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MASTER'S THESIS

Pressure Surge analysis (water hammer) in Firewater deluge system

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I confirm that the work is self-prepared and that references/source references to all sources used in the work are provided, cf. Regulation relating to academic studies and examinations at the Western Norway University of Applied Sciences (HVL), § 12-1.

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This thesis is a part of the master's program in Fire Safety Engineering at Western Norway University of Applied Sciences. The author(s) is responsible for the methods used, the results that are presented, the conclusion, and the assessments done in the thesis.

Preface

The thesis is the final mandatory work to complete the master's degree in fire safety.

I have been working in the fire safety industry since 2008, then I decided to enhance my academic knowledge about fire safety so I started the master's degree in fire safety in HVL. To choose a practical topic for my master's thesis I was looking for a topic to combine both my technical know-how in active fire protection with the academic knowledge that I gained during the master's study. meanwhile, I experienced a damaged deluge value during the priming of the ring main due to a pressure surge so I decided to further investigate this phenomenon in my thesis to demonstrate how to design a deluge system more reliable and more efficient.

Transient flow dynamics is not only a complicated phenomenon but also very interesting and may lead to some surprising results. Hand calculation is not practical and computer analysis software is needed to solve many partial equations in very small-time steps E.g. 0.01 seconds. One of the well-known software used in the industry is a transient module of Pipenet software from Sunrise System Limited.

Pipenet can simulate the transient phases when a deluge valve starts to open until the steady state condition, calculating the peak pressures and time it takes to fill the dry pipes and all nozzles start to discharge water.

This is a very important analysis to make sure all the deluge network elements are strong enough to withstand the peak pressures during the filling phases.

This will help the fire safety engineer design a reliable deluge network to extinguish the fire in the worst-case scenarios efficiently.

Pouria Nazaran

Acknowledgments

I would like to thank my Supervisor Kristian Grimstvedt for his help and for sharing the knowledge and advice for more than a year—also, for his excellent support so I can have a Pipenet educational license.

I would also thank Øyvind Økland from Rosenberg Worley as an external supervisor for facilitating this project and inspiring me to do this thesis I appreciated his time to review and give comments on this thesis

I also would like to especially thank Fredrik L. Hemmingsson, Assisterende Instituttleder in HVL, and Magnus Aaderaa Department Manager of Technical Safety Rosenberg Worley for the great inspiration to do this master thesis and also financial support from their organization so I can have access to an educational license of transient module of the Pipenet which is an expensive software in the fire water industry.

Abstract

The deluge fire water system is usually designed based on steady-state conditions in which a system will be designed so there is enough flow rate and water spray coverage to extinguish/cool the fire in a predefined duration.

In steady-state conditions, the pressure within the deluge system network is always less than the inlet pressure. But during the initial stage of opening of Deluge valve, the water starts to follow through the empty pipes and expel air out of the nozzles until the steady state condition prevails, pressure in some cases can be much higher than inlet pressure Which might result in damaging the Deluge network.

For example, because the air discharges from the nozzles with less resistance compared to water there would be a considerable drop in flow velocity when it changes from air to water discharge from the nozzles and this phenomenon is usually more severe for the last nozzles to release the water. This reduction in velocity and momentum will result in a pressure surge for a very short period which can be destructive. Also, there are possibilities for the formation of cavitation and the collapse of cavitation which can cause a considerable pressure surge.

In this thesis, a software method is used to calculate the pressure surge and then various solutions are proposed to deal with this phenomenon such as a dead-end piece of pipe at the most remote nozzle, using a vacuum breaker and accumulator to reduce the pressure surge.

Various scenarios were modeled to illustrate the present of pressure surge and then applying different mitigations to reduce the pressure surge showing how efficient they are.

Sammendrag

Deluge brannvannsystemer er vanligvis designet basert på «*steady state*» tilstand, hvor et system blir utformet slik at det er tilstrekkelig vannstrøm og vanntetthet over systems dekningsarealet slik at brannen slokkes innenfor forhåndsdefinert tid.

I « *steady state*» er trykket i deluge systemet alltid lavere enn inntakstrykket. Men under den innledende fasen ved åpning av deluge ventilet hvor vannet begynner å strømme gjennom de tomme rørene og luft ventileres ut av dysene til «*steady state*» inntreffer, kan trykket i noen tilfeller være mye høyere enn inntakstrykket, noe som kan resultere i skade på deluge nettverket.

For eksempel, fordi luften strømmer ut fra dysene med mindre motstand sammenlignet med vann, vil det være en betydelig reduksjon i strømningshastighet når det skifter fra luft til vannstrøm ut dysene, og dette fenomenet er vanligvis mer alvorlig for de siste dysene som slipper ut vannet. Denne reduksjonen i hastighet og moment vil resultere i trykkstøt i en veldig kort periode som kan være destruktiv. I tillegg er det muligheter for dannelse av kavitasjon og kollaps av kavitasjonen som kan forårsake betydelige trykkstøt.

I denne rapporten brukes programvare for å beregne trykkstøt, og deretter blir ulike løsninger foreslått for å håndtere dette fenomenet, for eksempel et blindstykke av rør på den mest fjerntliggende dysen, bruk av en vakumbryter og en akkumulator for å redusere trykkstøtet.

Ulike scenarier er modellert for å illustrere tilstedeværelsen av trykkstøt og deretter er ulike tiltak anvendt for å redusere trykkstøt og vise hvor effektive de er.

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Definitions

Young Module, E, Young modulus or module of elasticity is a mechanical property of a pipe that shows the stiffness of the pipe, by definition it is the stress divided by strain.

Deluge Network: Dry pipe networks (unpressurized) with open sprinklers. It is connected to a pressurized pipe with a normally closed deluge valve. In case of fire, the deluge valve opens and releases the water to all nozzles to extinguish the fire.

Pressure Surge: a sudden rise in water or any other liquid pressure in the pipe due to fluid velocity change.

Water hammer: it is the result of pressure surge on the network, throughout this thesis both of them are used interchangeably.

Cavitation: when the liquid pressure becomes smaller than vapor pressure the vapor bubbles form in a pipe, sudden formation and collapse due to pressure rise inside a pipe is called cavitation

Vacuum breaker: a device to let some air be sucked into the piping system when the pressure drop below a predefine set point to prevent the fluid pressure drop below the vapor pressure and cavitation.

Priming time: In a dry pipe system the time from the opening of the Deluge valve until the water discharges from the most remote nozzle.

1. Introduction

A Deluge network is designed based on a steady-state condition. The steady state condition is the condition in which the fluid parameters such as pressure and flow does not change with time. Usually, in a deluge system the network is dry after the deluge valve and when the water discharge signal energizes the deluge valve sednoid, the valve opens and fills the entire pipe, and eventually the water spray will come out of all nozzles.

The transient state between the time when a deluge valve starts to open until the system reaches to steady state condition is also crucial to be analyzed because of pressure surge probability and maximum acceptable priming time.

The National Fire Protection Association (NFPA) recommended that water spray from all nozzles Without delay [1]

Pressure surge means the increase in the fluid pressure for a very short time (usually a fraction of a second) Pressure surge or water hammer can happen when the dry deluge network is filled. In some cases, the magnitude of pressure surge can reach a very high number which may damage pipes and fittings.

The pressure surge in the deluge network may happen because of decreasing the flow velocity when the flow changes from air to water in the last nozzle. The air can discharge from a nozzle much easier than water due to the lower viscosity. A sudden decrease in the flow velocity will result in a change in flow momentum and pressure increases.

Generally speaking, the firewater system shall be designed so that the magnitude and effect of pressure surge shall be minimized.

The filling process is called priming the deluge system, the system needs to start to extinguish the fire as quickly as possible so the time needed for that last nozzle to start discharging the water is also very important and there is a minimum requirement for fire water standards.

To calculate the pressure surge characteristics and priming time, the transient analysis shall be performed. Due to the complexity of this phenomenon, a software tool needs to be used. But this is not always performed comprehensively to find out every possible scenario for pressure surge and also find out what is the most effective way to tackle this problem.

In this Thesis, analyzing the transient periods will be demonstrated along with different solutions to reduce or eliminate the pressure surge. two deluge networks will be analyzed by using the software. The main focus is to investigate how to calculate the pressure surge accurately and apply different mitigations showing how efficient they are in Deluge systems.

Meanwhile, the cavitation and nozzle priming time is also considered to some extent because these three parameters are key and important in Deluge transient analysis. Some solutions to reduce pressure surge may increase the priming time of the system which is undesirable and should be avoided as much as possible.

Different mitigating measures were proposed and the effectivity of each solution was analyzed by a simulation. In one scenario a vacuum breaker was introduced into the system and the effect on pressure surge a cavitation was discussed.

Although the work on this thesis is limited to deluge networks many of the techniques and findings are also applicable to analysis the Ring main transient analysis as well.

2. Theory

Water-based suppression systems which generally known as Sprinkler systems are divided into many different types. The deluge system is one of them which we are particularly interested in analyzing in this Thesis. Because the Water hammer is more important in this type of system.

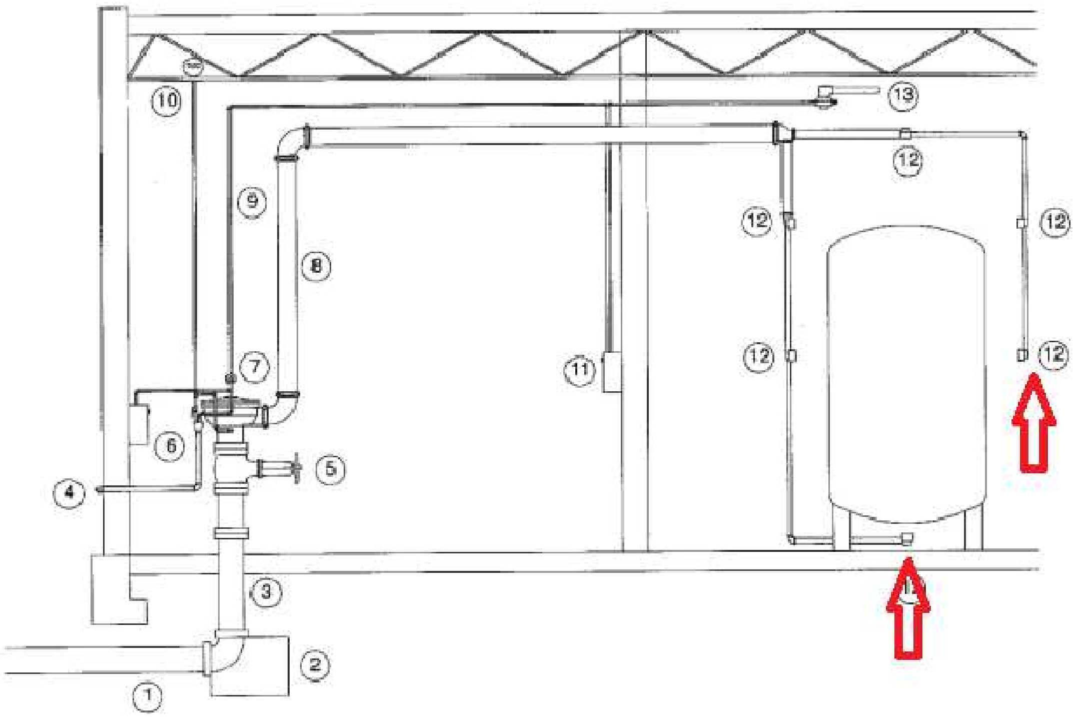

Figure2. 1 A dry-type deluge system with open nozzles (Courtesy of Viking Corporation) [2]

As seen in Fig 2.1, the system is in the closed position by the deluge valve (item 7) while all the nozzles (item 12) are open. As soon as the fire is detected, the Solenoids on the deluge valve will be activated by a fire alarm system and the water will start to flow through the dry pipes until the last nozzle starts to discharge the water. In this case, it might be either of the nominated nozzles in Fig 2.1

Fluid in motion inside any pipe has momentum, which is the mass multiplied by the velocity of the fluid. If the fluid is forced to stop or change direction, the momentum will be changed, which results in a pressure surge. The pressure surge will travel with the speed of sound in that fluid along the pipe and is called a pressure wave. This usually happens when a valve closes suddenly but could happen in other circumstances. E.g. in the Deluge system described here, when the water reaches the last nozzle, the flow velocity is forced to slow down because the water is more difficult to pass through the nozzle compared to air due to viscosity. This slowdown might be a considerable change in momentum and there might be a destructive pressure surge developed in the system.

The pressure surge mainly depends on the compressibility of the liquid and the rigidity of the pipe materials. Generally, when the fluid is less compressible, and the pipe is more rigid material (less elastic) larger water hammer will appear.

2.1. Simplified Analytical solutions

There are two approaches to analyzing the water hammer with a simple equation

First, when the valve is closing slowly compared to the time takes for shock waves to travel along the pipe, we can neglect the water compressibility and pipe elasticity so we have:

$\Delta p = \frac{\rho L v}{t}$ *Equation 1*

p: pressure (Pa)

ρ: fluid density in (kg/m3)

L: pipe length (m)

v: flow velocity (m/s)

t: valve closing time (s)

Second, when the valve is closing almost instantly. Generally, the density changes due to pressure variation are assumed zero in the hydraulic calculation but when the valve closes in a very short time and there will be a pressure surge in the system, the compressibility of water and elasticity of the pipe must be considered.

In this case, the Joukowsky equation can be used to calculate the maximum pressure as below

$\Delta p = -\rho c \Delta v$ *Equation 2*

c: wave speed or sound speed in the pipe

p: pressure (Pa)

ρ: fluid density in (kg/m3)

v: flow velocity (m/s)

$c = \sqrt{\frac{1}{\rho(\frac{1}{k} + \frac{D}{E * e})}}$ *Equation 3*

E: Pipe Module of elasticity, Pa

e: wall thickness, m

D: pipe diameter, m

K: bulk module of elasticity of liquid, Pa

2.2. Differential equation solution

Using the above equation in engineering work is limited due to the following.

- ➢ Valve closing time does not considered in the Joukowsky equation. Eq2
- ➢ It does not consider line-packing
- ➢ Several events cannot consider
- ➢ It is limited to the pipe only

Line packing can be explained as when the valve is going to be closed and the output flow becomes zero almost at the same time (blue line) there is still some flow upstream the valve (red line) due to pipe elasticity and fluid compressibility. So, the maximum pressure will be higher than the Joukowsky can predict see the fig 2.2

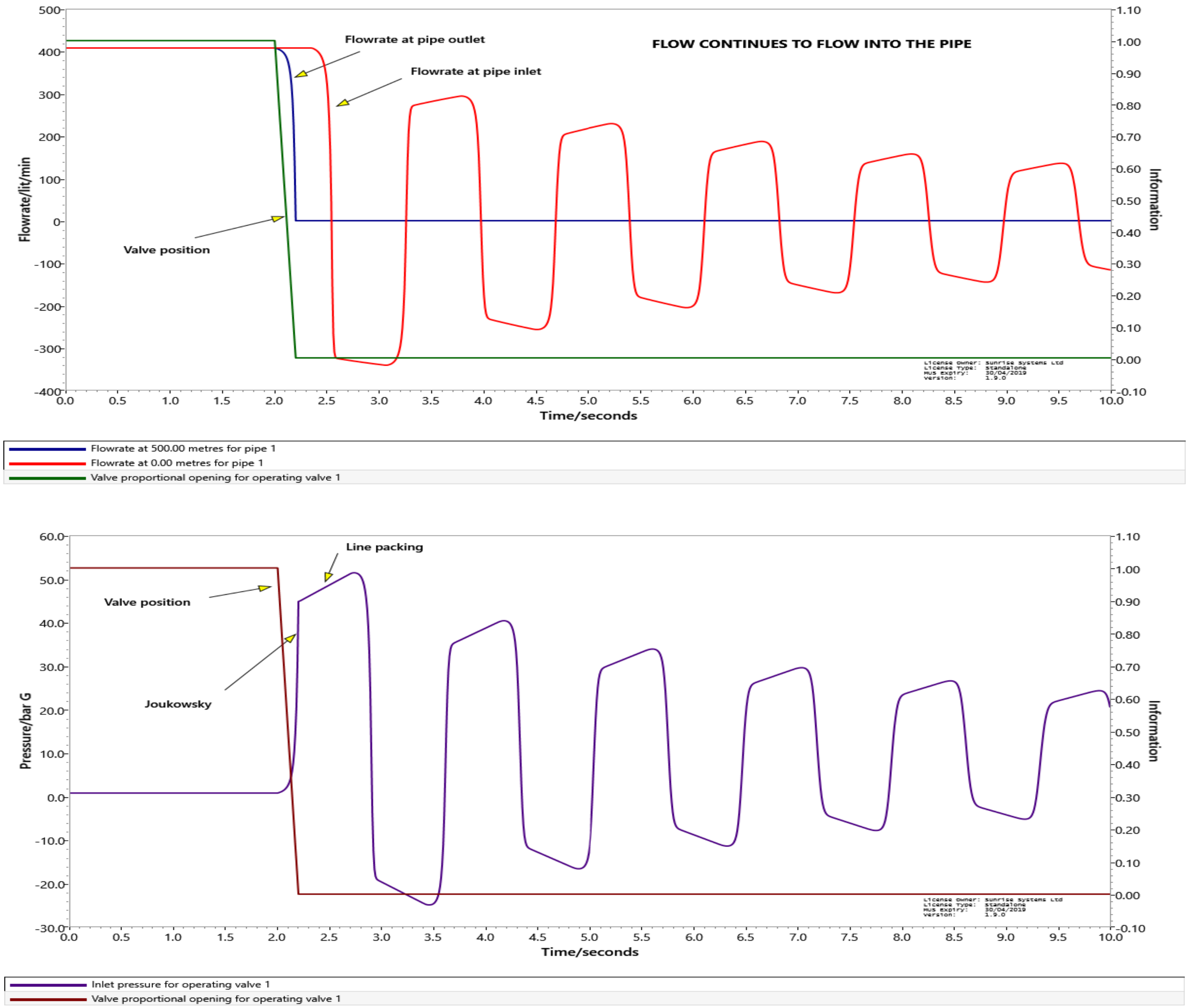

Figure2. 2 Line packing graph in Pipenet software, Above the valve position along with flow before and after the valve, bellow pressure surge and effect of line packing

So, we need to use the partial differential equations to better modeling this phenomenon *“Equations for the conservation of mass and momentum describe the transient flow in closed conduits. These equations are usually referred to as the continuity and momentum equations”[3].*

Considering a control volume inside the pipe

the continuity Equation is: $\frac{\partial P}{\partial t} + V\,\frac{\partial P}{\partial X} + \,\rho a^2\,\frac{\partial V}{\partial X} = 0$ *Equation 4 [4]* Wave speed $a^2 = \frac{\frac{K}{\rho}}{1+\frac{DK}{eE}}$

Equation 5

e: pipe thickness,

D: pipe diameter,

K: the bulk module of elasticity of a fluid

E: Young's Modulus for the pipe material

ρ : fluid density.

The momentum Equation is: $\frac{\partial V}{\partial t} + V\,\frac{\partial V}{\partial X} + \frac{1}{\rho}\frac{\partial P}{\partial X} + g\,sin\,\theta + \frac{f\,V\,|V|}{2D} = 0$ *Equation 6 [4]*

f: Darcy-Weisbach friction factor

θ: is the angle the pipe makes with the horizontal.

In the most engineering applications $V\,\frac{\partial P}{\partial X}$ and $V\,\frac{\partial V}{\partial X}$ are small relatively and also the slop term is usually small and may be neglected so these two equations will be [4]

$\frac{\partial P}{\partial t} + \rho a^2\,\frac{\partial V}{\partial X} = 0$ *Equation 7*

$\frac{\partial V}{\partial t} + \frac{1}{\rho}\frac{\partial P}{\partial X} + \frac{f\,V\,|V|}{2D} = 0$ *Equation 8*

The wave speed in a pipe is the speed at which pressure surges are propagated along the pipe. It depends on several factors, including the material and diameter of the pipe, and the bulk modulus of the fluid. For the Transient Module to make an automatic calculation of the wave speed, the user must provide a pipe schedule and define the fluid bulk modulus. [5]

3. Methods

To find the pressure surge, the peak transient pressure in all pipes and during the priming periods need to be known. So, the momentum and continuity equation need to be solved numerically to find the P and V with respect to x (distance) and t(time). One method to solve these equations is the method of characteristic.
The method of characteristics uses a technique to solve a first-order quasilinear partial differential equation given by
$f (x, y,z)\partial x\phi + g(x, y,z)\partial y\phi = h(x, y,z)$ [6] *Equation 9*

In practical problems, computer software is required to solve equations. One of the well-known software that is widely used in the Oil and gas and energy industry is Pipenet from Sunrise System Ltd. The transient Module of the software uses the Method of Characteristics to solve the above equations. In this thesis, I used the Pipenet Software version 1.11.0.3604 educational license to calculate the pressure surge.

The transient module of Pipenet Software is versatile, user-friendly, and extremely powerful for modeling the transient condition in the Deluge system. The software provides an efficient time base and distance base graph so a network behavior during the priming time can be thoroughly analyzed. It can simulate the flow behavior during the transient period.

The software uses the different forms of the momentum and continuity equation [5]

$\frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{\partial u}{\partial t} + g\,sin\,\alpha + \frac{4*f\;u\,|u|}{2D} = 0$ *Momentum equation 10*

$\frac{1}{\rho*A}u\frac{\partial\rho A}{\partial x} + \frac{1}{\rho*A}\frac{\partial\rho A}{\partial t} + \frac{\partial u}{\partial x} = 0$ *Continuity Equation 11*

P: pressure in the pipe

u: fluid velocity along the pipe

x: Distance along the pipe

t: time

A: Cross-section area of the pipe

d: pipe diameter

ρ: Fluid density

α: pipe angle makes to the horizontal

f: Fanning friction factor

g: acceleration of gravity

The fourth time multiplying factor in the momentum equation is since the fanning friction factor is used while the Darcy friction factor is four times the Fanning friction factor.

Also, the continuity equation mentioned recently used by Pipenet is expressed with the fluid velocity u and the fluid density ρ, which is the general and widespread form of this equation instead of pressure which was used in the previous section for continuity.

For a network, Pipenet solves large sets of partial differential equations, ordinary differential equations, and algebraic equations.

For pressure loss the software has two options, the Darcy Equation and the Hazen-Williams Equation, the friction factor in the Darcy Equation is given either by the Coulson-Richardson equation or by the Colebrook-White equation. In the Spray option of the software, the Hazen-Williams Equation is used to calculate the pressure drop.

Pipenet uses five parameters to define a fluid which are fluid density, viscosity, temperature, bulk module, and vapor pressure. [5]. In this thesis, the simulation is only limited to the water.

The software assumes that the pipe is anchored at both ends against longitudinal movement otherwise the wave speed should be specified by the user. In the deluge system, the software assumption is applicable. Default Wave speed is considered 1260 m/s. This is the software default value based on water flowing inside the anchored pipe.

The Pipenet can model the dry pipe in two ways. Dry pipe 1 and dry pipe 2

After the deluge valve opens it takes some time for the water to fill all pipes and come out of all nozzles, during this time the air is draining from the system via nozzles, this is called priming time.

According to NFPA 15, priming time is recommended to be less than 30 sec [1]

Dry pipe 1 assumes that the air pressure inside the dry pipe is 0 barg during the priming time and there is no obstacle to the airflow exit, this model runs faster and the result is accurate enough in most cases.

Dry pipe 2 assumes ideal gas law PV=nRT and considers some obstacles in air exit so it is a more realistic model and it takes longer to run but the results are more accurate. By selecting dry pipe 2 the software will consider the air-cushion effect.

The methodology used for calculating the pressure surge starts from modeling the Deluge network in the Pipenet software. Model 1 is relatively simple and was selected to demonstrate the pressure surge phenomenon clearly and apply basic solutions to reduce the pressure surge. The second model is more complicated and includes considerable elevation changes. Model 2 not only demonstrates the pressure surge and solutions but also analyzes the cavitation and different solutions to eliminate it.

For the modeling in the Pipenet, I started from the Options menu to set the title of the project, and module option which is very important. In the model option, a simulation time will be selected. We need to repeat some initial guesses to make sure that at the end of the simulation, the system will be well beyond the transient periods and all the parameters are almost steady against the time.

The timestep is also selected by default but I adjusted it in some simulations so the actual peak pressure will be shown correctly in graphs. There are options for cavitation here, it is recommended to run with no cavitation first and then we can select between three different options for cavitation. In this thesis, the Vapor cavitation was selected for model 2. Also, we can select between Darcy and Hazen-William Equations which the latter is usually used in the Fire protection industry. The initial condition of the pipes can be selected between dry and wet pipes.

I selected the SI units and the fluids selected unsaturated water with 0 brag in 20 degrees centigrade. Two types of pipes have been used ANSI B36.10 Sch 40 and BS 3505 (uPVC).

Then I used the Isometric methods to draw two networks and then the input and output node conditions were selected. The inlet pressure is constant but the Deluge valve opening varies according to the power ramp time function.

At this stage, we are ready to run the software for the first time and after finishing the calculation by the software, the initial results can be seen below.

- Selecting Pipe Max pressure from the menu so the network will be colored according to the pressure, See Fig 4.9
- Selecting the browse output with Max and Min so we can easily find the pipe with max and Min pressure and at what time.
- The result table can be sorted regarding the Max and minimum pressure

In this stage, I tried to modify the module option for more accurate results and also selected some pipes with critical conditions so the software would generate the graphs for them. See Fig 4.14. The critical conditions such as Max and Min pressure and Nozzle prime time. It is worth mentioning that if the results from graphs are different from tabular data, it is recommended to adjust the output timestep. Also, it is recommended to select the smart output so the software will better show the max and min points

I need to repeat the calculation a few times to make sure the software results are accurate enough. Now I try to investigate the various solutions to tackle the Pressure surge and cavitation and try to implement them into the model and by repeating the calculation a few times, I will illustrate the effectiveness of these solutions and in which scenarios they are the preferred solutions.

Software calculation is the only practical solution to calculate the pressure surge in real engineering problems due to the complexity and very time-consuming of solving the equations by hand calculation. Also building a network model to measure the pressure surge is not practical at all. Pipenet is a commercial software that has been widely used in the industry for a long time. However the actual pressure surge can be measured in the laboratory and validating the Pipenet result can be a topic for another Master's thesis.

4. Results

In this section, two different Deluge system networks have been modeled in the Pipenet and pressure surges in different scenarios were calculated. A different measurement will then be introduced in the system and the effect of pressure surge will be demonstrated.

4.1 Simple system(model1)

The deluge system consists of 10 identical permanently opened nozzles, the model is shown in Fig 4.1 and 4.2. The inlet pressure is Constand at 10 Barg. A pipe before the deluge valve is wet (full of pressurized water) and the deluge valve is closed at the initial state, all other pipes after the deluge valve are dry.
In this model, the Air cushion effect and cavitation are also considered. The inlet point is considered a reference with zero elevation and the elevation of other nodes is shown in Fig4.1.
These are the default assumptions in all Scenarios unless mentioned differently in Table 4.1

Nozzle K factor: 40 (LPM/bar½)
The deluge valve will start to open at t=1 S and it takes another 1 second to be fully open
Pipe: ANSI B36.10 Sch 40

Table 4.1 Different Scenarios to be modeled.

Scenario	Changes from Default value
1	The deluge valve takes 0.5 s to be fully open
2	Default
3	The deluge valve takes 5 s to be fully open
4	All nozzle's K factor is 100 (LPM/bar½)
5	Pipe 6 and 9 lengths increased from 2 to 30 Meter
6	Pipe materials changed to UPVC(BS3505)
7	Pipe 6 diameter increased from DN40 to DN100
8	Move the deluge valve about 100 m away from the network

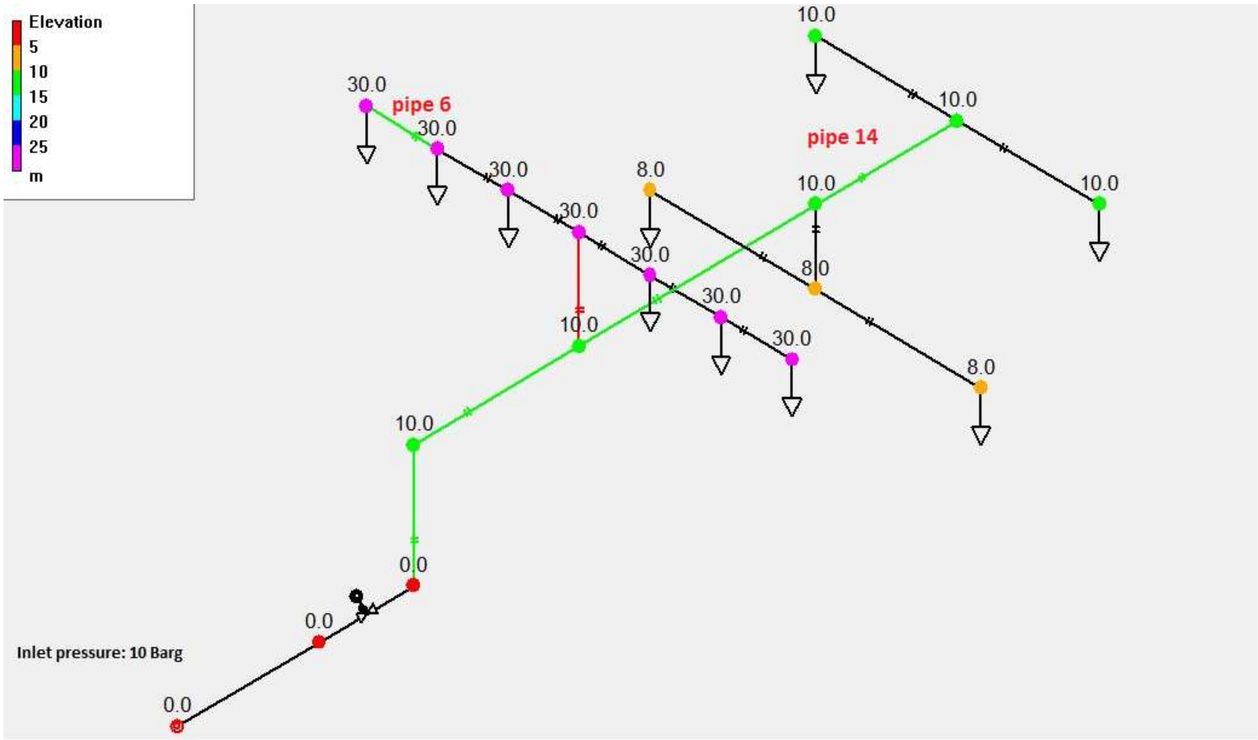

Figure4. 1 Node elevation with respect to inlet point

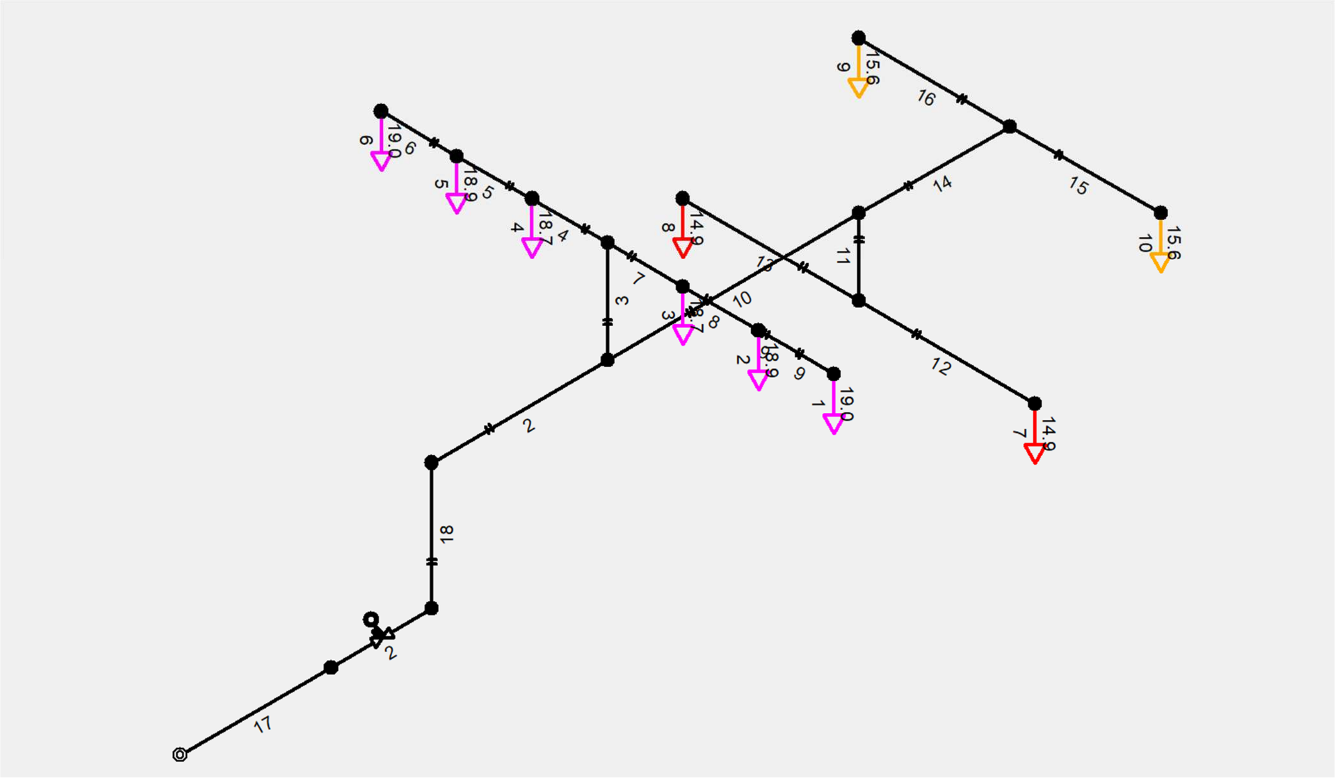

Figure4. 2 Pipe numbering and nozzle priming time in sec for scenario 1

4.1.1 scenario 1(Deluge valve opens very quickly)

Solving the network considering the timestep 0.001 second. The longest time for nozzle priming is 19 seconds which is within the acceptable limit of NFPA.

Fig 4.2 shows the priming time for each nozzle which the longest one is for nozzles 1 and 6 with 19 Sec.

After calculation the max pressure for each node will be shown by the software which is in pipe 6 so re-run the software with graph output for pipe 6. As already mentioned, there is a good correlation between velocity changes and pressure surge so in Fig 4.3 above both pressure and velocity graphs are shown.

The peak pressure surge is about 80 barg in pipe 6 around 19 sec from the start of the simulation. And there was no cavitation.

The pressure graph for the pipe 14 is also interesting to be shown due to two peak pressures

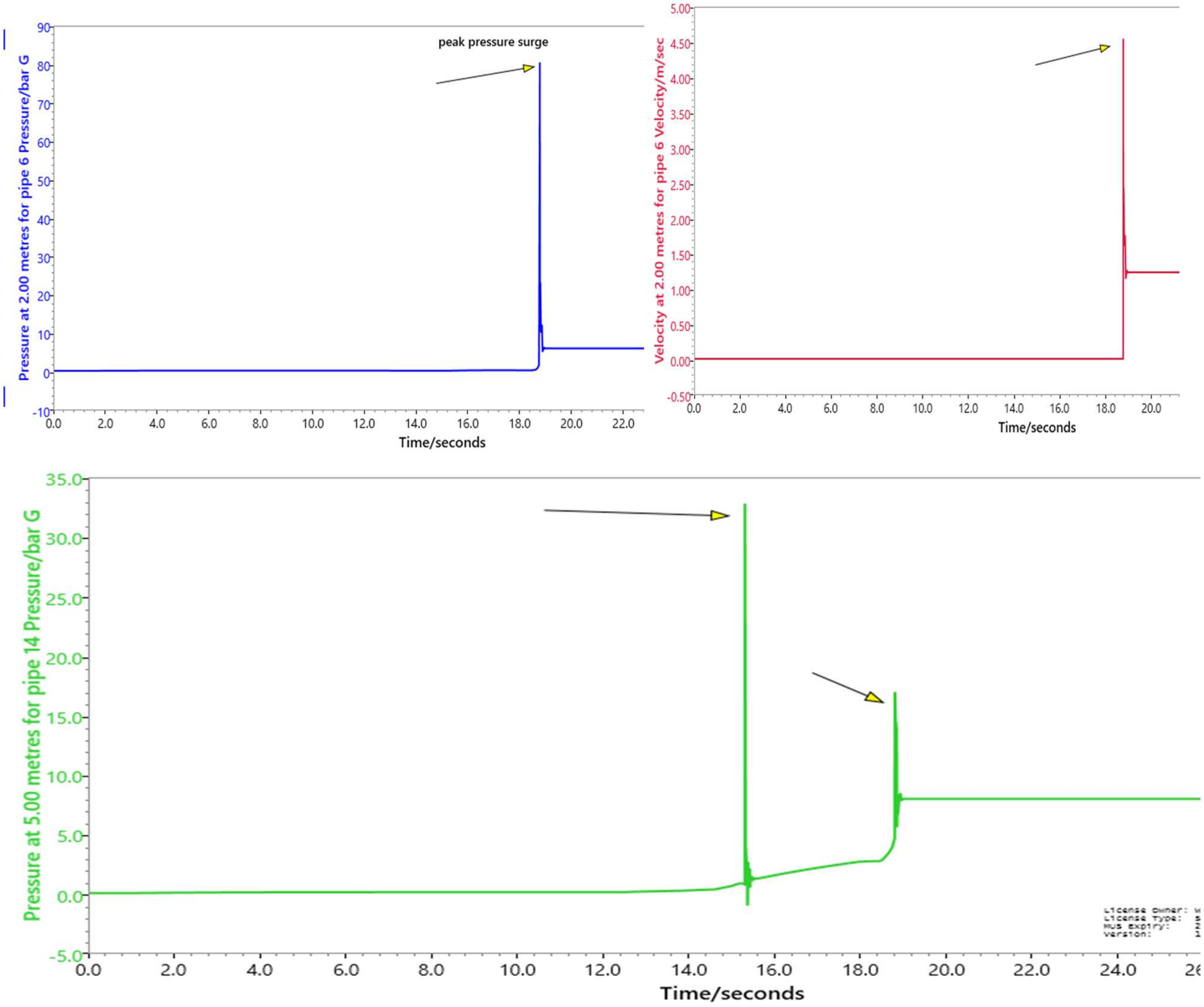

Figure4.3 The peak pressure and relevant velocity in pipe 6 and peak pressure in pipe 14

4.1.2 scenario 2(default configuration)

In this scenario, it takes 1 sec for the deluge valve to be fully open and the effect on the pressure surge is illustrated in bellow, Fig 4.4 below. There are no considerable differences to Scenario 1 (Fig 4.3).

The results have been discussed more in the next Chapter.

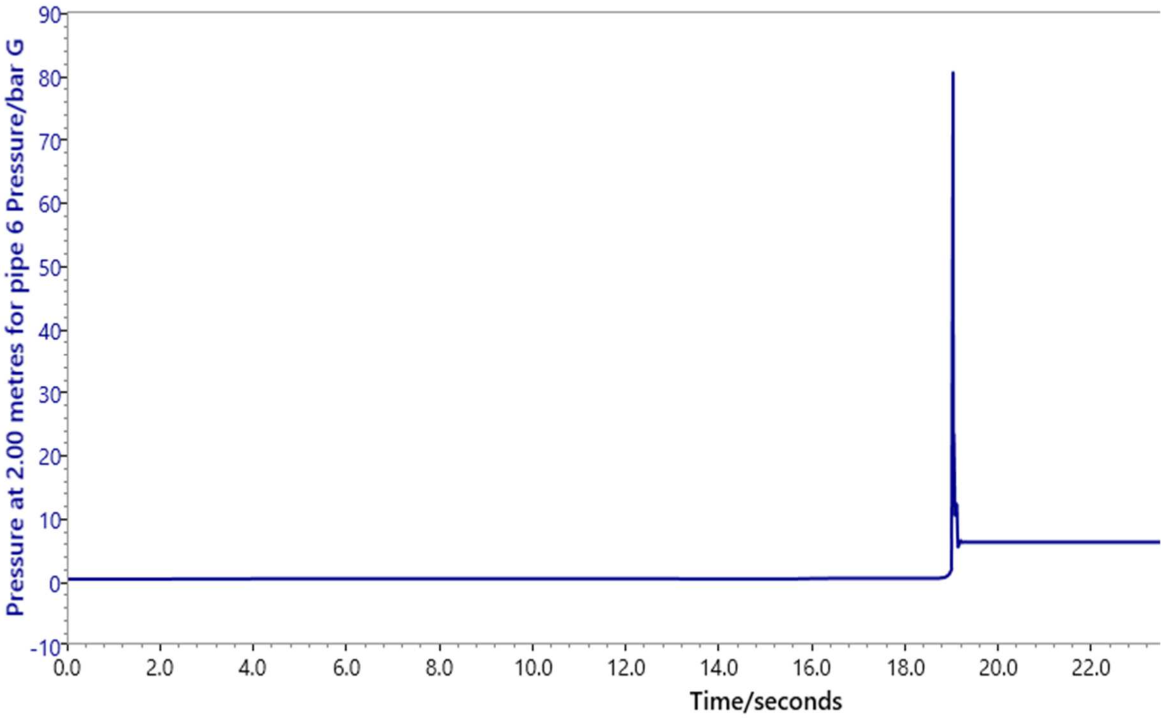

Figure4. 4 The effect of 1 Sec deluge valve opening time on pressure surge.

4.1.3 scenario 3(Deluge valve opens slowly)

In this scenario, it takes 5 sec for the deluge valve to be fully open and the effect on the pressure surge is illustrated in bellow, Fig 4.5 below.

This Fig can be compared to Fig 4.4 and 4.3 to see the effect of deluge valve opening time on pressure surge magnitude and time when the peak pressure happened.

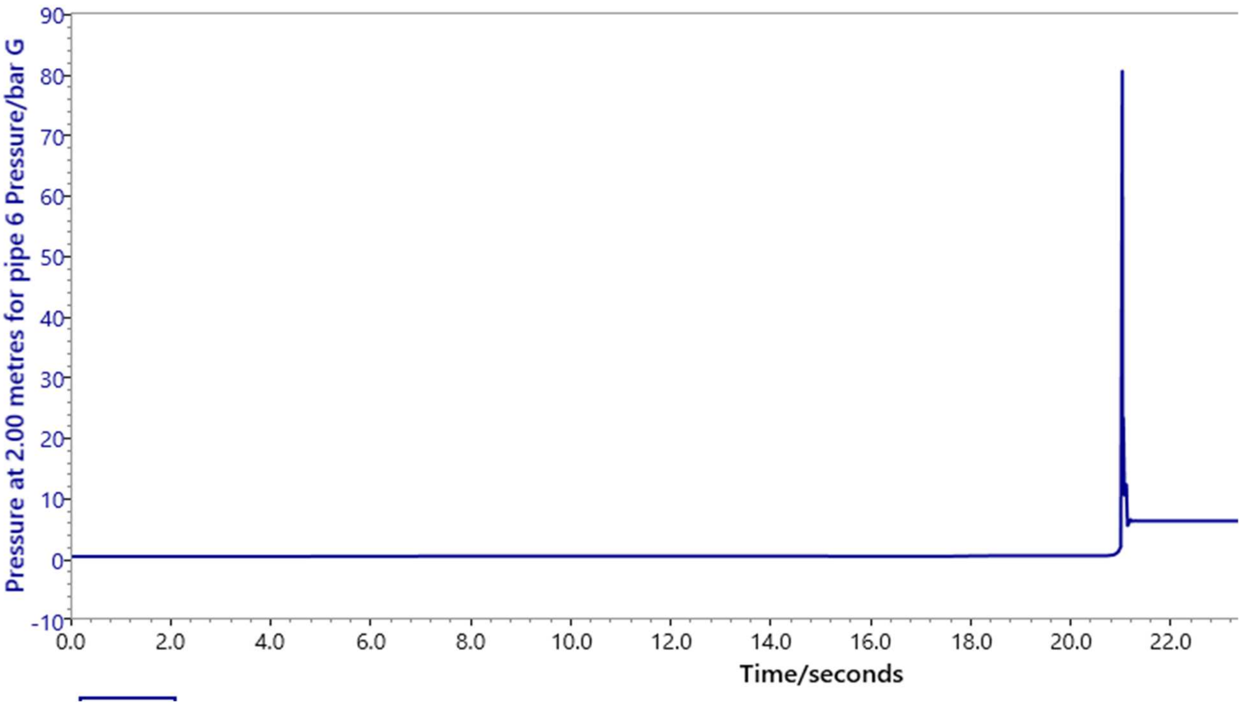

Figure4. 5 The effect of longer deluge valve opening time compared to Fig 4.3 and 4.4

4.1.4 scenario 4(increasing nozzle K factor)

Increasing the K factor of the nozzles has considerable effects on pressure surge, this matter is illustrated in Fig 4.6

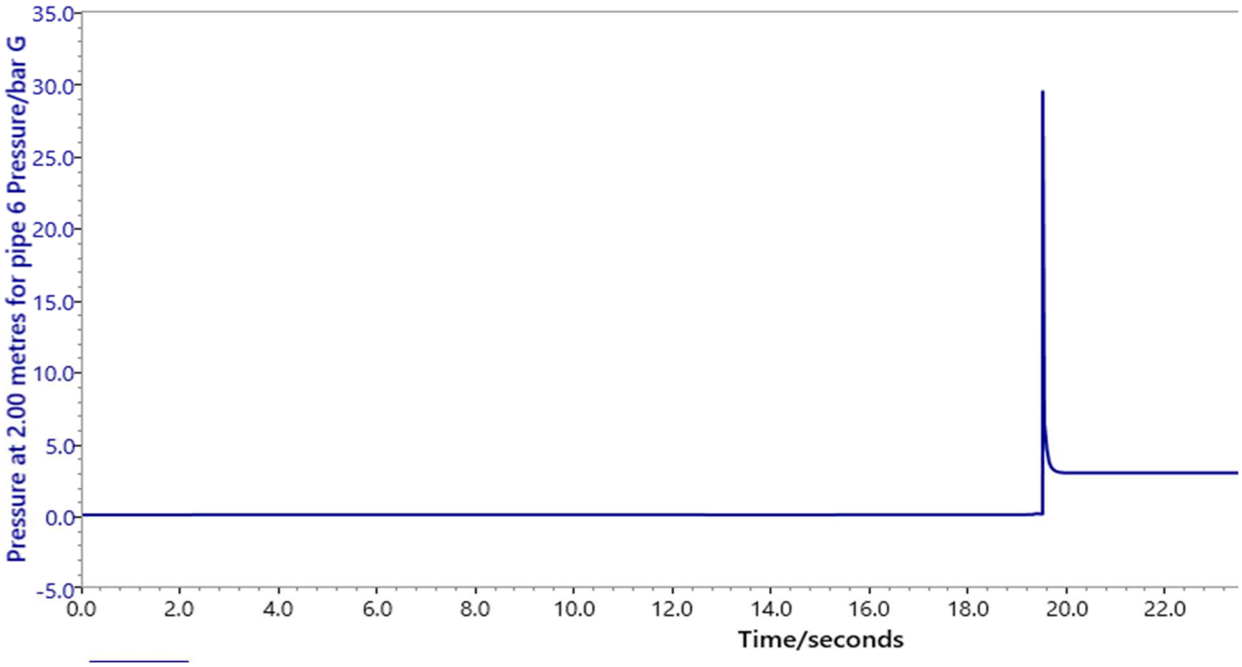

Figure4. 6 All nozzles K factor increased to 100

4.1.5 scenario 5(increasing pipe length)

In this scenario pipe 6 where we had the highest-pressure surge and the opposite branch (pipe 9) increased from 2 to 30 Meters, the pressure and velocity are illustrated in Fig 4.7. The velocity graph is presented to show a very good correlation between velocity and pressure changes.

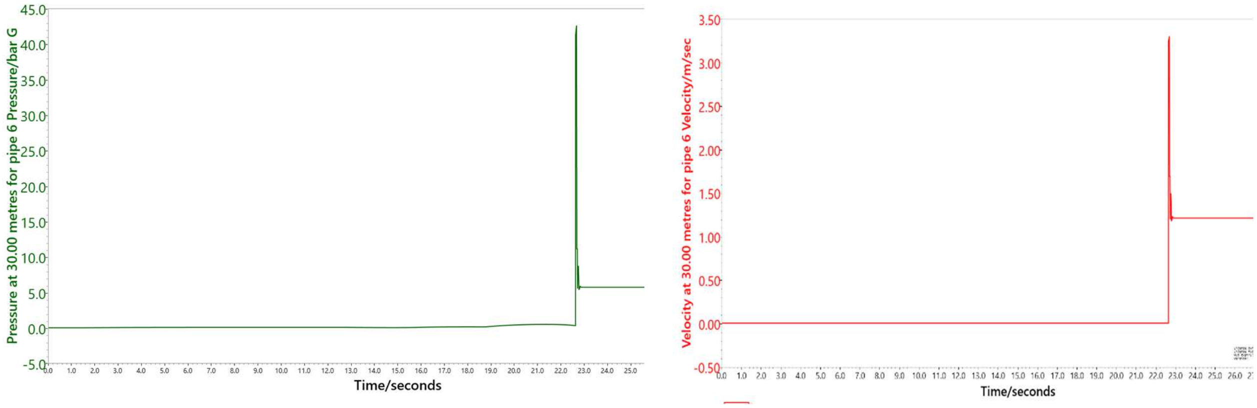

Figure4. 7 The effect of pipe length on pressure surge

4.1.6 scenario 6 (Pipe Material changed)

In this scenario, the pipe material has been changed to uPVC with Young modules of 3 GPa compared to the Carbon Steel pipe (B36.10) used in previous scenarios with Young modules of 203 GPa. The results are shown in Fig 4.8

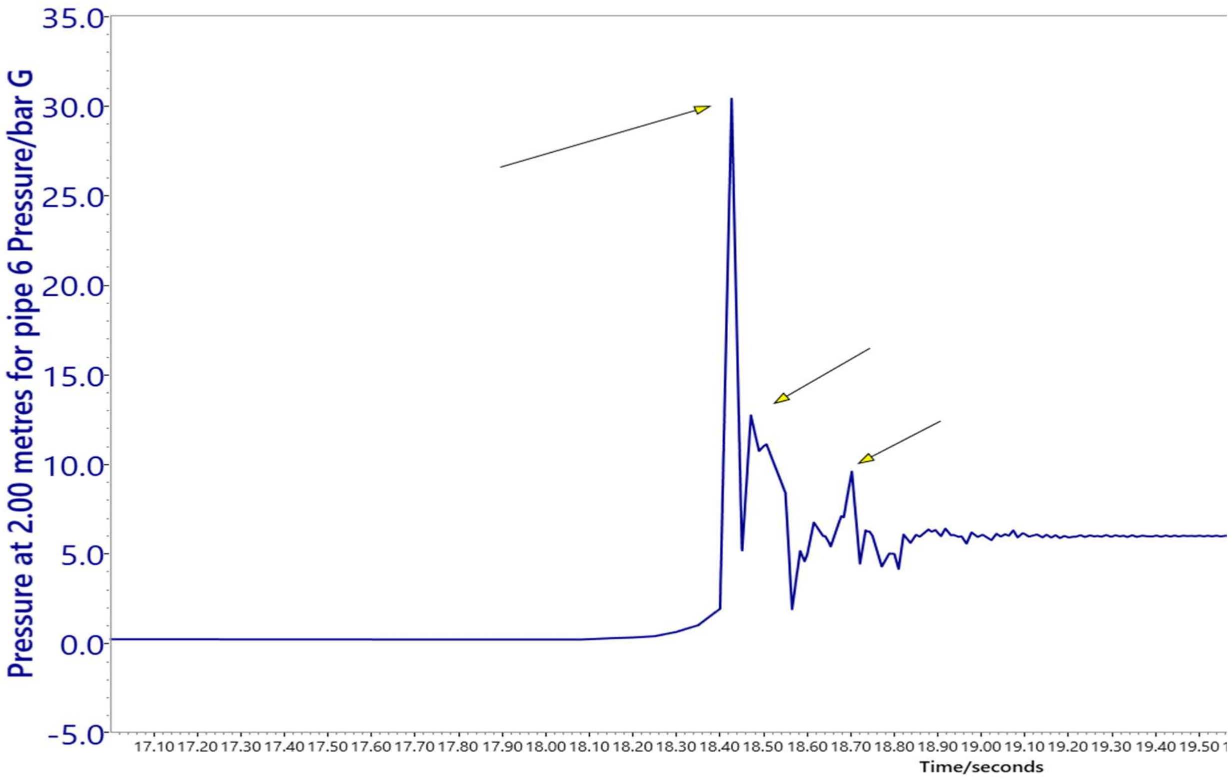

Figure4. 8 The effect of material on pressure surge using uPVC pipes instead of Carbon Steel

4.1.7 scenario 7(Pipe diameter changed)

In this section the size of pipe 6 which usually has the highest peak surge when it was DN40 will be increased to DN100, the peak pressure of the whole network is illustrated below in Fig 4.9 middle in this case the highest peak pressure will happen in other pipes.

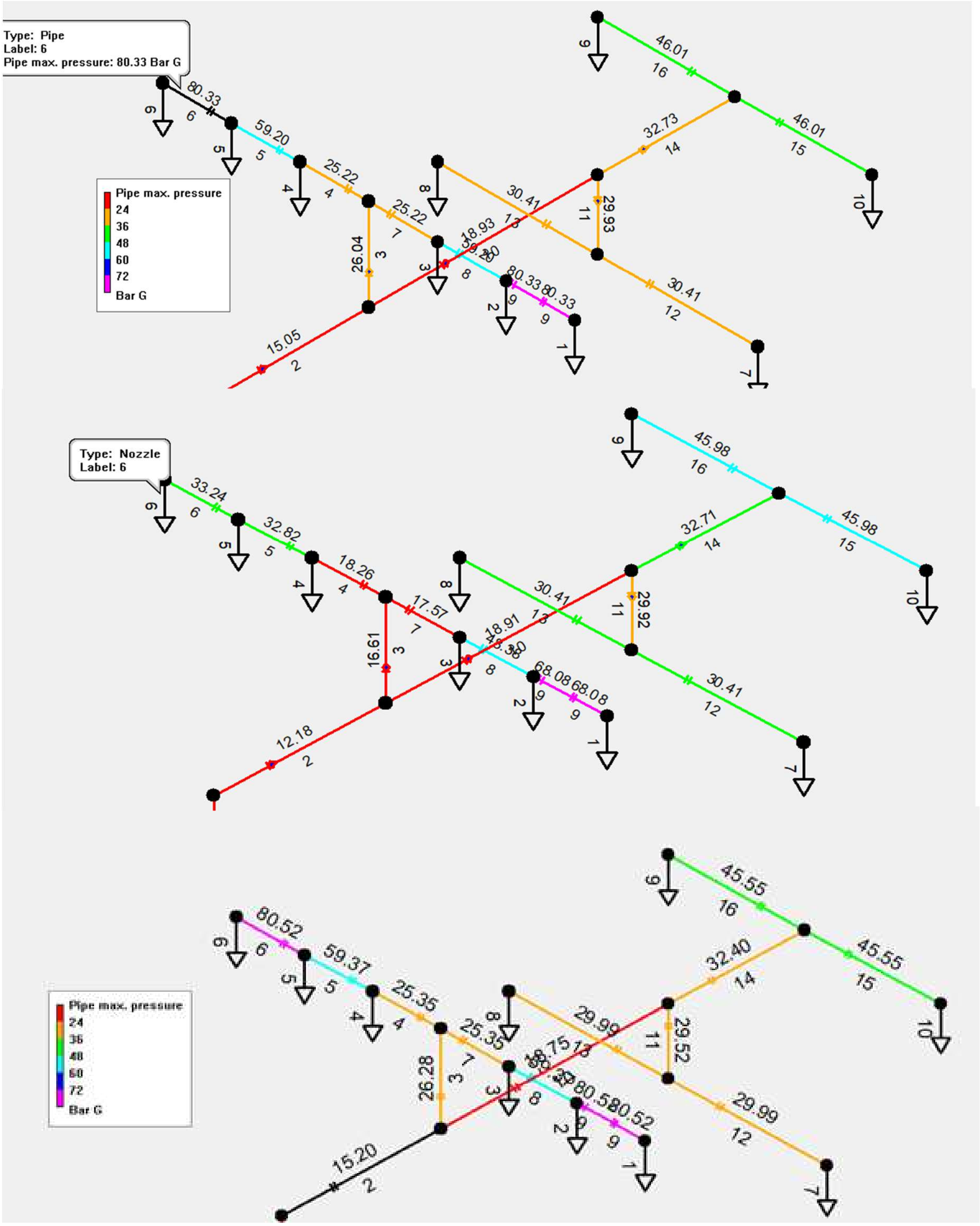

Figure. 9 Default pressure surge top, middle: scenario 7 and bottom scenario 8

4.1.8 scenario 8(Deluge valve away from the network)

In this Scenario the location of the Deluge valve is moved further away from the nozzle network and the length of pipe 2 is increased to 100 m. this pressure surge is shown in Fig 4.9. I will discuss the results of all Scenarios in the next chapter.

4.2 Solutions

There are a few solutions to reduce the pressure surge in the deluge network, one of the cost-effective ones is adding a piece of one-end closed pipe to the last primed nozzle with the highest-pressure surge. In this case, some air will be trapped inside this pipe and it will have a cushion effect similar to an accumulator and will absorb the pressure surge to some extent. An example of this is shown in Fig4.10. the peak pressure surge is shown in Fig 4.11 and it can be compared with Fig 4.9 top.

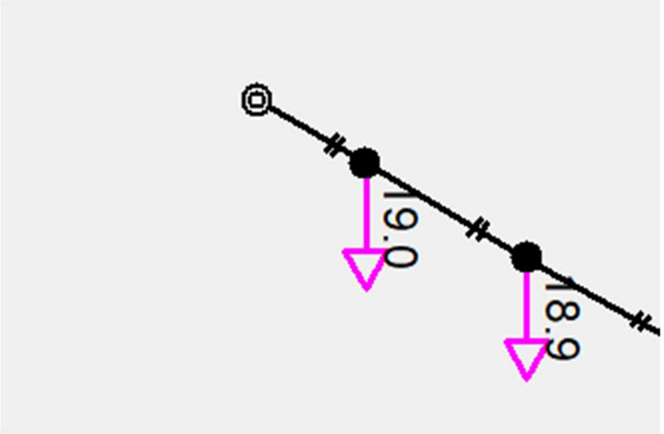

Figure4. 10 Adding a piece pipe to the last nozzle

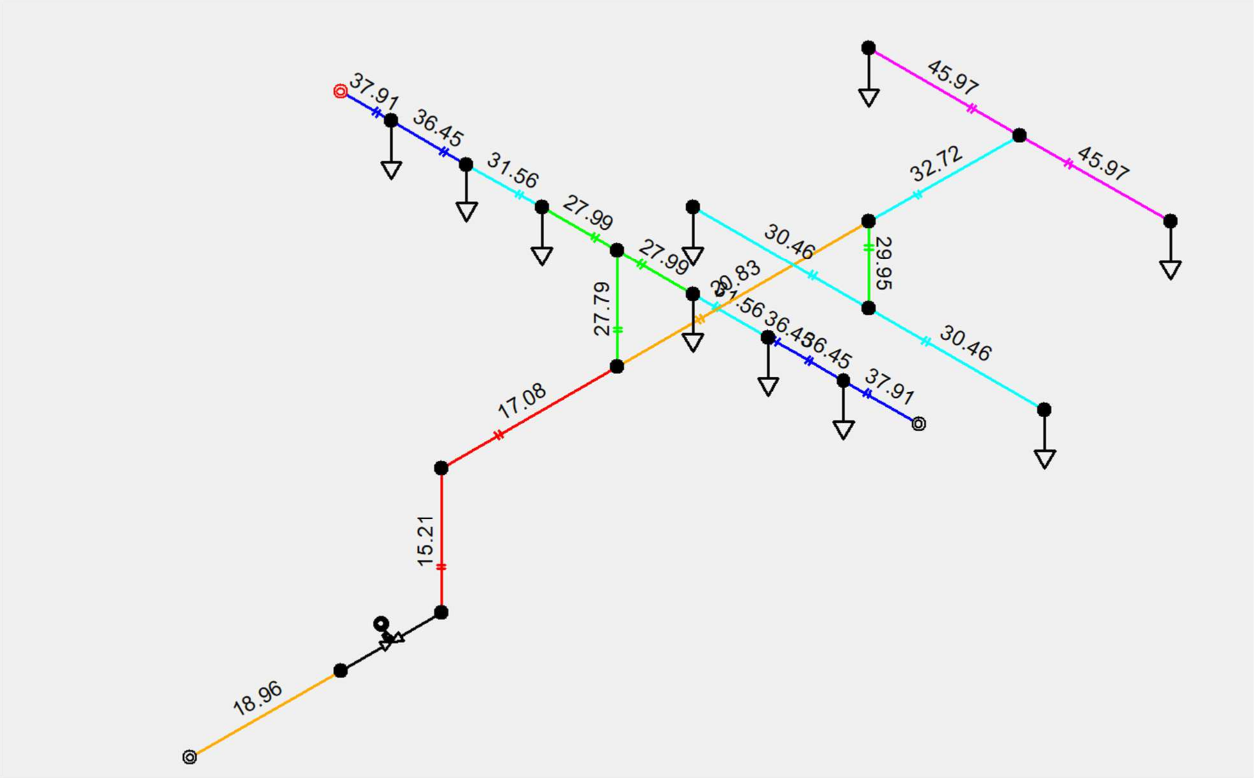

Figure4. 11 Introducing the dead-end pipes and Pressure surge reduction

4.3 Transformer water spray system(moel2)

In this section, a more complicated and realistic deluge network is modeled. This is the system to protect a transformer with a water spray system. All the nozzles are the same with a K factor of 40 and in open nozzles, the inlet pressure is 10 brag The system is illustrated in Fig4.12 which includes pipe number.

This type of network is widely used in the fire safety industry. The spray system is typically consisting of two or three rings to cover all surfaces of a transformer.

The primary goal is to cool down the transformer and reduce the chance of internal short circuits, oil leakage, and transformer total damage.

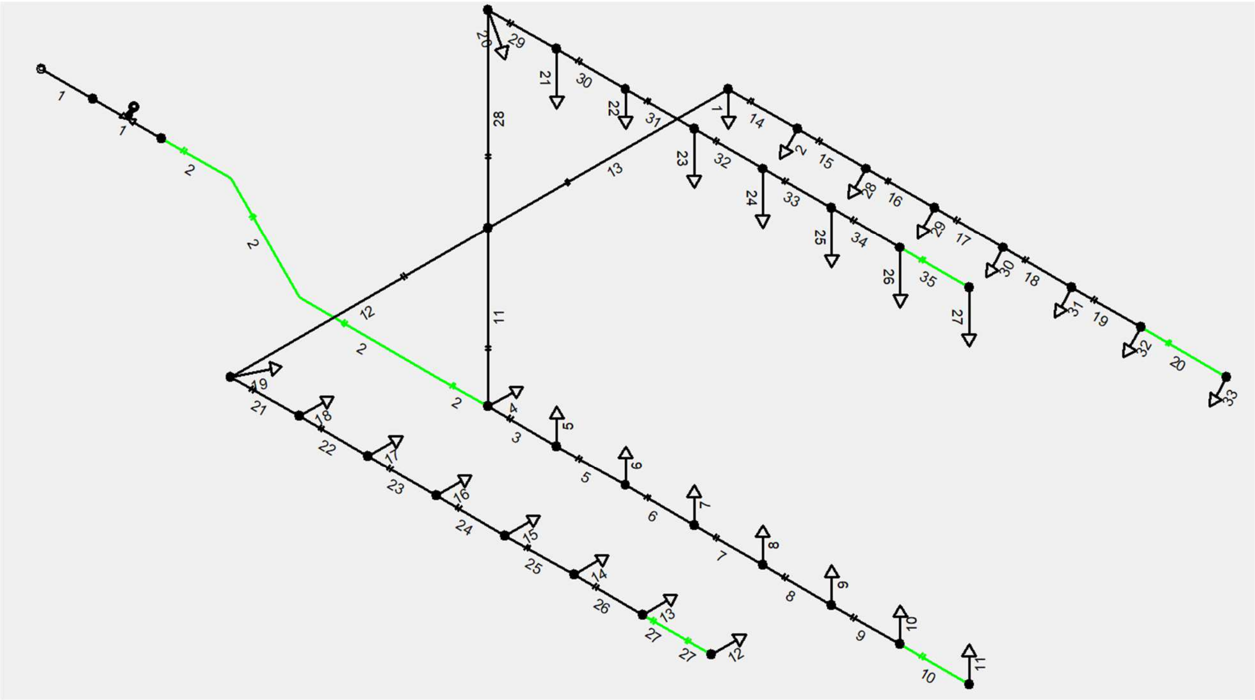

Figure4. 12 A typical deluge network to protect a transformer

Calculating the pressure shows the pressure surge on the last pipe of all branches but pipe 35 (upper branch) has the highest pressure surge in this model.

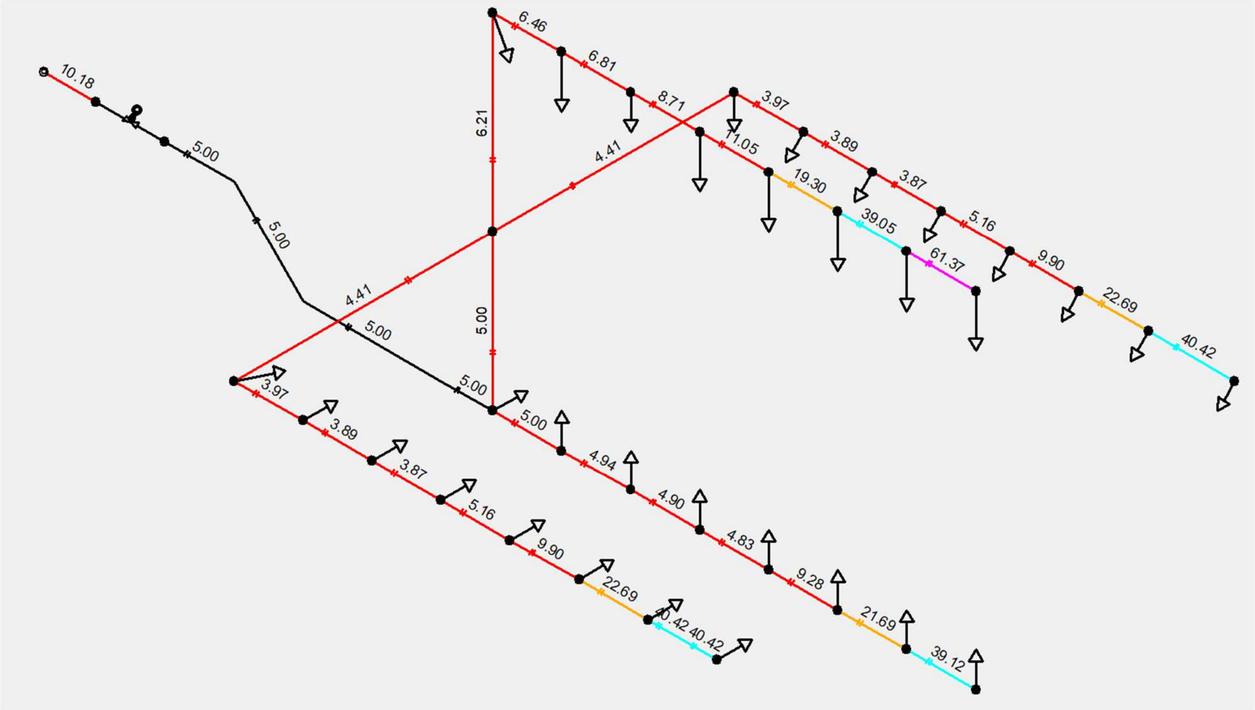

Figure4. 13 Pressure surge in the transformer protecting deluge system.

Figure4. 14 Pressure surge and cavitation in a deluge system

Fig 4.14 shows three important graphs, the blue line is the pressure in pipe 35 in which there is a considerable pressure surge of about 61 Barg, the red line is the pressure in pipe 2 which is the main inlet pipe, an important point for this graph is at 14 s with is about -0.95 Barg and there is a chance for cavitation, although it is quite close but the green line shows no cavitation. It shall be noted that the scale of the Y axis is not the same for all three graphs to better show the magnitude of each graph.

4.3.1 Solution

In this section, the solution of extending the pipe with pressure surge has been implemented in the network, for the middle ring a better solution is connecting the pipe 20 and 27 to complete a ring around the transformer. This matter will be discussed in chapter 5. See the Fig 4.15

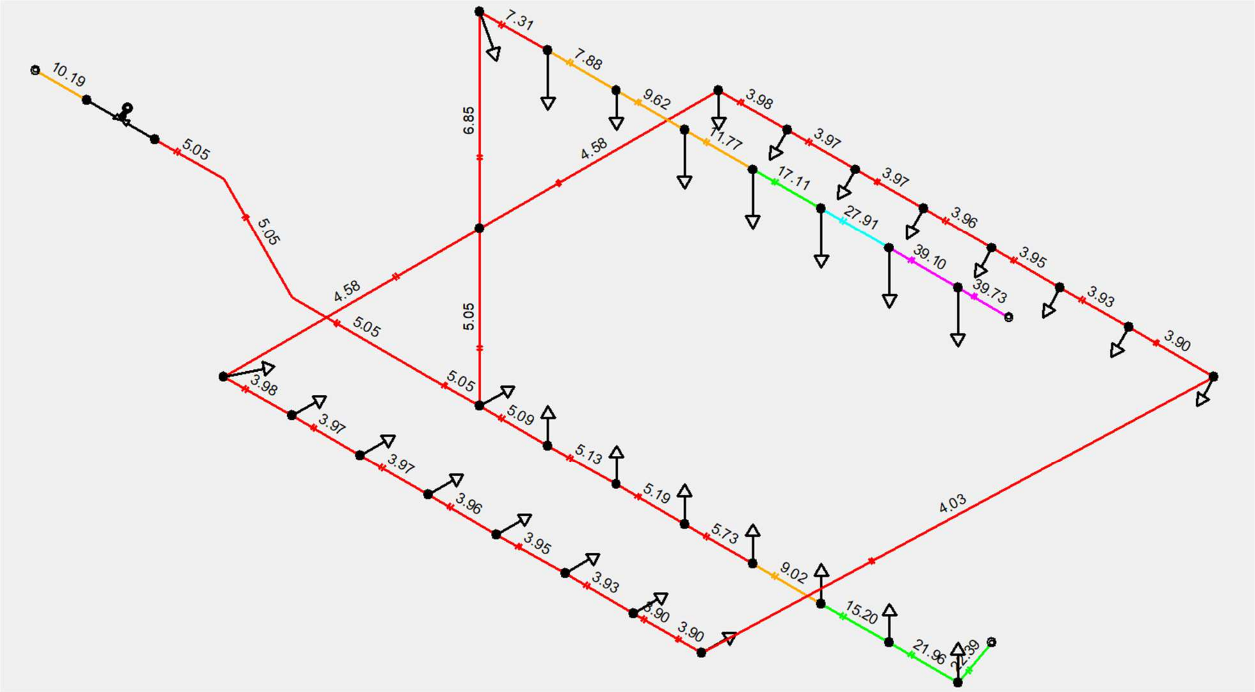

Figure4. 15 revised transformer deluge network to reduce the pressure surge

Changing the length of pipe 2 to 40 m with a net height change of -30 m will show an interesting result to be analyzed. in this case, we assume the deluge valve starts to open at 1 sec and will be fully open at the fifth sec. the maximum pressure and priming time for the nozzles are shown in Fig 4.16 below

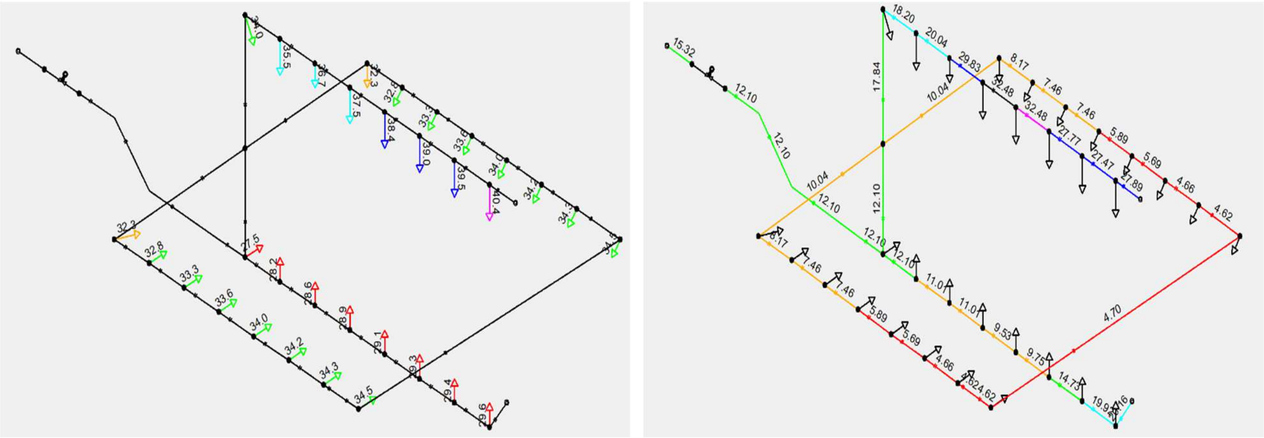

Figure4. 16 nozzle priming time (left) and pressure surge (right) in a network with a longer inlet

Adding a vacuum breaker to the system will significantly alter the nozzle peak pressure Fig 4.17.

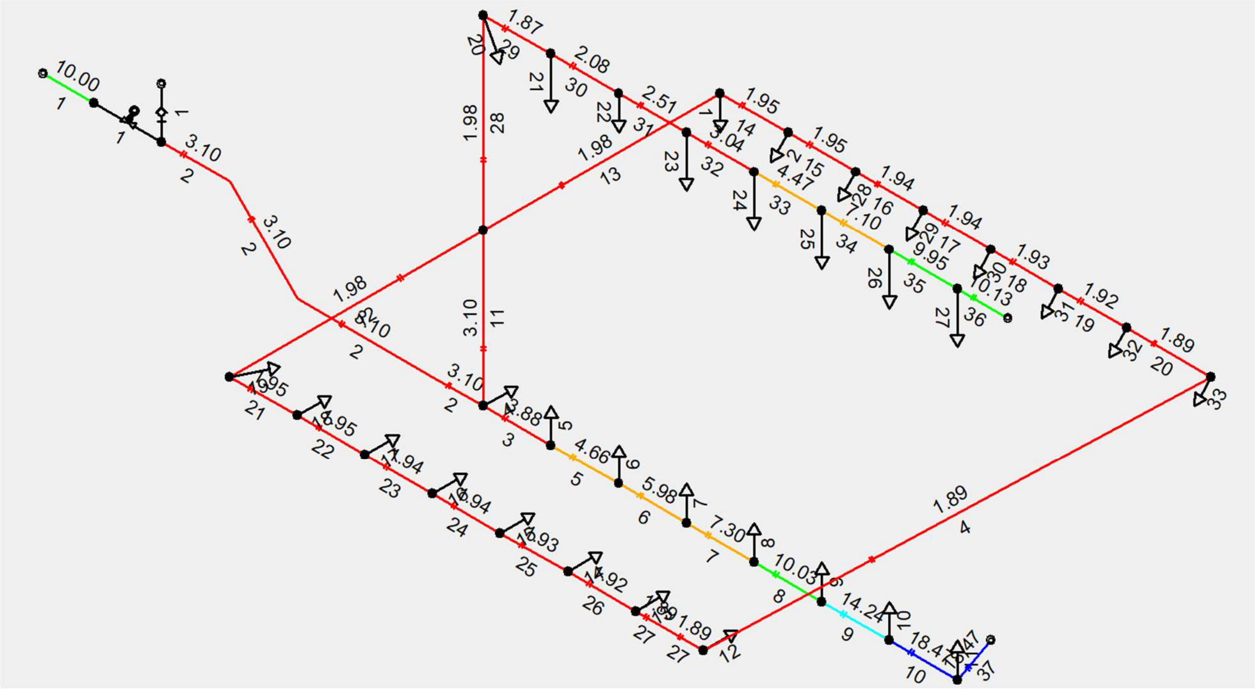

Figure4. 17 Effects of adding a vacuum breaker in a pressure surge

5. Discussion

As expected, and illustrated in Fig 4.2 and Fig 4.3, the time for peak pressure surge and the priming time for the most remote nozzle is equal. This means that exactly when the water reached the last nozzle the flow velocity reduced sharply which resulted in a pressure surge. As seen in Fig 4.3 when the water reaches the nozzle, the velocity drops sharply from 4.5 m/s to about 1.2 m/s. This sharp reduction in velocity or momentum will result in pressure surge which can damage the pipe. This pressure surge is not limited locally and will travel like waves through the pipeline as can be seen as the second peak in pipe 14 on Fig 4.3.

In Fig 4.3 the pressure graph for pipe 14 shows two peaks the first one is related to the last row of nozzles (nozzles 9 and 10) and the second one is for the first row of nozzles (nozzles 1 and 6). When the water reaches each set of these nozzles a peak surge pressure will be produced. It also clearly shows that the pressure surge will propagate through the network very fast (at the Sound Speed in the pipe) and it is not enough to check the pipe strength only at the point of peak pressure. It might spread to a point in another part of the network with less strength and cause some damage.

Comparing Fig 4.3 to 4.4 and 4.5, shows that the opening time has almost no effect on peak pressure surge but only the peak pressure will happen at a later time and the nozzle prime time will be longer. In other words a quick-opening Deluge valve does not have a considerable negative effect on pressure surge compared to a normal Deluge valve. See Fig 5.1

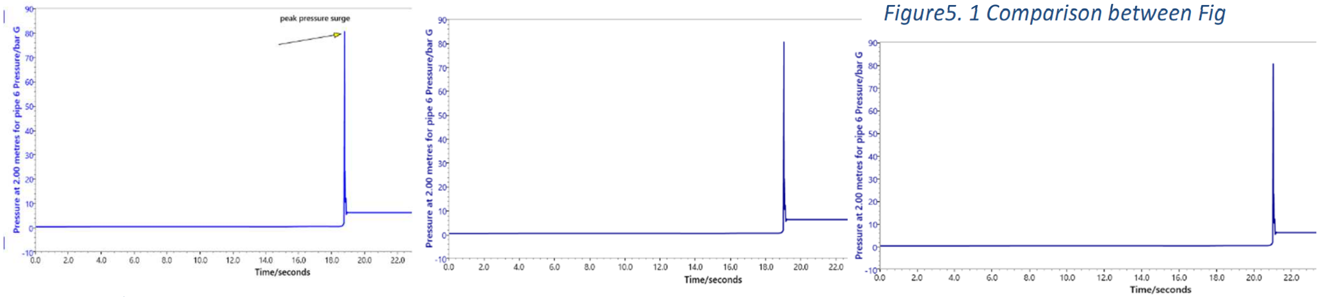

Figure5. 1 Comparison between Fig 4.3, 4.4, and 4.5

If a deluge valve opening time is unrealistically long e.g. 60 sec and the most remote nozzles' prime time is 45 sec, then in such case the longer opening time will reduce the pressure surge. In this case, it reduced to 60 Barg. It shall be noted that this is not a realistic scenario for a deluge valve to take so long to be open but it is beneficial to show how different parameters impact pressure surge.

Nozzle K factors play a major role in the magnitude of pressure surge. This matter is shown in Fig4.6. and it can be compared to Fig 4.9 top which is the pressure surge in the default scenario. Increasing the K factor from 40 to 100 in this scenario reduced the pressure surge considerably. The nozzle K factor shows how much water will pass through the nozzle at any pressure. A higher K factor means more water can pass the nozzles with less effort which results in less resistance to the water flow and less sudden reduction to the flow momentum so the peak pressure surge will be lower.

Another interesting result is increasing the pipe length of the last piece of pipe before the nozzle by comparing Fig 4.3 with Fig 4.7, the pressure surge will be decreased by increasing the pipe length and the reason behind this is a reduction in flow velocity which results in less momentum when reaching to the last nozzle so the water hammer is lower.

In Scenario 6 all the pipes in the deluge network are made of uPVC with a Young module of 3GPa compared to 203 Gpa for Carbone Steel.

Young modulus is a mechanical property of a pipe that measures the stiffness of the pipe. On the other hand, the deformation of the uPVC pipe is much larger than the Carbon Steel, this deformation will reduce the peak pressure sharply because of less resistance to the increasing peak surge pressure. When the peak surge pressure is going to happen, the pipe will start to swell, and increasing the volume will reduce the pressure. This matter is clearly illustrated in Fig 4.8 compared with Fig 4.3. Furthermore, more flexibility of the pipe causes more than one peak for the pressure surge which is also marked in Figure 4.8.

Pipe size plays an important role, this matter is illustrated in Fig 4.9 middle, in this step by increasing the pipe diameter from DN40 to DN100 the peak pressure has been reduced from 80 Barg to 33 Barg. Although the peak pressure in the whole network has been moved to some other pipes but it is still lower than 80 barg This can be considered as a solution to reduce the pressure surge in the system. The reason behind this can be explained as when the pipe is small the build of the pressure due to changes in momentum is easier compared to when the pipe is quite large because the duration of pressure surge is a fraction of a second, e.g. 0.1 second.

In another scenario, the location of the deluge valve changed which means the deluge valve moved further away from the protecting area. As seen in Fig4.9 bottom, moving the deluge valve further away will have no considerable impact on the pressure surge magnitude. The reason behind this is the peak velocity along the pipe will not change when increasing the pipe length, this matter is shown below in Fig5.2. The graph shows the velocity in 2 and 20 meters along pipe 2 when the length of the pipe is 20 meters and Fig5.3. the graph is the velocity of the pipe 2 when the length is 120 m. it can be seen the peak pressure along the pipe and also in both cases are the same as about 2.6 m/s

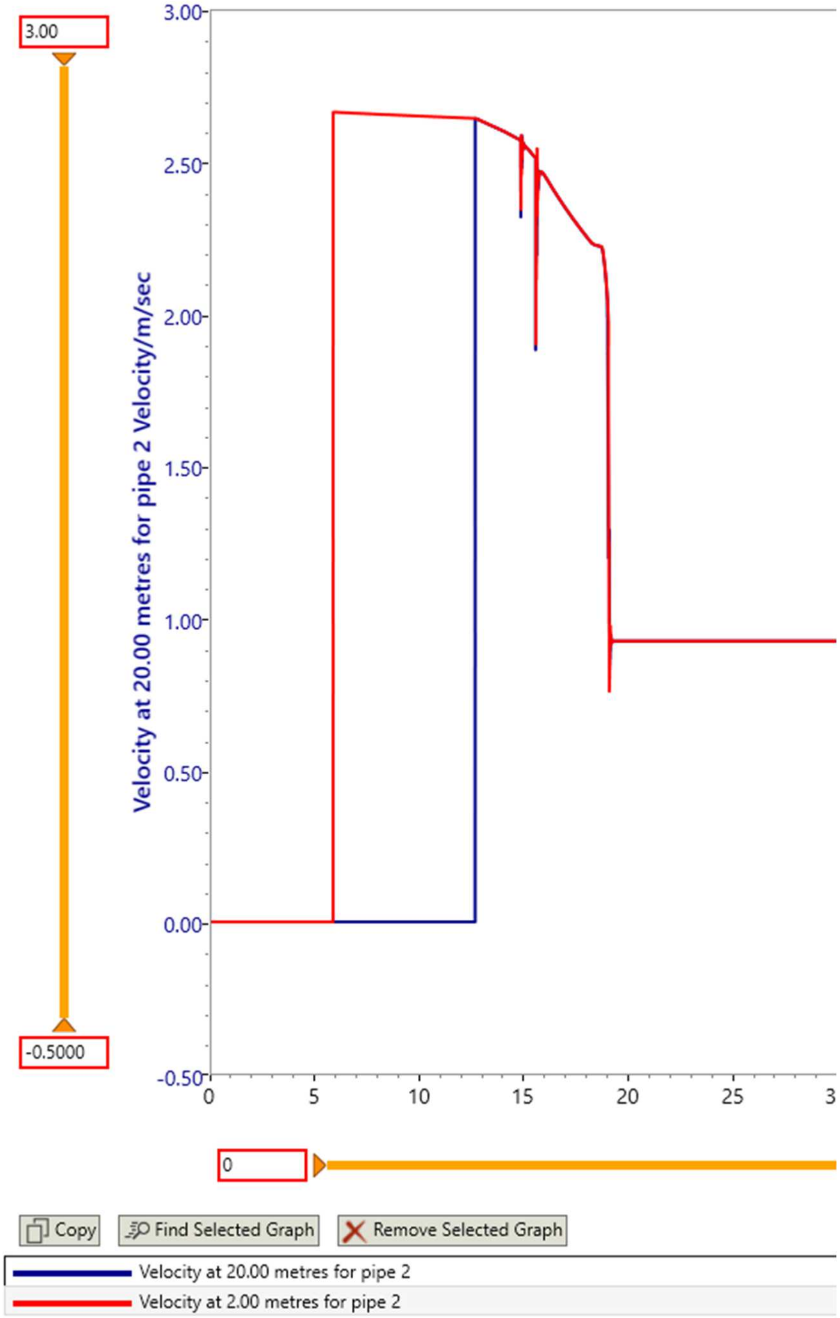

Figure5. 2 Flow velocity along the pipe 2 when the length of the pipe is 20 meters

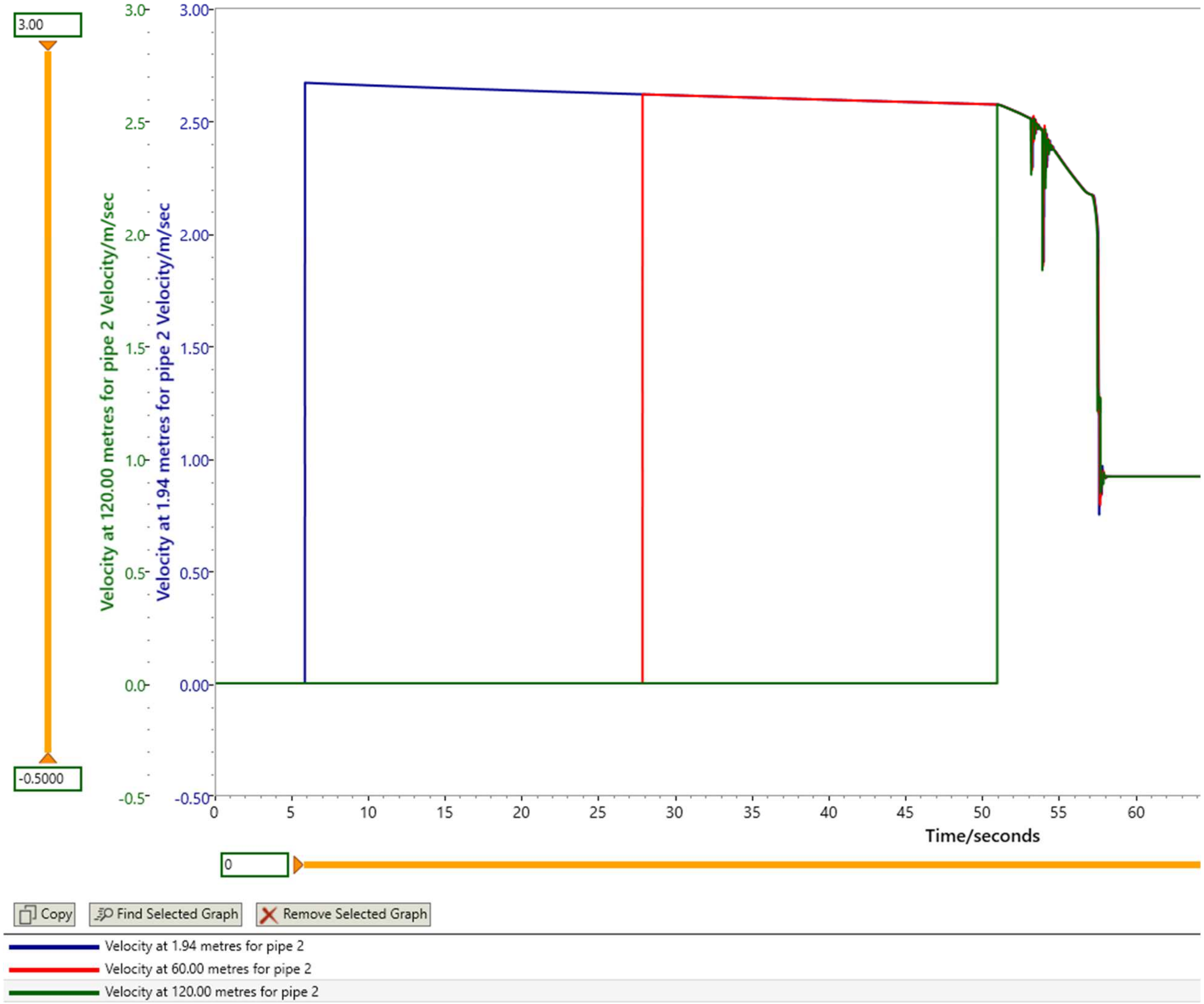

Figure5. 3 Flow velocity along the pipe 2 when the length of the pipe is 20 meters

5.1. Dead-end pipe solution

The result of adding a dead-end pipe to the last nozzle on the pressure surge is illustrated in Fig 4.11. Comparing this figure with Fig 4.9 top, showing a huge reduction in pressure surge. The air trapped in this section has a cushion effect and will absorb the pressure surge to some extent. The bellow Fig 5.4 illustrates three graphs, the red line is the pressure surge in the dead-end pipe, although there is still a pressure surge of about 38 Barg but it had a significant reduction from about 80 brags, in case without the end pipe. The green line represents the mass of air inside the pipe which increased slightly due to pushing a small amount of air into this pipe, the amount is pretty small, around 1 gram of air because most of the air will be discharged through the open nozzles. The blue line is the volume of the air which is about 0.65 L before the water compressed the air to almost 0.04 L and then stabilized around 0.22 L. The shape of the blue line is resembling a behavior similar to an accumulator.

Reducing the pipe size will decrease the cushion effect and increase the pressure surge in the pipe.

In this example adding a 50 cm pipe results in the 38 Barg peak pressure. A similar analysis was repeated with an 80 cm pipe and a peak pressure of 30 Barg.

Another benefit of adding this piece of pipe is collecting debris in the pipe and preventing clogged nozzles. That is the reason that this pipe is something called a dirt trap.

Another analysis was performed by installing a safety valve at the nozzle with the highest pressure surge but surprisingly, it had almost no effect, and the very little flow discharged from the safety valve (less than a milliliter). The reason behind this is the pressure surge will happen in a very short time and the function of the safety valve is not helping to reduce the pressure surge enough. In other words, when fluid first hit the last nozzle or the safety valve, there was some resistance to the free flow of the water and this will result in a change in momentum and pressure surge. So, the analysis shows the pressure surge even by adding a safety valve.

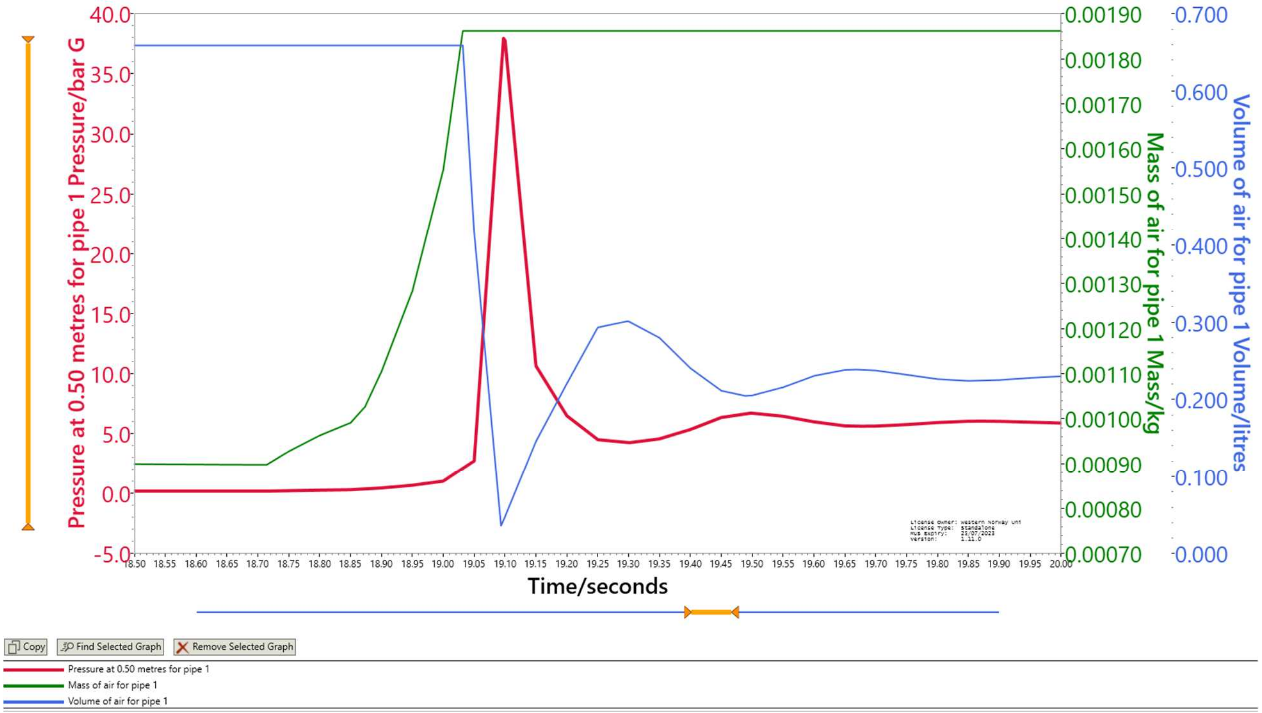

Figure5. 4 Pressure, air volume and mass in the dead-end pipe

Another model was analyzed in section sec4.3 and again the pressure surge was observed in the last section of each pipe the reason is when the water reaches the last nozzle there is a reduction in flow velocity because of the change of discharge flow from air to water. Fig 4.14 is an important graph that shows that due to the reduction in elevation in pipe 2, there is negative pressure in this pipe with the lowest pressure at 14 s from the start of the simulation, in such case it is important to check for the cavity which in this case the green line shows no cavity.

By adding a dead-end pipe and connecting the middle ring, the peak pressure surge was reduced considerably (Fig 4.15). In the middle ring when the pipe 20 and 27 were connected, there was almost no pressure surge (Fig 5.5). In fact, due to the symmetric configuration of this pipe air is trapped inside the connecting pipe and will act with a strong cushion effect. In Fig 5.6 brown graph shows the air volume compressed during the priming time and when the water reaches the nozzle and pressure surge is about to happen, this compressed air will act as a cushion effect efficiently. It is interesting to know that about

17% more air mass will be pushed inside the connecting pipe during the priming as seen in the red line in Fig 5.6.

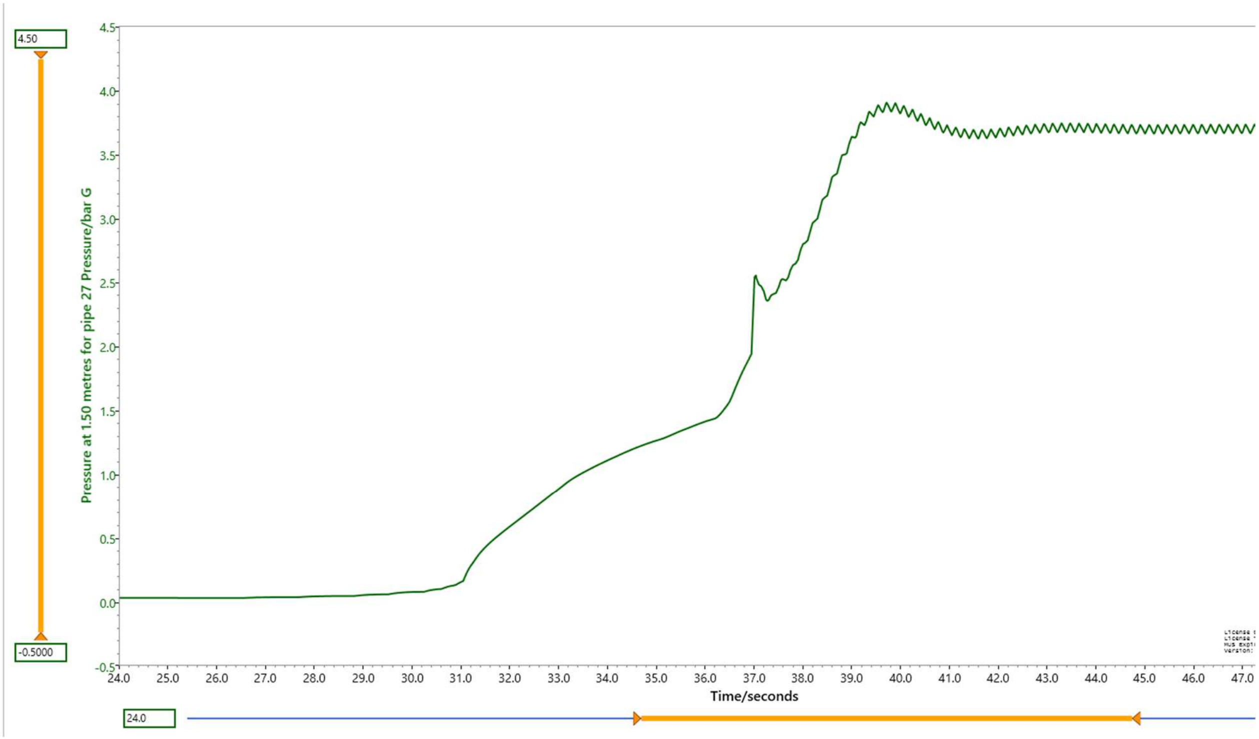

Figure5. 5 Pressure graph in middle ring, implementing the surge reduction solution

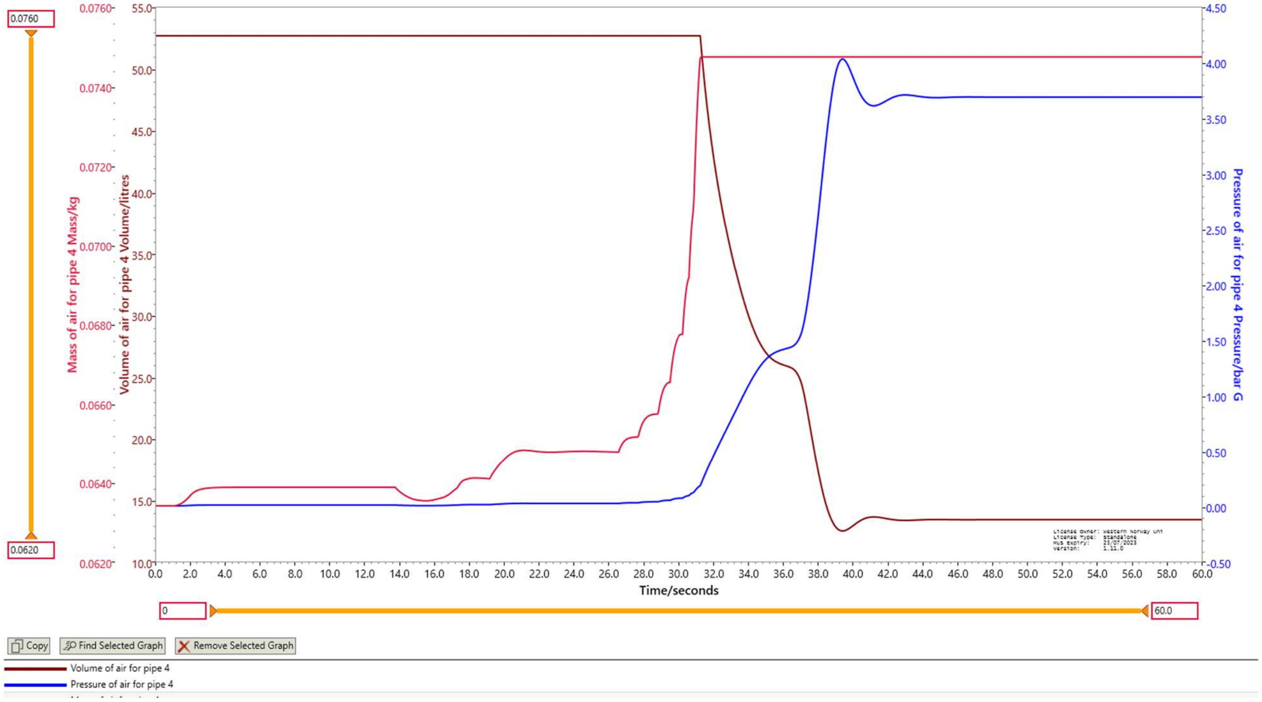

Figure5. 6 Air volume and pressure in connecting pipe in middle ring

5.2. Vacuum breaker solution

To further analyze this network, the length of the main inlet pipe (pipe2) increased to 40 meters with a -30 m net height change, this means in pipe 2 the height of the outlet is 30 m less than that inlet. The priming time and max pressure are shown in Fig 4.16. Surprisingly, the max pressure surge did not happen when the last nozzle was primed (the last nozzle primed at 40 s but the pressure surge happened 12 s later). To investigate this phenomenon, there could be another reason for the pressure surge.

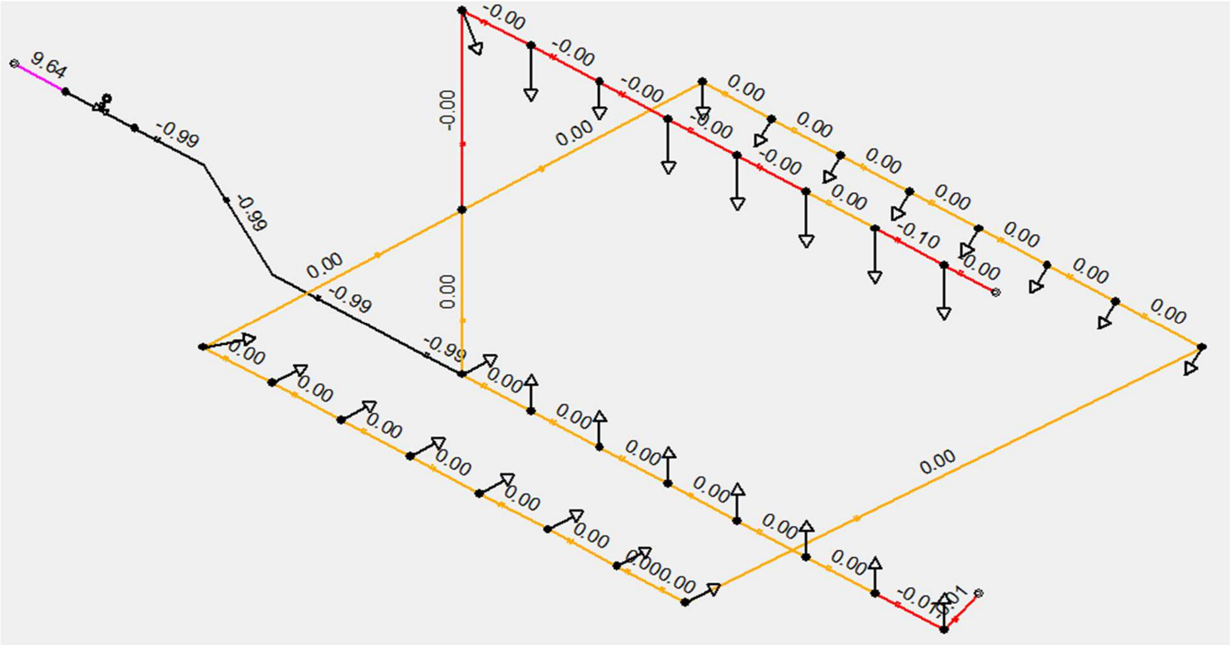

Figure5. 7 Minimum pressure in the network

Pipenet can calculate the minimum pressure as well which could be important in some cases . As seen in Fig 5.7 the minimum pressure happened in pipe 2 which is the inlet to the deluge network.

When the minimum pressure is close to water vapor pressure it is always recommended to check for cavitation.

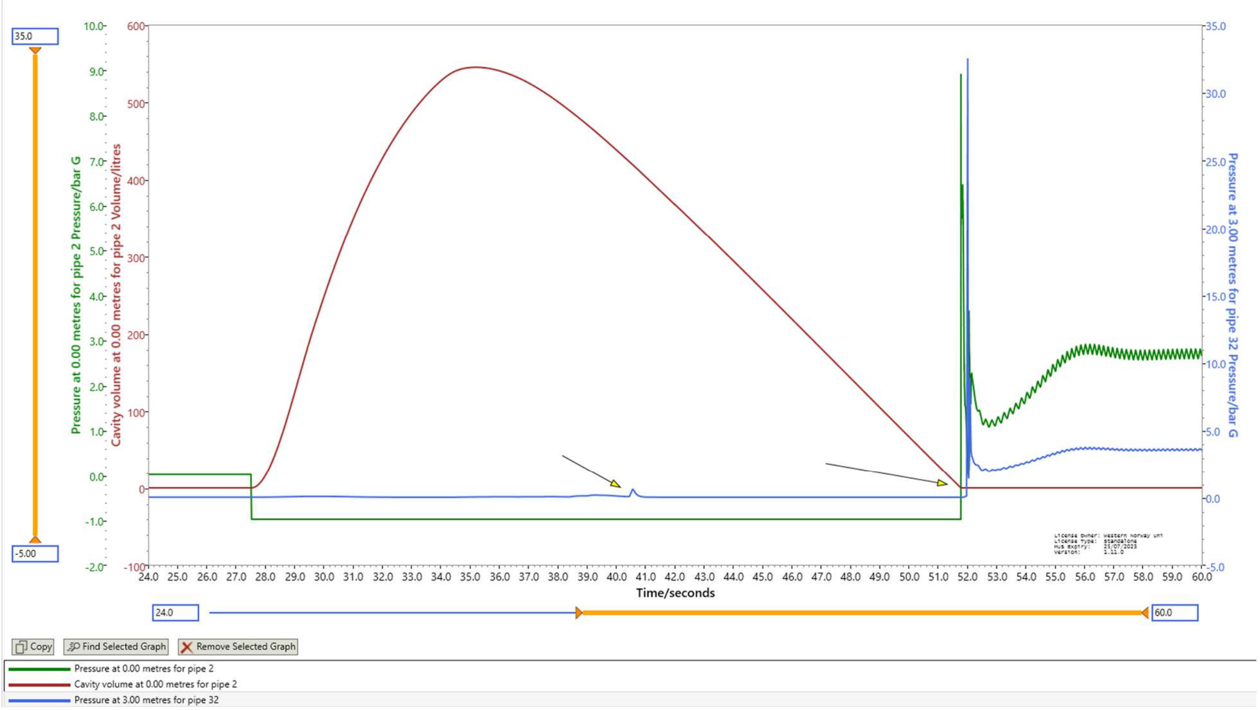

Figure5. 8 Pressure and cavitation in Pipe 2 and Pipe 32

In the above figure, the green line is the pressure in pipe 2 (main inlet pipe). From the 28th sec to the 52nd sec the pressure is -0.99 Barg which is below the water vapor pressure of about -0.98 so the cavitation will occur. The red line shows the huge cavitation volume in the pipe which will collapse at 52nd sec and then will cause a pressure surge spread in the pipe network. Although the peak pressure on pipe 2 is about 10 bar but the peak pressure on pipe 32 will be 32 Barg. The pressure graph of pipe 32 is shown in blue. Again, a notice of different scales of pressure in the Y-axis

A small peak in the blue line at 41st sec is the end of network priming and the water reaches the last nozzle so there is a pressure surge because there is another point with very low pressure so this pressure surge cannot grow to a large number

So not only at the end of priming, the deluge network can cause the pressure surge but also a cavitation may happen in the deluge pipe network and this can cause the pressure surge.

To solve this kind of pressure surge, one solution is to install the vacuum breaker at the highest point or where we have the lowest pressure which is the inlet of pipe 2. A simulation ran again with a vacuum breaker and the Figure 5.9 shows the differences.

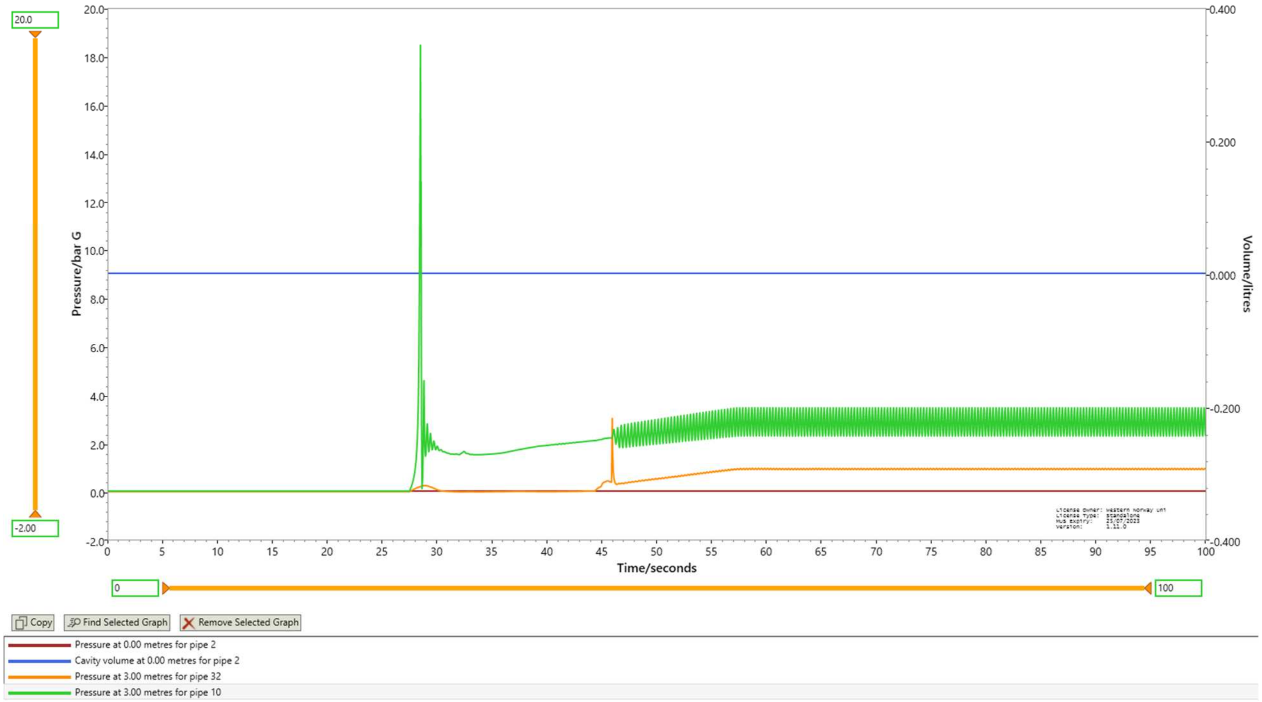

Figure5. 9 Pressure and cavitation in Pipe 2, pipe 32, and 10

No cavitation in this configuration and also the pressure surge reduced considerably to about 18 barg in pipe 10 and the pressure in pipe 32 was reduced even more to 3 barg.

Although this is a very good result from a pressure surge point of view but the steady state pressure of the nozzles shall be checked again for the minimum working pressure of the nozzle to make sure the network can operate properly. The vacuum breaker valve diameter can be changed to have the required minimum pressure at the nozzles.

vacuum breakers are widely used in ring mains with many deluge network outlets. In a large network with some elevation differences, when a fire happens and the fire pump and deluge valve start to operate at the same time but before the pump can pressurize the whole system, there would be a negative pressure in the uppermost locations which the vacuum breaker is vital to be used.

Pipenet can model this scenario very well and size the vacuum breaker.

5.3. Fittings effects on pressure surge

Fitting increases the peak pressure upstream of the fitting but if the peak pressure surge location is downstream of the fitting it reduces the surge peak pressure. It can be seen in the below network, Fig 5.10. In the left branch in pipe 6, there is an elbow but on the right branch, it is symmetrical except there isn't any elbow in pipe 9. The peak pressure on pipe 6 is about 58 Barg compared to pipe 9 which is about 61 Barg and the reason is the elbow reduces the flow speed. Because Pipenet is an analyzing rather than modeling software so the elbow on pipe 6 is included in the pipe but does not show explicitly.

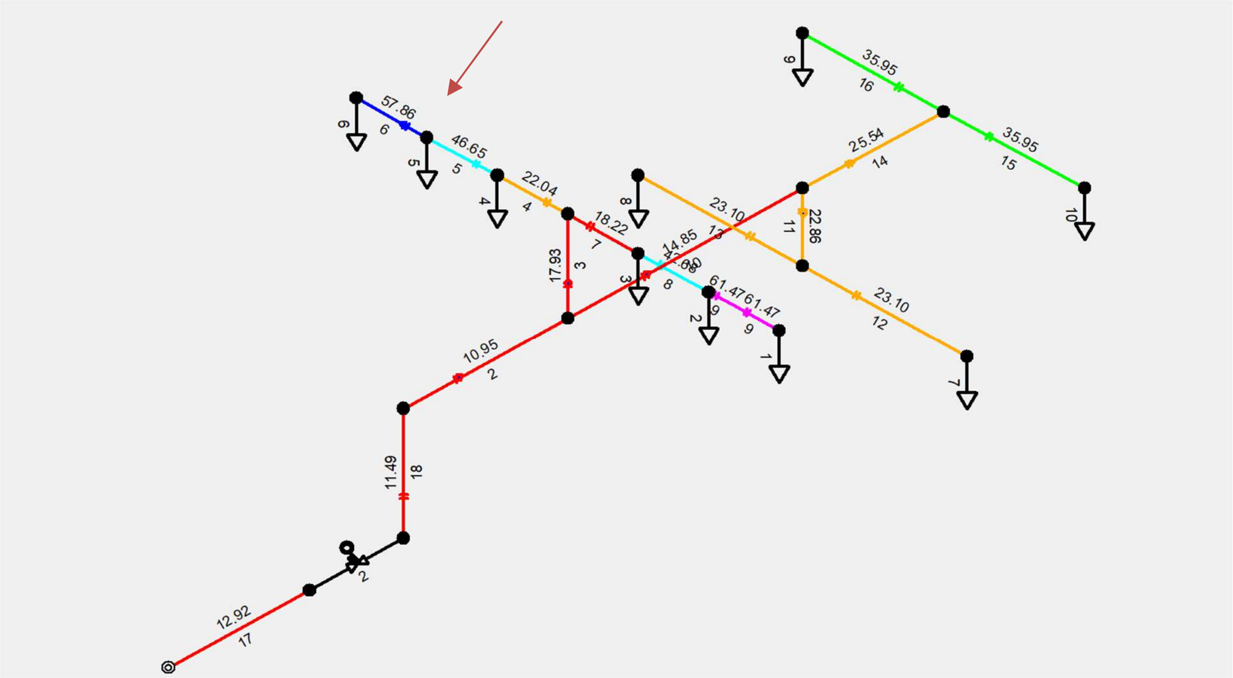

Figure5. 10 Effects of the fitting on pressure surge

As discussed above, the pressure surge can happen in many cases due to changes in momentum, so it is vital to explore different solutions to reduce it as much as possible. The transient analysis shall be started as soon as the initial design of the system is finished, otherwise, there might be a costly change. The designers shall be careful of the negative pressure, especially at the highest point, and avoid unnecessary Height changes

The proposed solutions don't have any major negative other than a minor cost for equipment.

5.4. Acceptable criteria for pressure surge

Although this is not directly part of this thesis the ASME B31.3 can be used to calculate the required pipe thickness under the occasional load such as pressure surge. In this case, the formula is the same as Sustained loads but the allowable stress is quite higher, See section 303 [7]

6. Conclusion

In this thesis, the pressure surge phenomenon was explained and its relationship with Nozzle priming time and cavitation was demonstrated in detail.

It was found out that due to the complexity of the transient phenomenon and its equations, software needed to calculate these three parameters accurately. In this thesis, the Pipenet 1.11 was used for calculation and investigating the solutions to reduce the water hammer. It was understood that the pressure surge can reach much higher than the system design pressure and can cause pipe failure if above the system's ultimate strength. So, it is important to do the transient calculation to make sure the pressure surge within the pipe strength and the priming time are according to NFPA requirements [1]. If not, the following solutions can be implemented.

- higher K factor nozzles are less prone to pressure surge, the solution of having the most remote nozzle with a higher K factor can also be considered.
- Pipe material can significantly affect the pressure surge, a more flexible and less Young module pipe develops a lower pressure surge compared to pipes with a higher Young module such as Carbone steel.
- Enlarging the pipe diameter wherever applicable, a larger pipe is less susceptible to pressure surge
- Adding a dead-end piece of pipe where the peak pressure surge is, the length of the pipe needs to be calculated so the pressure surge is whiting the acceptable limit.

Furthermore, it is vital to check the minimum pressure and compare it to water vapor pressure to make sure the cavitation will not happen, and if there is any chance of cavitation the best solution will be to use a vacuum breaker to increase the minimum pressure well above the water vapor pressure.

It is also important that the transient calculation not be left for a later stage of the project which the required modification based on transient calculation results will be more costly.

7. Further work

The transient analysis of fire water systems is quite an extensive topic and many more aspects of it can be investigated in other theses. Below is the list of proposed future work

- Pressure surge and cavitation analysis in ring main and transient analysis during the fire including the fire water pump start time and ramp up. Considering overboard dump valve function, buffer skid
- This study only considers water-based fire suppression systems further study can continue for other fire protection media such as Novec 1230 which have a higher density and will fill the pipes and be released in a short time.
- Investigating the acceptable criteria for maximum allowable pressure surge in deluge network
- Measuring the pressure Surge in the Hydraulic Laboratory and comparing the result with the Pipenet calculation to validate it.

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9. Appendix

Pipenet provided numerous tables and graphs which some of them will be provided here for more information.

Here are some important parts of Brouse output for Scenario 2 (default). In the first section, Pipenet provides the Max and Min pressure for all parts of the system while in the second part, the Max and Min pressure are provided for each pipe size

```
PRESSURE EXTREMA
----------------

Maximum pressure is 80.3312 bar G
          on pipe 6 at the outlet
          at time 18.53076 seconds

The minimum pressure is -0.989858 bar G
          on pipe 10 2.500 meters from the inlet of the pipe
          at time 14.40916 seconds
```

```
PRESSURE EXTREMA FOR PIPE SIZES
-------------------------------
                                              Maximum Pressure
Minimum Pressure
Pipe type          Nom. Dia.   Pipe label   Pressure       Time   Position   Pipe label
Pressure       Time   Position
                    milli.m.                   bar G    seconds     metres                    bar
G    seconds     metres
--------------------------------------------------------------------------------------------------
-----------------------

ANSI B36.10 Sch.4     40.000            9     80.331     18.531     Outlet           16      -
0.990     15.120      Inlet
ANSI B36.10 Sch.4     50.000           11     29.930     14.355     Outlet           11      -
0.940     15.119      Inlet
ANSI B36.10 Sch.4     80.000           14     32.728     15.060     Outlet           14      -
0.990     15.120      2.500
ANSI B36.10 Sch.4    100.000            3     26.044     18.551      4.000           10      -
0.990     14.409      2.500
ANSI B36.10 Sch.4    150.000           17     16.185     18.572     Outlet            2      -
0.990     15.103      2.000
```

```
MAXIMUM/MINIMUM PRESSURE
------------------------

                               Maximum Pressure                       Minimum Pressure
Component               Pressure       Time   Position         Pressure       Time   Position
Pipe Type

                           bar G    seconds     metres            bar G    seconds      metres
--------------------------------------------------------------------------------------------------
-----------------------


pipe
2                         15.050     18.581      2.000           -0.990     15.103       2.000
ANSI B36.10 Sch.40
3                         26.044     18.551      4.000           -0.990     15.113       Inlet
ANSI B36.10 Sch.40
4                         25.223     18.538      Inlet            0.000      0.000       1.000
ANSI B36.10 Sch.40
5                         59.195     18.532     Outlet            0.000      0.000       1.000
ANSI B36.10 Sch.40
6                         80.331     18.531     Outlet            0.000      0.000       1.000
ANSI B36.10 Sch.40
7                         25.223     18.538      Inlet            0.000      0.000       1.000
ANSI B36.10 Sch.40
8                         59.195     18.532     Outlet            0.000      0.000       1.000
ANSI B36.10 Sch.40
```

```
9                         80.331     18.531     Outlet            0.000      0.000      1.000
ANSI B36.10 Sch.40
10                        18.926     15.064     Outlet           -0.990     14.409      2.500
ANSI B36.10 Sch.40
11                        29.930     14.355     Outlet           -0.940     15.119      Inlet
ANSI B36.10 Sch.40
12                        30.414     14.356     Outlet           -0.415     14.411      Inlet
ANSI B36.10 Sch.40
13                        30.414     14.356     Outlet           -0.415     14.411      Inlet
ANSI B36.10 Sch.40
14                        32.728     15.060     Outlet           -0.990     15.120      2.500
ANSI B36.10 Sch.40
15                        46.007     15.057     Outlet           -0.990     15.120      Inlet
ANSI B36.10 Sch.40
16                        46.007     15.057     Outlet           -0.990     15.120      Inlet
ANSI B36.10 Sch.40
17                        16.185     18.572     Outlet            8.364     15.094     Outlet
ANSI B36.10 Sch.40
18                        15.945     18.574      2.000           -0.845     15.100     Outlet
ANSI B36.10 Sch.40

Nozzle MAXIMUM/MINIMUM PRESSURE
------------------------

                                      Component Inlet
Component Outlet
                         Maximum Pressure         Minimum Pressure            Maximum Pressure
Minimum Pressure
Component               Pressure      Time       Pressure      Time          Pressure      Time
Pressure      Time
                           bar G   seconds          bar G   seconds             bar G   seconds
bar G   seconds
-------------------------------------------------------------------------------------------------
-----------------------

operating valve
2                         16.185    18.572          8.364    15.094            13.528    18.572
0.000     0.000
--------------------

nozzle
1                         80.331    18.531          0.000     0.000
2                         59.195    18.532          0.000     0.000
3                         25.175    18.536          0.000     0.000
4                         25.175    18.536          0.000     0.000
5                         59.195    18.532          0.000     0.000
6                         80.331    18.531          0.000     0.000
7                         30.414    14.356          0.000     0.000
8                         30.414    14.356          0.000     0.000
9                         46.007    15.057          0.000     0.000
10                        46.007    15.057          0.000     0.000

PRIMED TIME OF NOZZLES
----------------------

        Label          Primed Time
                           seconds
       -----------------------------------

            1            0.185E+02
            2            0.184E+02
            3            0.182E+02
            4            0.182E+02
            5            0.184E+02
            6            0.185E+02
            7            0.144E+02
            8            0.144E+02
            9            0.151E+02
           10            0.151E+02
```

```
INITIAL AND MAXIMUM/MINIMUM VELOCITY
------------------------------------

A POSITIVE velocity means the flow is directed along the pipe orientation.
A NEGATIVE one means it is directed against the pipe orientation.

                                    Initial               Maximum Velocity
Minimum Velocity
Component           Diameter        Velocity        Velocity       Time    Position
Velocity       Time   Position
                    milli.m.           m/sec           m/sec    seconds     metres
m/sec    seconds     metres
-------------------------------------------------------------------------------------------------
-----------------------

Pipes
2                      154.1          0.0000          2.6666      4.645      Inlet
0.0000      0.000      Inlet
3                      102.3          0.0000          5.2324     15.296      Inlet
0.0000      0.000      Inlet
4                       77.9          0.0000          3.9137     17.698      Inlet
0.0000      0.000      Inlet
5                       40.9          0.0000         13.8525     18.212      Inlet
0.0000      0.000      Inlet
6                       40.9          0.0000         12.6788     18.361      Inlet
0.0000      0.000      Inlet
7                       77.9          0.0000          3.9137     17.698      Inlet
0.0000      0.000      Inlet
8                       40.9          0.0000         13.8525     18.212      Inlet
0.0000      0.000      Inlet
9                       40.9          0.0000         12.6788     18.361      Inlet
0.0000      0.000      Inlet
10                     102.3          0.0000          3.7350     13.660      Inlet
0.0000      0.000      Inlet
11                      52.5          0.0000          5.7777     13.601      Inlet
0.0000      0.000      Inlet
12                      40.9          0.0000          4.6532     13.920      Inlet
0.0000      0.000      Inlet
13                      40.9          0.0000          4.6532     13.920      Inlet
0.0000      0.000      Inlet
14                      77.9          0.0000          5.1347     14.405      Inlet
0.0000      0.000      Inlet
15                      40.9          0.0000          7.8926     14.783      Inlet
0.0000      0.000      Inlet
16                      40.9          0.0000          7.8926     14.783      Inlet
0.0000      0.000      Inlet
17                     154.1          0.0000          2.7789      2.024      Inlet
0.0000      0.000      Inlet
18                     154.1          0.0000          2.7788      2.024      Inlet
0.0000      0.000      Inlet
```