

ANALYSIS OF THERMAL STRATIFICATION IN THE PRIMARY CIRCUIT WITH THE CFX CODE

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Abstract

The thermal stratification can 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. These stresses can limit the lifetime of the piping, or lead to penetrating cracks. For the strength analyses, the determination of the thermal hydraulic parameters of the stratified flow is necessary, which can be simulated by Computational Fluid Dynamics (CFD) codes. The results of the simulation show the time development and the breaking up of the stratification and the temperature distribution of the stratified flow. The main difficulty of these CFD simulations is the uncertainty of the boundary conditions because of the unknown flow circumstances. In this paper some results of CFX simulations are presented concerning the pressurizer surge line, and the injection pipe of the HPIS for VVER-440 type reactors.

Introduction

If two medium with different densities (i.e. with different temperatures) flows inside a pipe, thermal stratification can occur. The development and the stability of the stratified flow depend on the temperature difference and on the relative velocity between the fluids. The stratified flows induce thermal stresses in the piping through different manners. There is a “global” stress caused by the temperature differences of the upper and lower layer of the coolant, which can induce a new crack in the pipe wall, or the growing of an existing crack. The waving of the middle mixed coolant layer (the so-called thermal striping) and the so-called “turbulent penetration” cause stresses fluctuating with high frequency. The maximum value of these fluctuating stresses is on the inner pipe wall, and it decreases going outside of the pipe, because of the inertia of the pipe wall. Turbulent penetration occurs when coolant of higher mass flow penetrates into a pipe with stagnating or nearly stagnating coolant. A typical occurrence of turbulent penetration is at the connection of the pressurizer surge line and the main loop.

According to the international operating experiences, the material fatigue of the NPP piping caused by thermal stratified flows may limit the lifetime of the pipes, therefore the consideration of thermal stratification is crucial in the aging management and for the lifetime-extension of nuclear power plants. In PWRs the most affected pipes are usually the feed water lines of the steam generator, the pressurizer surge line, and the injection pipes of the emergency core cooling systems. The stratification is caused mainly by leaking valves. In the US, more than a dozen penetrating cracks have been identified since 1979, as a result of thermal stratification. Cracks due to the stratification were found in France, Belgium and Japan, as well. The Loviisa NPP in Finland reported a penetrating crack at the pressurizer surge line in 1994 as a common result of thermal stratification and material defects. The settled temperature monitoring system confirmed the existence of a stratified flow with temperature differences of 220-270 °C.

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), therefore it is not included in the design base of the plant.

For the determination of mechanical effects of the stratified flows, strength analyses have to be done, for which the thermal-hydraulic parameters of the flow (e.g. the maximal temperature differences along the given pipe section and the frequency of the temperature changes) are required as an input parameter. The thermal-hydraulic behavior of the flow can be simulated by Computational Fluid Dynamics (CFD) codes. 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 measured at the boundaries of the flow region.

In this paper, some CFD calculations are presented concerning the development of thermal stratification in VVER-440 type reactors. With the CFX code, stratified flow in the pressurizer surge line, and in the injection pipe of the HPIS of VVER-440 has been investigated.

Thermal stratification in the pressurizer surge line

The surge line of the VVER-440 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, after a short vertical section, the surge line is divided into two legs signed as YP10 and YP20 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 line is thermally insulated.

During the operation of the pressurizer heaters, the high temperature medium of the pressurizer dilates, and flows into the surge line. This warmer coolant can be stratified on the lower temperature coolant of the surge line and flows stratified above the cooler layer toward the main loop.

In normal operation, the pressurizer heaters operate periodically. The pressurizer temperature is then about 325 °C, while the coolant of the hot leg of the main loop has a temperature of about 297 °C. In the surge line, there is an alternating flow with very low coolant velocities in the surge line in both directions. The heating of the primary circuit during the start-up of the reactor is managed in part with the pressurizer heaters that mean they operate almost continuously. Therefore, the temperature of the pressurizer is always higher than the main loop temperature, so there is a slow permanent flow downward from the pressurizer during the heat-up period. The maximal temperature differences can reach even 140-150 °C.

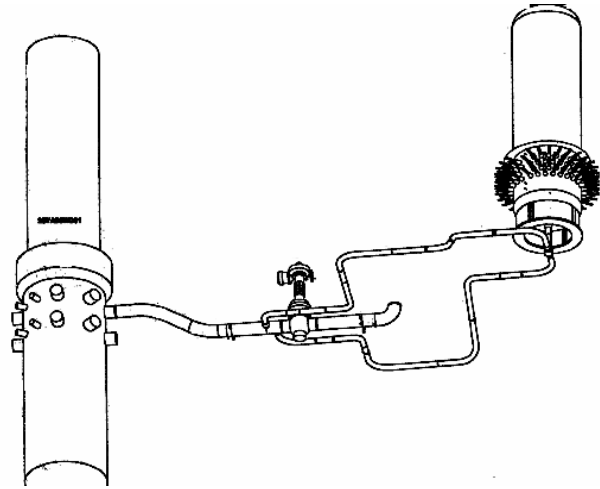


Figure 1: Arrangement of the pressurizer surge line

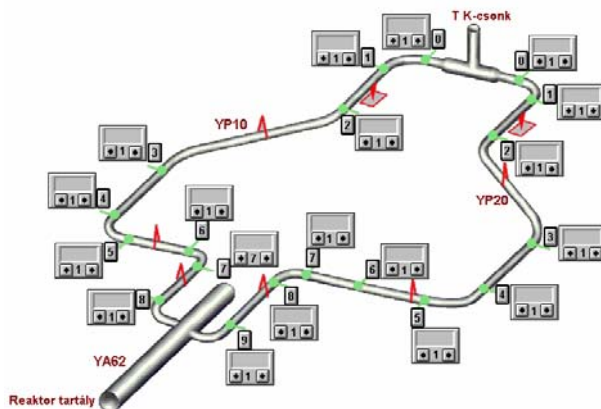


Fig. 2: Planned measuring positions on the surge line (realized only on the YP20 leg) [2]

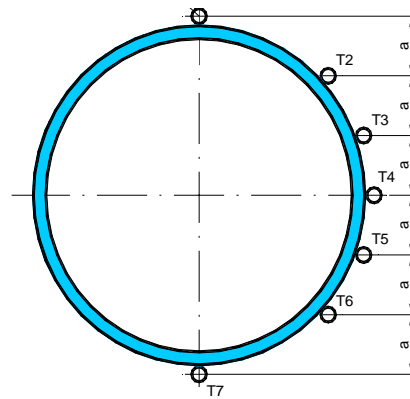


Fig. 3: Thermocouples at one measuring position [2]

Temperature monitoring system in the pressurizer surge line in the Paks NPP

In the Paks NPP, an extensive temperature measurement program was implemented in 2000 in order to find out the possible thermal stratification in the pressurizer surge line. Altogether 70 Pt resistance thermometer was settled on the YP20 leg of the surge line of the Unit 1. 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).

The monitoring system collected temperature data minutely for about three months. The operating period included the start-up of the unit, and normal operation as well. The measured temperatures – about 100 000 data per thermometer – were recorded by the unit computer.

The measurements show that in normal operation there is a periodic stratification in the surge line with a cycle period of about 45 minutes which corresponds to the operation of the pressurizer heaters. However, the maximum of the temperature differences is about 30 °C, therefore no critical fatigue occurs in normal state. On the other hand, the monitoring system confirmed the existence of a stable stratification during the heat-up period (see Fig. 4). The maximum of the temperature differences reaches 130-140 °C. The stratification is very stable, particularly in the first horizontal section of the pipe. (The monitoring system was settled only on the YP20 leg of the surge line, so the possibly asymmetric flow fields could not be proven.)

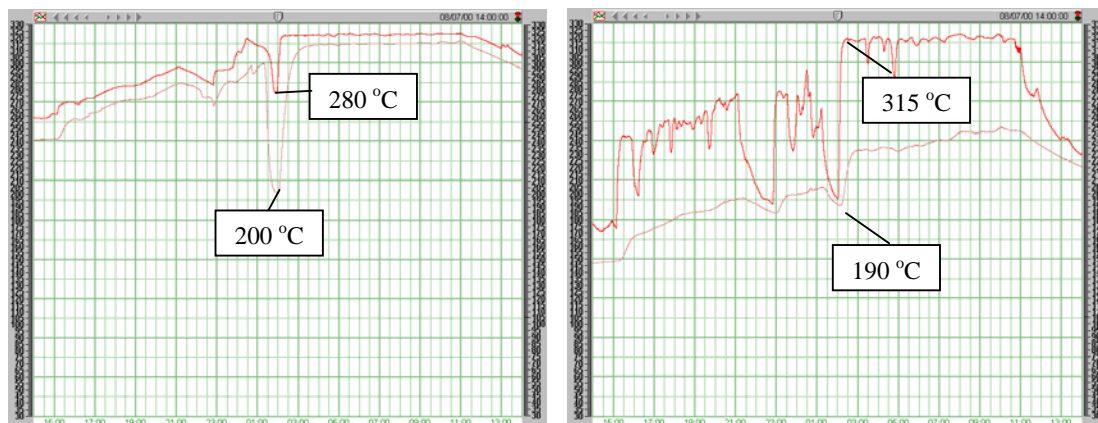


Fig. 4: Measured temperatures at the cross-sections 0 (near the vertical inlet nozzle) and 4 (lower horizontal section) for the same 24-hours period, on the top and the lowest thermometers, during the heat-up of the Unit 1

CFX simulation of thermal stratification in the surge line

The development of the thermal stratification during the start-up of the reactor has been investigated with the CFX code. For the simulation of the stratification, the CFX model of the pressurizer surge line has been built, which contained the T-junction at the pressurizer, the two legs of the surge line, and a short (1 m) section of the main loop (see Fig. 5). For the simulation, a volume mesh of 350 000 hexahedral elements was created. The maximal edge length was set to 4 cm, the maximal height to 1 cm. At the pipe walls, inflated layer has been defined with a maximal height of 4 mm (Fig. 6).

With the model of the surge line, transient CFX calculation was performed concerning the development of the stratified flow. The simulation run 1250 s, with a timestep of 1 s, assuming laminar flow. The boundary conditions were estimated based on the unit operational indicators and were set as follows: the coolant with higher temperature (240 °C) enters from the pressurizer into the surge line with a velocity of 0.03 m/s. In the main loop, coolant with lower temperature (140 °C) flows with a mass flow of 1500 kg/s. As outlet boundary condition, 0 Pa relative pressure was set at the main loop.

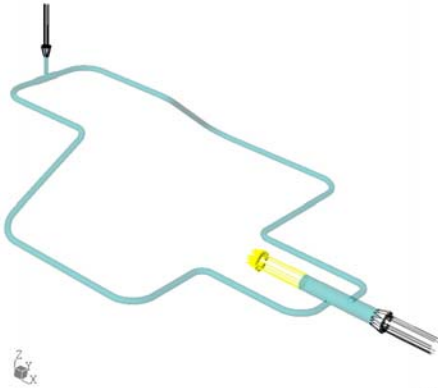


Fig. 5: CFX model of the surge line

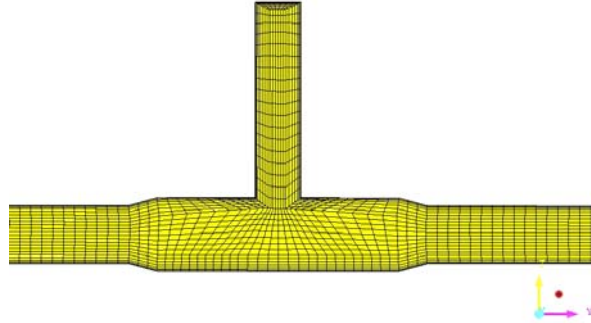


Fig. 6: Hexahedral mesh of the model

The simulation confirms the development of a stratified flow in the surge line. The stratification is very stable in the first horizontal section of the surge line, the maximal temperature difference between the upper and lower layer is about 100 °C during the whole transient. However, the results show a very asymmetric flow in the surge line that eventuates in an asymmetric stratification in the lower sections of the surge line (see Fig. 7).

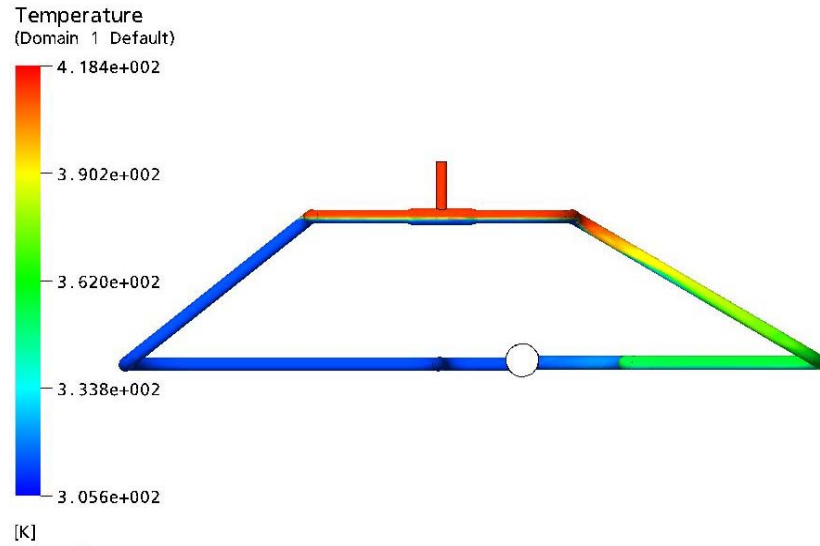


Fig. 7: Coolant temperature in the surge line at t=1200 s

The cause of this special flow field is that - 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 into the main loop. The recirculating coolant blocks the flow of the warmer coolant coming from the pressurizer in the lower section of one of the legs, therefore it can flow only in the other leg. This result is not supported by the measurements in the Paks NPP, where only one of the legs has been monitored, and no definite sign of flow blocking was noticed. The differences between the measured and calculated development of the stratification can be originated possibly from the uncertainties of the boundary conditions (mainly the inlet velocity, which is calculated from the pressurizer level). To bypass this problem an extensive parameter study should be made, which is quite time-demanding. However, some measurements in the Bohunice NPP confirm the existence of this type of recirculation.

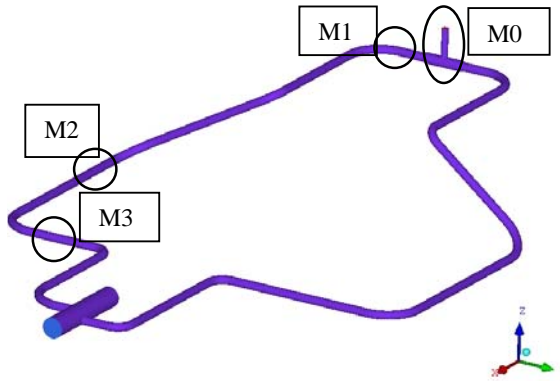


Fig. 8: Position of the monitor-lines

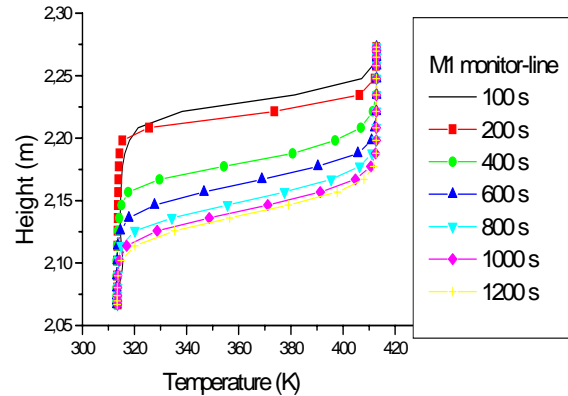


Fig. 9: Temperature at M1 during the transient

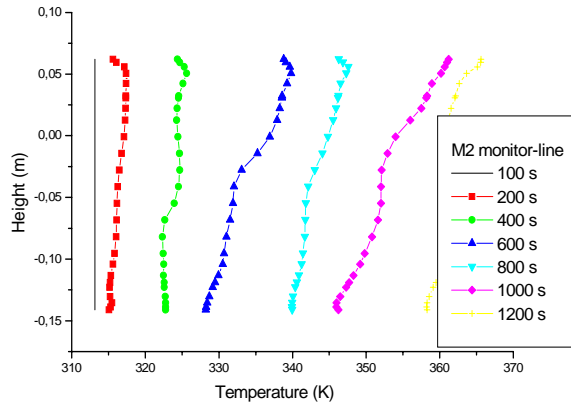


Fig. 10: Temperature at M2 during the transient

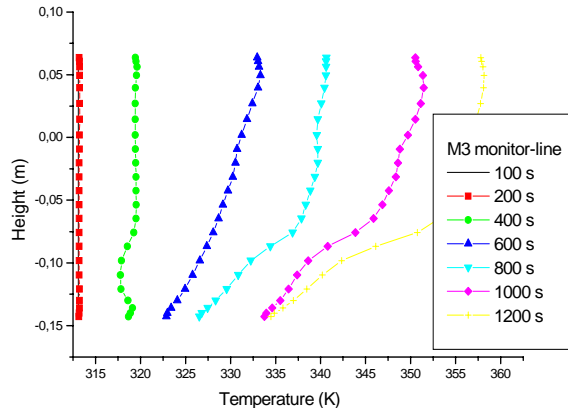


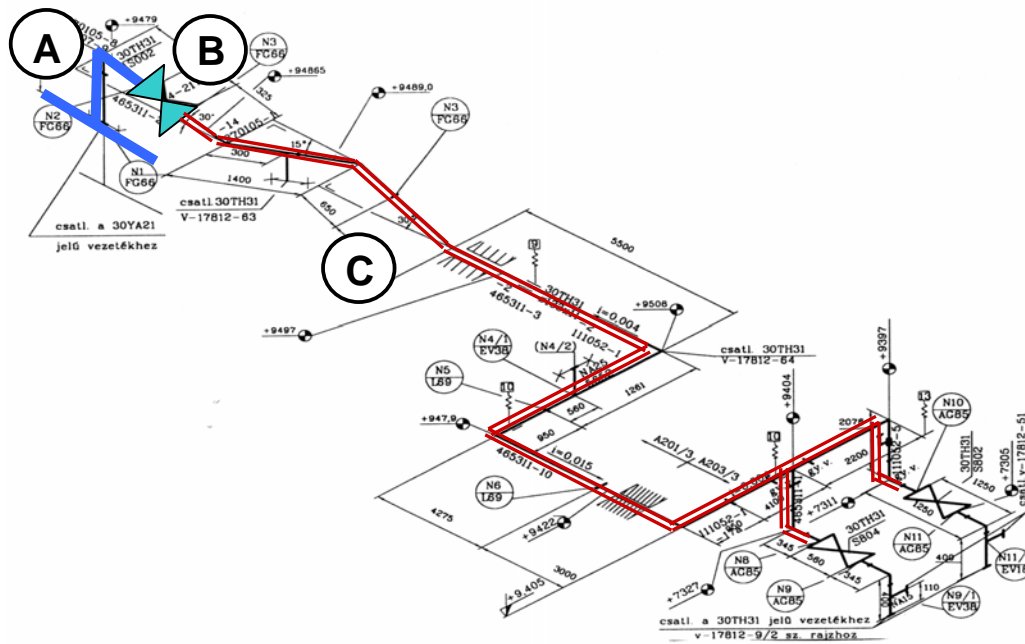
Fig. 11: Temperature at M3 during the transient

Figures 9-11 show the coolant temperature during the transient at three vertical monitor-lines (M1, M2 and M3) shown in Fig. 8.

In Fig. 9 it can be seen that the stratification with about 100 °C temperature difference remains during the whole transient, but the position of the mixed layer sinks lower in time. At the M2 monitor-line (see Fig. 10), there are much lower temperature differences: the maximum is about 15-20 °C. The warmer coolant from the pressurizer reaches the monitor-line at 200 s and then the temperature of all points of the monitor-line increases during the transient. 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. 11). The maximal temperature differences are about 20-25 °C.

Thermal stratification in the surge line of the high pressure injection system (HPIS)

According to the international operating experiences, the surge lines of the emergency cooling systems can be affected concerning the thermal stratification. 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 and 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 and after it, the pipe legs join together again (see section C in Fig. 12) and connects after a check valve (see “B” in Fig. 12) to the main loop (see section A). The surge line is thermally insulated along the section A, but after the check valve, it is not insulated.



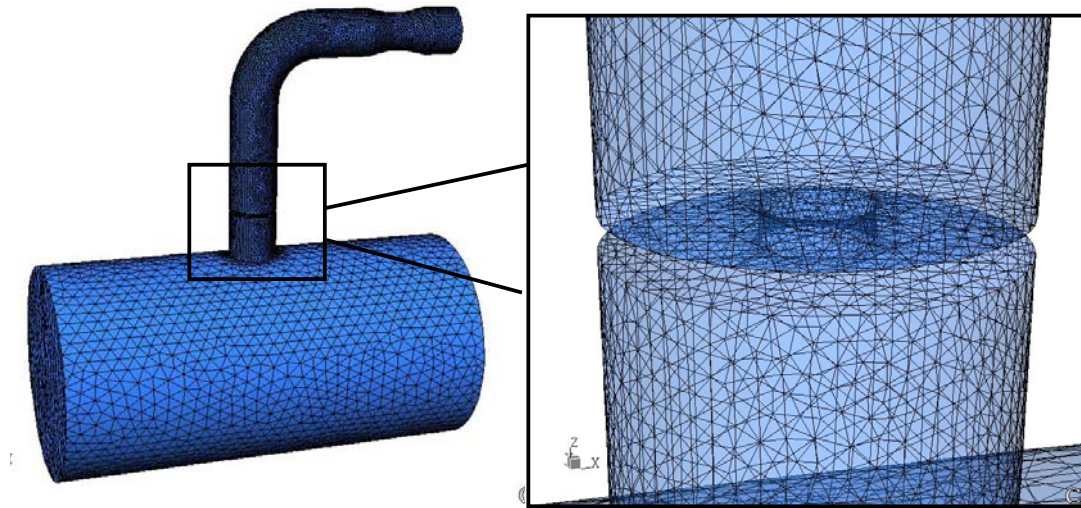


Fig. 13: CFX model and meshing of the first section of the HPIS surge line

The transient simulation performed with the model run 180 s with a time step of 1 s, with assuming laminar flow and with the following boundary conditions: 1500 kg/s mass flow in the main loop (according to the normal operation) with a temperature of 267 °C. 1200 W/m² heat flux was specified at the wall of the surge line (according to the analytical calculations, assuming no insulation conservatively), 5000 W/m² heat flux at the closed end of the surge line (according to the CFX simulation of the check valve). According to the calculation, no stratified flow evolved in the first section of the HPIS surge line because the maximal temperature differences are only 4-5 °C (see Fig. 14). The coolant cools down 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.

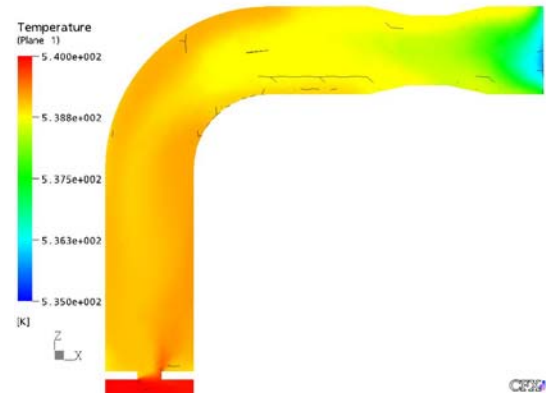


Fig. 14: Coolant temperature in the surge line at t=180 s

For the simulation of the second section of the HPIS surge line (see section “C” in Fig. 12), the CFX model of the pipe section has been built, assuming the leakage of the check valve. The model contained the surge line between the check valve and the quick-stop valves. The valves are modeled as a simple closed end of the pipe. The volume mesh of the model contained 174 000 hexahedral volume elements (see Fig. 15).

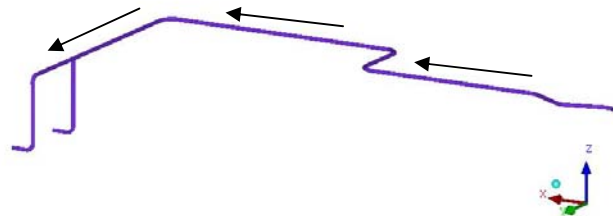


Fig. 15: CFX model of the second section of the HPIS surge line

The development of the stratification was investigated with a transient simulation which ran for 420 s, with a time step of 1 s, assuming laminar flow in the pipe. As inlet boundary condition, 1 t/h mass flow from the primary circuit with a temperature of 267 °C, as outlet boundary condition, 0 Pa relative pressure at the quick-valves were assumed. The heat losses through the pipe wall were neglected.

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. The maximal temperature difference reaches 200 °C in the first section of the pipe for a short period (see Fig. 16). The thermal striping (the waving of the mixed layer) can be observed as well (see Fig. 17).

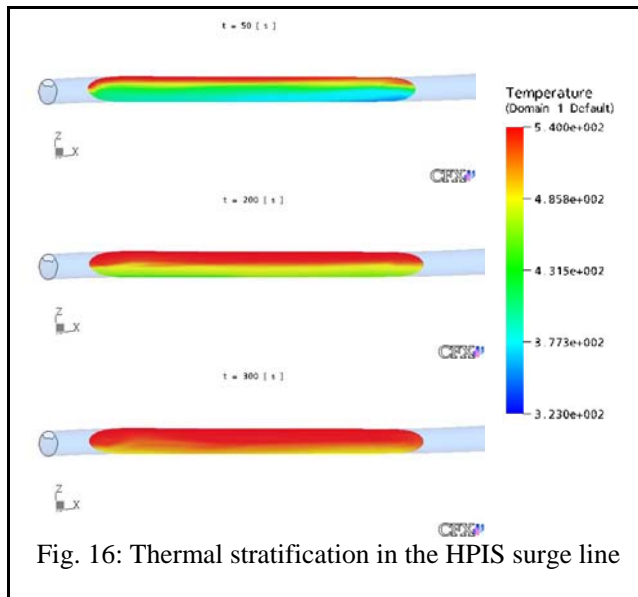


Fig. 16: Thermal stratification in the HPIS surge line

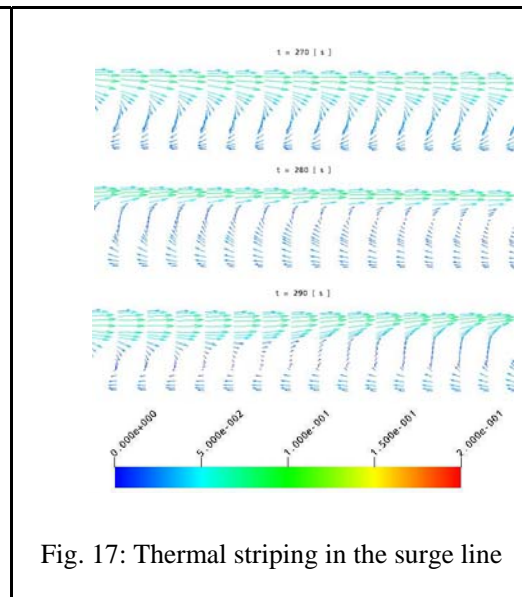


Fig. 17: Thermal striping in the surge line

Summary

In the paper, some results of CFX simulations concerning the thermal stratification in primary piping of VVER-440 were presented. The calculations – in accordance with the available measured data – confirm the development of stratified flow in the surge line of the pressurizer during the heat-up of the reactor. However, the CFX simulation shows a stable asymmetric flow in the surge line, which is not directly confirmed by the measurements.

In the second part of the paper, simulations of thermal stratification in the HPIS injection line were presented. The investigation of the surge line of the HPIS shows similar stratification, in case the check valve is assumed to be leaking. These simulations cannot be validated by Hungarian measurements. For the precise description of the boundaries (as the leakage mass flow rate on the check valve) the extensive study of the international operating experience is necessary.

The results showed that the CFD codes provide an effective method for the demonstration of the thermal stratification when sufficient operational data are available for the concerned piping. Otherwise, measurements or additional simulations are required, and additional sensitivity studies should be performed for the accurate analysis. Qualitative CFD simulations can also play an important role in the ageing management of NPP piping: they can help deciding, whether the possibility of thermal stratification exists in given pipe sections.

References

- [1] VEIKI: „Ageing management of nuclear power plant equipment - Piping”, Background material for regulatory guidelines, in Hungarian, 1998
- [2] „Assessment of the results of the temperature monitoring system, settled on the pressurizer surge line”, Paks NPP, 2001, in Hungarian