

Investigations of a Long-Distance 1000 MW Heat Transport System with APROS Simulation Software

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1 ABSTRACT

This paper presents a computer model and simulation results for a long-distance heat transport system. The modelled system is designed to transport 1000 MW of heat over a distance of 77 km for district heating purposes. This kind of a nuclear combined heat and power (CHP) option is being investigated as one option within Fortum's Loviisa 3 NPP project. The heat produced in Loviisa NPP would be utilized for the district heating of Helsinki metropolitan area in Finland. The objective of this study is to carry out simulations to examine the behaviour of such a large-scale heat transport system and to perform safety analyses for the purposes of preliminary planning of a heat transport system between Loviisa and Helsinki. The model was created using APROS (Advanced Process Simulation Environment) simulation software.

Several transients including pump trips and leaks from the circuit into the surrounding service tunnel are simulated and their effects in the pipeline are investigated. The safety risks of the transients are analyzed. Major leaks cause the pressure in the circuit to fall drastically. The tripping of pumps can also cause challenging pressure transients. However, the consequences of the transients can be substantially limited with proper safety systems.

2 INTRODUCTION

Nuclear energy has been used for district heating in several countries both in dedicated nuclear heating plants and in combined heat and power (CHP) plants. Energy Company Fortum is applying to build a new nuclear power plant (NPP) in Loviisa, Finland. It has been suggested that this new NPP could be a CHP plant. The heat produced in Loviisa NPP could be utilized for the district heating of Helsinki metropolitan area (Fortum, 2009). This would require transporting of heat over a distance of approximately 77 km. The longest existing delivery distance for nuclear district heating is 24 km in Slovakia (IAEA, 1998).

This kind of a long-distance heat transport system transporting heat over 77 km is studied in this paper. The transported heat power considered is 1000 MW. Modelling is an important tool in designing such a system. Modelling and simulations are especially useful when the behaviour of such a large-scale system under transients is examined. Tripping of pumps or leaks from the circuit into the surrounding tunnel can cause safety risks which can be examined with an extensive model of the system. This paper presents a computer model for a long-distance 1000 MW heat transport system and simulation results for different transients. Safety of the heat transport system is also discussed and ways to improve it are presented.

3 MODEL

Heat transport system was modelled with APROS (Advanced Process Simulation Environment) simulation software. The model includes pipeline, pumps, valves, heat accumulator, tunnel and some automation. The principle of the modelled circuit is seen in Figure 1. One dimensional 6-equation model is used for the water and steam in the circuit.

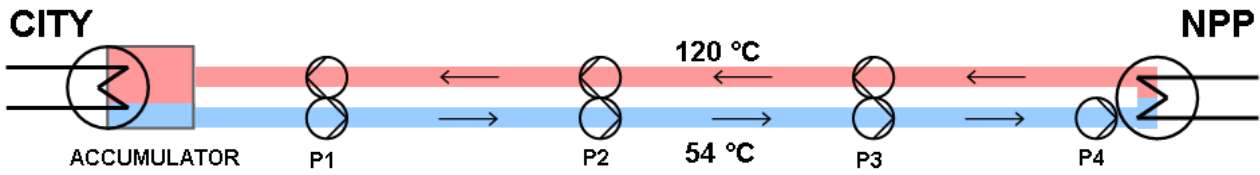


Figure 1. A greatly simplified representation of the modelled heat transport circuit. There are two 77 km long pipelines and 7 pumps arranged in 4 pump stations in the model.

Pipeline is modelled to both directions in the circuit (i.e. hot and cold leg). Pressure losses and heat losses in the pipeline are modelled. The pipeline is modelled as a steel pipe with a diameter of 1.2 m and a polyurethane insulation layer with a thickness of 100 mm. Pipeline is divided into calculation nodes and the length of the nodes is limited to a maximum of 200 m. An elevation profile for the pipeline is modelled. The pipeline is thought of as being in an underground tunnel and the elevation profile of the tunnel determines the profile of the pipeline. The profile is taken from a realistic elevation profile scenario for the tunnel. Elevation difference between the lowest-lying and highest-lying points in the pipeline is almost 90 m.

Four pump stations are modelled in the pipeline as can be seen in Figure 1. Three of these pump stations include a pump in both hot and cold leg and one pump station has only one pump in the NPP end of the circuit. All the pumps are identical and operated at the same rotation speed. This gives a symmetric pressure head in the pipeline.

Pressure balancing lines between the hot and cold leg are modelled. These lines are located on both sides of the points where hot and cold lines have equal pressure as shown in Figure 2. In total there are six pressure balancing lines. There is a check valves in each of the lines. These pressure balancing check valves are positioned so that under normal operation they do not let flow through. Under transients they can let flow through and level down pressure changes if pressure in either of the legs increases or decreases significantly.

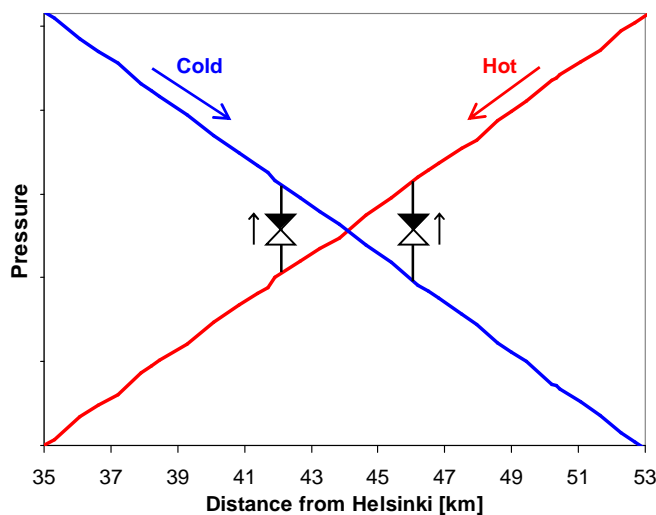


Figure 2. Pressure balancing lines. Red and blue lines represent the pressure in the hot and cold legs respectively. Pressure balancing lines are located on both sides of the point where the hot and cold legs have equal pressure. Check valves in the pressure balancing lines do not let flow through under normal operation conditions.

There are also sectioning valves modelled in the pipeline every 2 km. These valves can be used to separate the circuit in 2 km sections in the case of a leak.

A heat accumulator is modelled in the city end of the circuit. The accumulator is atmospheric and connected directly to the transport pipeline. The district heating circuit of the city is separated from the accumulator by heat exchangers. The purpose of the accumulator is to store heat and to keep a constant pressure in the circuit. The liquid volume of the accumulator was modelled to be 50 000 m³.

The calculation model includes also a part of the underground tunnel so that the total behaviour of the system can be simulated. The modelled tunnel is a 2 km section of the 77 km tunnel. This section is thought of as being separated from the rest of the tunnel by fire doors. The modelled tunnel is divided into 100 m nodes which are connected by water and gas branches. Ventilation shafts connected to the environment are modelled in both ends of the tunnel. The cross-sectional area of the tunnel is 30 m².

4 SIMULATIONS

Simulated properties of the heat transport system in steady state are shown in Table 1. Also different temperatures and flows were simulated but those values shown in Table 1 were used as initial state for all the simulations presented in this paper. The pressure profile in the circuit in steady state is shown in Figure 3 and Figure 4. The effect of hydrostatic pressure is removed from the pressure profile in Figure 4 (i.e. the pressure is normalized to sea level). There are also a 25 bar limit pressure curve and boiling limit curves for 120 °C and 50 °C water in Figure 4.

Table 1. Basic information of the modelled circuit in steady state.

Mass flow	3580	kg/s
Volume flow:		
• cold leg	3.63	m ³ /s
• hot leg	3.79	m ³ /s
Flow velocity:		
• cold leg	3.21	m/s
• hot leg	3.35	m/s
Inner diameter of the pipes	1200	mm
Hot water temperature	120	°C
Cold water temperature	54	°C
Transferred heat power	1000	MW
Power of circulation pumps:		
• cold leg	5.8	MW/pump
• hot leg	5.5	MW/pump
• total power	39.7	MW
Heat losses from the pipes	11	MW

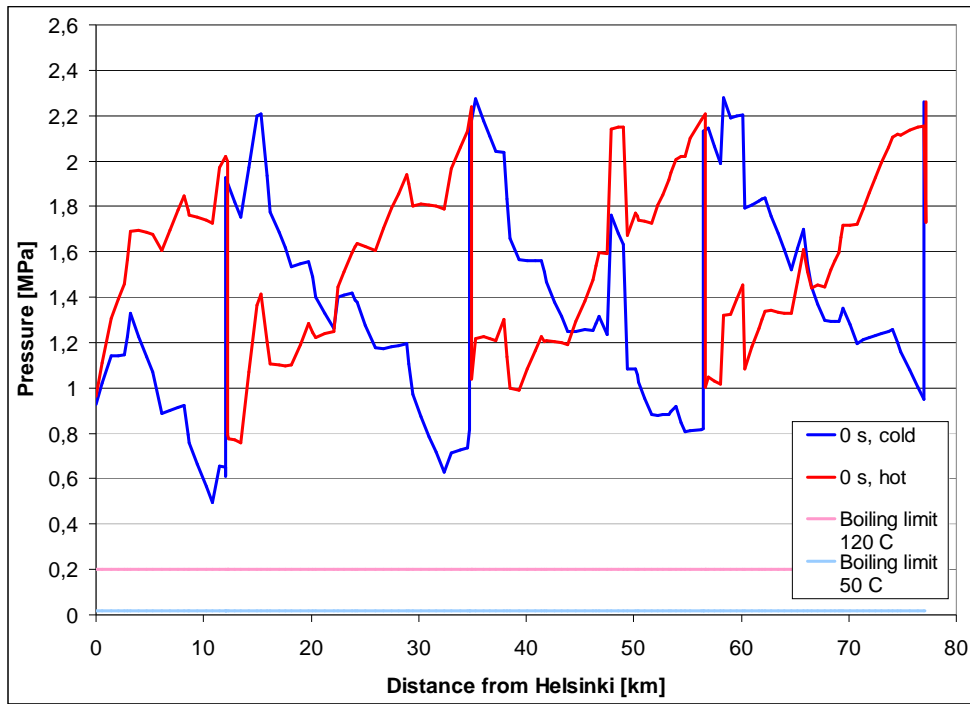


Figure 3. Simulated absolute pressure profile in the circuit in steady state. Pressure profile is determined by pipeline elevation profile, pressure losses and pressure increase by pumps.

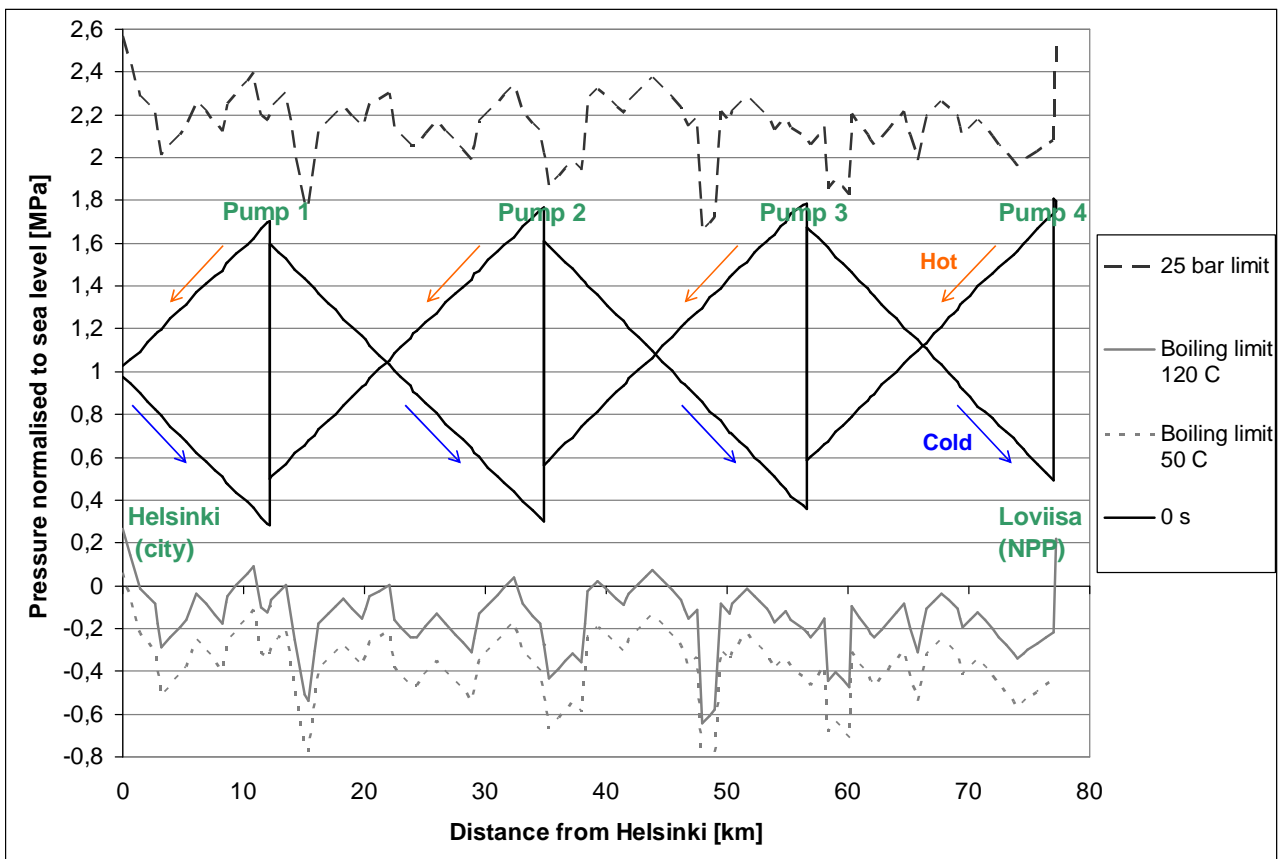


Figure 4. Simulated pressure profile in steady state. Hydrostatic pressure is removed from the profile. There are also pump stations' locations and pressure limits shown in the picture.

Pump trips and leaks are possible safety risks in this kind of a circuit. Therefore we studied various cases of both pump trips and leaks. They included tripping of a single pump, tripping of a pump pair and

tripping of all the pumps simultaneously. The emphasis was on investigating the behavior of pressure balancing check valves during transient conditions. The simulations included different sizes of leaks from the pipeline into the tunnel. The sectioning of the pipeline in order to isolate the leak point from the rest of the circuit was simulated.

Pump trips can cause high pressure in the circuit that can damage the system. They can also cause pressures so low that vigorous boiling occurs inside the pipeline. Leaks from the pipeline into the tunnel cause the pressure to drop in the pipeline. Obviously conditions in the tunnel can get very severe when over 100 °C water leaks into atmospheric pressure.

Time step of the simulation was set short enough in order to simulate pressure wave propagation in the circuit with good precision. 10 ms time step was used for the simulations shown in this paper.

5 RESULTS

5.1 Pump trips

Tripping of a single pump causes a pressure wave to propagate in the pipeline. Simulated behaviour during the first 10 s after a pump trip can be seen in Figure 5. It is obvious of Figure 5 that tripping of one pump can cause very high pressure in the circuit if mitigating measures are not appropriately designed. It can also cause the pressure to drop down to boiling limit in the hot or the cold pipeline. Pressure balancing check valves were not included in simulation in Figure 5. However, even if the pressure balancing check valves are in operation, tripping of a single pump can cause similar risks. Pressure profile 120 s after a single pump trip with pressure balancing check valves can be seen in Figure 6. Absolute pressure as high as 31 bars is reached.

The pumps in the model are arranged as pairs. Tripping of a pump pair can have worse consequences than tripping of a single pump. However, the consequences depend strongly on whether there are pressure balancing check valves in the circuit or not. Pressure profile 120 s after pump pair trip without pressure balancing check valves is shown in Figure 7 and with pressure balancing check valves in Figure 8. The importance of pressure balancing check valves for the safety of the system is obvious from these pictures. The valves let flow through and level out the big pressure difference between the hot and the cold pipeline. Actually, the tripping of a pump pair is a considerably safer transient than tripping of a single pump as long as there are pressure balancing lines between the pipelines.

Since the consequences of a single pump trip are worse than a pump pair trip, the tripping of only one pump should be prevented. Pump system should be designed so that a pair of pumps always operates at a common rotation speed. If despite of this a single pump would trip, the consequences of a single pump trip could be avoided by stopping the other pump of the pump pair soon after the trip. Simulations showed that the results were similar to a pump pair trip when the other pump of a pump pair was stopped for example 5 s after the tripping of one pump.

Operating of the heat transport system with one pump pair out of operation and pressure balancing lines open is not reasonable because of mixing of hot and cold water. Closing of pressure balancing lines increases pressure difference between the hot and cold pipeline. Therefore, if the pressure balancing valves are closed after a pump pair has tripped, the rotation speed of the pumps that are still in operation should be decreased. In this way the system can be operated safely with reduced power when one pump station is out of operation.

Simultaneous tripping of all the pumps does not cause any high or low pressure peaks. The system stabilizes in a couple of minutes and no direct safety risk is caused for the heat transport circuit. Tripping of all the pumps stops the heat transport in the circuit immediately. In that case the hot water reservoir of accumulator can still be used for district heating. If the pumps are operating normally but heat transfer from the NPP stops, there is additional 87 000 m³ hot water reservoir in the pipeline.

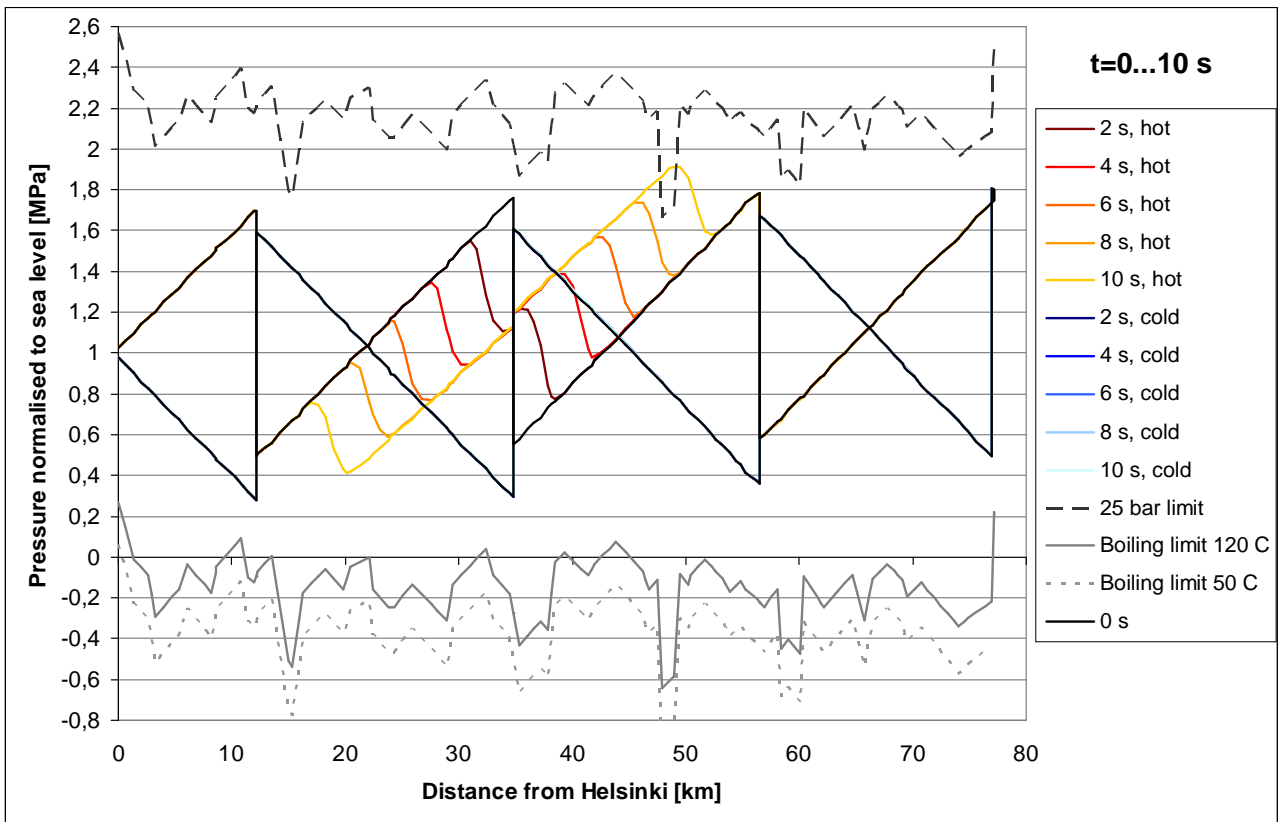


Figure 5. Pressure profile development during the first 10 s after tripping of a single pump in the hot leg of the circuit. The tripped pump is the second pump from the city end of the circuit. Pressure profile is plotted with intervals of 2 s. Pressure balancing lines are not in operation in this simulation. Pressure in some parts of the hot leg increases to about 27 bars in approximately 9 s.

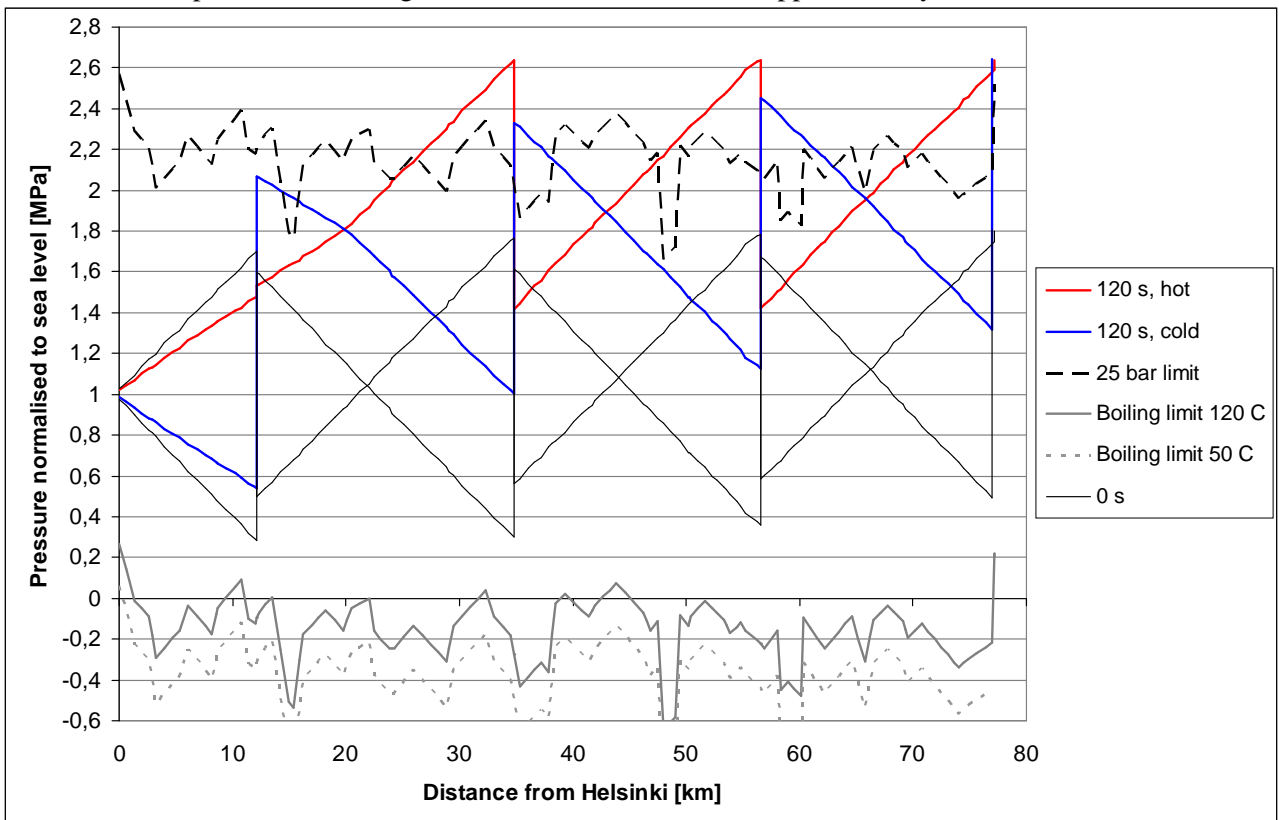


Figure 6. Pressure profile 120 s after tripping of a single pump in the hot leg of the circuit. The tripped pump is the first pump from the city end of the circuit. Pressure balancing lines are in operation in this simulation. Absolute pressure reaches value as high as 31 bars.

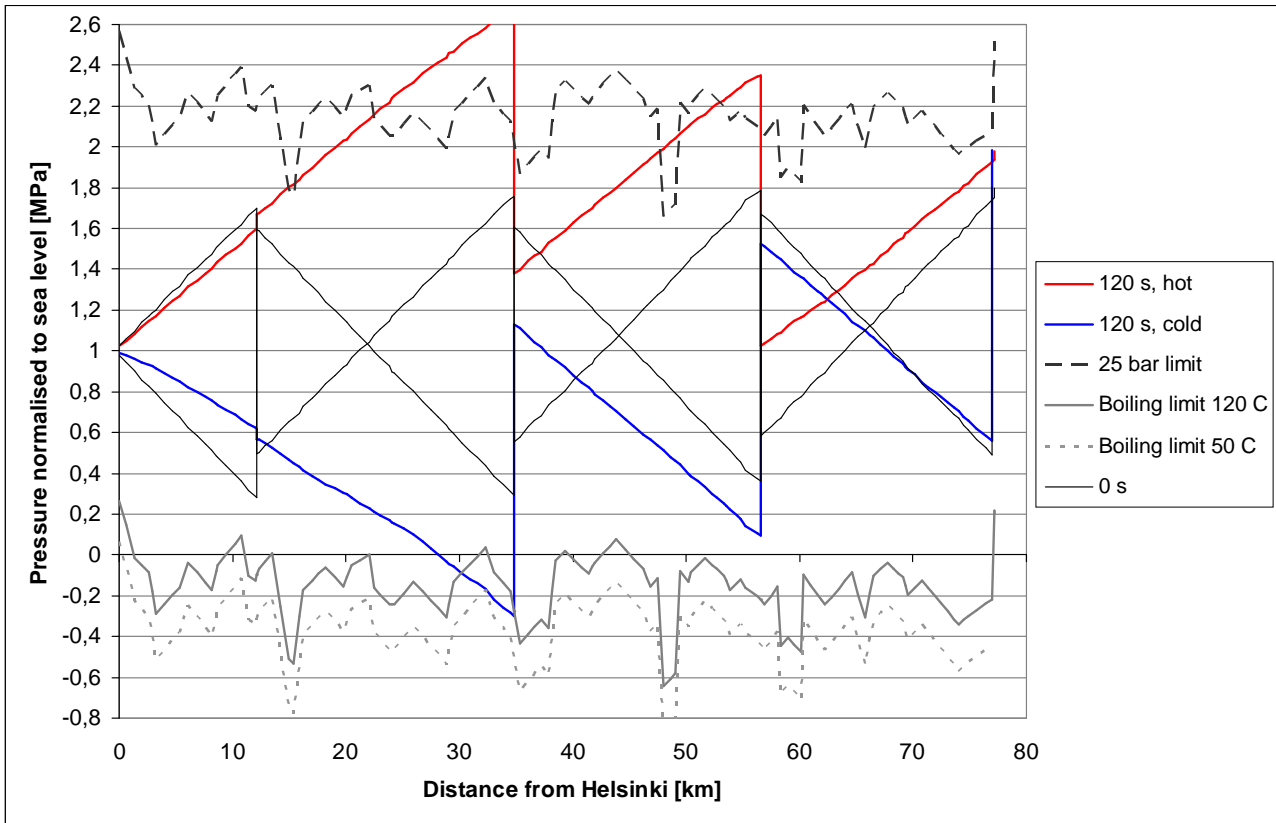


Figure 7. Pressure profile 120 s after tripping of the first pump pair from the city end of the circuit. Pressure balancing lines are not in operation in this simulation. Absolute pressure increases above 31 bars in the hot leg and decreases down to the boiling limit in the cold leg.

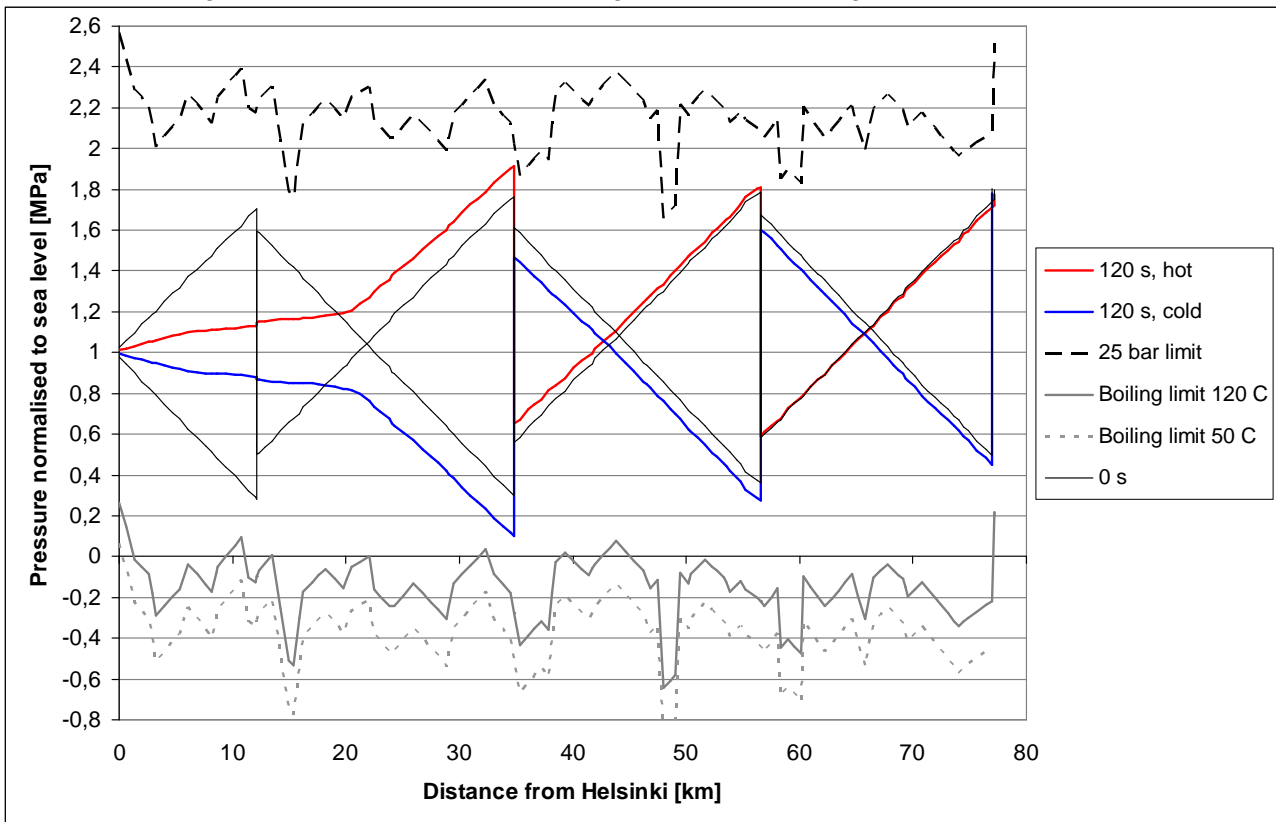


Figure 8. Pressure profile 120 s after tripping of the first pump pair from the city end of the circuit. Pressure balancing lines are in operation in this simulation. Pressure balancing check valves let flow through levelling down the pressure difference between the hot and the cold leg significantly. Pressure behaviour is much safer than without pressure balancing lines (see Figure 7).

5.2 Leaks

Leaks from the pipeline into the modelled 2 km section of tunnel were simulated and the consequences in both the pipeline and tunnel were investigated. Pressure behaviour in the pipeline with a leak of a size of 1 % of the flow area of the pipe is shown in Figure 9. Pressure falls immediately in the leak point inside the pipeline which causes a pressure wave to propagate in the circuit. Eventually the pressure in the whole circuit has dropped and remains below the original value.

The effects of leaks of size 10 % or 100 % of the flow area of the pipeline are much stronger than those of a 1 % leak. In these bigger leaks the pressure inside the pipeline falls immediately down to the boiling limit. Pressure profile in the pipeline after a 100 % leak is shown in Figure 10. The circulation pumps in the circuit were stopped 10 s after the beginning of the leak in the simulation because the pressure drop is so drastic that it is not reasonable to keep the pumps in operation. The falling pressure causes vigorous boiling in the pipeline. This makes the pressure behaviour inside the pipeline complicated and rapidly varying. The leaks have also serious consequences inside the tunnel. The effects of leaks inside the tunnel were also investigated but those results are not presented in this paper. For the conditions inside the tunnel it is crucial whether the leaking water is above or below 100 °C. However, in the pipeline even water with temperature below 100 °C can boil if there is a leak. This is mainly due to the elevation profile of the pipeline. Pressure near the leak falls close to the atmospheric pressure but the pressure can fall considerably lower in other parts of the circuit.

Limiting a leak by closing the sectioning valves in the model was also simulated. Sectioning valves were modelled in the circuit at intervals of about 2 km. Simulations showed that all the sectioning valves in the circuit should be closed instead of only the valves next to the leak to ensure safe pressure behaviour in the circuit. Closing the valves does not stop the leak immediately – there is about 2260 m³ of water in a 2 km section of pipeline. The smaller the leak the longer the leak goes on even after the sectioning valves are closed. The leak mass flows for 1 %, 10 % and 100 % leaks are shown in Figure 11 for cases where sectioning valves with 600 s driving time are closed 20 s after the beginning of a leak.

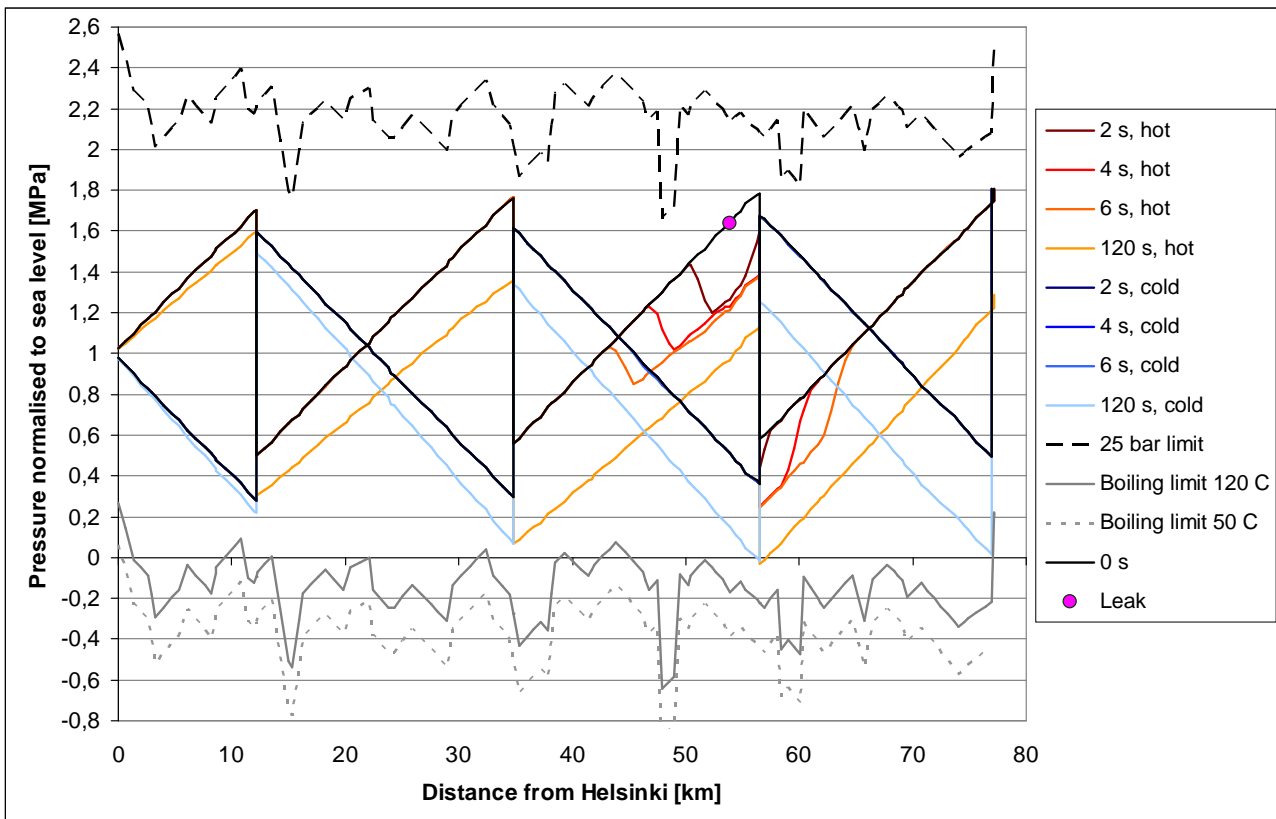


Figure 9. Pressure profile development during the first 6 s and pressure profile 120 s after the beginning of a leak of size 1% of the flow area of the pipeline. Pressure falls in the leak point immediately and after 120 s the pressure in the whole circuit has settled down to a lower level.

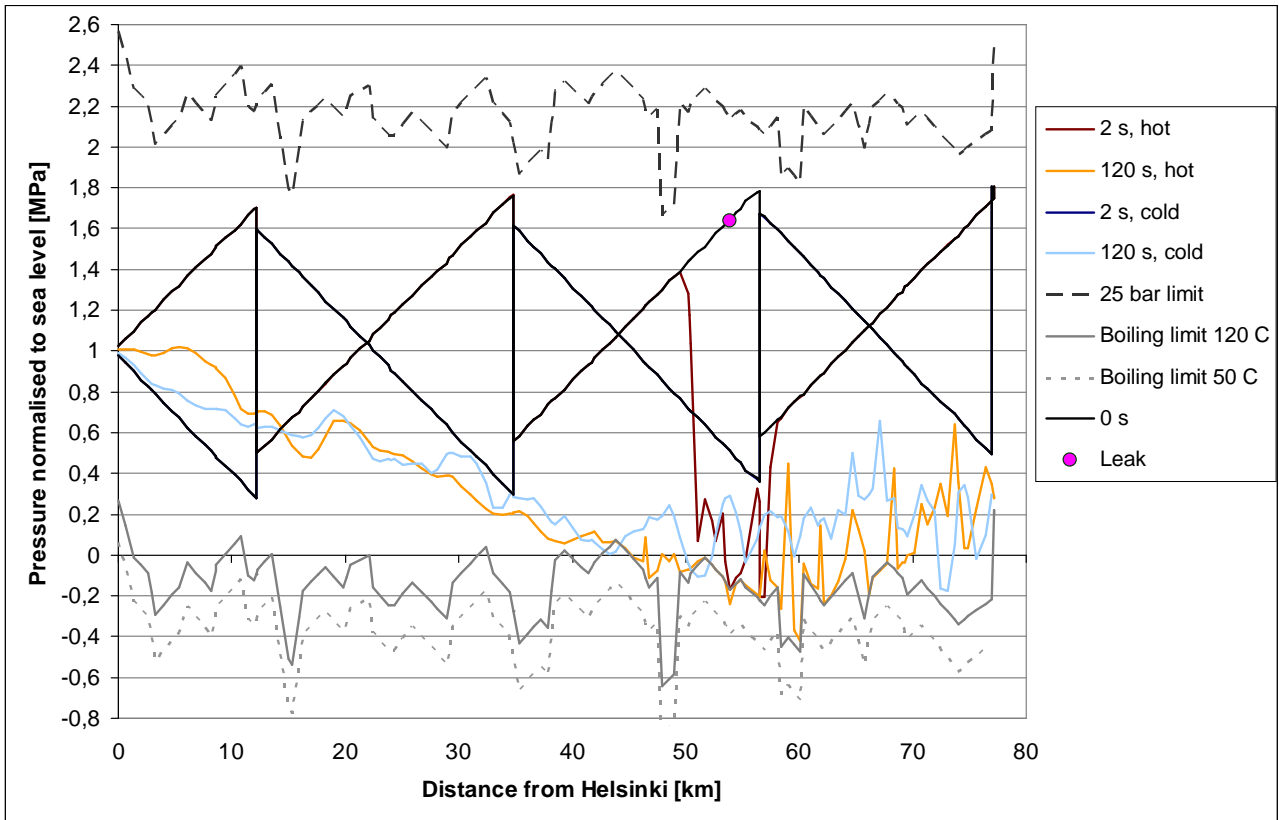


Figure 10. Pressure profile 2 s and 120 s after the beginning of a leak of size 100 % of the flow area of the pipeline. Pressure falls in the vicinity of the leak point immediately down to boiling limit.

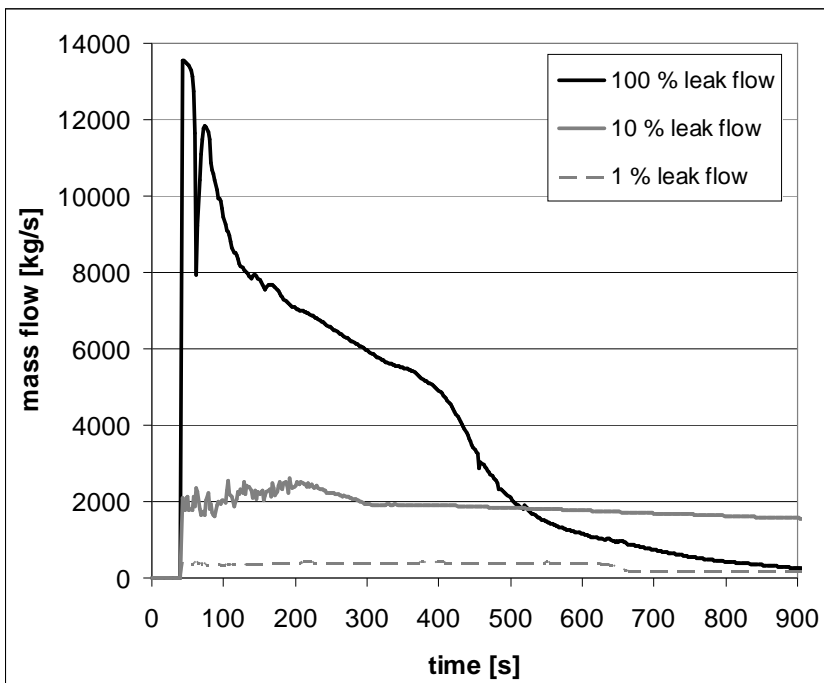


Figure 11. 1 %, 10 % and 100 % leak mass flows the circuit into the tunnel. The closing of sectioning valves begins 20 s after the beginning of leak. It takes 600 s to fully close the valves.

6 CONCLUSION

A computer model was developed and various transient simulations run and analyzed for a long-distance 1000 MW heat transport system. The aim of these investigations was to study the technical feasibility and safety of such a large-scale system for the purposes of preliminary planning. Both pump trips and leaks can cause challenging transients in the system. There are, however, ways to prevent or limit the consequences with proper safety systems. Pressure balancing check valves between the hot and cold leg level out pressure differences between the pipelines under transients. Single pump trips should be prevented so that two pumps are always tripped instead of one. Leaks can be limited by sectioning valves and the valves should be closed in all the circuit to ensure safe pressure behaviour.

The developed model can be expanded to study a more detailed system. It can also be attached to an APROS NPP model to study the behaviour of a whole CHP plant.

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