Temperature distribution in the Temelín NPP primary circuit piping

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Abstrakt

The presentation deals with the issue of measurements of processes and their relation to the assessment of nuclear power equipment safety. The example of thermal field non-homogeneity in the reactor hot legs is used to document that the safety of nuclear power equipment and its reliable operation at required parameters is not only a question of the equipment technical level but first of all a question of knowledge of processes which are running in the equipment.
Current top specialists have passed years of experience from the commissioning of nuclear units at Dukovany, Mochovce and Temelín and from related experimental activities.
The ingoing generation has only operated nuclear units available where every minute of operation for non-commercial purposes means economic losses.
Therefore, there is naturally a doubt that within seven to ten years there is nobody who would be able to analyze process changes or tendencies and to formulate conclusions whether these trends and changes are anomalous or not.

1. Introduction

The VVER 1000 reactors installed at both the Temelín NPP units are four-loop reactors with the loops placed in such a way that they form two couples of loops. Each loop consists of a so called hot leg (from the reactor outlet to the steam generator) and a cold leg (from the steam generator via main circulation pump to the reactor inlet). The core consists of fuel assemblies supplied by Westinghouse.

In order to determine the reactor thermal output it is necessary to determine the value of coolant heating in the core. The heating value is determined as a difference of coolant temperatures in hot and cold legs. At the nominal reactor output it is approximately 30°C. Temperatures are measured by means of resistant thermometers. In each loop there are 6 sensors installed in the hot leg and 6 sensors in the cold leg The first three sensors are wide-range sensors (range of 0-350°C) and the other three sensors are narrow-range sensors (range of 260-350°C).
One sensor of each group is used (a narrow-range sensor during the power operation) in one control system division. The system contains 3 divisions. Information concerning measured temperature from a particular place of a respective leg is processed and evaluated by the system logic.

Within the power start-up tests only such nuclear unit operation modes were carried out when only 2 or 3 MCPs are in operation. It was detected during these modes that there are differences in some cases of as much as 15°C between temperatures in hot legs measured by individual RTDs.
The first evaluation of the process showed that after the MCP shut-down and stabilisation of back flow in the loop with a shut-down MCP a non-homogeneous temperature field was formed in the neighbouring operating loop caused by the mixing of flows above the reactor core. Based on this fact it was decided to perform

an analysis of the process and to try to clarify the patterns and carry out possible technical predictions based on a calculation model.

2. Nuclear unit mode effect on the temperature field non-homogeneity

It was unambiguously proved during the start-up of both units that the non-homogeneity increases with increasing output. Fig. 1 shows the dependence on the output of maximum range of data from 6 RTDs and on the uncertainty on the level of 95% probability for loop 2 of the ETE Unit 2. These are modes with 4 MCPs in operation.

Both the dependencies are quadratic. Up to the output of 30%, i.e. thermal 900 MW, and 300 MW electrical respectively, the differences between the data of individual RTDs are not significant. However, at the full output the range approximates 5°C and the mean temperature uncertainty on the level of 95% probability is almost 2°C. Due to the fact that heating of coolant in the reactor core is 30°C, such high uncertainties do not allow to determine with sufficient accuracy the nuclear unit thermal output based on the primary circuit balance. In any case, the nuclear unit safe operation is not effected since it is the output determined from the secondary circuit thermal balance which is decisive.

Similar dependence of the temperature range and uncertainties on the reactor output is applicable also for the modes with lower number of operating MCPs. In those cases the differences between individual temperatures are even higher.

3. Rise of temperature non-homogeneity

During the back-flow in the loop with a shut-down MCP, cold water of the operating loop hot legs temperature (approx. 288°C) transfers its thermal energy in the steam generator and is cooled down by that even more. Then it enters into the reactor at the level of the core outlet where water is heated by nuclear reaction. It immediately flows into the “closely adjacent” hot leg. In the space above the core both flows cannot be homogenized, i.e. water split into temperature tongues flows through the hot leg. The rule that hot water is in the upper and cold water in the lower part of the piping is not applicable here.

During the POOP and OPPO modes always “closely adjacent” pumps are in operation. Water from non-operating loops can be mixed during its way through the entire reactor diameter and that is why the non-homogeneity is substantially lower during these modes.

4. Mathematical analysis

The task of the mathematical analysis was to evaluate the temperature differences which can be expected at a given radial and axial distribution of the ETE reactor core output at the core outlet and in the area of temperature-measurement pits.

Calculation parameters:

Number of operating MCPs:	4
Reactor output:	3000 MW
Coolant flow trough the core:	85896 m3/h

Core inlet temperature: 288.1°C

A 3d model of the core and reactor outlet part based on the PHOENICS 3.4 system CFD was used for the analysis. This system is designated for the modelling and calculation of problems in the area of flow.
The PHOENICS system allows to model the flow from the most simple problems of potential flow through laminar to turbulent flows. It is possible to solve the flow of both incompressible and compressible liquids, single-phase and double-phase flows, stationary and non-stationary issues, tasks of forced and natural convection. The PHOENICS allows to solve these tasks in Cartesian coordinates in 1d, 2d, 3d geometry, in polar (cylindrical) coordinates and general curvilinear coordinates.

5. Calculation results

The results of stationary thermohydraulic calculation using the PHOENICS 3.4 program were processed graphically by means of a post processor PHOTON and by means of a user program allowing statistic evaluation of temperature profiles at the core outlet and in the area of temperature-measurement pits. Coolant temperatures in the core area gradually increases according to the given radial and axial distribution of output from the inlet temperature of 288.1°C to the values of 315 – 331°C at the core outlet. The temperature profile is balanced and in the IO piping in the area of temperature-measurement pits the difference of the maximum and minimum temperature value is approx. 1°C according to the calculation.
The temperature field shape is given first of all by radial distribution of the core output. The mean outlet temperature from the core weighted through mass flow is given by the flow through the core and by the total output.
The calculated temperature span at the core outlet in the range of 315 – 331°C corresponds well with the measured values during the operation. The values were in the range between 310 – 333°C, however, the in-core thermocouple inaccuracy shall also be taken into consideration. On the other hand, the temperature span in the area of temperature-measurement pits is actually about 4 times higher than the calculated one – measured 4°C against calculated 1°C.

6. Conclusion

Temperature non-homogeneity in the VVER 1000 reactor primary piping hot legs was detected during the commissioning of Units 1 and 2. The quantification of temperature differences was carried out as well as explanation of its causes. Further on, mathematical analysis of the effect was carried out using the PHOENICS 3.4 calculation system. A good correspondence was reached between the analysis results and the actual condition of nuclear unit in the area of the core outlet. Another analysis is to be performed to reach a correspondence in the area of the RTD temperature-measurement pits in the primary circuit hot legs.

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Fig. 1 - Temperature non-homogeneity in hot legs during the PPPP mode