NUCLEAR COMBINED HEAT AND POWER - ANALYSES OF HOT WATER PIPELINE BREAKS IN A SERVICE TUNNEL WITH APROS SIMULATION SOFTWARE

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ABSTRACT

This paper presents a computer model and simulation results for a long-distance heat transport system. The system can be used e.g. to transport heat from a nuclear power plant with combined heat and power (CHP) production. CHP production is considered for new build NPP projects in Finland.

Emphasis is on the environmental conditions during a hot water pipeline break in a service tunnel. The modelled pipeline system is designed to transport 1000 MW of heat over a distance of 77 km for district heating purposes. The hot water pipeline is assumed to be 1200 mm diameter with a water temperature of 120 °C. Cooled water returns with a temperature of 55 - 60 °C in a similar 1200 mm diameter pipe. Both pipelines are installed to a service tunnel which is excavated into bedrock and divided into 2 kilometres long compartments.

Both the 77 km long pipeline and the tunnel are modelled with Apros simulation software. A leak is modelled from the pipeline to the tunnel and the results are analyzed. This paper includes three different leak sizes (1 %, 10 % and 100 % of the pipeline's cross-sectional area). The leaks are calculated with water temperatures of 95 °C and 120 °C in the pipeline. Apros calculates dynamically the phenomena inside the pipeline with two-phase 6-equation calculation model. The tunnel conditions are calculated with a lumped parameter model.

The size of the leak has a substantial effect on the leak’s consequences in the tunnel. Also the water temperature in the pipeline influences the results strongly. If the water temperature is over 100 °C, a considerable amount of the water boils as it leaks to the tunnel. The boiling of water makes the conditions in the tunnel much more severe than they would otherwise be. If there is a substantial flow out of the tunnel, the air in the tunnel can be replaced by hot steam. Obviously, this can mean hazardous conditions in the tunnel.

1. 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. 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 [1,2]. This would require transporting of heat over a distance of approximately 77 km. To our knowledge, the longest existing delivery distance so far for nuclear district heating is 24 km in Slovakia [3].

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.

The diameter of the pipeline was chosen to be 1200 mm. A large enough diameter is required to restrict the flow velocity and pressure losses. It is essential to make sure that this pipeline works reliably for the designed lifetime of 60 years. Mechanical failure is one example of failure mechanisms that may result in a pipeline break. These mechanical failures can be, however, avoided with high certainty if appropriate maintenance and inspection measures are taken. This paper studies the conditions inside the service tunnel in this highly unlikely pipeline break.

In our case, the 77 km long pipeline is assumed to be located in an excavated tunnel in the solid bedrock. The tunnel guarantees a reliable physical protection for the pipeline. Operations and maintenance works can be easily done in the tunnel, as it is large enough for a service vehicle. Tunnel solution also minimizes the harms to the landscape and the environment.

The environmental conditions inside the service tunnel are important to know in order to guarantee the safety at work for the service crew working inside the tunnel. Detailed study of the environmental conditions can be used to reveal possible risks and can be used e.g. to create evacuation plans for the service crew.

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.

2. Calculation model

2.1 Apros simulation software

Heat transport system is modelled with Apros (Advanced Process Simulation Environment) simulation software. The pipeline model includes pipeline, pumps, valves, heat accumulator, tunnel and some automation. The pipeline model is presented in detail in reference [4].

The same Apros calculation model included the pipeline with six-equation calculation for the water and steam as well as the tunnel modelled with lumped parameter calculation. The principle of the modelled pipeline circuit is seen in Figure 1. One dimensional 6-equation model is used for the water and steam in the circuit.

2.2 The pipeline

The pipeline is modelled to both directions in the circuit (i.e. hot and cold leg). Pressure losses and heat losses in the pipeline are included in the solution. 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 follows a realistic elevation profile scenario of 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 cold leg. All the pumps are identical and operated at the same rotation speed. This gives a symmetric pressure head in the pipeline.

There are also sectioning valves included in the modelled pipeline at 2 km intervals. 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 operates in atmospheric pressure and is 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 chosen to be 50 000 m^3.

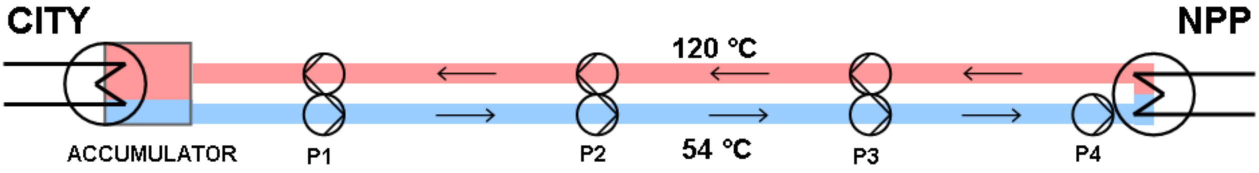

Fig 1. A greatly simplified representation of the heat transport circuit. There are two 77 km long pipelines and 7 pumps arranged in 4 pump stations in the model.

2.3 The tunnel

A 2 km section of the 77 km long underground tunnel is modelled. This section is separated from the rest of the tunnel by fire doors. The cross-sectional area of the tunnel is 30 m^2. The elevation of the tunnel floor is 42-62 metres below sea level. The tunnel has a slope of 2 %. Each end of the 2 km long tunnel section includes a 2 m^2 ventilation shaft which is connected to the environment and remains open at all times. The nodal structure of the modelled tunnel section is shown in Figure 2.

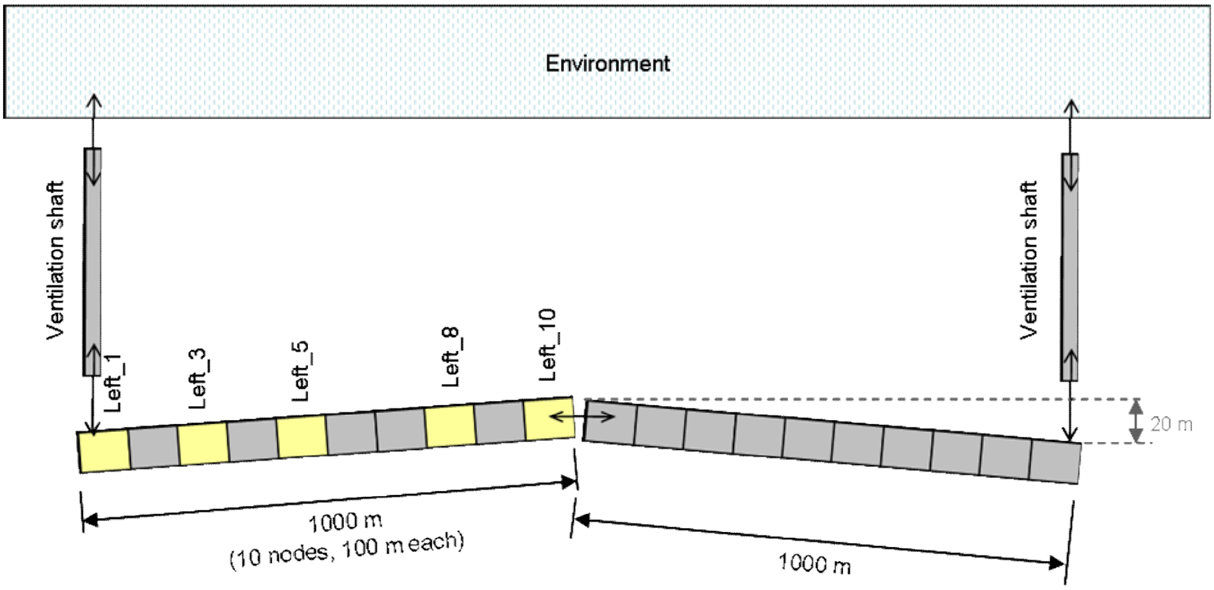

Fig 2. The principle of the tunnel section. The tunnel consists of 20 calculation nodes each 100 m long.

The tunnel is divided into 20 nodes each 100 meters long. Nodes are connected with gas and water branches and also heat structures. The principle and the geometry of a single node can be seen in Figure 3. The ventilation shafts are modelled with one calculation node each.

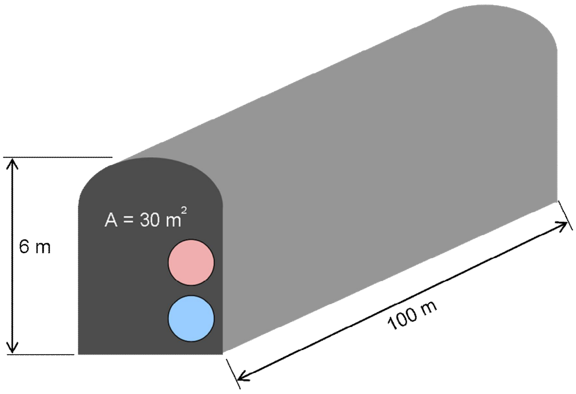

Figure 3. The principle of one node in the tunnel.

Walls, floors and roofs are modelled with 2 m thick heat structures. 90 % of the heat structures are plain rock and the rest 10 % have 0.2 m shotcreted concrete on top of a 1.8 m thick layer of rock. Initial conditions in the tunnel are: temperature of the gas region and heat structures is 15 °C and relative humidity is about 60 %.

3. Simulations

Simulated properties of the heat transport system in steady state are shown in Table 1. The pressure profile in the circuit in steady state is shown in Figure 4. The effect of hydrostatic pressure is removed from the pressure profile (i.e. the pressure is normalised to sea level). There is also a 25 bar reference pressure curve and also 120 °C and 50 °C water boiling limit pressure curves in Figure 4.

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

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

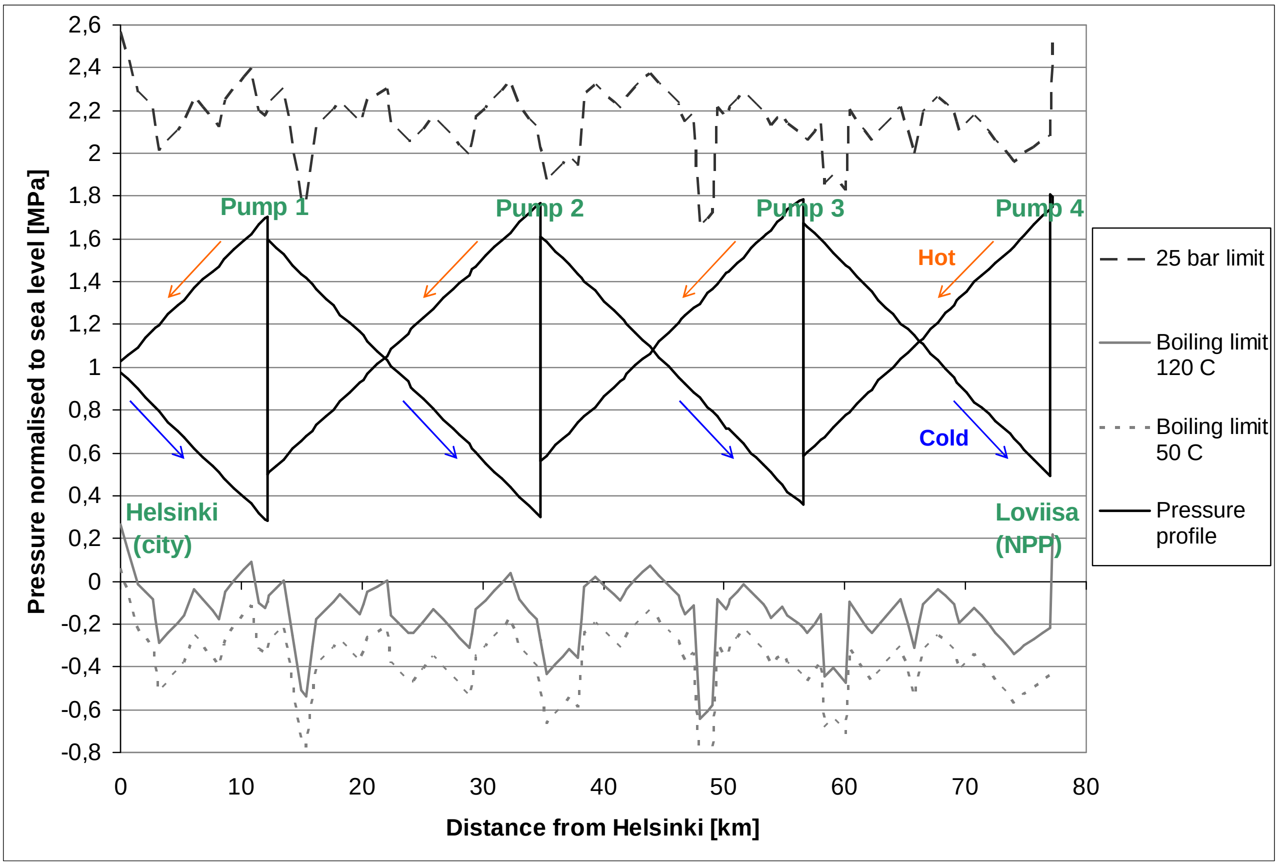

Fig 4. Simulated pressure profile in steady state. Hydrostatic pressure is removed from the profile. Pump stations' locations and pressure limits are also shown in the picture.

Three different leak sizes were simulated: 1 %, 10 % and 100 % of the pipeline's cross-sectional area. Also the temperature in the circuit was varied: 95 °C, 120 °C and 150 °C leak temperatures were studied. However, the most important aspect to consider is whether the temperature is above 100 °C or not. If the temperature is above 100 °C, much of the leaking water will boil inside the tunnel and lots of steam is formed inside the tunnel. Therefore leaks cause remarkably higher risks inside the tunnel when the temperature is above 100 °C. Detailed results in this report are shown only for 120 °C water leaks. The leak was connected to node "Left_10" as seen in Figure 2. That node is almost in the middle of the 2 km tunnel section.

The pressure inside the pipeline falls close to the leak point - the more the bigger the leak. Eventually the pressure drop extends to the whole pipeline. Since it is not feasible to operate the heat transport system after a major leak has occurred, all the pumps were stopped in the simulation 10 s after the beginning of a leak. Also all the sectioning valves in the circuit were closed gradually after the leak to limit the consequences. There were sectioning valves every 2 km in the circuit. Closing of the valves was simulated to be three-staged - slowing down towards the end of the closing - and to have a total closing time of 10 minutes. Obviously, closing of the sectioning valves does not stop the leak. In a separated 2 km section of a pipe with 1.2 m diameter there is 2260 m^3 water. Even though the leak cannot be stopped, it is important to limit it.

4. Results

The effects of a leak were strongly dependent on the leak size, as expected. The simulated leak mass flow for 1 %, 10 % and 100 % leaks is shown in Figure 5. Critical mass flow limits the flow from the pipeline into the tunnel considerably. The pressure in the tunnel increases when steam is formed. The increased pressure can cause very fast flow out of the tunnel. The flow velocities in the ventilation shaft are shown in Figure 6.

High flow velocities - up to 100 m/s and above - obviously create a safety risk in the ventilation shaft. The pressure increase and flow out of the tunnel also means that some of the air in the tunnel is replaced by hot steam. This happens especially in the vicinity of the leak. All the consequences of a leak are worse the bigger the leak is. Some simulation results are gathered in Figure 7. Gas temperature and steam volume fraction in the tunnel are shown in 5 different nodes for 1 %, 10 % and 100 % leak.

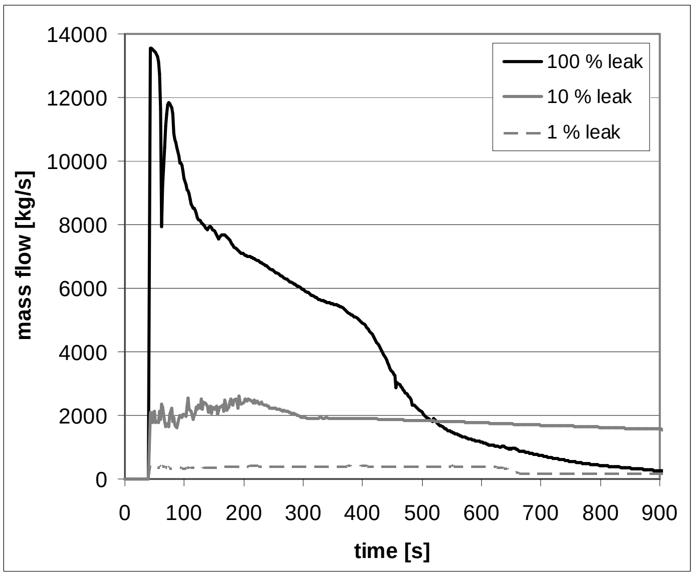

Fig 5. Simulated leak mass flow for three different leak cases (1 %, 10 % and 100 % leak).

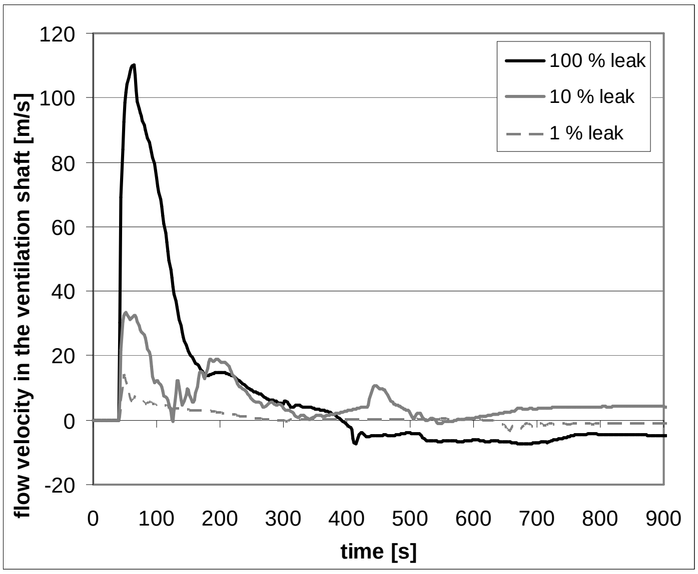

Fig 6. Simulated flow velocity in the ventilation shaft for three different leak cases (1 %, 10 % and 100 % leak). The flow area of the shaft is 2 m^2.

A leak of any size poses a risk if there are workers inside the tunnel near the leak. However, if the leak is relatively small (1 %), the severe conditions remain quite local - 200 m away from the leak the conditions remain tolerable in 10 minute time scale as can be seen in Figure 7. If the leak size is larger, the conditions in the tunnel become unbearable more rapidly and further away from the leak. If there is a full 100 % leak, the conditions can get dangerous in the entire 2 km tunnel in a few minutes. As a precaution, it would be good to minimize the time spent by the maintenance staff in the tunnel when there is over 100 °C water in the pipeline. It should be noted, though, that a major leak is a very improbable event in a well constructed, maintained and operated pipeline. Another question concerning a leak is how well the system (e.g. fire doors and pipeline support) can handle the consequences.

Water level and water temperature on the tunnel floor is shown in 5 different nodes for 10 % leak in Figure 8. The tunnel had a slope away from the leak in the simulation. Therefore, the highest water level is eventually accumulated 1 km away from the leakage in the end of the tunnel. Water temperatures remain high in the entire tunnel for a long time.

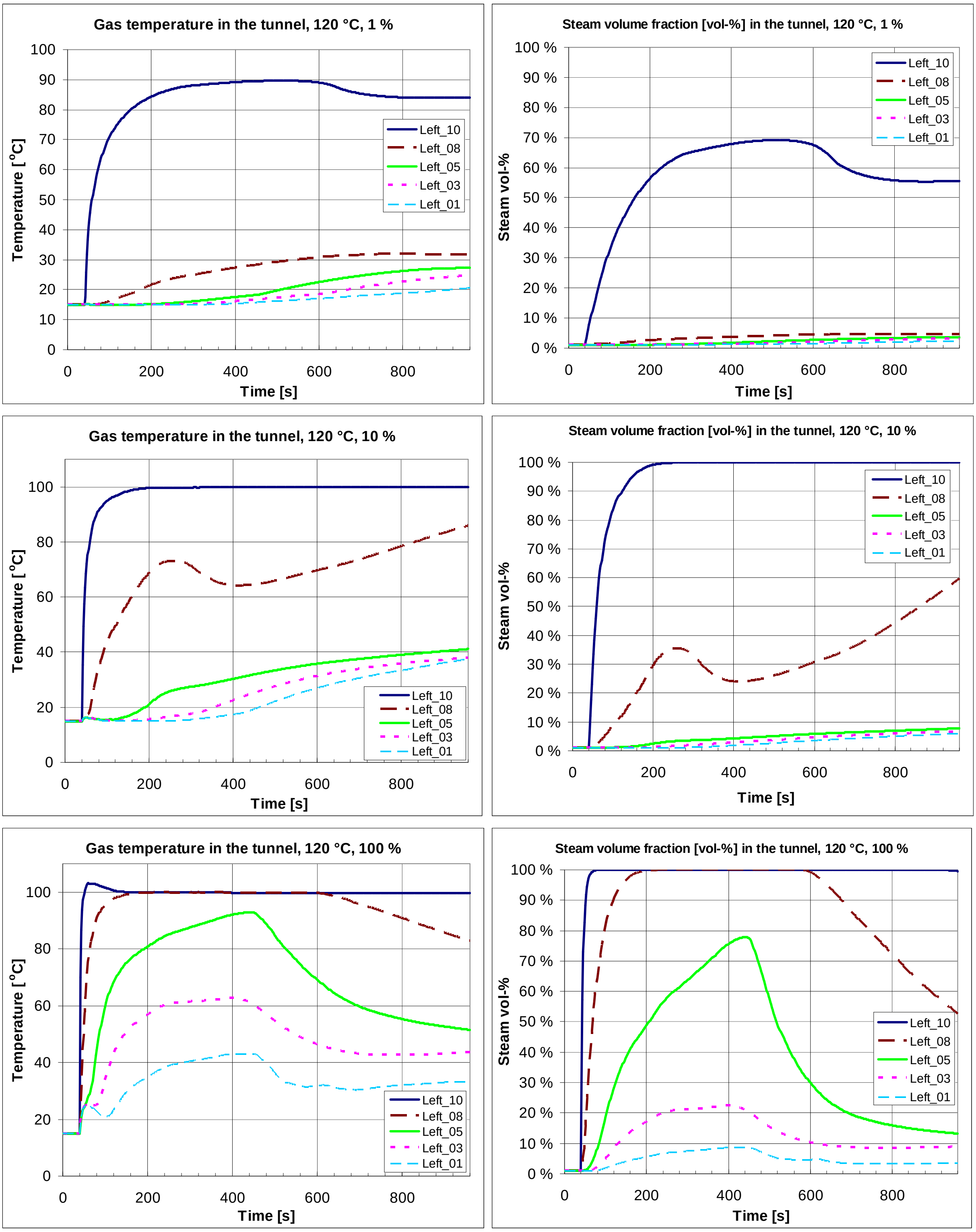

Fig 7. Gas temperature and steam volume fraction in 5 different nodes inside the tunnel for the simulation cases of 1 % (top), 10 % (middle) and 100 % (bottom) leak. The leak begins at time 60 s.

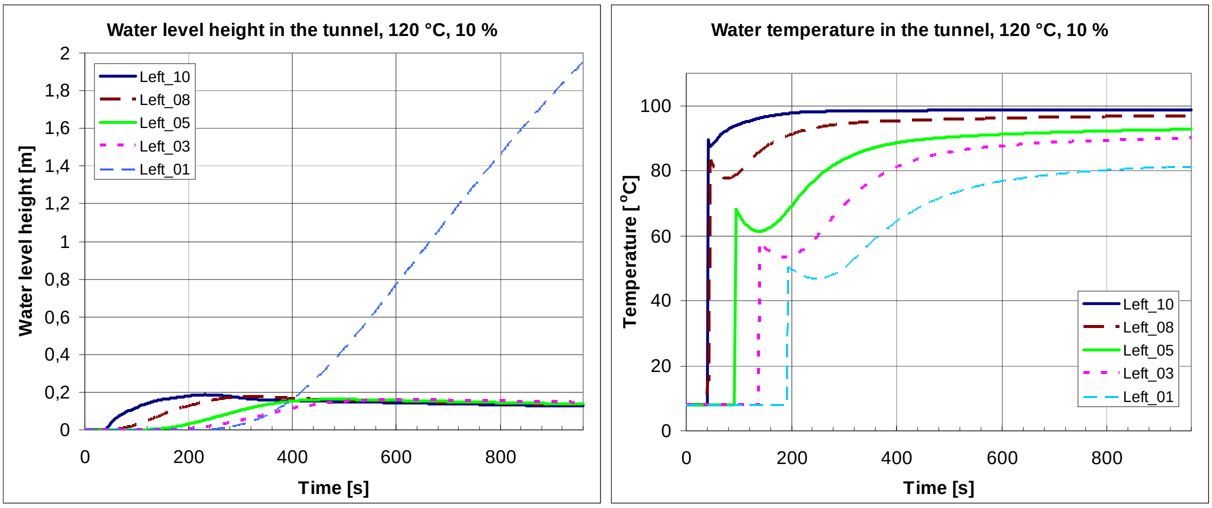

Fig 8. Water level and water temperature in 5 different nodes inside the tunnel for the simulation case of 10 % leak.

5. Conclusion

The pipeline and a 2 km section of the tunnel were successfully modelled with Apros simulation software. The whole heat transport system was modelled dynamically and various leak transients were simulated. Water having temperature over 100 °C boils when it leaks into the tunnel and can thus cause challenging transients. The bigger the leak, the faster and further away from the leak the conditions inside the tunnel become dangerous, as expected. The model can be used to study transients and improve the safety of a heat transport system. The system under investigation was a nuclear CHP heat transport system but the obtained results are also applicable to any other type of service tunnel containing hot water or steam pipeline.

6. References

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