The thermal stratification may lead an important role in the aging of the NPP piping because of the stresses caused by the temperature differences and the cyclic temperature changes. Therefore it is essential for the strength analyses to point out the affected pipes, and the thermal hydraulic parameters of the stratified flow.

For the investigation of the stratified flows the CFD codes provide an effective tool, with which the development and the breaking up of the stratification and the temperature distribution can be determined. The main difficulty of these CFD simulations is the uncertainty of the boundary conditions.

In this paper some results of CFX simulations are presented concerning the pressurizer surge line, the primary loops and the inlet of the HPIS. The results show that the thermal hydraulic analysis of certain pipes can be performed with CFD simulations, but for the determination of the boundary conditions further simulations with system codes, or measurements are required.

1. INTRODUCTION

The operational experiences from all around the world show that the material fatigue of the NPP piping caused by thermal stratified flows – together with stresses induced by other type of loads - may limit the lifetime of the pipes. Therefore thermal stratification has to be taken into account in the aging management and for the lifetime-extension of nuclear power plants. The particular importance of the problem of the thermal stratification in the Paks NPP is caused by the fact, that the significance of the phenomenon was not known at the construction of the plant (as in other plants of similar age).

The stratified flows induce thermal stresses in the piping through different manners:

- There is a “static” stress caused by the temperature differences of the upper and lower regime of the coolant in a given cross section of the pipe. The stratification causes axial and radial stresses as well, the largest stress can be experienced near to the mixed layer. These stresses may induce a new crack in the pipe wall, or the growing of an existing crack. For the strength analysis the stress-concentrating locations (welds,
elbows, etc.) have to be taken into account. According to the international operating experiences penetrating cracking usually occur at geometrical discontinuities.

- The waving of the middle mixed layer (the so-called thermal stripping) causes stresses fluctuating with high frequency. The special feature of this stress is that, because of the delay in the temperature changes caused by the inertia of the pipe wall, its maximum is on the inner pipe wall, and it decreases going outside of the pipe. Because of the delay, these rapid temperature changes cannot be monitored outside of the wall.
- The so-called “turbulent penetration” (the penetration of the coolant of higher mass flow into an other pipe with stagnating or nearly stagnating coolant) causes high-frequency stresses as well if the temperatures are different in these connecting pipes. The maximal stresses can be found at the inner pipe wall. A typical occurrence of turbulent penetration is at the connection of the surge line and the main loop.

For the determination of the effect of thermal stratification on the piping, strength analysis have to be done. As input parameter for these calculations, the maximal temperature differences along the given pipe section and the frequency of the temperature changes are needed. These parameters can be monitored with settled thermocouples, or calculated with 3D Computational Fluid Dynamics (CFD) codes. CFD provides an effective tool for this purpose with considerable lower costs than the measurements. Because of the quite simple geometry the modeling may be performed with reasonable low computational efforts. The main difficulties of the simulations are the uncertainties of the boundary conditions, because the necessary parameters are usually not (or not in detail) measured at the boundaries of the flow region. For example at the modeling of the pressurizer surge line, for the analysis the temperature and velocity of coolant is needed at the top of the surge line. In real, the velocity is not known exactly, because only the coolant level in the pressurizer is measured, and the level changes are composed of coolant transport into the surge line, and of the evaporation / condensation of the coolant within the pressurizer. For this reason, sensitivity studies have to be made to evaluate the effect of the uncertain parameters.

In this paper the first calculations of thermal stratification with the CFX code are presented for the pressurizer surge line, and for the HPIS surge line.

2. THERMAL STRATIFICATION IN THE PRIMARY CIRCUIT OF THE VVER-440

In accordance with the international operational experience, for the initiation of the authority within the frame of ageing management research activities, the VEIKI [1] has drawn up the following list of the possibly affected primary pipes:

- Primary loops,
- Pressurizer surge line,
- Pressurizer spray system,
- Surge line of the HPIS (High Pressure Injection System),
- Surge line of the hydro accumulators,
- Surge line of the LPIS (Low Pressure Injection System),
- Feedwater pipe into the steam generator,
- Auxiliary emergency feed water connection into the steam generator.
The operational experience shows that from the point of view of the thermal stratification the most important pipe could be the pressurizer surge line. Therefore, a series of measurements have been performed at the pressurizer surge line of the Unit 1 of the Paks NPP. The measurements justified the presence of a stable stratified flow in certain operating states.

3. CFX SIMULATION OF THERMAL STRATIFICATION IN THE PRESSURIZER SURGE LINE

3.1. Operation of the pressurizer surge line

The surge line connects the lower nozzle of the pressurizer to the hot leg of the loop 6 (in Units 1 and 3) or to the loop 1 (in Units 2 and 4). Under the pressurizer the surge line is divided into two legs that follow a shifted path to the main loop (see Fig. 1.). The inner diameter of the surge line is 207 mm, the length of one leg is about 14 m. The surge lines are thermally insulated.

![Figure 1.: Arrangement of the pressurizer surge line](image)

In the surge line, thermal stratification may occur when, as consequence of the operation of the pressurizer heaters, coolant with higher temperature enters the surge line from the pressurizer and flows stratified above the cooler layer toward the main loop.

In normal operation there is about 30 °C difference between the temperature of the pressurizer (325 °C) and the hot leg of the main loop (297 °C). Since the heaters do not operate continuously, there is an alternating flow with very low coolant velocities in the surge line in both directions.

During the start-up of the reactor the pressurizer heaters, from a given phase, operate almost continuously, so the temperature of the pressurizer is always much higher than the main loop
temperature, therefore there is a slow permanent flow downward from the pressurizer. The maximal temperature differences depend on the exact state of the operational indicators, but it can reach even 140-150 °C.

3.2. Temperature measurement on the surge line at the Paks NPP

To find out the possible thermal stratification in the pressurizer surge line, a temperature monitoring system was settled on the YP20 leg of the surge line of the Unit 1 of the Paks NPP in 2000 [2]. The temperature of the pipe wall was measured at ten positions between the pressurizer and the main loop (see Fig. 2.). In one measuring position there were 7 thermocouples operating, arranged vertically equidistant (see Fig. 3.).

![Fig. 2.: Planned measuring positions on the surge line (realized only on the YP20 leg) [2]](image)

![Fig. 3.: Thermocouples at one measuring position [2]](image)

The measurements show that in normal operation there is a periodic stratification in the surge line, with a cycle period of about 45 minutes (see Fig. 4.). This corresponds to the operation of the pressurizer heaters. However, the maximum of the temperature differences is 30 °C, therefore no critical fatigue occurs in normal state.

![Fig. 4.: Measured temperatures at the 1., 4. and 7. thermocouples of the 0. cross section in normal operation [2]](image)

![Fig. 5.: Measured temperatures at the 1. and 7. thermocouples of the 4. cross section during the start-up of the unit [2]](image)
The monitoring system operated from July 2000 until October 2000 including the start-up of the reactor. According to the measurements, during the heat-up period there is a thermal stratification almost all time in the surge line. The maximum of the temperature differences reaches 130-140 °C (see Fig. 5.). The stratification is very stable, particularly in the first section of the pipe.

3.3. CFX model of the pressurizer surge line

For the simulation of the stratification, the CFX model of the pressurizer surge line has been built (see Fig. 6.). The model contains:
- the T-junction at the pressurizer,
- the two legs of the surge line,
- and a small part of the main loop.

The volume mesh of the geometry contains 350 000 hexahedral volume elements, with a maximal edge length of 4 cm, and with a maximal height of 1 cm. At the pipe walls flat volume elements have been defined with a maximal height of 4 mm (see Fig. 7. and 8.).

With the surge line model a transient simulation has been performed for the investigation of the development of the stratification, assuming a laminar flow. The simulation ran for 1250 s, with a time step of 1 s. As initial condition stagnating coolant with a temperature of 140 °C has been defined in the surge line. The boundary conditions were set as follows:
- Inlet1 at the lower nozzle of the pressurizer: v=0.03 m/s, T=240 °C (in accordance with the operational indicators),
- Inlet2 at the main loop: m=1500 kg/s, T=140 °C,
- Outlet at the main loop: 0 Pa relative pressure.
3.4. Results

The results of the simulation confirm the development of a stratified flow in the surge line, but the simulation predicts a very asymmetric flow. According to the calculation there is a permanent recirculation of colder coolant in the lower layer, caused by the asymmetric arrangement of the surge line legs and the asymmetric connection of the two legs to the main loop. The recirculating coolant blocks the flow of the warmer coolant coming from the pressurizer in the lower section of one leg, it can flow only in the other leg. This result is not supported by the measurements in the Paks NPP, where only one leg has been monitored, and no sign of flow blocking was noticed. However, some measurement in the Bohunice NPP confirms the existence of this type of recirculation.

The simulation results show a very stable stratification in the first section of the surge line (in both legs). The temperature difference between the upper and lower layer is 100 °C, and this difference remains during the investigated time interval.

Figure 9.: Coolant temperature in the surge line at t=1200 s

Figure 10.: Coolant temperature in the first section of the surge line at t=400 s and t=1200 s
For the demonstration of the stratified flow, the coolant temperature has been drawn at three vertical monitor-lines during the transient. The positions of the monitor-lines are shown in Fig. 11.

The temperatures at M1 monitor-line are shown in Fig. 12. It can be seen, that the $100 \, ^\circ\text{C} \Delta T$ remains during the whole transient, but the position of the mixed layer sinks lower and lower.

At the M2 monitor-line (see Fig. 13.) there are much lower temperature differences: the maximum is about 15-20 $^\circ\text{C}$. It can be observed, that the warmer coolant from the pressurizer reaches the monitor-line at 200 s, then the temperature of all points of the monitor-line increases during the transient.

In contrast with the M2 line, the temperature of the lower point of the M3 line increases much slower, which means that a stratified flow develops in the pipe section (see Fig. 14.). The maximal temperature differences are about 20-25 $^\circ\text{C}$.

Figure 11.: Position of the monitor-lines

Figure 12.: Coolant temperature at the monitor-line M1 during the transient
Figure 13.: Coolant temperature at the monitor-line M2 during the transient

Figure 14.: Coolant temperature at the monitor-line M3 during the transient
4. CFX SIMULATION OF THERMAL STRATIFICATION IN THE SURGE LINE OF HPIS (HIGH PRESSURE INJECTION SYSTEM)

The surge line of the High Pressure Injection System is connected to the cold leg of the loops 2., 3. and 5. The surge line runs from the HPIS pump to the box wall on one path, then it is divided into two legs, that are closed with pneumatic quick-stop valves. Inside the box wall there are inner quick-stop valves, then the pipe legs join together again, and connects after a check valve to the main loop (see Fig. 15.). The surge line is thermally insulated between the main loop and the check valve, afterwards it is not insulated.

From the viewpoint of thermal stratification the first two section of the surge line (main loop – check valve, and check valve – quick-stop valves) has been investigated separately with the CFX code, because it is assumed that the quick-stop valves do not leak. In these sections thermal stratification may develop in two ways:

- Due to heat losses through the (insulated) pipe wall, or
- Because of the leakage of the check valve.

4.1. CFX model of the surge line between the main loop and the check valve (Section “A”, see Fig. 15)

The thermal stratification evolved by the heat losses through the pipe wall has been investigated. For the determination of heat losses additional calculations have been performed. The heat transfer through the pipe wall has been calculated analytically. Assuming no insulation the heat transfer coefficient was calculated to be $\alpha = 4.496 \text{ W/m}^2 \text{ K}$, what means 1200 W/m² heat flux on the pipe wall. Assuming 50 mm thick asbestos insulation $\alpha = 3.925 \text{ W/m}^2 \text{ K}$, what means about 10% difference.
A more difficult question is the determination of the heat losses on the body of the check valve. The valve is assumed to be uninsulated. There is heat transfer through the valve body into the box atmosphere and through the valve disk into the coolant of the (closed) surge line. For the calculation of the heat losses the CFX model of the valve has been built, because the geometry is too sophisticated for the analytical analysis (Section B, see Fig. 15.). The geometry and the CFX model of the valve can be seen in Figure 16. The CFX model, made with geometrical simplifications contained 173 000 tetrahedral volume elements.

![Figure 16.: Geometry and CFX model of the check valve](image1)

The flow regions of the model are shown in Fig. 17. The initial conditions were set as follows:

- Coolant of primary circuit: water with a temperature of 267 °C. At the boundary of the model so-called “Opening” boundary has been set with a relative pressure of 0 Pa, that allows flow in both direction.
- Coolant of the surge line: water with 50 °C temperature. At the boundary of the model “Opening” boundary has been set with a relative pressure of 0 Pa.
- Atmosphere of the box: air with a temperature of 50 °C. At the walls of the box “Opening” boundary has been set with a relative pressure of 0 Pa.
- The body of the check valve was defined as steel, with a conduction coefficient of $\lambda=14.6$ W/mK

![Figure 17.: Flow regions of the CFX model of the check valve](image2)
According to the calculation buoyancy driven flow develops in the pipe of the surge line at the check valve disk (see Fig. 18.): at the primary side the coolant cool down and flows downward at the valve disk, while at the closed side the coolant warms up, and flows upward. The temperature changes are, however, very low (3-4 °C, see Fig. 19.). Near to the valve there is a natural circulation in the box air as well. The results give an average heat flux of 5000 W/m² through the valve disk (see Fig. 20.). This value was used for the further calculations.

Figure 18.: Coolant velocity in and around the check valve

Figure 19.: Calculated temperatures in and around the valve

Figure 20.: Heat flux at the inner surface of the check valve
The presented simulation has been used as a boundary condition for the simulation of the first ("A") section of the HPIS surge line, without any leakage of the valve. Therefore, the CFX model of the pipe section has been built, that consisted of the surge line up to the check valve (without exact modeling of the valve) and a small part of the main loop (see Fig. 21.). The volume mesh of the model contained 157 000 tetrahedral volume elements.

With the model transient simulation has been run with the following boundary conditions:
- Inlet: 1500 kg/s mass flow at the main loop (according to the normal operation) with a temperature of 267 °C
- Outlet: 0 Pa relative pressure at the other end of the main loop section.
- 1200 W/m² heat flux at the wall of the surge line (according to the analytical calculations)
- 5000 W/m² heat flux at the closed end of the surge line (according to the CFX simulation of the check valve).

The simulation ran for 180 s with a time step of 1 s, assuming laminar flow.

Figure 21.: CFX model and meshing of the first section of the HPIS surge line

Figure 22.: Coolant temperature in the surge line during the transient
The results show, that – assuming no leakage at the check valve – there is no stratified flow evolved in the first section of the HPIS surge line. The reason is that the maximal temperature differences are only 4-5 °C (see Fig. 22.). The coolant cools down best at the valve disk, but this is not enough for the formation of stratification, the colder coolant flows in large eddies and mixes with the warmer water in the surge line.

4.2. CFX model of the surge line between the main check valve and the quick-stop valves (Section “C”, see Fig. 15.)

For the simulation of the stratified flow developing in the second section of the HPIS surge line, the CFX model of the pipe section has been built, assuming the leakage of the check valve (see Fig. 23.). It contains the surge line between the check valve and the quick-stop valves. The valves are not modeled in detail, only as a simple closed end of the pipe. The volume mesh of the model contained 174 000 hexahedral volume elements.

For the calculation the following boundary conditions were defined:
- Inlet: 1 t/h mass flow from the primary circuit with a temperature of 267 °C, that means the leakage of the check valve.
- Outlet: 0 Pa relative pressure at the quick-valves.
- Adiabatic surge line wall. (Because of convergence problems, the real heat flux in the pipe wall could not be assumed.)

The transient calculation ran for 420 s, with a time step of 1 s, assuming laminar flow in the pipe.

Figure 23.: CFX model of the second section of the HPIS surge line (the arrows show the flow of the leaked coolant from the primary circuit)

The results show the development of a thermal stratification in the surge line, but the stratified flow is not stable, at t=300 s the layers break up in the first section of the investigated pipe (see Fig. 24.). The maximal temperature difference reaches 200 °C in the first section of the pipe. The thermal striping (the waving of the mixed layer) can be observed as well.
5. SUMMARY

Former results showed that thermal stratification may develop in case of certain operational conditions in the surge line of the pressurizer and of the high pressure injection system. The occurrence of stratification is confirmed by measurement data in the Paks NPP that could be use as verification of the calculations.

This paper describes the CFX simulation performed for the simulation of the phenomenon in the concerned components. According to the calculations within the pressurizer surge line, during the startup of the reactor, a stable stratified flow develops with a maximal temperature difference of 130-140 °C. In the HPIS surge line, assuming the leakage of the check valve, the results shows that the maximal temperature difference reaches 200 °C, although the stratification is not really stable, it disappears within a few 100 seconds.

The results showed that the CFX is applicable for the demonstration of the thermal stratification, however additional sensitivity studies should be performed for more accurate analysis.

REFERENCES


[2] „Assessment of the results of the temperature monitoring system, settled on the pressurizer surge line”, Paks NPP, 2001, in Hungarian