PDAM Tirtawening

Additional Thesis

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Investigating flow problems in the supply pipeline of PDAM Tirtawening.

by

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Project duration:	September 1, 2018 – March 31, 2019
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Abstract

The drinking water company PDAM Tirtawening has two pipelines that supply raw water to the treatment plant. The pipelines stretch out for 31 kilometers from Chikalong(small nearby town) to the treatment plant in Badaksinga in Bandung. For one of those pipelines the current flow to the treatment plant is well below the design flow. The original design flow of the pipeline is 850 liters per second, currently the pipeline transports roughly 580-650 liters per second.

This is not a critical problem at the moment because the treatment plant does not have the capacity to treat and distribute more water, but in the nearby future PDAM Tirtawening wants to increase its capacity and supply more water to the people of Bandung. This means that the supply of raw water to the treatment plant also needs to be increased.

From the study it can be concluded that the flow drop was caused by human decisions to throttle the flow, based on the fact that there was severe burst ("explosion") of the pipeline somewhere in the year 2005.

The burst was caused by a water hammer incident, occurring during maintenance. During this maintenance period the water flow was stopped and a water body was standing stagnant in the lower end of the pipeline. When the operators opened valve again at the intake point, to start up the flow in the pipeline, the water mass accelerated downwards towards the stagnant water body below. The air trapped between these two water bodies could not escape in time thereby being compressed causing peak pressures. These pressures where of a much higher magnitude than the pressure which the pipeline was designed for, causing the "explosion" of the pipe. The reason why the trapped air could not escape through the air valves is because they are sealed to reduce the chance of locals stealing water.

To avoid air entrapment and thereby reducing the risk on water hammer the following three throttling locations along the pipeline where investigated.

- keep regulating the inflow at the intake point at Chikalong.
- regulate inflow at the first intersection (OVS1) 3 kilometres downstream of Chikalong.
- regulate inflow downstream at Badaksinga at the outflow point of the pipeline.

From these three options throttling at OVS1 is preferred. The peak pressures along the pipeline stay well below the design pressure. However, throttling at preset at Chikalong has gone 'sufficient' looking at PDAM's standards for more than 25 years already. Regulating at Badaksinga (throttling and closing) is not feasible. Very high pressures and problems with cavitation of the intake valve will increase the chance on pipe bursts and damage to the valve.

Also, it is recommended to PDAM to slowly open the valve at the intake point after maintenance in order to slowly increase the volume of the flow. This action will insure that the pipeline will slowly fill up with water thereby giving the trapped air the chance to escape, this will decrease the chance on peak pressures and "explosions" in the future.

Introduction

This study was initiated within the context of a partnership between the Civil Engineering faculty at TU Delft, PDAM Tirtawening(PDAM) and the Institute Technology of Bandung(ITB). Within this partnership, the TU Delft and ITB contribute to PDAM by sharing their knowledge on water treatment and water distribution. Simultaneously, PDAM provides an environment for the TU Delft and ITB where they can increase and validate their knowledge on the basis of actual case studies in real life situations.

Bandung is the capital of West-Java and the 3th largest city in Indonesia. The population of Bandung is growing each year and the city will shortly be home of more than 2.5 million people. This rapid growth and urbanization are the cause of many new challenges for Bandung and its people. One of these problems is the extensive pressure put on PDAM to generate and distribute enough clean water to the growing demand of the ever-growing population of Bandung.

Because of the growing demand for clean water, and the fact that many people do not yet have access to clean water, PDAM has decided to increase its capacity. This means PDAM will increase the capacity of the treatment plant as well as the capacity of its distribution network.

PDAM uses raw water from a small town nearby Bandung called Chikalong for its production of clean water. PDAM uses two pipelines which both roughly follow the same path to transport this raw water to the treatment plant. One of these pipelines does not operate on its design capacity, thereby transporting less water to the treatment plant as intended. Currently this is not a problem, because the capacity of the supplying pipelines matches the treatment plant clean water production. However, PDAM wants to increase its production in the nearby future and the current water supply of the pipelines will be insufficient to meet this future demand. The easiest way to ensure enough raw water is supplied to the treatment plant is by increasing the capacity of the investigated pipeline. the purpose of this study is to determine why the pipeline does not meet its design capacity. Subsequently, recommendations will be formulated to find a cost effective solution for this problem.

research questions

The following research questions have been formulated to achieve the purpose of this study.

- The first research question: What is the reason/problem why the supplying pipeline does not meet the design capacity?
- The second research question: Which effective measures can be taking to increase the capacity of the supplying pipeline?

In order to answer these research questions multiple fieldwork activities where performed in order to collect data. This data consists of pressure measurements (collected at various points along the pipeline), visual inspections at the intake point and the end point of the pipeline and interviews with personnel of the PDAM organization.

The pressure measurement data were used as a benchmark for an Epanet model. With this model the pressure along the length of the pipeline were simulated and compared with the actual pressure measured in the field. The results of this comparison were analyzed in the results and conclusion section of this study, Subsequently the findings were used to answer the research questions.

The visual inspection, performed at the intake point and at the end point of the pipeline were used to determine if there are problems regarding the intake and outflow point of the raw water.

Interviews with personnel, performed with a pre-written questionnaire were used to validate the visual inspection and the pressure measurements. The interviews where also used to fill possible knowledge gaps that could not be answered with the other information sources.

Any problems or irregularities discovered were also analyzed in the results and conclusion section of this research rapport.

Background Pipeline

In this chapter the pipeline and its most important characteristics will be discussed.

3.1. History

The pipeline was constructed more than 50 years ago and many changes were made to the position throughout the years. A few parts of the pipeline are newly constructed from concrete. The exact location of these pieces are hard indicate because of the many changes in operational staff during the years. The capacity of the pipeline was met until 10 years ago, somewhere around the year 2005. After the year 2005 the capacity decreased to 60 percent and that is still the capacity to date.

Somewhere in the recent past the pipeline bursted ("exploded") a few kilometres downstream of the intake point at Chikalong. People who were present at that event mentioned that there was a loud "bang" and water was "shooting" more than 20 meters in the air. Whether this information is correct or not, the occurrence of water hammer seems likely. More information on this incident can be found in the results part and a summary of the interviews with the people present can be found in appendix A

3.2. Outline pipeline

The transmission pipeline is approximately 31 km long and has a diameter of 850 mm. The pipeline extends from Chikalong to Badaksinga through an urban area. The water is transported by gravity to the water treatment plant, therefore no pumps are located in this pipeline system see figure 3.1 and figure 3.2. Both figures are a scan copy made from the original blue prints which were made when the pipeline was constructed. The highest point of the pipeline is 852 meters above sea level and is located at the intake point at Chikalong. This is, also the start of the pipeline, the lowest point of the pipeline is 8 kilometers down stream of Chikalong and 660 meters above sea level.

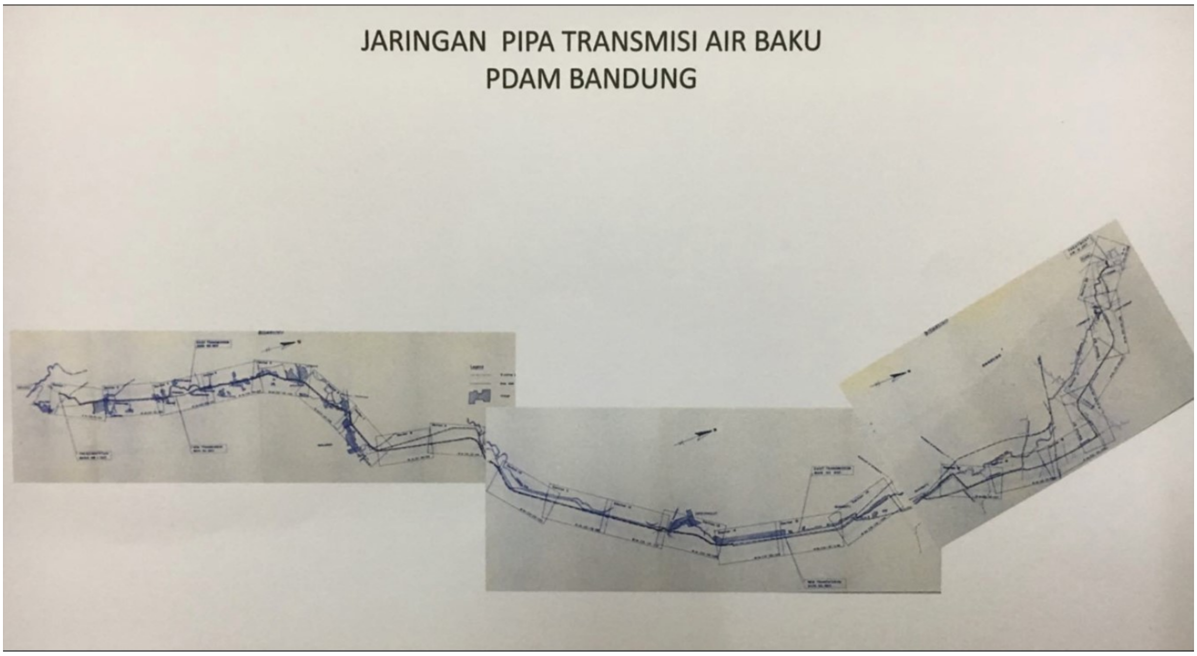


Figure 3.1: overview picture of pipeline

The pipeline ends at Badaksinga which is 752 meters above sea level. The water flows “freely” to the treatment plant. This means that the pressure drops to atmospheric level right after it leaves the pipeline. The pipeline has 35 air valves where the pressure in the pipeline can be measured. It also contains 30 washouts to clear the pipeline of debris. One of the problems PDAM is facing is that many of these air valves and washouts do not work properly or cannot be reached because of traffic.

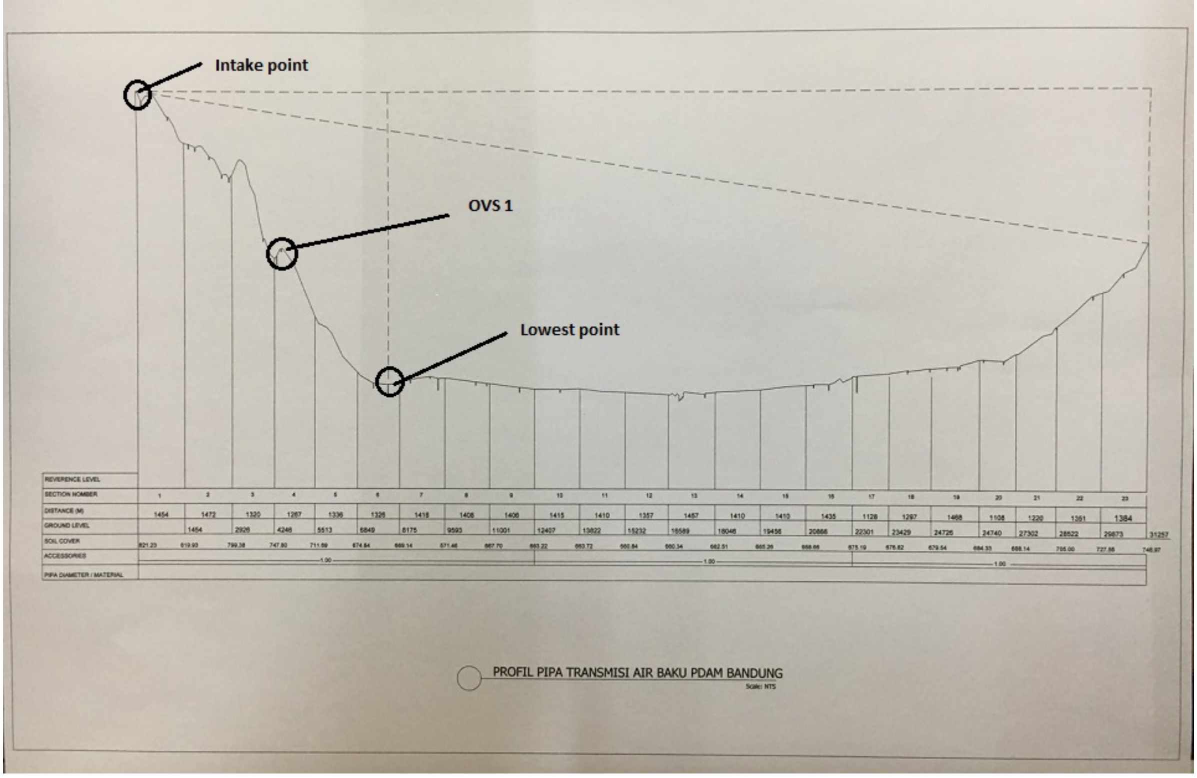
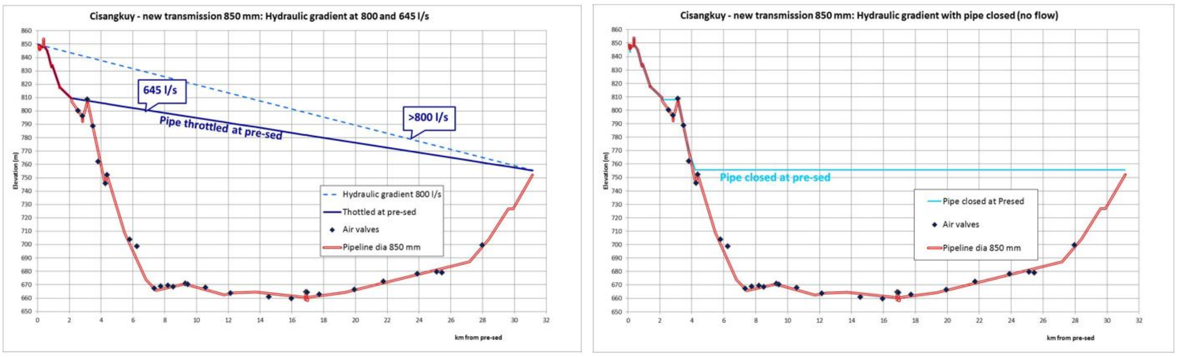


Figure 3.2: cut trough picture of pipeline

Because of the lay-out of the pipeline it is full of water for the largest part when it is not in use. The pipeline under study is connected to a second supply line at a location called OVS1, as shown in figure 3.2. This location is a few kilometers downstream the intake point. This connection point was constructed for the purpose of security, if one of the pipelines breaks the other one could partly take over the the raw water supply. This connection point is currently not in use because of lack of maintenance. figure 3.2 also shows where the lowest point along the length of the pipeline and the location of intake point.

At this moment the water intake of the pipeline is regulated at the intake point of the pipeline at Chikalong by a valve that is controlled by an operator.

Figure 3.3a shows the hydraulic gradient presented for the design flow and the current flow. In figure 3.3b the hydraulic gradient is presented when the pipeline is closed. The pipeline is closed several times a year for maintenance and inspection. Because the water intake is regulated at the top of the pipeline at Chikalong, stagnant water cannot be removed as shown in figure 3.3b.



(a) pipeline gradient for 800/s and 645 l/s

(b) Gradient when pipeline is closed

Figure 3.3: overview figures of gradient pipeline

Theoretical Background, materials and methods

In this chapter the theoretical background of different aspects concerning this study will be discussed. These aspects include possible flow obstructions and how and why different calculations are made.

4.1. Water Hammer

When investigating a pipeline, water hammer should be taken into account. A water hammer phenomenon occurs when a sudden fluctuation in velocity triggers a fluctuation in pressure. The fluctuation in flow velocity is possibly created by closing or opening the regulating valve at Badaksinga. When this regulating valve as illustrated in figure3.2 is opened or closed relatively a pressure wave in the water flow interacts with the pipe wall. This reaction inducts axial bending and torsional stress waves within the pipe wall of the investigated pipeline.[Baliño et al., 2001, Brosi et al., 1995] This Water Hammer phenomenon expresses the relationship between kinetic and pressure energy.[Ghidaoui et al., 2005].

Also, these induced pressure fluctuations can cause local low pressure situations where the fluid vaporizes. This phenomena is called cavitation, which will be discussed in the next section[Geng et al., 2017].

Kinetic and pressure energy caused by water hammer phenomenon's have to be kept within limits described by the design load of the investigated pipeline. This have to be done by adequate rules on control and operation. Applying control devices or redesigning a pipeline layout when water hammer occurs can be necessary for the investigated supply pipeline[Yazdi, 2019].

A rupture may occur if the pressure induced by water hammer equals or exceeds the maximum design pressure. Today the designer is compelled to introduce a safety margin in his/her design. The safety margin applied to the investigated supply line is unknown, therefore in this study calculations will be done as if there is no safety margin.

Water hammer can cause ruptures or other forms of irregularities that can influence the flow[Stone, 2006]. Special attention when it comes to the water hammer phenomenon will be allocated to maintenance work that occurred in the recent years. During maintenance the investigated pipeline is closed off in order to perform cleaning and inspection. When this action takes place there is a high possibility of water hammer taking place. If water hammer indeed is a problem that is part of the problem then maintenance moments are well worth investigating.

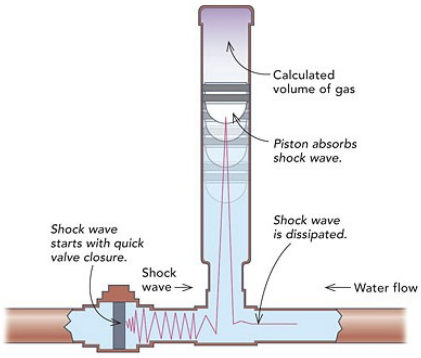


Figure 4.1: water hammer principle and air valve mitigating measure
Ghidaoui et al. [2005]

figure 4.1 an illustration is presented on how water hammer occurrence can be mitigated and even prevented. However, one has to keep in mind that in this situation most air valves do not work properly thereby increasing the chance on water hammer.

In this study, first the possibility of water hammer causing the problem will be investigated. If there is indeed a chance that water hammer is a factor for the problem than further calculations will be performed on this matter.

4.1.1. mitigation measures

Water hammer phenomena can be reduced in several ways.[Triki, 2016], [Kerr, 1951]

- Reduce the pressure of the water supply to the building by fitting a regulator.

Water pressure reducing regulators can be installed along the length of the pipeline. A reducing regulator can be in the form of a spring-loaded diagram, this diagram reduces the water pressure within the valve body. Water will thereby by constricted when it comes into the valve and then released at desired reduced pressure.

- Lower fluid velocities.

By lowering the fluid velocities the impact and likelihood of water hammer can reduced. Fluid velocity can be reduced in several way. For the studied situation the fluid velocity can be reduced by reducing the inflow or by constricting the flow along the length of the pipeline by decreasing the flow trough possibilities by narrowing the pipeline.

- Fit slowly closing or opening valves.

Slowly closing or opening valves increase or decrease the flow at a slower rate. By lowering the flow flux water hammer impact can be mitigated because the energy transition is dispersed over a longer period of time. peak energy transition is thereby mitigated reducing the impact of the consequences.

- Accumulators or expansion tanks

An expansion tank or expansion vessel is a open or closed tank used to protect closed pipeline systems from excessive pressure. Peak pressures during a water hammer event are mitigated by forcing additional fluid into the tank thereby reducing pressure. Figure 4.1 illustrate a situation where a fluid is forced into a tank thereby relieving the pipeline system of excessive pressure.

- Specify vacuum relief valves.

A relief valve is a device that reliefs the pressure by inlet static pressure. They opening increases proportional to the inlet pressure of the valve. It may be provided with an bonnet, that acts like a spring housing. The opening pressure can be adjusted to the desired maximum pressure needed in a pipeline system.

4.2. Cavitation

Cavitation is the process by which, in this situation, gas or vapour bubbles nucleate, grow, and then collapse inside the pipeline. Cavitation happens in a turbulent liquid when the local pressure becomes lower than the vapour pressure. In atmospheric pressure water turns into gas at 100 degrees Celsius, but when the pressure becomes lower so does the temperature where a this phenomenon takes places.[Shu, 2003]

The initial process by which bubbles are formed is called nucleation, it occurs in a homogeneous or heterogeneous manner. Homogeneous nucleation refers to the spontaneous formation of bubbles in the water, whereas heterogeneous nucleation occurs by growth of pre-existing gas present on particles suspended in the bulk solution and in cracks on solid surfaces, which in this case would be the wall of the pipeline.[Wilkinson and Vitek, 1983]

For water between 10 to 40 degrees Celsius the vapor pressure ranges from 0.012 to 0.073 atmospheres. The total dissolved gas pressure in normal conditions ranges between 0.8 and 1.2 atmospheres. When the pressure is decreased below the total dissolved gas pressure, gas bubbles will tend to grow at locations referred as nucleation's sites. Scardina et al. [2006]

The formations of bubbles caused by cavitation are easily observed when opening a pressurized carbonated beverage. Figure 4.2 gives a schematic overview of cavitation occurrence.[Ganz and Gutierrez, 2012]

The pipeline under investigation has many irregularities such as bends and constrictions. Within these irregularities the flow of water can be disrupted making cavitation likely to occur. Cavitation can cause damage to the inner wall of the pipeline. This damage will increase the roughness which results into a decrease of the overall performance of the pipeline. This can contribute to the flow drop which is currently under investigation.

The safety margin regarding to cavitation applied to the investigated supply line is unknown, therefore in this study calculations will be done as if there is no safety margin.

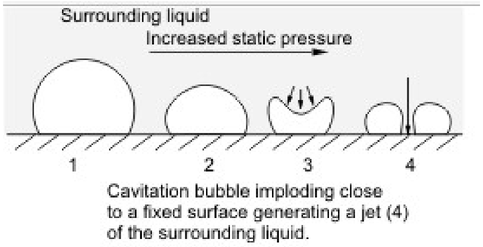


Figure 4.2: cavitation principle
Kalkwijk and Kranenburg [1971]

Cavitation on it's own should not be responsibly for the flow drop in the supply line. However, it's important to take the effects of cavitation into account. Cavitation is likely to occur in the investigated situation because of the turbulent flow in the supply line. Cavitation just like water hammer can for example cause ruptures or other forms of irregularities that can influence the flow.

4.2.1. mitigation measures

Cavitation is mitigated by reducing the pressure fluctuations along the length of the pipeline. This can be obtained by installing pumping stations and decreasing the impact of obstructing factors such as bends or sudden altitude drops. As mentioned before, decreasing the chance and impact of water hammer will also decrease cavitation impact.[Geng et al., 2017], [Shen, 1987]

Devices like an air vessel or surge tank can be used to decrease the impact of cavitation when necessary. The presence of these devices decreases the pressure waves considerably. However, installing such a device will be costly to construct and maintain.[Kalkwijk and Kranenburg, 1971]

4.3. Epanet

Epanet is a software program, which is capable of performing hydraulic simulations within pressurized systems. With these simulations data is produced which engineers can use to understand and improve pressurized systems such as in this case study. With the help of Epanet a model can be produced of the pipeline. Results form this model can be compared and validated with data acquired by pressure measurements taken from the actual pipeline. Irregularities between the two datasets show the differences between our real life case study and the hypothetical 'optimal' situation as modelled in Epanet.

The pipeline is simulated in EPANET with the help of figure 3.1 and figure 3.2. The coordinates of the pipeline in vertical and horizontal direction can be found in these figures. The diameter as already mentioned is 0.85 meter and the roughness coefficient will be slightly higher than average because of the old age. Along the length of the pipeline multiple disruptive elements can be found that influence the results of the simulation. These disruptive elements consist of sharp bends, concrete sections and sections used for maintenance. These elements have influence on the flow, energy level and other results. These elements have been simulated as much as possible, but an error margin caused by this has to be accepted. What also has to be kept into mind is the fact that Epanet can only be used to model pressurized systems. If a system has parts that are not pressurized, additional measures have to be taken in order to model these parts. The pressure dataset obtained from the field measurements will be compared with the data obtained from the Epanet model. This comparison will be used to determine possible flow interrupting obstacles. These obstacles include sediment build-up, air pockets and corrosion which where previously discusse in this chapter.

4.4. Field Measurements

The pipeline has 35 air valves along the entire length of the pipeline. On those air valves pressure meters were installed to obtain additional data data which will be used to validate the modelling data. A device called mano-meter was installed on an air valve to measure the pressure on that exact location. The pressure was measured in kg/mc^2. This way of measuring is relatively accurate but still some errors can occur because two reasons.

- The air valve opening could be not completely clean and therefore measuring a pressure that is too low.
- Before a day of field measurements activities, all of the mano-meters where calibrated. however, during the day it could be possible that the mano-meters obtained an off-set because of the poor quality and old age.

(a) pressure check

(b) pressure check

Figure 4.3: In field measured pressured over total length pipeline

Figure 4.3 shows how the measurements in the field were performed. Every complete set of measurements consisted of 36 pressure checks performed at air valves that are located along the total length of the pipeline. These measurement sets have been performed four times to obtain data strings that give an accurate understanding of what the pressure is under varying conditions. Each set of measurements was performed under different flow levels. The data strings can be consulted in appendix B.

4.5. Sediment Build-up

The Bernoulli Equation expresses an phenomenon known as the ”Bernoulli effect”. This effect is best described as the conservation of energy appropriate for flowing fluids such as water. The fluid pressure inside a system is lowered at locations where the flow velocity is increased. This increase in flow velocity is increased, caused by constriction, this causes for the kinetic energy to be increased at the expense of the hydraulic pressure energy. The Bernoullie principle is illustrated in figure 4.4.

Sediment build-up within distribution pipelines is a common problem. Undissolved sediments are transported with the raw water and can settle at several locations along the pipeline. Sediment build-up happens when the velocity of the water does not reach above the required 0.3 m/s on a regular basis.[Burns et al., 2012]

Sediment build up is also caused by elements that disrupt the flow within the pipeline. In this study, it is difficult to check for sediment build-up within the pipeline.

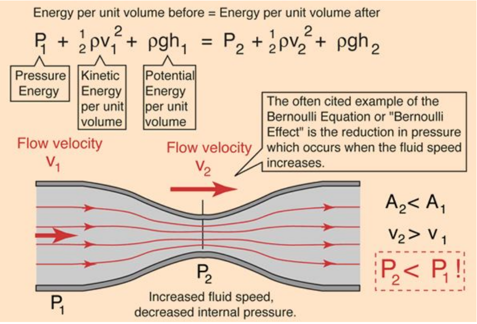


Figure 4.4: Bernoulli principle

Because of old age and sealed of air-valves there are no methods to check the inside of the pipeline. If irregularities are discovered in obtained pipe-pressure data that corresponds to certain sections of the pipeline actions can be taken to check if this is linked to sediment build-up. These actions can range from various ways of looking inside the pipeline with a camera or climbing inside. When taking these actions the water supply needs to be closed off, of course.

Sediment build-up in a pipeline effects the flow in a negative way. Therefore it is important to mitigate sediment build-up and flush a supplying system when necessary. In this particular situation it is likely that there is sediment build-up within the pipeline. This is mainly because of the questionable quality of the pipeline because of its old age and absence of maintenance. This causes flow drops in the pipeline which causes sediment build-up. The raw water that is transported through the pipeline also contributes to the sediment build-up because it contains the sediment. The amount of sediment within the water is difficult to determine. However, it is clear that the raw water is not filtered before entering the pipeline and by visual inspection it is clear that there is a significant amount of sediment in the water. This can be seen in figure 5.1

There are several points along the pipeline where the altitudes increases 'the pipeline goes up'. These points are extra vulnerable for sediment build-up.

4.5.1. mitigation measures

Sediment build-up is mitigated by flushing points shown in figure 4.3. These washout points are cleaned once a month and are located at the same locations as the air valves. However, many of these washouts are not reachable or do not perform up to standards, caused by lack of maintenance. In this particular situation sediment build up is a likely cause for the pipeline not meeting its design flow.

4.6. Corrosion

When the inside surface of a pipeline is corroded the roughness coefficient will increase thereby decreasing the flow. Corrosion of the inside of a pipeline is difficult to spot, creating a potential off set between the Epanet model and measured pressure data. Corrosion can also affect the quality of the water and cause potential health risks.

In order to locate corrosion within the pipeline a visual inspection needs to take place. As mentioned before this is a difficult task and have to be performed when the pipeline is not used.

4.7. Air Pockets

Air pockets can be formed inside a pipeline when air intake takes place. These air pockets will most likely form at locations where the pipeline is at an altitude peak and can considerably disrupt the flow, thereby lowering the final outflow. The formation of air pockets within this pipeline is a likely occurrence.[Malekpour et al., 2018]

Because hydrostatic pressure variation are negligible in a gas, a uniform pressure will form in the thin stream of water flowing below the air pocket. The water loses potential energy(height) along the course of a gravity pipeline and will not increase in pressure at the end of the air pocket, because the pressure remains the same in the stream below the air pocket. Therefore, the kinetic energy is the same at the beginning and at the and of an air pocket.

This makes the pressure loss the difference in elevation of the beginning and the end of an air pocket. This pressure drop can be measured with the help of the field work measurements and the Epanet model, thereby locating potential air pockets.[Bucur and E.C., 2008]

The formation of air pockets is mitigated with air valves that are installed along the length of the pipeline as shown in figure 4.3. Approximately 30 air valves are installed at the same location as the wash-out points used for sediment build up. This results in easier maintenance but reduces the effect because the air valves are not located at local altitude peaks along the length of the pipeline. However, it is questionable how much of those air valves work properly because of poor maintenance. Most of these air valves are closed down by PDAM because local people were stealing water from these locations.[Zhou and Liu, 2013]

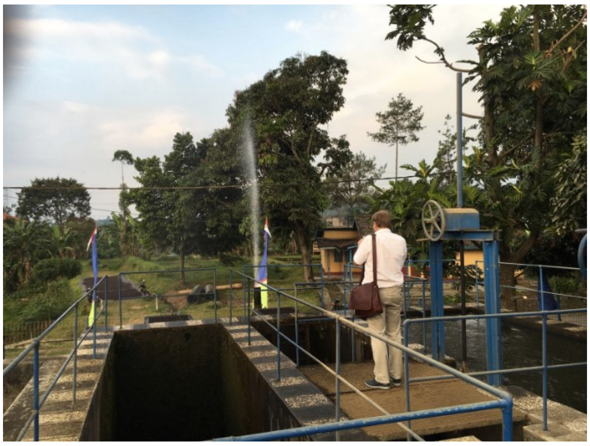
Results

5.1. Qualitative data, visual inspection

Figure 5.1a illustrates that the intake point of the pipeline is not completely submerged during the visual inspection, thereby letting in air into the pipeline. Figure 5.1b illustrates the total intake system which consist out of two open water basins both supplying the pipelines of raw water. These open water basins are fed with rain water from the catchment area upstream. Figure 5.1c illustrates a release valve located just a few meters below the intake point. This valve releases much air, which is a clear indication of air trapped inside the pipeline. Consequences of this trapped air are risk on cavitation, corrosion and air pockets.

(a) air intake pipeline

(b) open water basin intake point



(c) air release valve

Figure 5.1: overview pictures of intake point

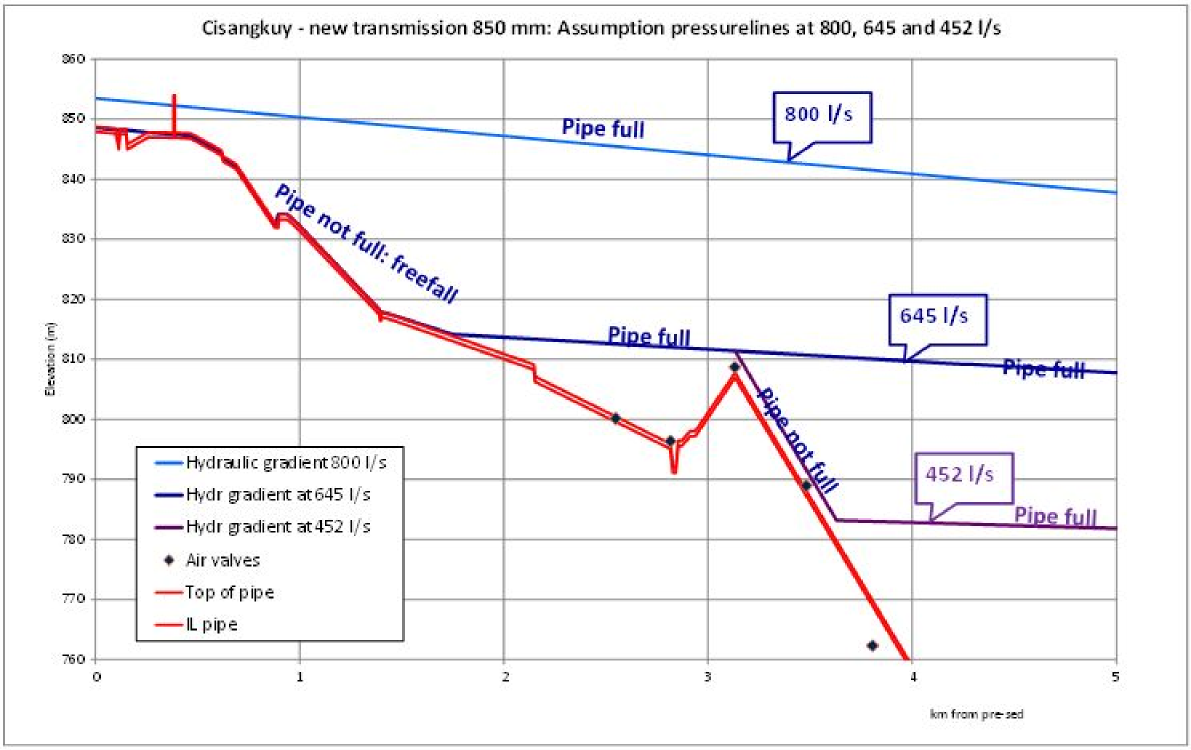


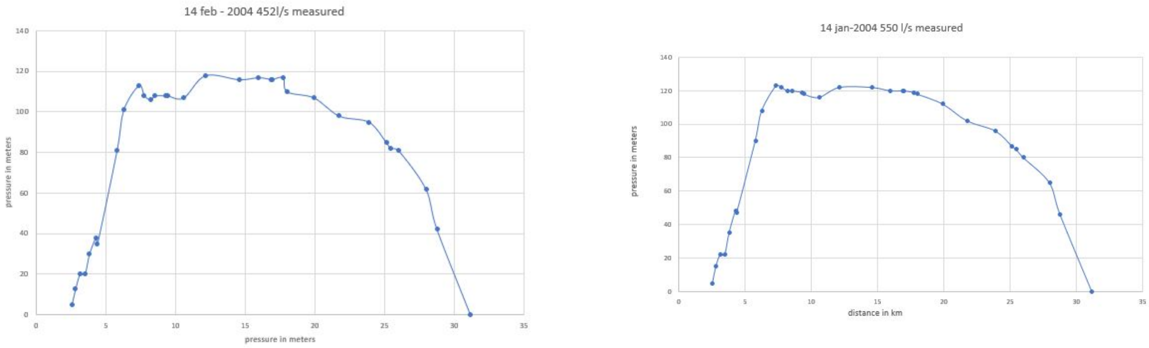
Figure 5.2: Assumptive pressure lines for the first section, 800 l/s - 645 l/s - 452 l/s

5.2. quantitative data, pressure measurement

Four in field pressure measurements where performed with the use of mano-meters. A team of professionals conducted these measurements during field trips as shown in figure 4.3. The data collected with these field measurements are presented in appendix B. In figure 5.3 the pressure is illustrated along the pipeline with different debit levels.

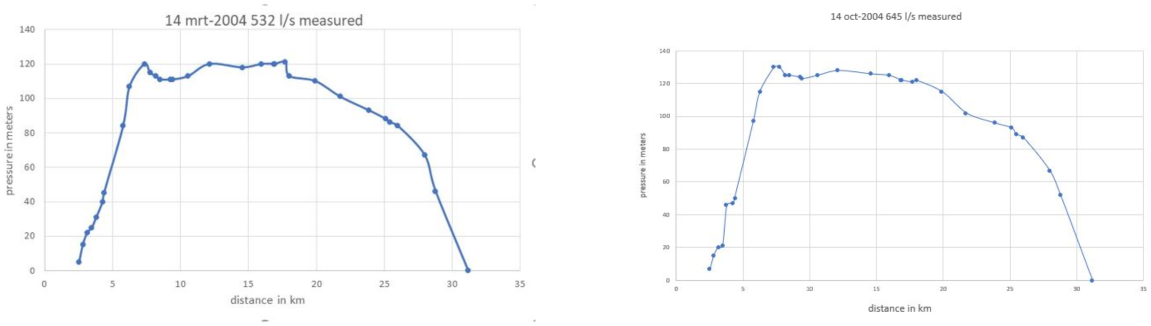
What becomes clear is that the first part of the pipeline acts like an open channel and the pressure is not high enough to completely fill the pipeline. When analyzing the first part of the pipeline figure 5.2 can be constructed with the resulting gradients for a debit of 452 l/s, 645 l/s and 800 l/s for the first part of the pipe line.

The first pressure measurement from down stream to upstream where the pressure was zero indicated the point where the pipeline non-pressurized zone starts. This non-pressurized zone goes all the way upstream to the intake point at Chikalong. This non pressurized part acts like an open channel and the transported raw water is in free fall. The hydraulic gradient for a debit of 800l/s was not constructed with pressure measurement data but with theoretical knowledge and is merely for additional understanding of the hydraulic gradient of the pipeline.



(a) 452 l/s , 14-02-2016

(b) 550 l/s , 14-01-2016



(c) 532 l/s , 14-03-2016

(d) 560 l/s - 02-10-2016

Figure 5.3: In field measured pressured over total length pipeline

5.3. Qualitative data, interviews

interviews have been conducted with mister Makmur, misses Dine, mister Rusnandi, Mister Tin Tin and several persons that live along the length of the pipeline.

The following results can be concluded from the interviews conducted. A resume of all interviews can be found in Appendix A

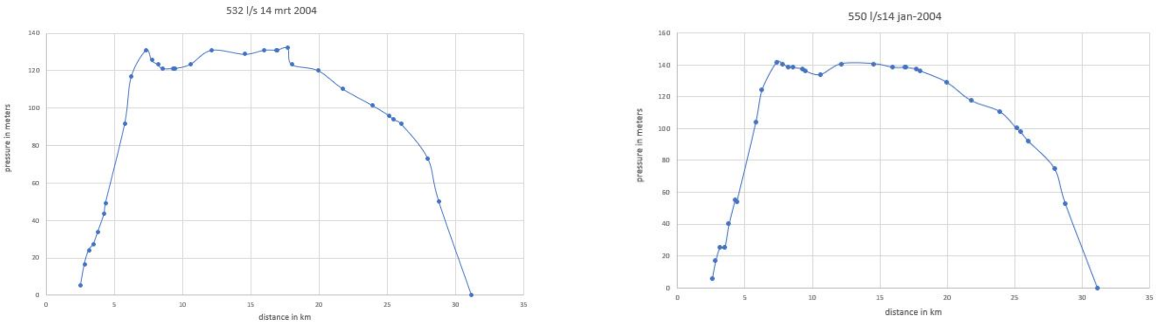
- The debit through the pipeline during fieldwork was 532 l/s at 21-03-2016, 550 l/s at 18-01-2016, 530 l/s at 14-10-2016 and 545 l/s at 10-02-2016.
- The design flow is 800 l/s when the pipeline was constructed in its original form.
- The route and components of several parts of the pipeline have been altered during its life time. The material shifted from steel to concrete, which most likely increased its roughness coefficient. The exact locations of these alterations cannot be validated accurately.
- There is air intake at the intake point of the pipeline. This is also concluded with the help of the results obtained by visual inspection. The cause of this is the water intake throttling by PDAM at the intake point.
- Several air valves and wash out points do not functions for different reasons. Reasons for this is the likelihood of theft and poor maintenance.
- If a change is made towards the location of the intake valve then it should be relocated to the outtake point at Badanksinga or the OVS1 location. These are the only locations where it is practically possible to construct a new intake valve.
- Local residents state that there is a significant adversity towards the pipeline because it runs through several neighborhoods impacting peoples personal lives. The occurrence of theft is also expressed by local residence. Furthermore, several local residence claim that they witnessed or at least heard about several large explosions somewhere during the last 10 years. One of these explosions has such an impact that it killed several people and did significant financial damage.

- Several air valves are shut off or broken. Which air valves are non-function is unknown.
- The maximum design pressure of the pipeline was 23.5 bar.

The interviews where conducted in a semi-informal setting. All of the interviewees have been submitted to a certain amount of pre-determined questions.

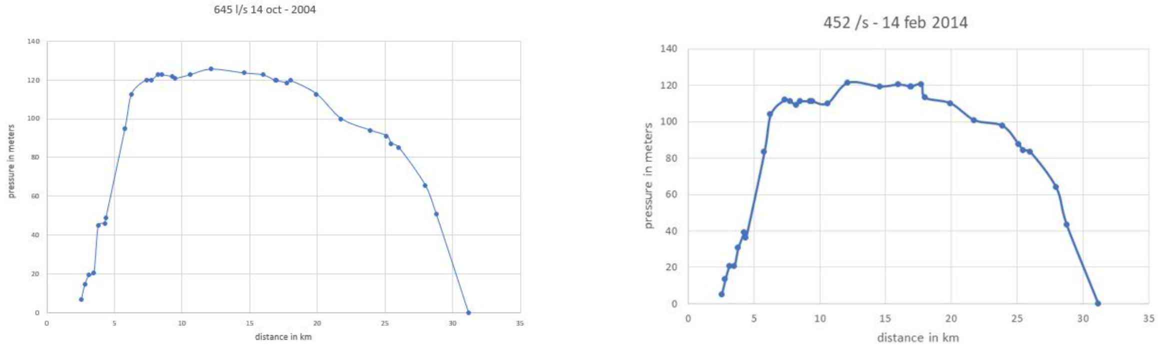
5.4. quantitative data, Epanet model

The pipeline was divided into sections and from every section characteristic locations were selected and processed into Epanet. The roughness coefficient was set on 0.85 for regular parts of the pipeline. Subsections where irregularities occur, such as location OVS1, old or concrete sections, the roughness coefficient was set to a higher value. Because the pipeline runs through the city for 30 kilometers it is impossible to model all of these regularities, thereby accepting a margin of error.



(a) 532 l/s , 21-10-2016

(b) 550 l/s , 18-10-2016



(c) 532 l/s , 14-10-2016

(d) 545 l/s - 10-10-2016

Figure 5.4: Modelled pressured over total length pipeline

In figure 5.4 a graphical overview of the four modelled pressure lines along the length of the pipeline are presented. The debit flow used in the model is equal to the debit flow measured in the field. These graphs will be compared with the pressure data obtained from field measurements.

5.5. Additional points for water inlet regulation

With the use of Epanet an estimation of the pressure and the hydraulic gradient along the pipeline is also calculated for two extra water intake regulating locations. The choice for checking the parameters of the system is based on data that states that these two locations are the only places where a regulating point can be constructed and could potentially improve the hydraulic properties of the pipeline, thereby making them worthwhile to investigate. The hydraulic properties of the system will be different for these two extra options and could thereby be beneficial for the final recommendation. The three in total possibilities are as followed.

- keep regulating the inflow at the intake point at Chikalong.
- regulate inflow at the first intersection (OVS1) 3 kilometres downstream of Chikalong.
- regulate inflow downstream at Badaksinga at the outflow point of the pipeline.

In figures 5.5a, 5.5b the pressure along the pipeline during operation and during downtime are illustrated for all three options. In figures 5.5c, 5.5d the hydraulic gradients for the three options are illustrated.

Keeping the status-quo also referred to as solution one is the cheapest and 'easiest' to apply in the current situation. As the inflow is increased to 850 L/s the pressure along the pipeline increases with it. The pipeline is strong enough to withstand these pressures. The risk that comes with this solution is that with a sudden increase of the inflow after for example an maintenance service water hammer can occur.

Second alternative: regulated inflow at the first intersection (OVS1) 3 kilometres downstream of Chikalong. The pressure in the first part of the pipeline will be increased compared to regulating the inflow at Chikalong but well below the design pressure of the pipeline. The chance of air coming into the pipeline is low. However, this will be a costly solution because the water inflow has to be regulated from OVS1. This point is in an urban area and far away from any PDAM's infrastructure. It is also difficult to install a regulator at this point because the intersection is old and does not work properly.

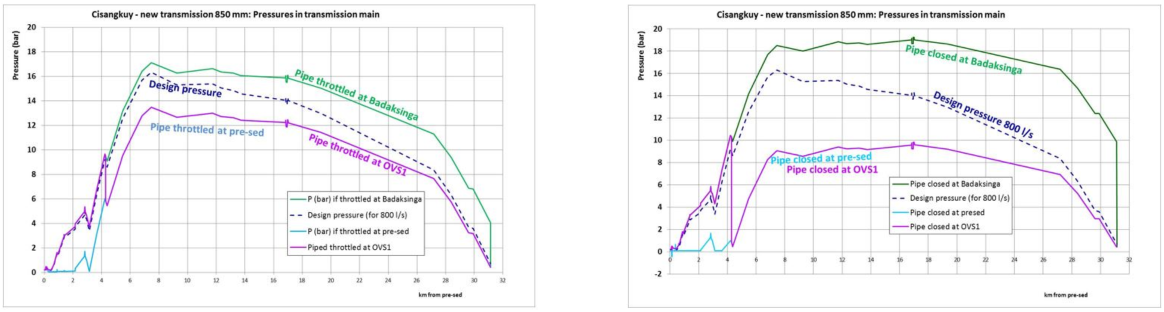
Third alternative: regulating inflow downstream at Badaksinga at the end of the pipeline. At first sight this seems like a good solution. The changes of air coming into the pipeline are diminished. However, it became clear that the pressure along the pipeline becomes significantly higher compared to the current situation. This is because in this situation the whole pipeline is always completely pressurized. This increase in pressure is significant and can lead up to a 10 bar increase in pressure as shown in table 6.1. This large increase in pressure is caused by the significant height difference along the length of the pipeline. If a pipeline with this amount of height difference is always filled with water higher pressures along the length of the pipeline can be expected. If you take into account the fact that the pipeline is more than 50 years old than this might create some extra potential risks. Also, after the outflow point the pressure will drop to zero because the water flow will end in a free fall. So if PDAM wants to throttle the water flow at Badaksinga, air can flow into the pipeline at the outlet point which can causes several problems. The specifications of the pipeline say that the maximum design pressure is 23.5 bar so in theory this solution is possible.

The estimated pressures along the pipeline for the three solutions were modelled by Epanet. It was clear that the pressure is the highest when throttling the inflow at Badaksinga.

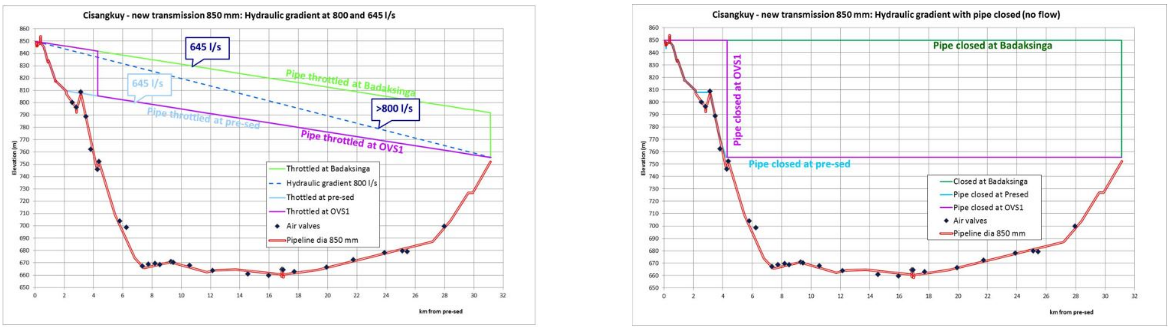
Table 5.1: maximum pressure for every possible solution

Regulate at:	While operating	While closed
1. At intake	13.2 bar at 8 km	9.2 bar at 8 km
2. Badaksinga	18 bar at 9 km	20 bar at 18 km
3. OVS1	13 bar at 8 km	11 bar at 5 km

Table 5.1 shows the maximum pressure (bar) for the three options. Appendix C contains calculations performed on collected data presented in appendix B. Also, the data in table 5.1 referrers to the data in appendix C.



(a) pressures in pipeline during operation (b) pressures in pipeline when closed



(c) hydraulic gradient in pipeline during operation (d) hydraulic gradient in pipeline when closed

Figure 5.5: Hydraulic gradient and pressure levels

5.6. Validation and data comparison

The in field collected data indicate that the first few kilometers of the pipeline where not pressurized at that time. This observation is supported by the visual inspection which also clearly indicates that there is intake and presence of air inside the pipeline, thereby validating this statement.

The modelled data and the data collected in the field are both compared and validated with with the measured pressure data obtained at 14-01-2016. The reason for choosing this data set as reference is because it is most likely to have the lowest error margin. At this date the team performing the measurements where using new mano-meters and the pressure measurements where performed twice at every air valve. The Epanet and field measurements both show good correlation to each other, possible causes for pressure drops such as air pockets, corroded locations and sediment build-up should be significant towards the offset between the data strings.

Conclusion

In this part both research questions will be answered and findings on different aspects of the case study will be answered.

6.1. research question 1

The first research question: What is the reason/problem why the supplying pipeline does not meet the design capacity?

After analyzing and comparing the measured data with the modelled data it can be concluded that the pipeline is still in good condition. The likelihood of entrapped air pockets, cavitation issues or corrosion inside the pipeline causing the drop in flow is thereby unlikely.

After studying the other gathered data it became clear that a water hammer inflicted a burst somewhere along the length of the pipeline. After this incident the operator decided to throttle the flow intake at Chikalong in order to prevent recurrence. Based on the data from the interviews and the story of the operator the burst caused by the water hammer happened as followed.

The water hammer incident occurred during a maintenance situation. During this time the water flow was closed off and water was stagnant at the lower end of the pipeline. When the operator decided to open valve at the intake point to start up the flow, the water mass accelerated downwards towards the standing water below. The air trapped between these two water bodies could not escape in time thereby being compressed causing peak pressures. These pressures where of a much higher magnitude than the pressure which the pipeline is designed for. The exact magnitude of this peak pressure is hard to define. What is known from consulted literature is that pressures caused by a phenomena like these can be as 20 times as high as normal water pressures.

Thus the reason that PDAM throttles the inflow of the water upstream at Chikalong was a burst in the pipeline. The explosion happened somewhere 10 years ago. After the explosion the pipeline was rebuild and taken back into operation with a lowered debit flow.

6.2. research question 2

To answer of the second research question: Which measures can be taking to increase the capacity of the supplying pipeline, three alternatives have been formulated. These alternatives describe the possible locations of the regulating flow intake valve as mentioned in the results section of this study.

- 1: keep regulating the inflow at the intake point at Chikalong.

Pro's:

- Lowered pressure along the pipeline
- Low financial costs.
- Quick and easy implementation.
- Keeping the use of existing infrastructure.

Con's:

- High risk on water hammer occurrence.
- Vulnerable for human error.
- Air intake into the pipeline at Chikalong.

- 2: Regulate inflow at the first intersection (OVS1) 3 kilometres downstream of Chikalong.

Pro’s:

- Lowered pressure along the length of the pipeline.
- Lowered chance on air intake at Chikalong.

Con’s:

- High operational cost.
- Investment needed for new infrastructure.

- 3: Regulate inflow downstream at Badaksinga at the outflow point of the pipeline.

Pro’s:

- Water intake is regulated at the water treatment plant, which add to the convenience and possible reduces the chance on human error.
- Low chance on air intake at Chikalong.

Con’s:

- Investment needed for new infrastructure.
- High pressures along the length of the pipeline.
- High chance on air intake at outlet point at Badaksinga.

All of these alternatives have benefits and drawbacks on both engineering and economical level. In the recommendation section of this rapport the optimal solution will be stated.

Recommendation

To avoid air entrapment, throttling at OVS1 is preferred. The peak pressures along the pipeline stay well below the design pressure. However, throttling at the preset has been up to PDAM's standards for more than 25 years already. Regulating at Badaksinga (throttling and closing) is not feasible. Very high pressures and problems with cavitation caused by air intake will increase the chance on pipe bursts and damage to the valve.

If PDAM starts throttling at OVS1 several upgrades to PDAM's infrastructure will have to be made. Accessibility and communication will have to be improved and the possibility for employees to spent the night at OVS1 will have to be realized as well. Also, the pipeline section at OVS1 will have to be adjusted to fit the regulating valve. PDAM can also decide to keep regulating the debit at preset at Chikalong. In order to do this safely PDAM will have to develop a protocol, which every employee will have to know and follow. A contractor will design and build a device, called a 'delaying box'. This delaying box is a so called red button that can be integrated in the process of opening or closing the flow regulating valve upstream at Chikalong. If the decision is made to change the flow through the pipeline than this button has to be pressed. This action will set a progress in motion where a motorized machine will open or close the valve for you. This machine will open the regulating valve with a pre-set speed that ensures a save situation. This box will ensure that it will technically not possible to suddenly increase the inflow of water. The installation of this box is recommended because it's always uncertain how individual employees will follow standard procedure.

In any case it is recommended to PDAM to slowly open the intake valve wherever it may be located after maintenance in order to slowly increase the volume of the flow. This action will insure that the pipeline will slowly fill up with water thereby giving the trapped air the chance to escape, this will decrease the chance on peak pressures and "explosions" in the future, also being able to increase the flow in the pipeline.

Before increasing the inflow of the pipeline at Chikalong it is recommended to ensure that the entire pipeline is in good condition. The pressure in the pipeline was very low at some parts for many years. Therefore it is unknown if these parts can withstand the added pressure. To make sure that even these parts of the pipeline can withstand the extra pressure because of the extra inflow an extra pressure strength test is needed. To do this a contractor needs to be hired and research the pressure strength of the pipeline at these various points.

Discussion

In this chapter the assumptions and results of the modelling will be discussed.

First of all, I would like to comment on my time with PDAM Tirtawening in Indonesia. Living in Bandung was a challenging experience during the first weeks, but after a while I got used to the busy traffic and streets. I made a lot of friends and experienced numerous new exiting things. All of these made my time enlightening on educational and personal level.

The field pressure measurement data where acquired with the help of professional personnel working at PDAM Tirtawening. The data also showed consistency though out the measurements. These two factors make this data reliable and therefore usable. Certain parts of the pipeline where not reachable from time to time therefore making the pressure measurement data incomplete for some data sets. This incompleteness had some influence on the results but the data over whole was still very much usable.

The Epanet model is based on visual data acquired in field and x and y coordinates acquired from the blue prints drawn up when the pipeline was build. These blue prints do not represent the actual situation completely but are still highly accurate. Figure 5.4 shows similarities with the data acquired from the field but inconsistencies are visible. In a situation like these, one could ask himself if the model was usable if the flow drop was indeed caused by irregularities within the pipeline. The pressure drop within the pipeline caused by these irregularities has to be larger than the 'noise' created by the offset between the measured and the modelled data. In this case study there was no irregularity that caused a lowered flow and thereby lowered pressure. Therefore, the usability of the created model could not be validated in this way. In the future the usability for the methodology used in this case study can still be explored with other case studies.

The visual data gave a general overview on the current state of the pipeline. The data was mostly used as an additional source for making the Epanet model. The first part of the pipeline is not pressurized thereby making the pressure measurements not usable. The visual data filled a lot of knowledge gaps thereby making it very usable. The Interviews conducted with personnel of PDAM Tirtawening is missing a lot of information but is consistent throughout. These interviews filled a key role in discovering what was causing the investigated problem and helped answering the first research question of the conclusion.

The final conclusion was of course not what was expected. The fact that the flow drop was caused by a human decision and not by a technical problem is very much interesting. Looking at the conclusion and the recommendation it becomes clear that not a technical problem was solved but a communication problem. If the executive staff better communicated with its working personnel this situation likely would not have occurred. Why this communication problem came to existing and how it can be solved can be researched in the future. It would be interesting to investigate how the Indonesian culture plays part in this communication problem.

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Appendix

A.1. interviews

This appendix contains summaries of interviews that were conducted with employees of the PDAM Tirtawening BANDUNG. Employees where selected from different levels of the organization, all of them have responsibilities of different aspects of the pipeline in question.

Miss Dine, manager of the water treatment plant.

The pipeline in question is old and has gone trough several chances during its lifespan. Two sections of the pipeline have been under maintenance because of leakage problems. These two sections are located 16 kilometers upstreams of the outlet point in Badaksinga. The route of one section of the pipeline has been altered because of the construction of new real estate such as roads and housing. The exact sections that have been altered is not known to the interviewee because it happened before here time at the company. The most likely cause of the lowered debit is the increased roughness of the inner wall of the pipeline. Other reasons could be sediment build-up or trapped air pockets. The interviewee explains that air pockets air almost certainly present inside the pipeline because of non functioning air valves.

Mister Makmur, Operational manager at the intake point of the pipeline at Chikalong.

Mister Makmur states that the intake point of the pipeline consist out of two basins, one inlet point and two outlet points. Both outlet points are connected to both the old and new pipeline. The basins are in turnarounds cleaned and have a long retention time to let sediment settle. At the intake point the valve that controls the flow is not completely opened because Mister Makmur and his team think that the amount of water flowing trough the pipeline should not be to high. The exact flow amount favourable by the team remains unclear, the reason why the intake valve cannot be completely opened and let the maximum amount of water through remain also unclear. Mister Makmur underlines the fact that air is sucked into the pipeline and that the air valves at several locations are inactive. Mister Makmur was able to show on a map which air valves where non functioning, reasons for this is the likelihood on theft and poor maintenance.

Mister Tin Tin, Operational manager, responsible of hydraulic operations of the pipeline at Badaksinga.

Mister Tin Tin states that regulating the flow at the intake point causes problems such as air intake and thereby arising air pockets. The pipeline is also old and has gone through a lot of changes, these changes could also add to the lowered flow through the pipeline. Changing the intake point to Badaksinga could be a solution to several problems but also increase the pressure along the pipeline. Taking OVS1 as the point where the intake is regulated could be an option that is from a hydraulic perspective favourable. however, several construction and implementation challenges will have to be dealt with. Difficulties with communication between the 'upstream' crew at Chikalong and the 'downstream' crew at Badaksinga creates from time to time an offset between the debit through the pipeline and the needed debit at the water treatment plant. Mister Tin Tin was also able to validate the debit flow through the pipeline when pressure checks where performed. He was also able to validate the fact that 800 L/s is indeed the original design flow through the pipeline. The maximum design pressure of the pipeline was 23.5 bar.

Local people along the length of the pipeline. Most people where interviewed at the OVS1 location.

The interviews with local people describes a situation where criminals steal water from the pipeline at several locations. Most attempts are made at air valves, but holes created in the outside wall of the pipeline are also common. A lot of local people have a negative view on the pipeline because it runs through there community thereby pushing people out of there homes. Several people remembered several bursts in the last 10 years along the length of the pipeline. One of these bursts was so powerful that several people died because of it.

Dr. Ir. Rusnandi, professor at ITB(Bandung Institute of Technology).

The pipeline is old and sections of its course has been shifted many times. Several sections of the steel pipeline have been reconstructed with concrete like material. It is my understanding that several air valves and washout points are not functioning. The build-up of sediment and air pockets inside the pipeline is likely the cause of the lower debit through the pipeline. If a decision is made on changing the location of the intake valve mister Rusnandi advises to take the outlet point and OVS1 in consideration. These locations are easily accessible and have the potential to improve the hydraulic properties of the pipeline.

Appendix

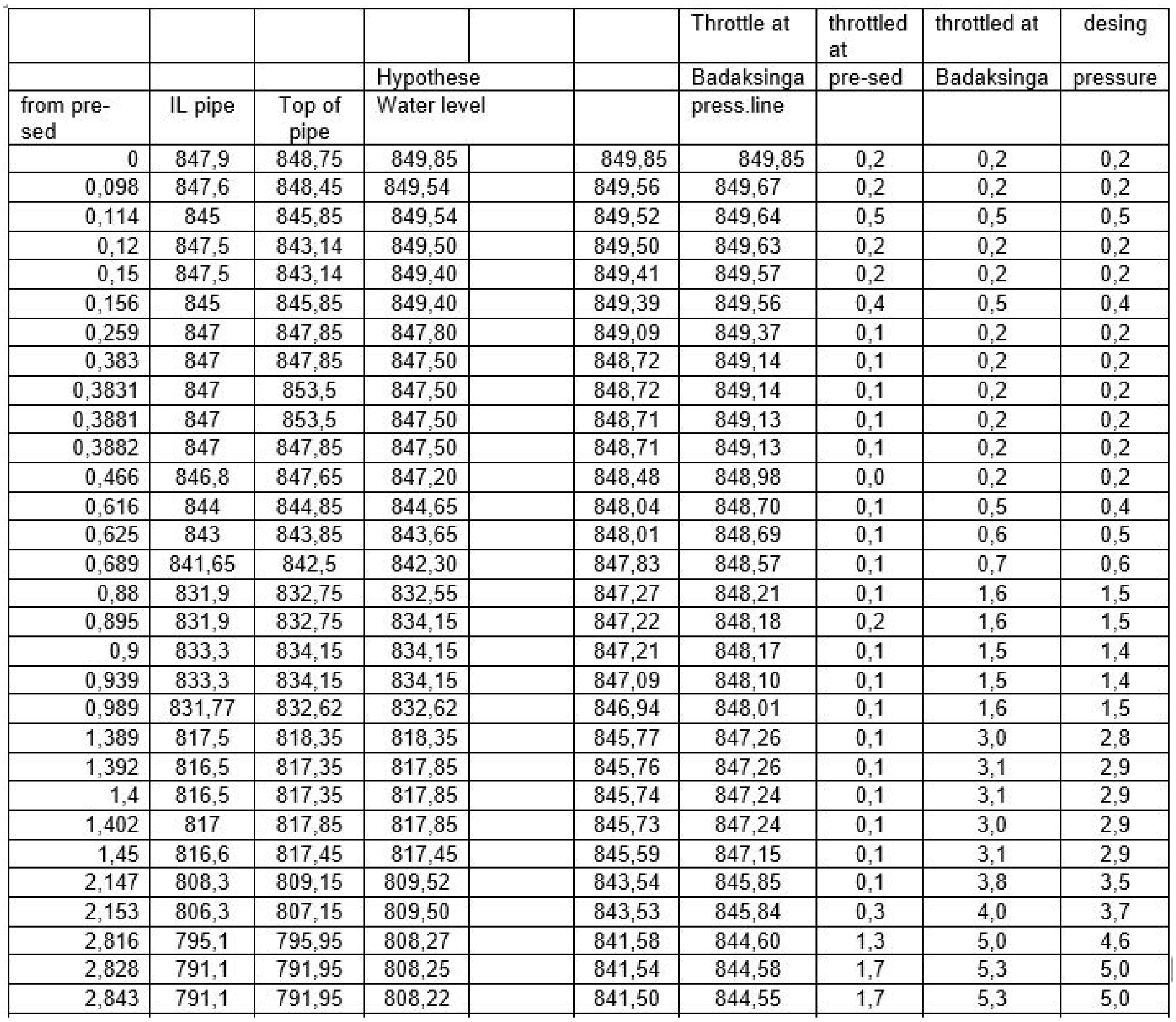
B.1. air valves/pressure measurement points

Table B.1: Add caption

	Measured pressure (m)						
	Min flow 452/s		Max flow 645/s		550 l/s		532 l/d
0	feb-14	0	oct-14	0	jan-14	0	mrt-14
2,549	5	2,549	7	2,549	5	2,549	5
2,817	13	2,817	15	2,817	15	2,817	15
3,132	20	3,132	20	3,132	22	3,132	22
3,482	20	3,482	21	3,482	22	3,482	25
3,807	30	3,807	46	3,807	35	3,807	31
4,273	38	4,273	47	4,273	48	4,273	40
4,373	35	4,373	50	4,373	47	4,373	45
5,78	81	5,78	97	5,78	90	5,78	84
6,26	101	6,26	115	6,26	108	6,26	107
7,347	113	7,347	130	7,347	123	7,347	120
7,753	108	7,753	130	7,753	122	7,753	115
8,2	106	8,2	125	8,2	120	8,2	113
8,521	108	8,521	125	8,521	120	8,521	111
9,287	108	9,287	124	9,287	119	9,287	111
9,448	108	9,448	123	9,448	118	9,448	111
10,574	107	10,574	125	10,574	116	10,574	113
12,13	118	12,13	128	12,13	122	12,13	120
14,558	116	14,558	126	14,558	122	14,558	118
15,958	117	15,958	125	15,958	120	15,958	120
16,871	116	16,871	122	16,871	120	16,871	120
16,947	116	16,947	122	16,947	120	16,947	120
17,716	117	17,716	121	17,716	119	17,716	121
18	110	18	122	18	118	18	113
19,934	107	19,934	115	19,934	112	19,934	110
21,748	98	21,748	102	21,748	102	21,748	101
23,885	95	23,885	96	23,885	96	23,885	93
25,118	85	25,118	93	25,118	87	25,118	88
25,437	82	25,437	89	25,437	85	25,437	86
26	81	26	87	26	80	26	84
27,967	62	27,967	67	27,967	65	27,967	67
28,767	42	28,767	52	28,767	46	28,767	46
31,16	0	31,16	0	31,16	0	31,16	0

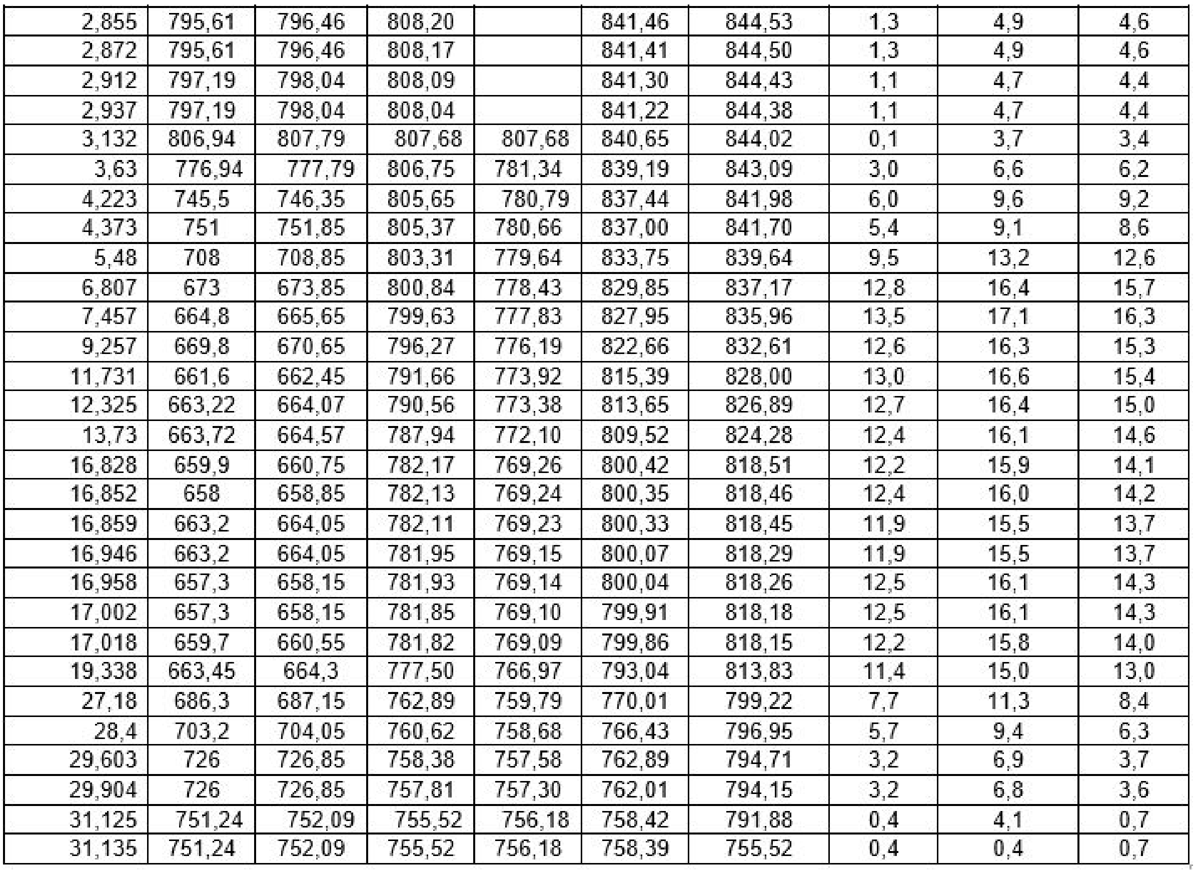
Appendix

C.1. Data used for pressure calculations in the discussion section, three possibilities



						Throttle at	throttled at	throttled at	desing
			Hypothese			Badaksinga	pre-sed	Badaksinga	pressure
from pre-sed	IL pipe	Top of pipe	Water level			press.line			
0	847,9	848,75	849,85		849,85	849,85	0,2	0,2	0,2
0,098	847,6	848,45	849,54		849,56	849,67	0,2	0,2	0,2
0,114	845	845,85	849,54		849,52	849,64	0,5	0,5	0,5
0,12	847,5	843,14	849,50		849,50	849,63	0,2	0,2	0,2
0,15	847,5	843,14	849,40		849,41	849,57	0,2	0,2	0,2
0,156	845	845,85	849,40		849,39	849,56	0,4	0,5	0,4
0,259	847	847,85	847,80		849,09	849,37	0,1	0,2	0,2
0,383	847	847,85	847,50		848,72	849,14	0,1	0,2	0,2
0,3831	847	853,5	847,50		848,72	849,14	0,1	0,2	0,2
0,3881	847	853,5	847,50		848,71	849,13	0,1	0,2	0,2
0,3882	847	847,85	847,50		848,71	849,13	0,1	0,2	0,2
0,466	846,8	847,65	847,20		848,48	848,98	0,0	0,2	0,2
0,616	844	844,85	844,65		848,04	848,70	0,1	0,5	0,4
0,625	843	843,85	843,65		848,01	848,69	0,1	0,6	0,5
0,689	841,65	842,5	842,30		847,83	848,57	0,1	0,7	0,6
0,88	831,9	832,75	832,55		847,27	848,21	0,1	1,6	1,5
0,895	831,9	832,75	834,15		847,22	848,18	0,2	1,6	1,5
0,9	833,3	834,15	834,15		847,21	848,17	0,1	1,5	1,4
0,939	833,3	834,15	834,15		847,09	848,10	0,1	1,5	1,4
0,989	831,77	832,62	832,62		846,94	848,01	0,1	1,6	1,5
1,389	817,5	818,35	818,35		845,77	847,26	0,1	3,0	2,8
1,392	816,5	817,35	817,85		845,76	847,26	0,1	3,1	2,9
1,4	816,5	817,35	817,85		845,74	847,24	0,1	3,1	2,9
1,402	817	817,85	817,85		845,73	847,24	0,1	3,0	2,9
1,45	816,6	817,45	817,45		845,59	847,15	0,1	3,1	2,9
2,147	808,3	809,15	809,52		843,54	845,85	0,1	3,8	3,5
2,153	806,3	807,15	809,50		843,53	845,84	0,3	4,0	3,7
2,816	795,1	795,95	808,27		841,58	844,60	1,3	5,0	4,6
2,828	791,1	791,95	808,25		841,54	844,58	1,7	5,3	5,0
2,843	791,1	791,95	808,22		841,50	844,55	1,7	5,3	5,0

Figure C.1: pressure calculations pipeline



2,855	795,61	796,46	808,20		841,46	844,53	1,3	4,9	4,6
2,872	795,61	796,46	808,17		841,41	844,50	1,3	4,9	4,6
2,912	797,19	798,04	808,09		841,30	844,43	1,1	4,7	4,4
2,937	797,19	798,04	808,04		841,22	844,38	1,1	4,7	4,4
3,132	806,94	807,79	807,68	807,68	840,65	844,02	0,1	3,7	3,4
3,63	776,94	777,79	806,75	781,34	839,19	843,09	3,0	6,6	6,2
4,223	745,5	746,35	805,65	780,79	837,44	841,98	6,0	9,6	9,2
4,373	751	751,85	805,37	780,66	837,00	841,70	5,4	9,1	8,6
5,48	708	708,85	803,31	779,64	833,75	839,64	9,5	13,2	12,6
6,807	673	673,85	800,84	778,43	829,85	837,17	12,8	16,4	15,7
7,457	664,8	665,65	799,63	777,83	827,95	835,96	13,5	17,1	16,3
9,257	669,8	670,65	796,27	776,19	822,66	832,61	12,6	16,3	15,3
11,731	661,6	662,45	791,66	773,92	815,39	828,00	13,0	16,6	15,4
12,325	663,22	664,07	790,56	773,38	813,65	826,89	12,7	16,4	15,0
13,73	663,72	664,57	787,94	772,10	809,52	824,28	12,4	16,1	14,6
16,828	659,9	660,75	782,17	769,26	800,42	818,51	12,2	15,9	14,1
16,852	658	658,85	782,13	769,24	800,35	818,46	12,4	16,0	14,2
16,859	663,2	664,05	782,11	769,23	800,33	818,45	11,9	15,5	13,7
16,946	663,2	664,05	781,95	769,15	800,07	818,29	11,9	15,5	13,7
16,958	657,3	658,15	781,93	769,14	800,04	818,26	12,5	16,1	14,3
17,002	657,3	658,15	781,85	769,10	799,91	818,18	12,5	16,1	14,3
17,018	659,7	660,55	781,82	769,09	799,86	818,15	12,2	15,8	14,0
19,338	663,45	664,3	777,50	766,97	793,04	813,83	11,4	15,0	13,0
27,18	686,3	687,15	762,89	759,79	770,01	799,22	7,7	11,3	8,4
28,4	703,2	704,05	760,62	758,68	766,43	796,95	5,7	9,4	6,3
29,603	726	726,85	758,38	757,58	762,89	794,71	3,2	6,9	3,7
29,904	726	726,85	757,81	757,30	762,01	794,15	3,2	6,8	3,6
31,125	751,24	752,09	755,52	756,18	758,42	791,88	0,4	4,1	0,7
31,135	751,24	752,09	755,52	756,18	758,39	755,52	0,4	0,4	0,7

Figure C.2: pressure calculations pipeline