VERY LARGE AND COMPLEX SURGE MODELLING OF NEW DELUGE FIREWATER SYSTEM

M. Bouman, P. Pennings
Dynaflow Research Group B.V.
Laan van Oversteen 20, 6E, 2289 CX, Rijswijk, The Netherlands
Tel: +31 (0) 85 058 0046
Email: mick.bouman@dynaflow.com

Abstract

This paper describes the modelling of a very extensive and branched deluge firewater system using the surge analysis software BOSfluids®. The models used for the case study are built using input from 5140 isometric drawings. A comparison between the full detailed model and a simplified model based on general arrangement drawings will touch upon the general setup of such an analysis as well as the key parameters to look at when analyzing such a system.

The comparison shows that general trends in flow rate, pressures, and unbalanced forces are well captured by the simplified model. Maximum surge pressures are within 10% of the detailed model, and unbalanced forces are within 15%.

Some parameters of the detailed model were not included in the simplified model. Only 1% of the bends was included and no elevation was taken into account. This results in a 150% underestimation of the system pressure drop and missing hydrostatic pressure from elevation differences. The system pressure drop was corrected by increasing the pipe-wall roughness.

Cavitation in the headers of the system is well represented by the simplified model. Cavitation is highly dependent on the geometry of local piping and the specific elevation. Therefore only a detailed model can resolve the highest surge pressures due to cavity implosion in local piping.

1. Introduction

During engineering cooling water or firewater systems in many cases a surge analysis is required to assess whether the transient pressures stay within the limits of design. Due to advances in software and computing power the recent trend is to perform surge analyses for ever larger models with ever more detail. The systems may span kilometres of branched networks including, pumps, vessels, valves, many connected clients and boundary conditions and deluge systems which amount to hundreds of equipment items and (pressure or flow) boundary conditions.

Most surge analysts make assumptions on the pipe routing and limit the size of the modelled system by splitting the large system into smaller subsystems or by simplifying the routing of the branched network. In the process of simplification, details in the time histories of the pressures and the unbalanced forces are invariably lost. It is generally assumed that in this simplification process the most important details such as largest and lowest pressure found during the analysis remain relatively well approximated by the simplified surge model.

Developments in modelling on the basis of 3D-model files as opposed to manual modelling make it feasible to perform surge calculations for the actual piping geometry for very large models. This added detail comes at the cost of an increase in computational cost. In this paper, a comparison is made between the surge analysis performed for a full geometry firewater system and the surge analysis for a simplified geometry of the same firewater system. The applicable firewater network is shown in Figure 1 and consists of a mixture of glass-fiber reinforced pipe and carbon steel pipe.

Section 2 describes the model and methods used. Section 3 shows the results of the scenarios. The differences between the models are discussed in Section 4. Finally, the considerations for a large surge analysis are concluded in Section 5 .

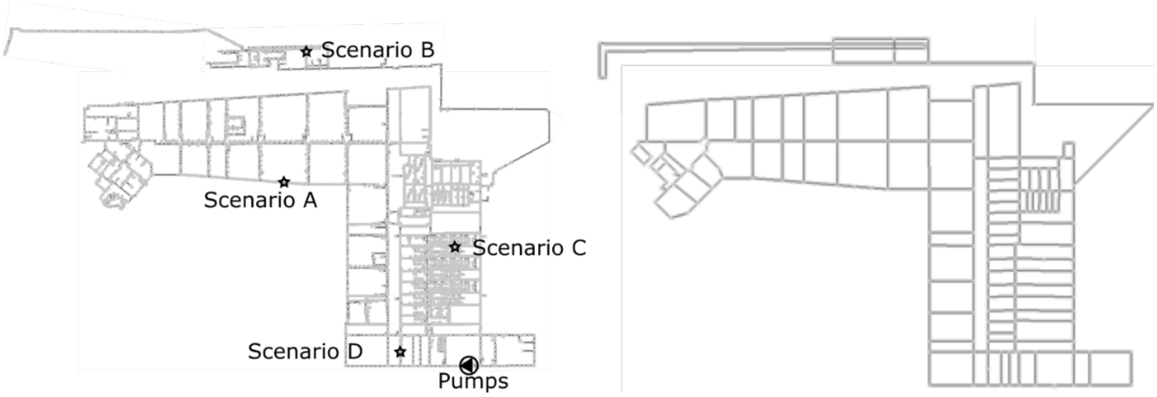

Figure 1 | Overview of the high-fidelity model (left) and low-fidelity model (right) of the firewater system including Scenario outflow and pump locations. The size of the model is 5 km wide by 4 km long.

2. Method

The surge analysis is performed with the in-house software package BOSfluids® 5.4.3. BOSfluids® is an interactive computer simulation package that models steady-state and transient flow in liquid or gas-carrying piping systems. The software package analyses fluid transients and relates this information to the forces, pressures, flow rates, and velocities experienced in the piping system with engineering accuracy.

High fidelity model

BOSfluids® provides the option to import large numbers of piping component files (PCFs) automatically. The high-fidelity model is based on these files with all geometrical details.

Low fidelity model

The low-fidelity model is based on General Arrangement (GA) drawings. The pipe elevation is not included in the GA and therefore not included in the low-fidelity model. The low-fidelity model is 13% smaller in volume than the high-fidelity model due to the absence of dead-end branches and any piping smaller than DN 250 in diameter.

System Description

- Firewater is supplied from storage tanks that provide at the lowest liquid level at least 0.5 barg suction pressure to the pumps.
- A jockey pump ensures small leakage flow compensation and a pressurization of the system to 11 barg.

- There are 5 main pumps that provide a rated flow rate of 1100 m3/h at 11.7 barg. At one time there are a maximum of 3 main pumps in operation simultaneously. All pumps have a check valve positioned at each pump discharge. The start-up speed from stationary to full rotation rate is 1.5 s.
- The boundary of the scope of the presented analysis is at the deluge valves where a discharge pressure of at least 10 barg is required.
- All pipe elements except those of the pump station are buried. In the model, this is incorporated by increasing the wave speed due to additional radial pipe stiffness.

The geometry of the piping downstream of the deluge valve is not modelled. Since this section is initially dry, there is a lack of back pressure when opening the deluge valve. When the deluge system fills the back pressure rises and reaches its final value abruptly when the complete deluge system is filled. At the moment the deluge system fills completely, the flow rate drops. The total discharge pressure drop is chosen to provide the required flow rate at a discharge pressure of 10 barg.

Scenarios

The steady states and transient action of the scenarios are shown in Table 1.

Table 1 | Description of steady states and transient actions

Main feature	Scenario	Steady state*	Features of the transient scenario
Pump start-up	A	- No flow - System pre-pressurized to 11 barg	- Opening of scenario outflow valve(s) - Start of first pump - Additional pumps are started at a delay of 10 seconds with respect to the time the last pump started. (2 for scenario A, 1 for scenarios B, C and D)
	B		
	C		
	D		
Single pump trip	A	- Flowrate 3165 m^3/h - Flow velocity 1.6 m/s at DN 600 header - Pump discharge pressure 12.2 barg, 10.1 barg at deluge valve	- At 2 seconds after the steady state a single pump trips. - No backup pump starts.
	B	- Flowrate 1846 m^3/h - Flow velocity 1.8 m/s at DN 600 header - Pump discharge pressure 12.9 barg, 10.9 barg at deluge valve	
	C	- Flowrate 1888 m^3/h - Flow velocity 2.7 m/s at DN 500 header - Pump discharge pressure 12.8 barg, 12.4 barg at deluge valve	
	D	- Flowrate 1812 m^3/h - Flow velocity 4.0 m/s at DN 400 header - Pump discharge pressure 12.9 barg, 12.3 at deluge valve	

* Difference in steady-state flowrate and pressures between high and low fidelity models is below 1%

Tuning low fidelity model

The pressure drop in the system is related to minor piping details. The number of bends is significantly reduced in the low fidelity model resulting in lower system resistance. The correct pressure drop compared to the high fidelity model is realised by increasing the pipe-wall roughness. The flow resistance in BOSfluids® is based on the Darcy-Weisbach equation. The Darcy friction factor is tuned by increasing the pipe-wall roughness. With the correct system pressure drop the steady-state flow-rates are approximately the same. This is important to correctly compute the highest surge pressures.

All model boundary conditions and transient actions of the scenarios between the two models are equal. This leaves the minor piping details, system volume, missing flow paths and elevation as differences between the two models. The quantitative model differences are listed in Table 2.

Table 2 | Differences between high and low fidelity model

Parameter	high fidelity	low fidelity	difference
Model basis	5140 PCFs	5 GAs	-99.9 %
Number of pipe elements	22747	314	-98.6 %
Volume	1372 m^3	1195 m^3	-12.9 %
Number of 45 degree bends	4009	7	-99.9 %
Number of 90 degree bends	5726	26	-99.5 %
Total pipe length	1.3 x 10^5 m	7.2 x 10^4 m	-44.6 %
Additional frictional length due to missing bends	0 m	1.1 x 10^5 m	+153 % pressure drop
Scenario A pipe-wall roughness	0.05 mm	8 mm	
Scenario B pipe-wall roughness	0.05 mm	0.2 mm	
Scenario C pipe-wall roughness	0.05 mm	4 mm	
Scenario D pipe-wall roughness	0.05 mm	5 mm	
Mean pipe diameter	335 mm	450 mm	+ 34%
Scenario A estimated mean friction factor	0.013	0.046	+254 % pressure drop
Scenario B estimated mean friction factor	0.013	0.016	+23 % pressure drop
Scenario C estimated mean friction factor	0.013	0.037	+185 % pressure drop
Scenario D estimated mean friction factor	0.013	0.039	+200 % pressure drop

3. Results

This section describes the global results (Table 3), the detailed results of the two scenarios and the specifically the unbalanced forces are discussed. Scenario A pump start-up has the largest steady-state flow-rate where cavitation is a relevant mechanism in the highest surge pressure. Scenario D pump trip is chosen because it results in the highest surge pressure due to pump trip.

Global transient results

Table 3 | Comparison of extreme pressures between high and low fidelity models

Scenario	high fidelity	low fidelity	difference	high fidelity	low fidelity
	maximum pressure [barg]			minimum pressure [barg]	
A start	19.3	17.8	-8%	-0.9	-0.9
B start	15.7	15.2	-3%	-0.9	-0.9
C start	22.2	18.2	-18%*	-0.9	-0.9
D start	21.9	20.7	-5%	-0.9	-0.9
A trip	12.9	12.4	-4%	0.0	0.0
B trip	14.4	14.0	-3%	0.0	0.0
C trip	14.3	13.7	-4%	0.0	0.0
D trip	14.5	13.8	-5%	0.0	0.0

* Location of maximum pressure in Scenario C is not present in low fidelity model, it is located on a small bore parallel distribution line.

Description of Scenario A pump-start up results:

- Steady state; no flow, pressure maintained by jockey pump to 11 barg.
- t = 2 seconds; the pressure in Figure 2 and the flow in Figure 3 show the opening of the scenario outlet valve (deluge valve) in 8 seconds.
- t = 2 seconds; since the deluge system is initially dry there is not yet the pressure drop of the sprinklers. The pressure downstream of the deluge value is therefore 0 barg.
- t = 10 seconds; the scenario valve is completely open. This results in a maximum flow rate of approximately 3500 m3/h.
- t = 10 seconds; as the deluge system fills the back-pressure of this system starts to influence the flow. This additional pressure drop for a filled system is modelled by closing a valve, partially, that represents this pressure drop, within 1 second. This causes a rapid drop in local flow rate at the deluge valve.
- t = 11 seconds; the pressure in the pump discharge header drops below 10 barg (see Figure 4). The first pump start immediately resulting in an increase of pressure at the pump.
- t = 13 seconds; one of the branches in a remote part (see Figure 5) experiences a pressure drop down to vapor pressure causing cavitation (see Figure 6).
- t = 17 seconds; the pressure increment due to the filling of the deluge system reaches the branch in the remote part.
- t = 20 seconds; the maximum surge pressure for this scenario is found in a branch. This is due to the implosion of vapor pockets in the branch ends.
- t = 21 seconds; after a 10-second delay the second pump starts
- t = 31 seconds; after a 10 second delay the third pump starts

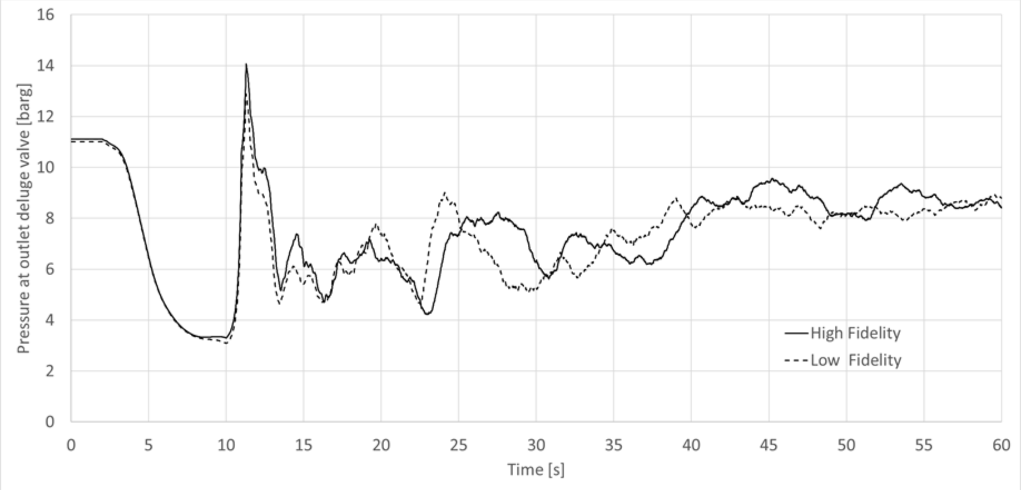

Figure 2 | Scenario A pump start-up, pressure at deluge valve. At 11.3 s the peak pressure is 14 barg for the high fidelity model and 13 barg for the low fidelity model. Low fidelity shows faster response to pump start-up at t = 21.3 s.

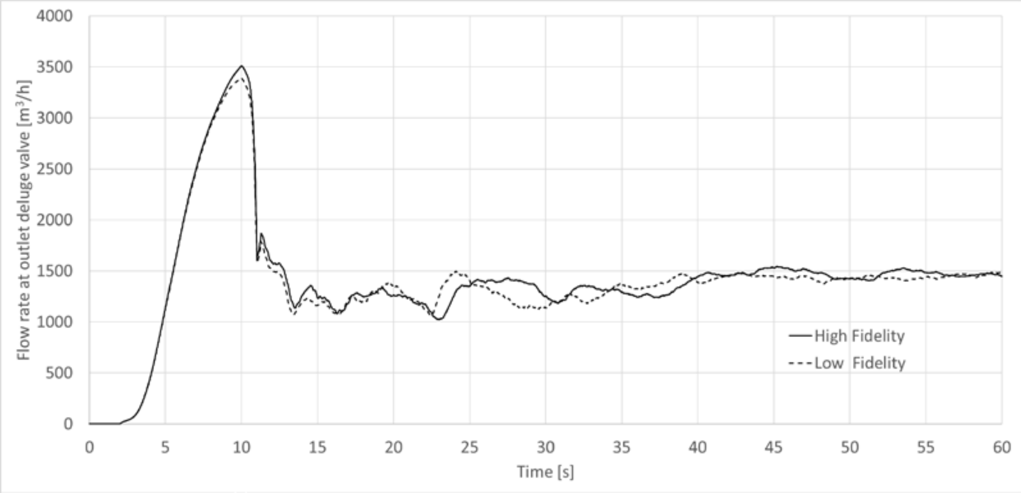

Figure 3 | Scenario A pump start-up, flow rate through one of the Scenario A deluge valves

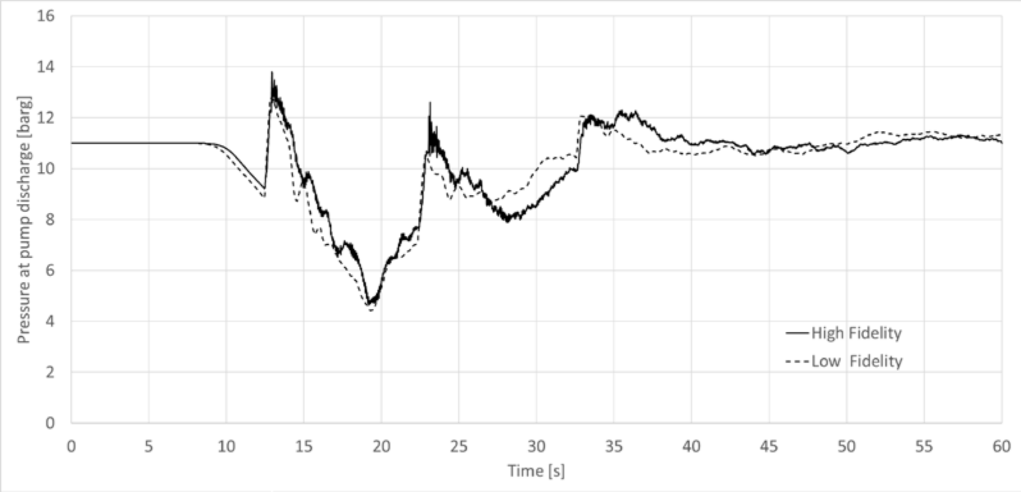

Figure 4 | Scenario A pump start-up, pressure at pump discharge

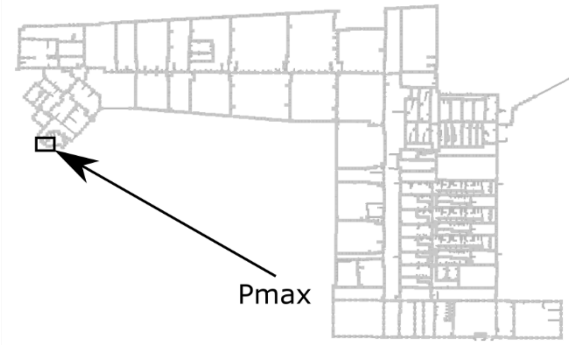

Figure 5 | Scenario A pump start-up, location of maximum surge pressure

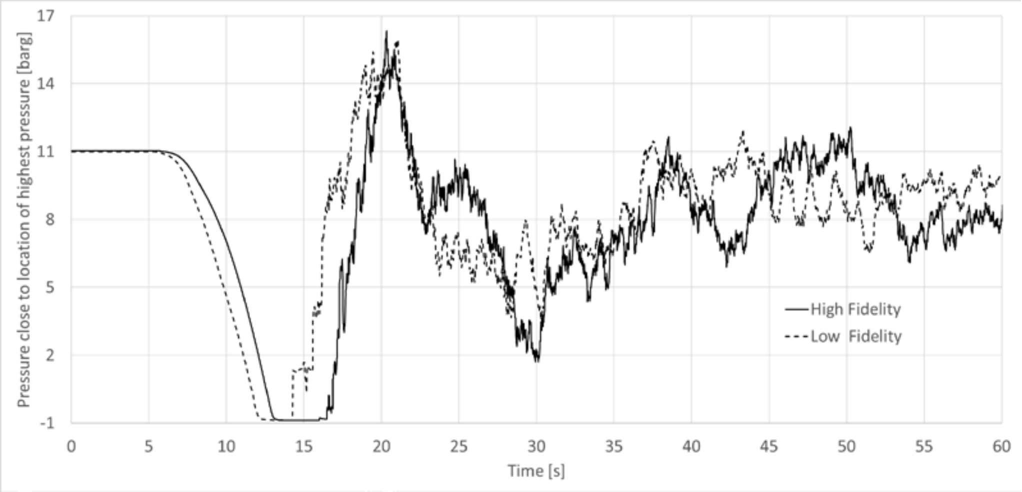

Figure 6 | Scenario A pump start-up, pressure at location close to maximum surge pressure in high fidelity model

Description of Scenario D pump trip results:

- Steady state; 2 pumps running, 12.9 barg pressure at pump discharge header, 12.3 barg pressure at the outlet valve (deluge valve). Flowrate 1812 m^3/h.
- t = 2 seconds; a main pump is tripped and stops on inertia. Initially the pressure at the pump discharge header drops (see Figure 7) after which the full discharge is taken over by the pump that remains running (see Figure 8). Therefore the pressure (see Figure 9) and flowrate (same trend as shown for pressure) decrease at the outlet is limited and gradual.
- t = 7 seconds; the flow fluctuations immediately following the pump trip result in the maximum pressures to the right of the pump area (see Figure 10). The combination of pressure waves in that particular location is typical for single pump trips in all scenarios (see Figure 11).

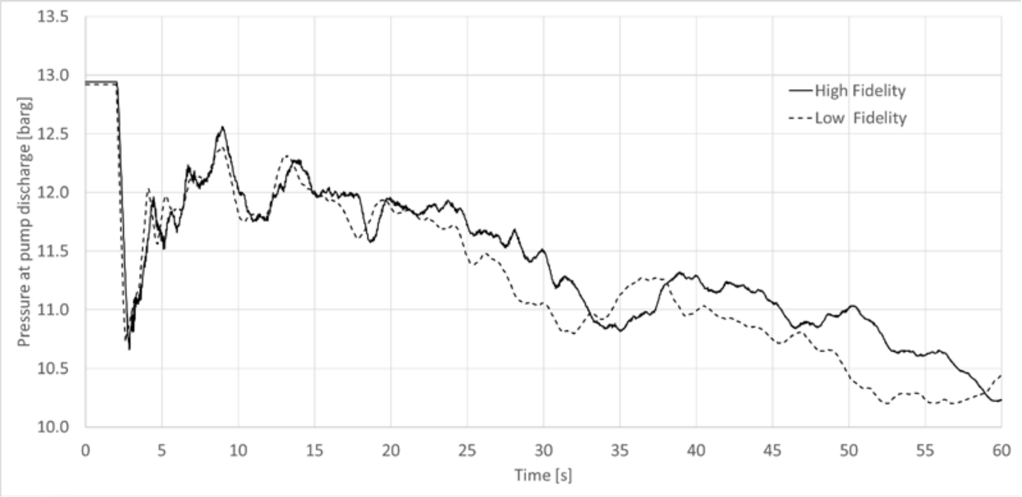

Figure 7 | Scenario D pump trip, pressure at pump discharge header

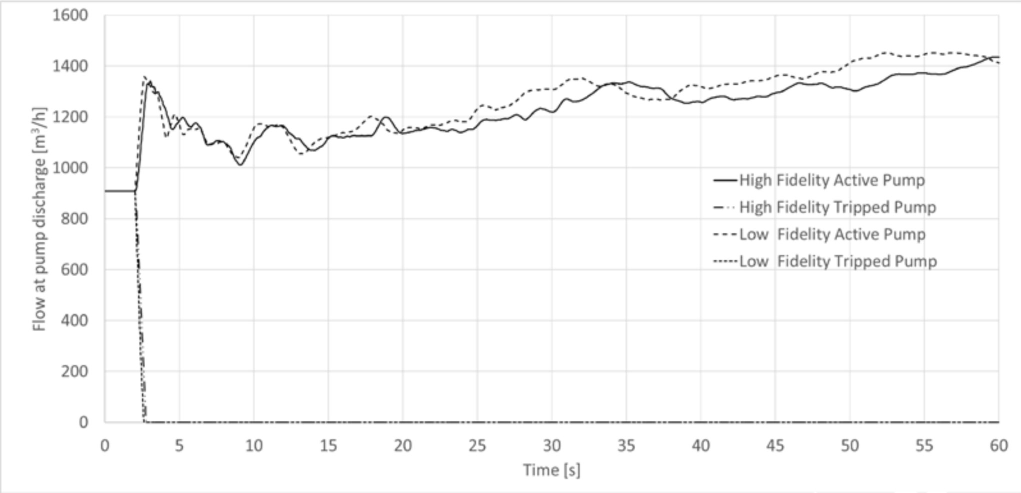

Figure 8 | Scenario D pump trip, flow rate at pump discharge

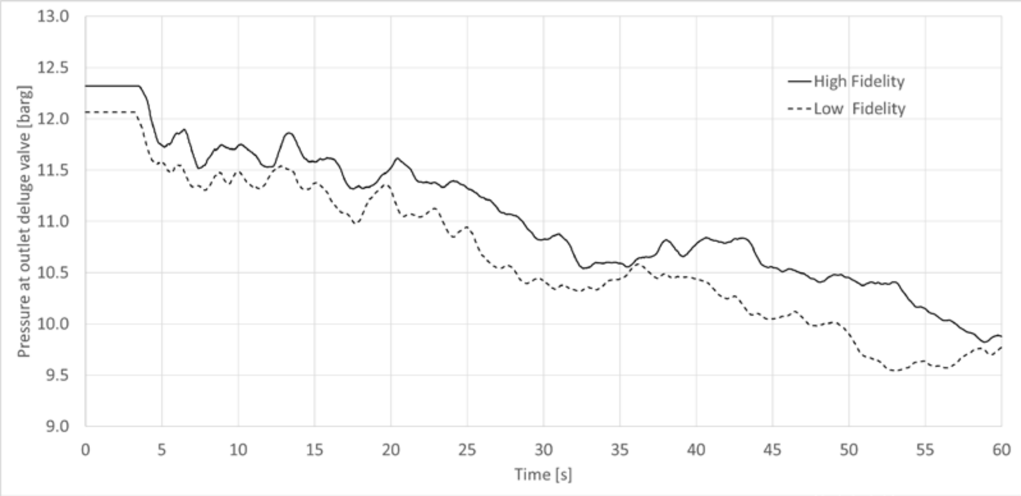

Figure 9 | Scenario D pump trip, pressure at deluge valve

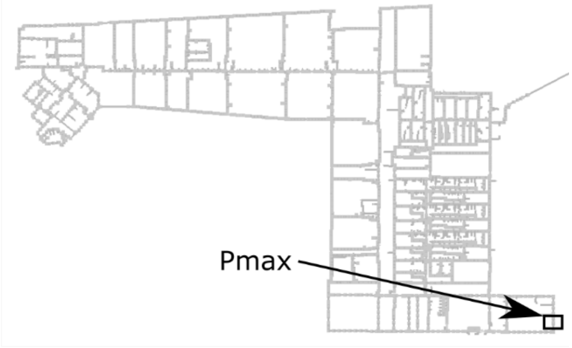

Figure 10 | Scenario D pump trip, location of maximum pressure

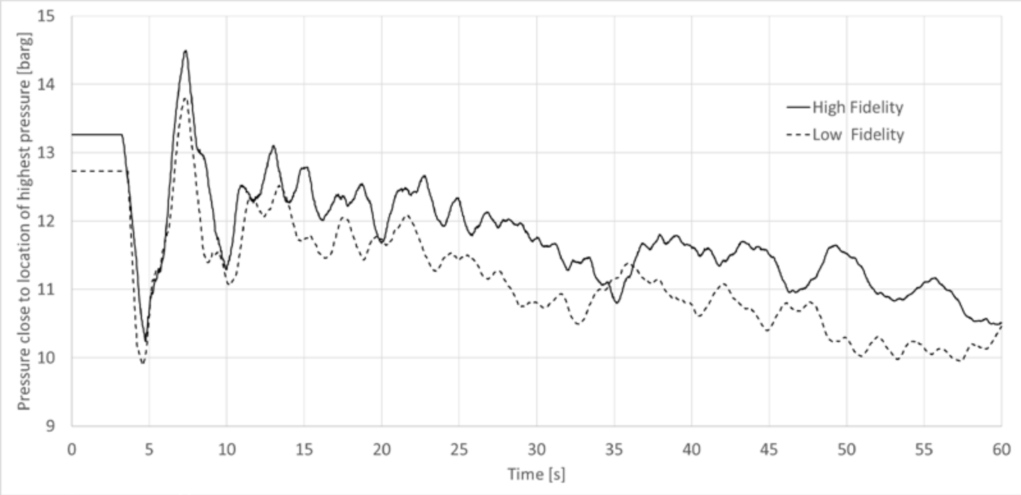

Figure 11 | Scenario D pump trip, surge pressure close to the location of maximum pressure

Unbalanced forces

After transient events, such as a valve opening or a pump start-up, pressure waves travel through the system. As these waves travel at a finite velocity, a pressure differential can arise at two opposite bends. The present system is large and therefore the pressure differential can be significant. Three areas are studied in more detail; around the pumps, in the center of the fire water system and the remote part close to the high flow-rate outlet. The stretches of pipe are indicated in Figure 12.

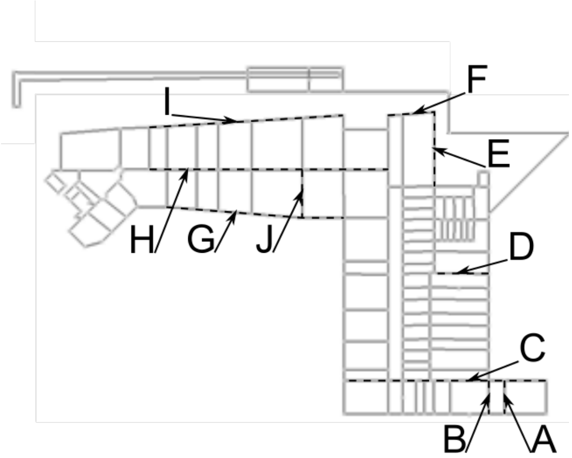

Figure 12 | Locations where unbalanced forces were evaluated

The quantitative results in the form of maximum forces are given in Table 4. Forces in the low-fidelity case vary between -15% to +15% around the high-fidelity baseline. Two specific locations (C and H) are discussed in more detail as shown in Figure 13 and Figure 14.

When the deluge valves are opened in Scenario A pump start-up the pressure decreases around the outlet. This results in a low pressure on the left side of pipe stretch C and H. The resulting force on these stretches is to the right, or negative in the graphs. The sharp upward gradient is the result of the additional outflow resistance at the deluge valve. The oscillations after the initial transient actions are summations of waves that travel through the system. The low-fidelity model shows an overall faster response to the transient actions. There is no clear trend in the difference between the models. In some parts of the model, the low-fidelity model produces higher maximum forces in others the highest forces are found in the high-fidelity model. As time passes, the correlation between the two models is lost due to the complexity of the pressure wave interactions.

Table 4 | Comparison of maximum unbalanced forces

Scenario A pump start-up, location	high fidelity force [kN]	low fidelity force [kN]	difference [-]
A	16	18	+13%
B	67	73	+9%
C	91	76	-16%
D	22	26	+18%
E	67	73	+9%
F	66	73	+11%
G	190	210	+11%
H	190	160	-16%
I	170	160	-6%
J	150	150	0%
Scenario D pump trip, location	high fidelity force [kN]	low fidelity force [kN]	difference [-]
A	7.0	7.4	+6%
B	30	32	+7%
C	48	42	-13%
D	5.8	5.8	0%
E	13	13	0%
F	7.9	6.7	-15%
G	22	20	-9%
H	25	24	-4%
I	26	24	-8%
J	5.7	5.4	-5%

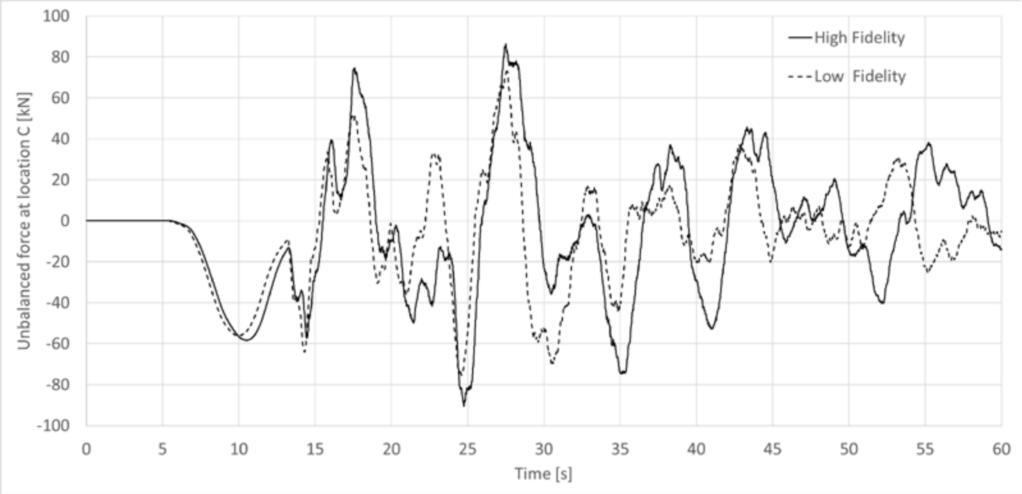

Figure 13 | Scenario A pump start-up, unbalanced force at location C

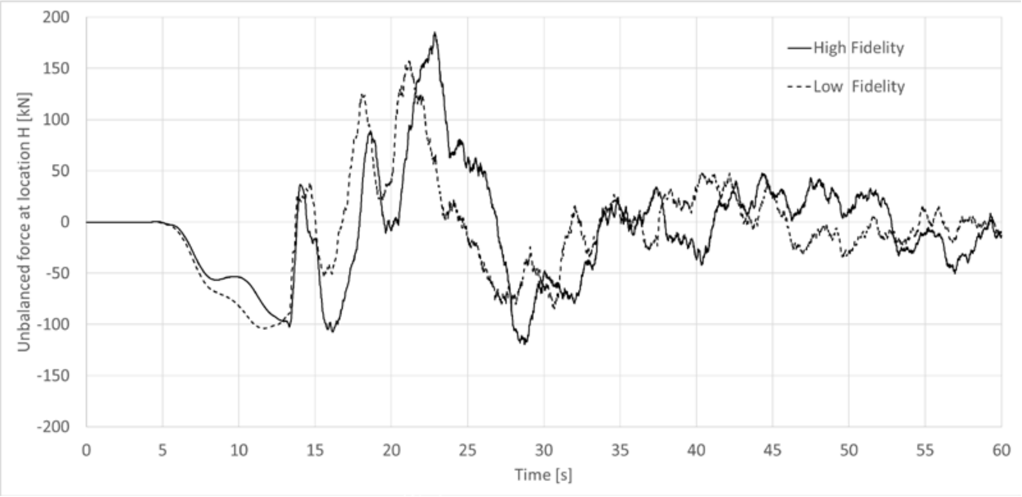

Figure 14 | **Scenario A pump start-up, unbalanced force at location H**

4. Discussion of differences between high and low fidelity models

Scenario A pump start-up shows only small differences between models.

- Due to smaller volume and adjusted pipe-wall roughness, the pressure drops to lower values when the deluge valve is opened (see Figure 2). This results in a smaller peak flow rate at the moment the deluge system pressure drop is added at t = 10 s. This peak flow rate affects the highest surge pressure close to the deluge valve that is 1 barg smaller in the low fidelity model.
- As there is little to no difference in the way the pumps are modelled, the pressure at the pump discharge header is approximately the same for both models.
- The maximum surge pressure in Scenario A pump start-up is governed by the collapse of a cavitation pocket in a branch in the extreme west of the model. As this branch is not modeled in the low-fidelity model a location on the header close to this branch was used for model comparison. Due to the smaller volume of the low-fidelity model, the system response to opening the deluge valve is faster.
- To investigate the influence of branch details a model variation was performed at the location of maximum surge pressure. The branch on which the highest surge pressure was found in scenario A is located on a 50 m long horizontal branch that spans 200 mm vertically. To approximate this effect, a 50 m long pipe horizontal pipe with a vertical elbow at the end was added in the low-fidelity model. The length of the vertical part was varied and the maximum surge pressure was obtained (see Figure 15).

  The nature of cavitation and cavity implosion is inherently dominated by fast pressure fluctuations (see Figure 6). Due to the spiky nature of the signal, the highest peak is not strictly governed by a simple relationship. This shows that it is hard to quantify the maximum surge pressure that will be encountered in the system during various forms of operation. Furthermore, any variations in system elevation can have a large influence on the maximum surge pressure in the system (10 barg variation as shown in Figure 15).
- The effect of system volume was studied on the low fidelity model Scenario A pump start-up. Four pipe diameters were selected that contribute approximately 75% to the system volume. These pipes were increased in diameter to match the system volume between the high and low-fidelity models. As the system pressure drop in the low fidelity model decreases with increased header size, the pipe-wall roughness is increased to obtain the same steady state (see Section 2

on model tuning). The result is a slower pressure decrease when the deluge valves are opened. However, due to the increased pipe-wall roughness the peak surge pressure at the deluge valve is lower. At the location of maximum pressure the system response of the adjusted volume low fidelity model is so slow that cavitation no longer occurs. The detailed system volume is not always available a priori and simplified adjustment based on this does not improve results.

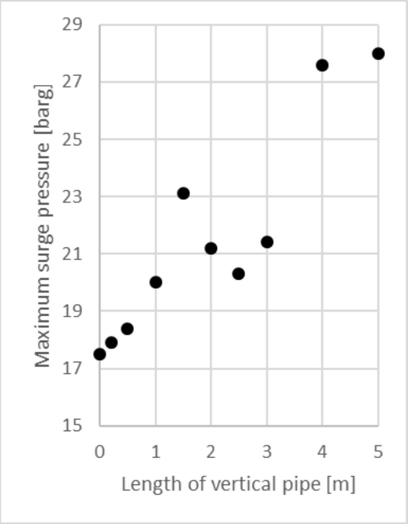

Figure 15 | Scenario A pump start-up (low fidelity model), maximum surge pressure at the vertical branch of varying length

Scenario D pump trip shows mainly an offset in pressure at the deluge valve and the location of maximum pressure. The trends in pressure and flow are the same between high and low-fidelity models.

- Pressure in the system is directly affected by the elevation of the local piping. Differences in piping elevation can be as large as 11 m in the complete model. The offsets in pressure in Figure 9 and Figure 11 are directly related to the missing elevation difference in the low-fidelity model. This is 2.6 m down from the pump to the deluge valve and a total of 5.4 m down from the pump to the location of maximum pressure.

5. Conclusion

Two options are presented in this paper for modelling a large and complex fire-water piping system for surge analysis. The high-fidelity model with maximum detail based on digital Piping Component Files (PCFs) and the low-fidelity model with minimum details based on General Arrangement (GA) drawings.

Small details in pipe routing and bends can result in significant differences in global pressure drop. When the difference in system pressure drop is accounted for in the pipe-wall roughness, the overall trend is that both the high-fidelity and the low-fidelity models show the same results. After the deluge valve opening (Scenario A pump start-up), the rate at which the pressure decreases is affected by the smaller volume in the low-fidelity model. This results in a lower system pressure and a consequently lower maximum flow rate.

Other transient effects such as surge wave collision in the system (Scenario D pump trip) are captured by the low-fidelity model. Both the location and amplitude match the high-fidelity model. To achieve this result, it is recommended to include piping elevation if this is available on the GAs (this was not done in the present study).

Cavitation is captured by the low-fidelity model. However, the sharp pressure fluctuations depend on the specific details of the local piping. A few meters of vertical piping can increase the maximum surge pressure by 10 barg. This consideration holds for both the high and low-fidelity models, as there is always a limit to the piping detail that is available at the design stage.

Unbalanced forces show similar dynamics of the dominant peaks. However, no clear relation is found in either under or overestimation of the low-fidelity model with respect to the high-fidelity model. Differences vary around -15% to +15% with respect to the high-fidelity baseline.

Certain parameters can only be obtained with a high-fidelity model:

- Accurate estimate of the system pressure drop
- Calculation of unbalanced forces in small branches and local distribution networks
- Peak surge pressures from implosion of cavitation pockets in branches

This study shows the conditions under which the low-fidelity model can be confidently used and when a high-fidelity model is required.