should be calculated and hence the differences are due to how the properties used are approximated. The far most likely parameter to differ is the specific volume since the programs use different models to calculate it.

Table 6

	RB7 pipe 1	**RB7 pipe 2**	**RB7 pipe 3**
Force new program	10,96	10,08	5,06
Force old program	8,54	7,92	3,19

Forces acting on the pipe outlets in RB7.

The relatively greater difference in pipe 3 is because the tank pressure used in the calculation by the old program never reached the known tank pressure of 7.5MPa (as was previously illustrated by figure 12 and table 5).

10 Conclusion

By using a homogenous model the program developed can well simulate two phase flow and calculate the pressure drop in a pipe system for saturated and unsaturated water. In combination with calculating the pressure inside a pressure vessel as a function of the removed liquid this allows the draining time to be determined. The program predicts similar results to the previously used program, the main difference being a quicker draining time during the second part of the process. As the program presents the total time as output instead of relying on calculations by the user to find a match between subprograms the manual error introduced is significantly less than before.

Acknowledgements

I would like to give thanks to Anders Littorin and Anders Fransson. Anders Littorin, who has been my supervisor, has spent a lot of time discussing and encouraging my work and for this I am grateful. In cases where neither he nor I have had answers Anders Fransson has been consulted and provided me with guidelines and motivation.

I would also like to especially thank Maria Henriksson for her great understanding of my needs and ambitions outside of work. Without this I would have had no motivation to work. She has also provided technical support on various subjects which I have no previous knowledge of.

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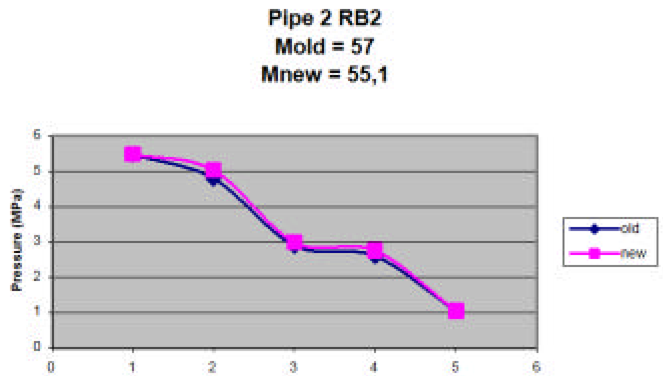
13. Lufkin Recovery Boiler test runs and calculations.

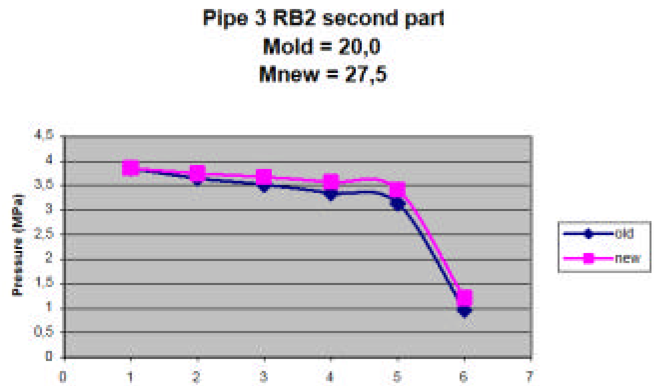
Appendix 1, RB7

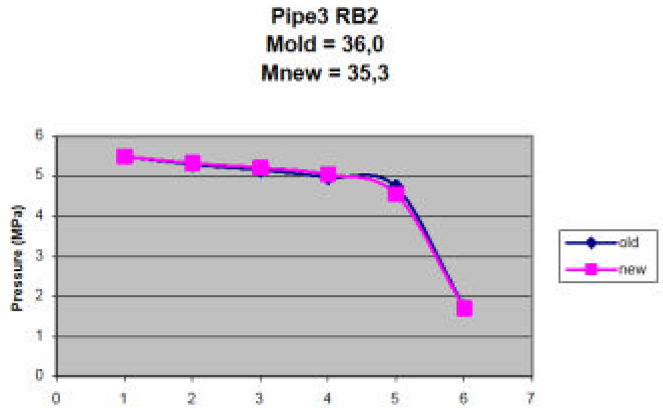
Appendix 2, RB2

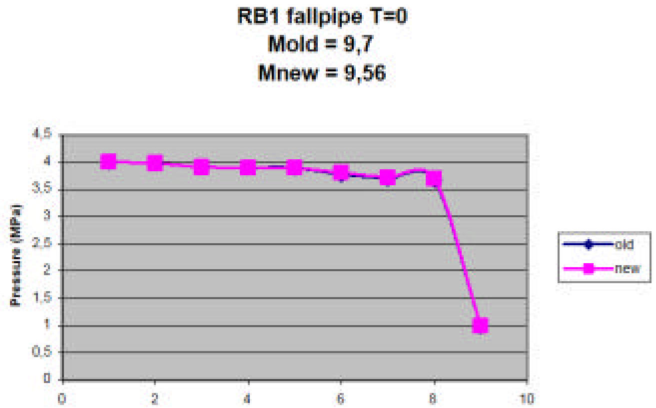
Appendix 3, Comparing of Pipe Pressures

Pipe 2 RB2	Old	New	Sec
Pstart	5,4841	5,4841	1
	4,7963	5,034	2
	2,902	2,9927	3
	2,6051	2,7541	4
	1,0387	1,0478	5
Flow	57	55,1	
Pipe 3 RB2	5,4917	5,4917	1
	5,2934	5,3237	2
	5,1623	5,2111	3
	4,9752	5,046	4
	4,7281	4,55	5
	1,7337	1,7094	6
Flow	36	35,34	
Pipe 3 RB2	3,8516	3,8516	1
	3,6508	3,7469	2
	3,5202	3,6782	3
	3,3489	3,5714	4
	3,1353	3,4208	5
	0,97	1,2054	6
Flow	20	27,5	
RB1 fallpipe T=0	4,0082	4,0082	1
	3,986	3,9878	2
	3,914	3,9143	3
	3,901	3,9039	4
	3,8955	3,8998	5
	3,778	3,8104	6
	3,7088	3,7299	7
	3,683	3,7016	8
	0,99	0,996	9
Flow	9,7	9,56	



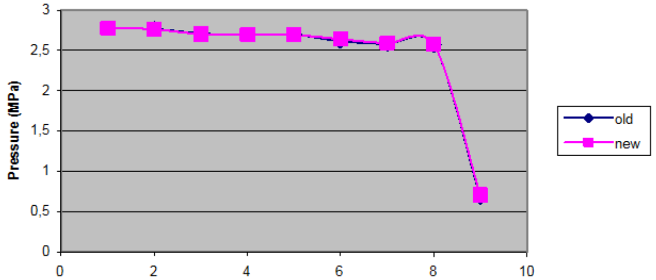




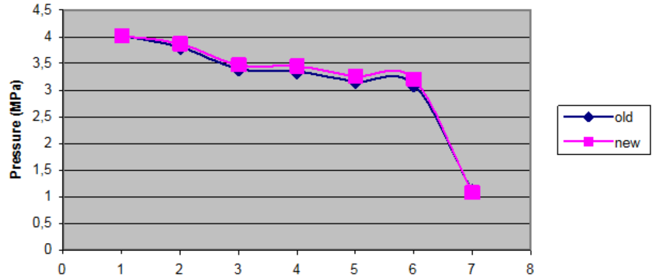


RB1 fallpipe T=10	3,2032	3,2032	1
	3,1918	3,1885	2
	3,1292	3,1242	3
	3,1179	3,1159	4
	3,1135	3,1128	5
	3,0208	3,0463	6
	2,973	2,9875	7
	2,956	2,9665	8
	0,79	0,843	9
Flow	8,3	8,17	
RB1 fallpipe T=20	2,7761	2,7761	1
	2,7677	2,7643	2
	2,711	2,7044	3
	2,7006	2,6971	4
	2,6978	2,6945	5
	2,6175	2,6394	6
	2,5813	2,5911	7
	2,5682	2,5737	8
	0,682	0,7099	9
Flow	7,57	7,37	
RB1 (np) T=0	4,024	4,024	1
	3,8037	3,864	2
	3,3993	3,4725	3
	3,3438	3,4443	4
	3,1652	3,2634	5
	3,1013	3,2025	6
	1,096	1,0785	7
Flow	39	37,9	
RB1 (np) T=10	3,2	3,2	1
	3,036	3,08	2
	2,71	2,79	3
	2,68	2,77	4
	2,54	2,63	5
	2,5	2,58	6
	0,87	0,86	7
Flow	33,5	32,6	

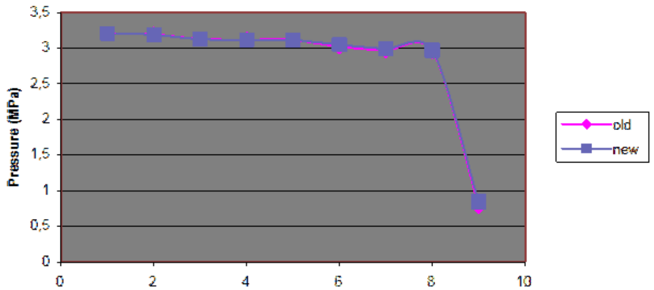
RB1 fallpipe T=20
Mold = 7,57
Mnew = 7,37



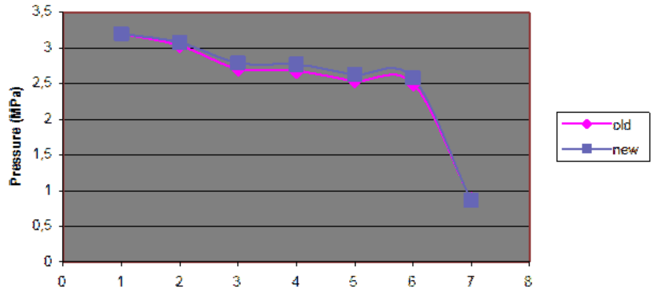
RB1 (new pipe) T=0
Mold = 39,0
Mnew = 37,9



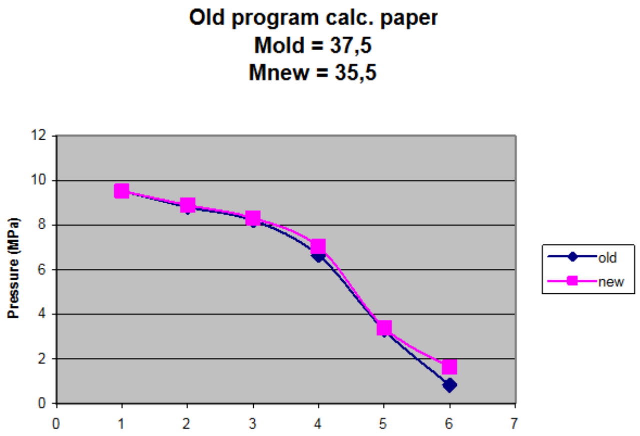
RB1 fallpipe T=10
Mold = 8,3
Mnew = 8,17

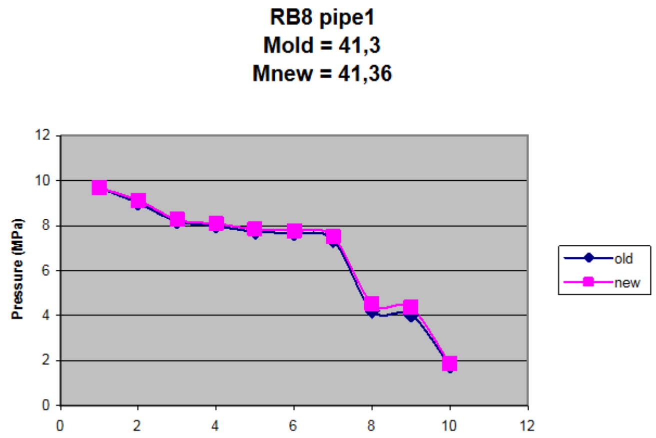


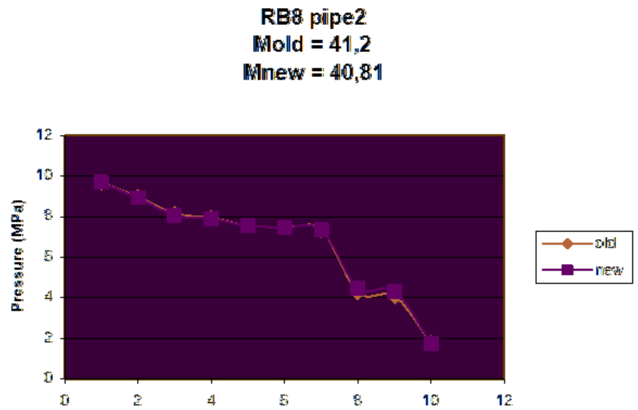
RB1 (new pipe) T=10
Mold = 33,5
Mnew = 32,6

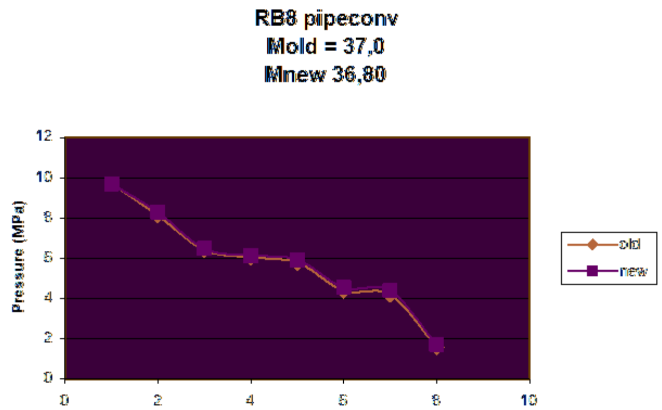


Old calc. Paper	9,53	9,53	1
	8,81	8,89	2
	8,21	8,31	3
	6,65	7,01	4
	3,3	3,41	5
	0,83	1,62	6
Flow	37	35,5	
RB8 pipe1	9,6963	9,6963	1
	9,0071	9,1357	2
	8,1931	8,2755	3
	7,9916	8,0948	4
	7,7328	7,8562	5
	7,6597	7,7875	6
	7,3601	7,5114	7
	4,2158	4,5202	8
	4,0268	4,3582	9
	1,7645	1,8612	10
Flow	41,3	41,36	
RB8 pipe2	9,6843	9,6843	1
	8,9824	8,9317	2
	8,1561	8,0826	3
	7,95	7,9029	4
	7,5558	7,5487	5
	7,4733	7,4737	6
	7,339	7,3494	7
	4,2667	4,4896	8
	4,0731	4,326	9
	1,7602	1,7421	10
Flow	41,2	40,81	
RB8 pipeconv	9,6944	9,6944	1
	8,1306	8,2854	2
	6,4033	6,4739	3
	6,0438	6,1364	4
	5,7771	5,9156	5
	4,3777	4,5413	6
	4,1968	4,3729	7
	1,5794	1,7	8
Flow	37	36,8	



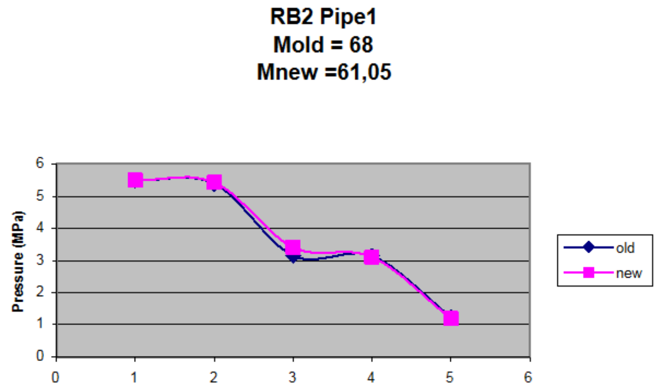


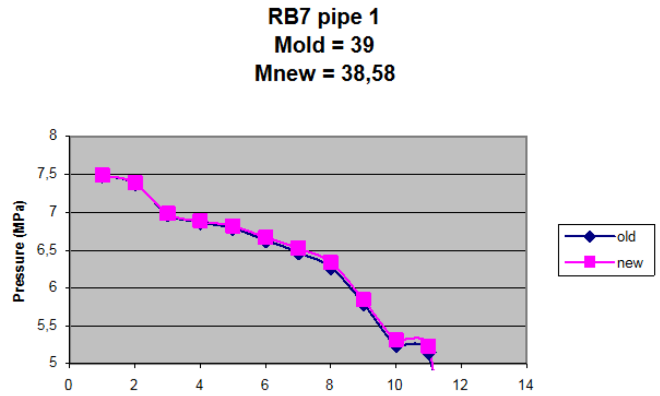


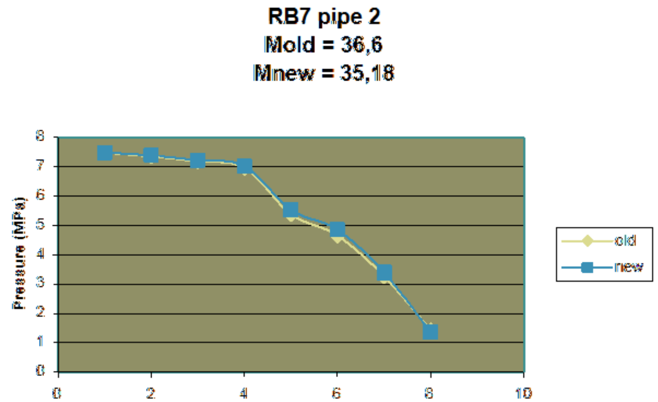


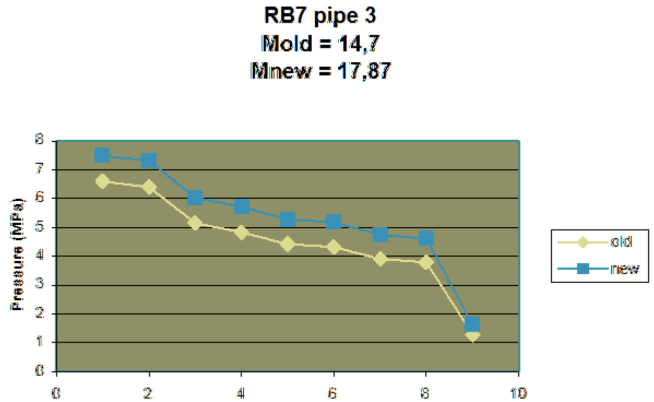
The old flow for this pipe is over predicted because it does not take into account that the pritical pressure at ending of section two has been passed. If pipe 2 is widend in new program a higher flow might be possible.

Pipe1 RB2	5,4898	5,4898	1	
	5,3883	5,4212	2	
<Pcrit = 3.2421	3,1483	3,4083	3	
	3,1432	3,1142	4	
	1,239	1,189	5	
Flow	68	61,05		
RB7 pipe 1	7,4874	7,4874	1	
	7,3819	7,3848	2	
	6,9711	6,979	3	
	6,8648	6,8846	4	
	6,7913	6,8185	5	
	6,6282	6,6677	6	
	6,4682	6,5223	7	
	6,2711	6,3359	8	
	5,7957	5,846	9	
	5,2456	5,3121	10	
	5,1463	5,2225	11	
	1,5188	1,5017	12	
Flow	39	38,58		
RB7 pipe 2	7,4874	7,4874	1	
	7,36	7,3869	2	
	7,176	7,2239	3	
	6,9661	7,0183	4	
	5,3918	5,5387	5	
	4,6604	4,853	6	
	3,2675	3,3984	7	
	1,4321	1,3706	8	
	36,6	35,18		
RB7 pipe 3	6,605	7,4874	1	
	6,4015	7,3111	2	
	5,1571	6,036	3	
	4,8382	5,711	4	
	4,4226	5,2755	5	
	4,326	5,1806	6	The initial pressure does not equal tank pressure.
	3,9114	4,7421	7	The real flow on old model should be higher.
	3,7864	4,6163	8	
	1,2796	1,6264	9	
Flow	14,7	17,87		









Appendix 4, Program Design

The main program consists of ten different files; **`Main_first_part_of_drainingprogram`, `Endpressurepart1`, `Sum_of_pipeflows_part1`, `Calculate_flow`, `Pressure_after_each_pipe_section`, `PC2`, `Pipepressure`, `Quality_at_P`, `Energy`, `Input data`, `Empty_output` and `Mediedata`.** In addition to these six more files; **`Eplh2o`, `Epvh2o`, `Eqth2o`, `Vplh2o`, `Vpvh2o` and `Vx2`** are used by **`Mediedata`** and **`PC2`** and are copied from the old program. Figure 13 illustrates how the main functions interact with each other.

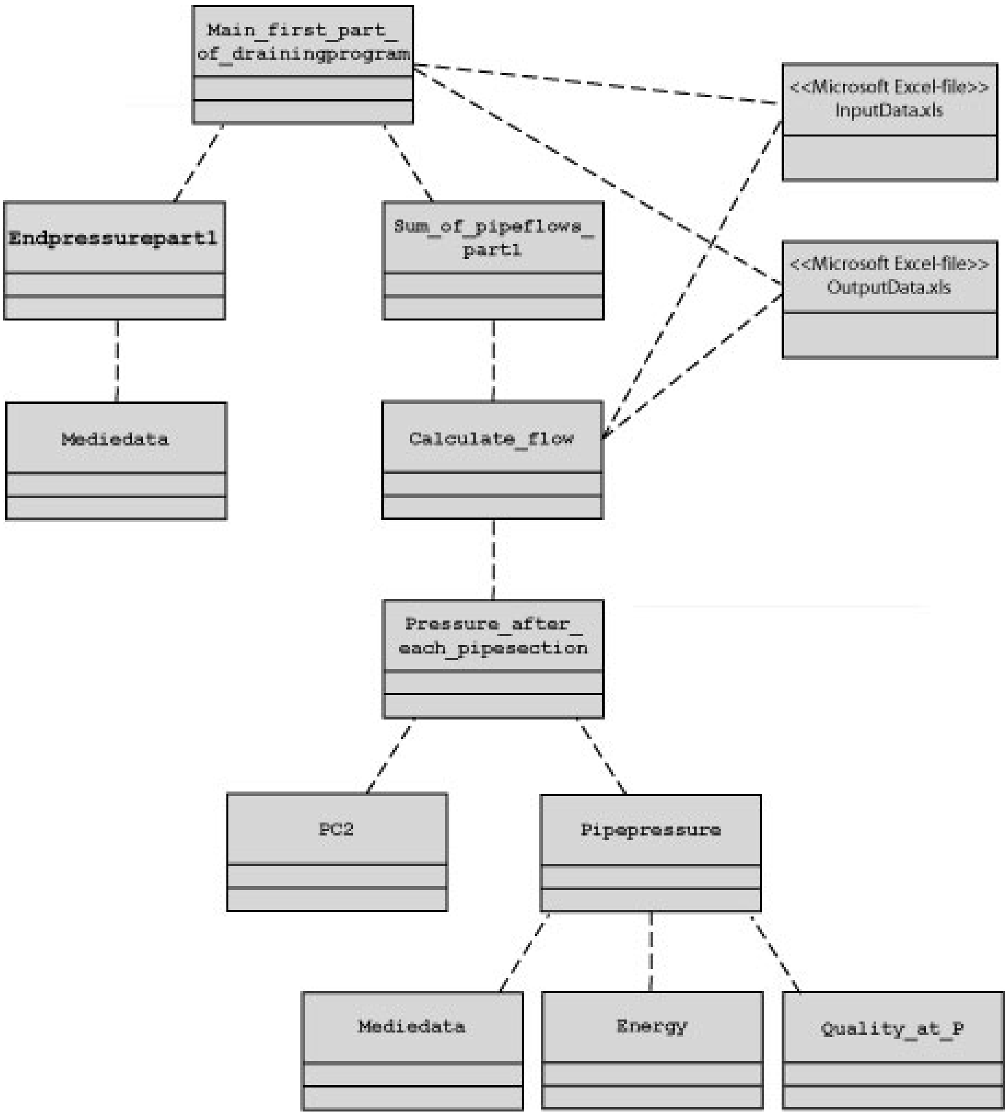


Figure 13: Schematic overview of the program.

Main_first_part_of_drainingprogram
This is the connecting part of the program; this file calculates the total time for the first part of the draining process. After the calculation the flow through each pipe, the time and the mean tank pressure for all volume elements are send to an excel file and presented to the user. Also the force on the pipe outlets, the end pressure and end volume will be included in this file.

The Microsoft Excel worksheet **`Input Data.xls`** is used as an input file to the program. Here, the user will present values for the parameters:

- Total volume of tank
- Initial pressure
- Liquid volume at the start of part 1
- Liquid volume at the end of part 1
- Directory and name of file where the results should be stored
- Backpressure
- Number of pipes

These values are then read by **`Main_first_part_of_drainingprogram`** which will create a copy of **`Empty_output`** (which contains only text) and store it in the directory chosen by the user. It will divide the volume that is to be removed from the tank into a number of volume elements and pass their data on to **`endpressurepart1.`** At the end of the calculation process the file receives information from **`Sum_of_pipeflows_part1`** of the flow through each pipe and can then calculate the time needed to drain each volume element.

Endpressurepart1
Calculates what the pressure inside the tank will be after a volume element has been emptied (which is done by change in density, vaporisation and draining). The main program calls the function for each volume element, resulting in a series of pressures during the draining. The mean value for each volume element is then used as tank pressure by the other files.

Input from **`Main_first_part_of_drainingprogram:`**

- Pressure before the draining of a volume element
- Liquid volume before draining of a volume element
- Liquid volume after draining of a volume element
- Number of volume elements
- Total volume of tank

Output to **`Main_first_part_of_drainingprogram:`**

- Pressure after draining of a volume element
- Mass which have left the control volume for each volume element
- Mass that have been vaporized for each volume element

Sum_of_pipeflows_part1
Defines the number of pipes so that its subprograms can be used for both part one and two of the process. It calls the function Calculate_flow and passes relevant information on to it.

Input from **`Main_first_part_of_drainingprogram:`**

- Average pressure for a volume element

Output to **`Main_first_part_of_drainingprogram:`**

- Flow for each pipe

Calculate_flow

The pipe current design is loaded and the **`Pressure_after_each_pipe_section`** file is run for different flows until the flow has stabilized itself. Forces on the pipe outlets and critical pressures are calculated in send to the excel file for results.

Input from **`Sum_of_pipeflows:`**
- Average pressure for the current volume element
- Information of which pipe it is

Input from **`Input data.xls:`**
- Design of the pipe system

Output to **`Sum_of_pipeflows:`**
- Resulting flow for current pipe and volume element

Pressure_after_each_pipe_section

The function calculates the pressure after each section of the pipe for the flow assumed. For each section **`Pipepressure`** and **`PC2`** are called.

Input from **`PC2:`**
- Critical pressure for each pipe section

Input from **`Calculate_Flow:`**
- Assumed mass flow
- Pipe design
- Average pressure for a volume element

Output to **`Calculate_Flow:`**
- Pressure after each pipe section
- Quality after each pipe section
- Critical pressure at the same points
- An indication of if critical pressure was reached and in that case in which section
- Force at end of a pipe section

PC2

Determines the critical pressure for a given mass flow and pipe section. It uses the subprograms **`eplH2O, epvH2O, eqtH2O, vplH2O, vpvH2O and vx2.`** How they interact has not been looked into since the function is a part of the previously used program.

Input from **`Pressure_after_each_pipe_section:`**
- Mass flux for the section being evaluated
- Stagnation enthalpy for current tank pressure

Output to **`Pressure_after_each_pipe_section:`**
- Critical pressure for the current mass flow and pipe section

Pipepressure

Calculates pressure and quality for a given mass flow in a number of steps along the pipe section. Handles both singular pressure drops and pressure gradients due to friction, static head and acceleration. If the pressure for the given mass flow falls below the critical or Pmot the calculations are terminated.

Input from **`Pressure_after_each_pipe_section:`**

- Stagnation enthalpy for the current volume element
- Pipe data for the section being evaluated
- Critical pressure for this section
- Start pressure for each section
- Start quality for each section
- Assumed mass flow

Output to **`Pressure_after_each_pipe_section:`**

- Pressure after each section
- Quality after each section
- Indication of if critical pressure was reached in this section

Quality_at_P

Calculates quality at a given pressure using an energy balance. It is used to account for singular pressure drops in a pipe.

Input from **`Pipepressure:`**

- Stagnation enthalpy for the volume element being drained
- Specific volume for gas and liquid
- Enthalpy of liquid
- Enthalpy of vaporisation
- Mass flux

Output to **`Pipepressure:`**

- Quality

Energy

The program **`Pipepressure`** uses the Matlab function fzero to find the quality at the end of a step that satisfies the energy equation. This file simply contains this expression.

Mediedata

Calculates enthalpy and specific volume for liquid and gas at a given pressure under saturated conditions. It uses the subprograms **`eplH2O, epvH2O, eqtH2O, vplH2O, vpvH2O and vx2.`** How they interact has not been looked into since the function is a part of the previously used program. **`Mediedata`** is used by **`pipepressure`** and **`endpressurepart1`**.

Appendix 5, User Manual

Make sure the following has been decided for each part of the draining process before attempting to use the program:

- Starting pressure.
- Liquid volume before draining.
- Liquid volume after draining.
- Total tank volume
- Number of pipes used during each part of the draining.
- Back pressure.
- The name (including .xls) and location of the file where the result from each part of the draining should be stored.
- Design of the pipe system to be evaluated including length, angle of elevation, diameter, roughness and singular resistance of each pipe section.

All of the above parameters are to be specified in the file “Input Data.xls” which must be saved in the same catalogue as the rest of the program files. Never change anything but the actual parameter values in this sheet as this might cause the program to read values from the wrong cell. Also note that if e.g. four pipes are used the data for these must be specified as the first four pipes in the input file. Data for pipes remaining from an earlier test can remain in the input file as long as the number of pipes used in the current test is specified. It is worth to once again point out that changing **anything** but the **numerical values** in the input file can cause the program to crash.

If one of the pipe sections does not have a length but only a singular resistance it is necessary to enter it as a short length (i.e. 0.01m) instead of zero. This way the singularity will still be accounted for. Finally, make sure to enter a zero in the “Length” cell to the right of the last section, this tells the program to stop when the pressure after the last section has been evaluated.

Should the pressures along the pipes be of interest, the parameter “flow_accurancy” should be decreased to 0.01kg/s or less. The default value is 0.05kg/s which works fine for most applications but it does not calculate the pressures along the pipe very precisely.

The program is started by choosing the correct directory in Matlab and typing “part1”. This initiates a calculation process that, depending on the computer used, will take about an hour to complete. The result is stored in the file specified in the input data.

This file contains one sheet per pipe with the following information:

- Flows tested by the program.
- Indication of if the critical pressure was reached for the flow tried and in that case in which section this occurred.
- Pressure at the end of every pipe section for all valid mass flows.
- Critical pressure in every pipe section for the last valid flow.
- Force at the pipe outlet.

In addition *sheet 1* includes information for each volume element about:

- Mean pressure in the tank.
- Combined mass that has been drained through the pipes.

- Mass evaporated which thus did not have to be drained.
- Time to drain the volume element.
- Flow through each pipe.

To start the second part of the draining one must open the input file and change:
- Starting pressure (using the end pressure from the first part).
- Liquid start volume.
- Liquid end volume.
- Other parameters that may be different for this draining.

The actual calculation is started by typing “part2” in Matlab. This part will take about the same time as the first part to complete. Make sure the file name specified in input data is not the same as the one used for the first part. This will cause the results for that part to be overwritten.

If the time calculated for part 1 or part 2 differs from 600 seconds it is recommended to re-design the pipe system and repeat the calculations.