ANALYSIS OF THE MEASUREMENTS ON A PHYSICAL MODEL OF THE FUEL ASSEMBLY OF THE NUCLEAR REACTOR VVER 440

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Safe and effective loading of nuclear reactor fuel assemblies demands qualitative and quantitative analysis of the relations between the coolant temperature in the fuel assembly outlet, measured by a thermocouple, and the mean temperature of the coolant in the thermocouple plane position. In the laboratory at the Institute of Thermal Power Engineering of the Slovak University of Technology in Bratislava, an experimental physical fuel assembly model of the VVER 440 nuclear power plant with V 213 nuclear reactors was installed. The aim of the measurements on the physical model was to analyze the temperature and velocity profiles in the fuel assembly outlet. The following article deals with the analyses of these measurements based on different mass flow of the water through a physical model of the fuel assembly, the temperature discontinuity generated by cold water flowing through triplet tubes and central tube in plane 1, and the positioning of the mixing CFD grid simulations of a fuel assembly outlet. All analyses were validated by means of measurements on the physical model of the fuel assembly.

Keywords : *nuclear reactor, fuel assembly, physical model, temperature profiles, measurements, CFD validation*

1. Introduction

Coolant flows along a 126 fuel rod bundle in the VVER 440 nuclear reactor fuel assembly. During the nuclear reactor operation, the temperature fluctuation is irregular in each single fuel rod, depending on the fuel properties, and the position of the fuel assembly in the reactor. In the fuel assembly outlet, the coolant temperature profile is irregular. In the fuel assembly, at the point where the flow cross section changes from hexagonal to circular, a mixing grid, which flattens the coolant temperature profile, is located. Subsequently, the coolant flows through the fuel assembly outlet where the cross section shape and area change. The next step in smoothing the coolant temperature profile is performed by a catcher. The coolant temperature in the fuel assembly outlet is measured by a thermocouple located on the fuel assembly axis, and is positioned 300 mm from the end of the fuel rods (Fig. 1, plane 3). Measurements are provided at one point. Safe and effective loading of nuclear reactor fuel assemblies demands qualitative and quantitative analysis of the relationship between the coolant temperature in the fuel assembly outlet, measured by the thermocouple, and the mean coolant temperature profile in the thermocouple plane position. It is not possible to perform the analysis directly in the reactor, so it is carried out using measurements on the

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physical model, and the CFD fuel assembly coolant flow models. The CFD models have to be verified and validated in line with the temperature and velocity profile obtained from the measurements of the cooling water flowing in the physical model of the fuel assembly.

2. Fuel assembly physical model

In the laboratory of the Institute of Thermal Power Engineering of the Slovak University of Technology in Bratislava, a physical experimental copy of the fuel assembly model of a VVER 440 nuclear power plant was installed. The model was created to a scale of 1:1.125. The measurements on the model were made with different water mass flow at four different positions on the mixing grid. The temperature and velocity profiles were measured with 2 combined probes located in 3 planes at the outlet of the fuel assembly in the physical model (Fig. 1):

- Plane 1 is situated between the end of the fuel rod bundle and the mixing grid
- Plane 2 is situated behind the mixing grid and the end of the central tube at the beginning of the cylindrical head of the fuel assembly outlet
- Plane 3 is positioned at the nuclear reactor fuel assembly thermocouple

Knowing the relationship between the experimentally measured and CFD calculated coolant temperature at the fuel assembly outlet, and the mean coolant temperature in the plane of the thermocouple position is a necessary condition for the safe and effective loading of the nuclear reactor fuel assemblies.

During experiments, due to the fuel assembly model design, the water pressure, temperature, the velocity, and temperature profile measurements are taken near the automodeling flow region. The coefficient of friction λ is constant, independent of the Reynolds number. The compliance between the size and physical dimensions of the fuel assembly model and the actual reactor fuel assembly is achieved by ensuring the results of the measurements on the model correspond with the coolant flow in the real fuel assembly outlet [1].

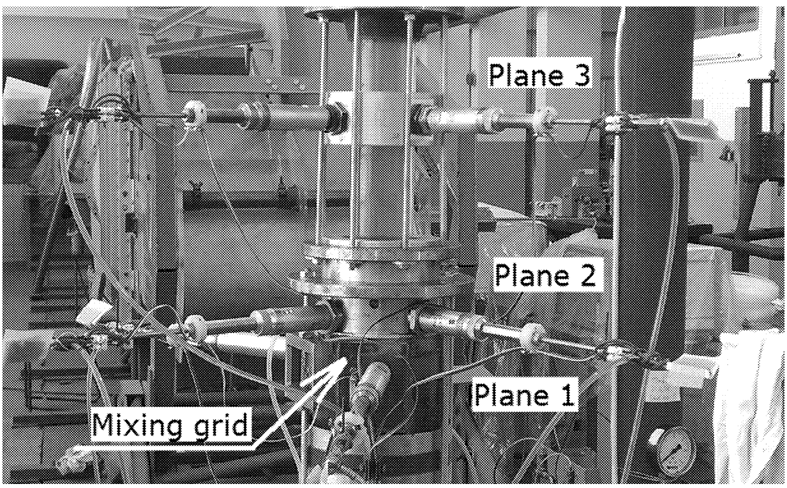

Fig.1: Physical model of the fuel assembly outlet with combined traverse probes devices located in planes 1, 2 and 3

In the plane of the fuel rod bundle end, temperature discontinuity is modeled by mixing the heated (primary) water that is flowing along the fuel rods bundle with cool (secondary) water flowing from one of the tube triplets α, β, γ, with an outer diameter of 8 mm and an inner diameter of 5.6 mm (Figs. 2 and 3) and/or a central tube with outer and inner diameters of 10 mm and 8.5 mm respectively (Figs. 2 and 3). Temperature and velocity profiles are measured with the combined probes 1A a 1B located in plane 1 in the zone between the rod bundle end and the mixing grid. Plane 2 is located between the end of the central tube and the catcher, together with combined probes 2A and 2B. In plane 3, where the thermocouple for measuring the outlet water temperature is located in the real fuel assembly, the traverse devices for combined probes 3A and 3B for temperature and velocity profile measurements were installed. At the outlet of the fuel assembly model, water flow mean temperature is measured with a Pt 100 thermometer.

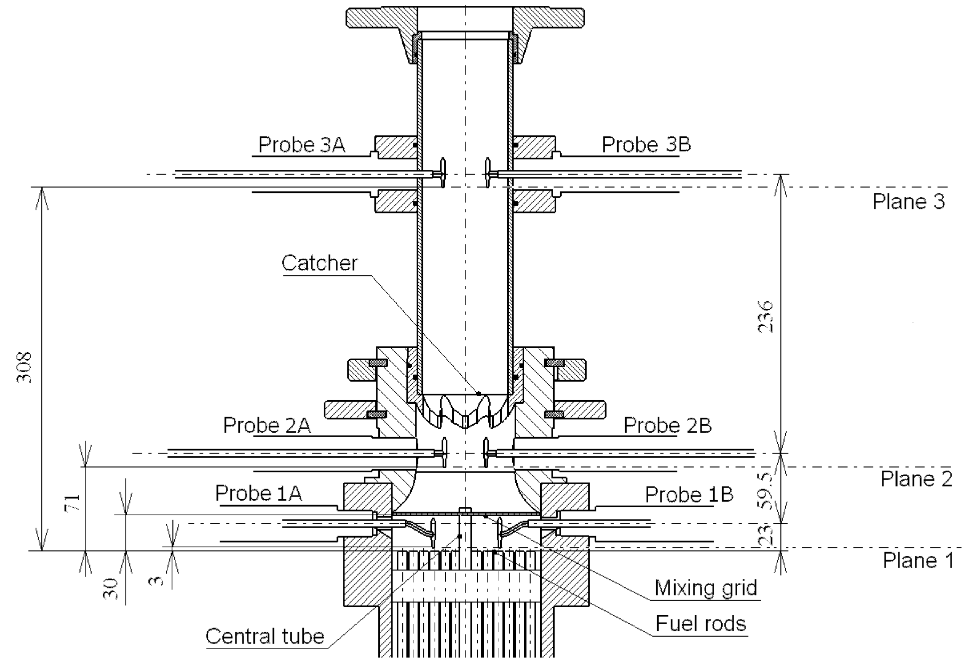

Fig.2: Outlet of fuel assembly physical model with combined probes in the planes 1, 2 and 3

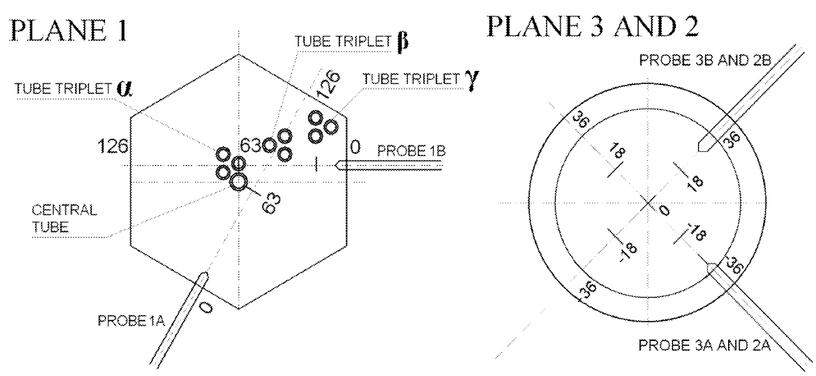

Fig.3: Location of combined probes 1A, 1B in plane 1 and probes 2A, 2B behind probes 3A, 3B in plane 3

It is possible to observe the mixing of the water flow through plexiglass walls, using colored cool water introduced into the fuel assembly outlet through triplet tubes or a central tube.

3. Measurements on the fuel assembly physical model

All together 37 measurements were carried out using four different mixing grid positions, and with a water flow of approximately 11, 10 and 5 kg s^{-1}, a cold water inlet through triplet tubes α, β, γ, and a central tube. The influences of these parameters on temperature profiles in planes 1, 2 and 3 of the fuel assembly physical model outlet were analysed.

In the fuel assembly physical model hydraulic system it is not possible to maintain the same temperature for consecutive measurements.

3.1. Influence of the water mass flow on the temperature profiles

Measurements with a flow rate through the fuel assembly physical model of 11.12 kg s^{-1}, 10.09 kg s^{-1}, 5.05 kg s^{-1} were performed with mixing grid position P1 (Fig. 10) and isokinetic cold water flow through triplet tube α and the central tube.

The temperature profile in plane 1 (Fig. 4) was measured with probe 1A partially influenced by cold water flow from triplet tube α. The measured temperature difference

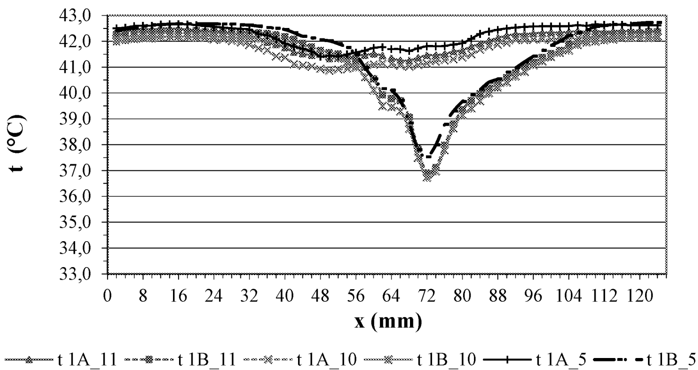

Fig.4: Temperature profiles in plane 1

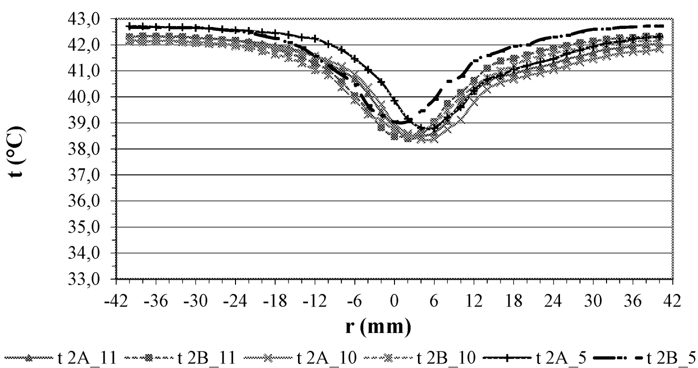

Fig.5: Temperature profiles in plane 2

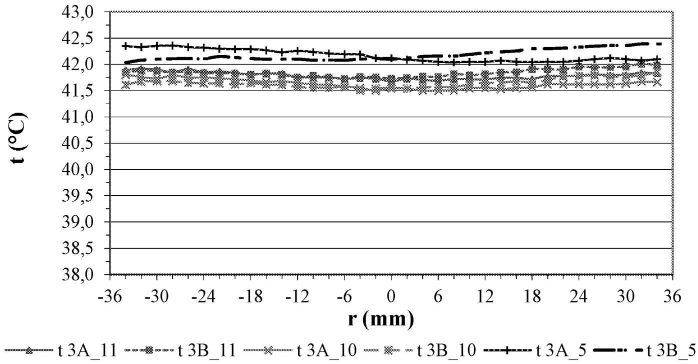

Fig.6: Temperature profiles in plane 3

was 1.3 °C. Probe 1B in position $x = 72$ mm was above tube triplet α with cold water flow. With probe 1B temperature differences up to 5.6 °C were recorded.

In plane 2 temperature differences fall to 4.09 °C (Fig. 5). Temperature profiles are similar for both combined probes and for each measurement. The temperature decrease in the center of the profile is caused by the flow of cold water from the central tube.

Temperature profiles in plane 3 (Fig. 6) are flattened, and a similar trend can be seen for both combined probes, with a difference between the maximal and minimal temperature of less than 0.5 °C.

3.2. Measurements by different temperature discontinuity in plane 1

Temperature discontinuity in plane 1 was modeled by cold water inlet to the fuel assembly physical model with central tube and one or more of triplet tubes α, β or γ. Measurements were performed with mixing grid position P1 (Fig. 10) and with a water mass flow through the fuel assembly model of approximately 11 kg s^{-1}.

Temperature profiles in plane 1 in each measurement are influenced by cold water and the different position of tube triplets α, β or γ (Fig. 7). The greatest difference between the maximal and minimal temperatures in plane 1 is 5.58 °C.

In plane 2 (Fig. 8) the temperature profile is similar, with a temperature decrease in the center of the profile caused by cold water flow from the central tube. Probe 2B with

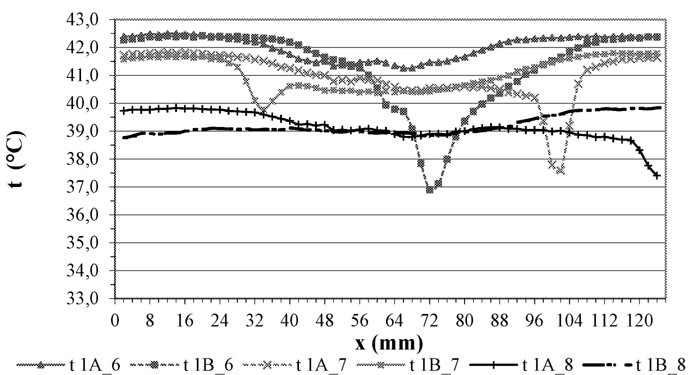

Fig.7: Temperature profiles in plane 1

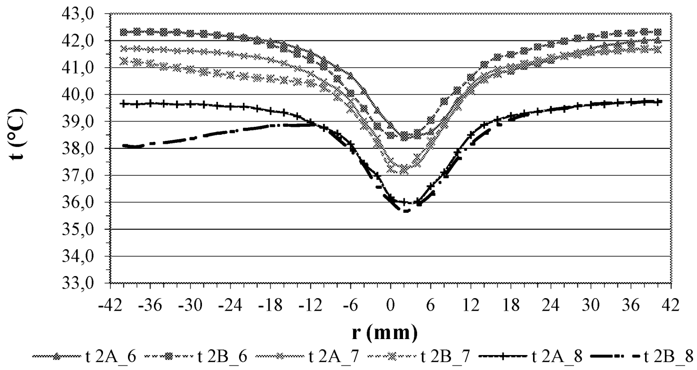

Fig.8: Temperature profiles in plane 2

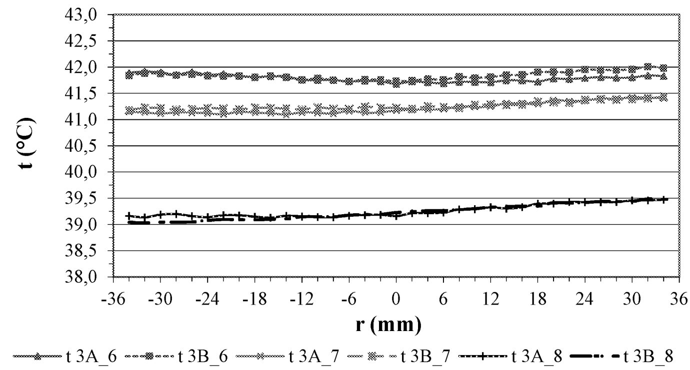

Fig.9: Temperature profiles in plane 3

temperature profile t 2B_8 (cold water inlet through triplet tube γ and the central tube), in the first part of traversation records the temperature of cold water flowing from the triplet tube. The greatest difference between maximal and minimal temperatures is 3.82 °C.

In plane 3 (Fig. 9) the temperature profiles are flattened, and the measured differences are enlarged by the distance of the coldwater inlet from the fuel assembly physical model axis. The greatest temperature differences between the maximal and minimal temperature is 0.48 °C during cold water flow from the triplet tube γ.

3.3. Measurements with different possible configurations of the mixing grid

The mixing grid has a significant influence on coolant mixing in the fuel assembly. It is situated 30 mm behind the plane of the fuel rod ends. The producer supplies the fuel assemblies with the mixing grid installed in two different positions, and two more positions are possible by different placing of the assembly in the reactor active zone (Fig. 10) [2]. The influence of the mixing grid position on the water flow in the fuel assembly outlet was analyzed.

The results of measurements with isokinetic water supply through triplet tube α and the central tube are presented. The modeled water flow was measured using a Venturi meter in the mixing grid positions P1, P2, P3 and P4 in the range from $m = 11.12\,\mathrm{kg\,s^{-1}}$ (P1) to $m = 11.14\,\mathrm{kg\,s^{-1}}$ (P4).

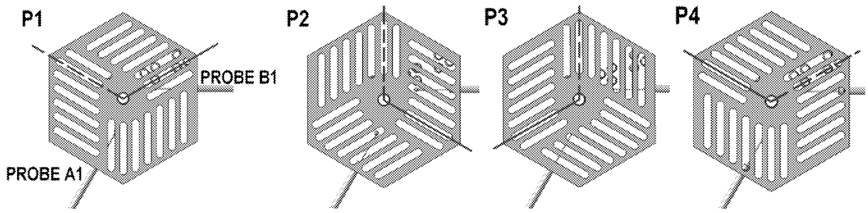

Fig.10: Positions P1, P2, P3 and P4 of the mixing grid in a nuclear reactor fuel assembly

In Fig. 11, the temperature profiles in plane 1 are illustrated for mixing grid positions P1, P2, P3 and P4. During traversing, probe 1A did not pass over the cool water input, therefore the temperature decrease t 1A_Px in the middle of the assembly is not significant. Probe 1B measured the temperature t 1B_Px in the middle of the assembly, which is influenced by cold water inflow through the triplet tube α. Differences between water temperatures $t_{\max} - t_{\min}$ in plane 1 are between 4.50 °C (position of mixing grid P2) and 5.60 °C (P1).

In plane 2 the temperature profile is flattened at the cross section periphery by the influence of the mixing grid (Fig. 12). The temperature profile is significantly influenced by the cool water input from the central tube. Differences of water temperature $t_{\max} - t_{\min}$ in plane 2 are from 3.20 °C (P3) to 3.92 °C (P1).

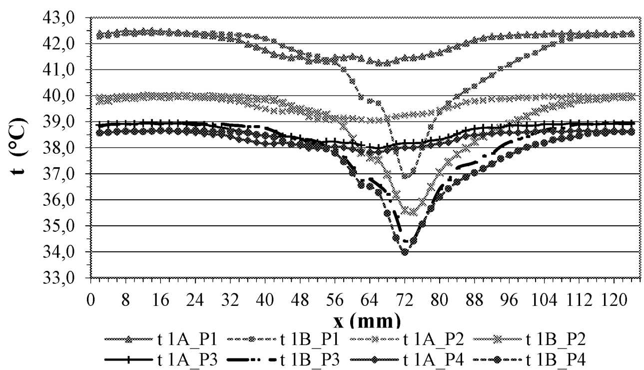

Fig.11: Temperature profiles in plane 1 for mixing grid positions P1, P2, P3 a P4

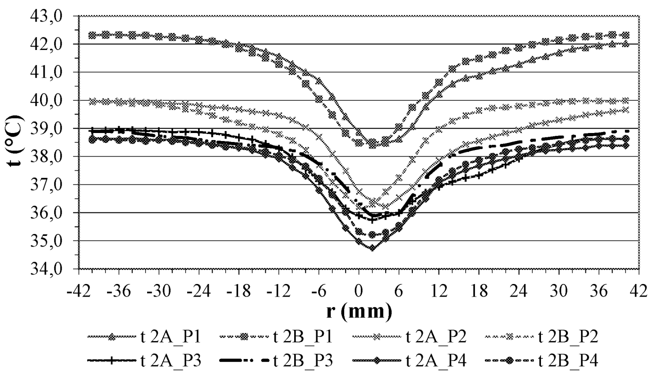

Fig.12: Temperature profiles in plane 2 for mixing grid positions P1, P2, P3 a P4

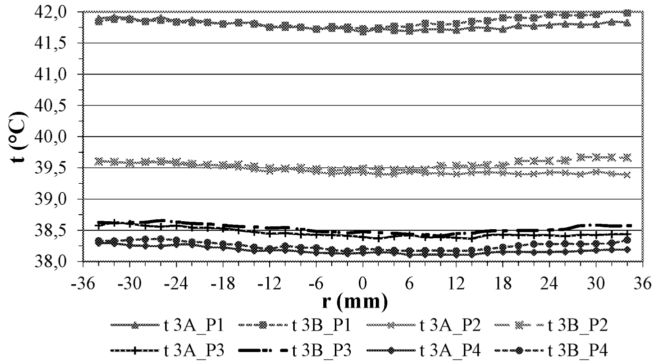

Fig.13: Temperature profiles in plane 3 for mixing grid positions P1, P2, P3 a P4

During the water flow between planes 2 and 3 the turbulence around the catcher causes another flattening of the temperature profile in plane 3 – the plane where the thermocouple in a real fuel assembly is positioned (Fig. 13). Differences of water temperatures $t_{\max} - t_{\min}$ in plane 3 are from 0.15 °C (P4) to 0.33 °C (P1).

4. Validation of the CFD fuel assembly model

The CFD simulations of the fuel assembly model have to be validated and verified for the purpose of further computational analysis. The objective is to achieve the maximum accuracy of the CFD simulations compared to real-time experiments. Hence suitable computational mathematical models were sought which would represent the physical phenomena of the experiment with minimal deviations.

With CFD model (Fig. 14) an analysis of three different, unstructured meshes was made: a coarse mesh grid with approximately 200,000 elements; a medium grid with 750,000 elements; and a fine grid with 2,000,000 elements (Fig. 15). An adiabatic wall, with velocity inlet boundary condition and with pressure outlet boundary condition was used for the simulations. The inlet boundary condition was set at 10.81 $\mathrm{kg\,s^{-1}}$ (1.52 $\mathrm{m\,s^{-1}}$) of water at 39.9 °C that was mixed with 0.201 $\mathrm{kg\,s^{-1}}$ of 36.5 °C water from the central tube and β triplet.

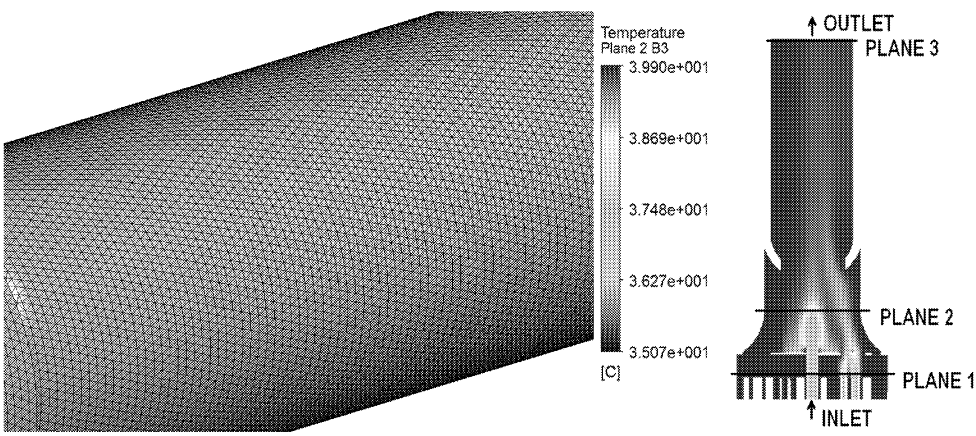

Fig.14: Computational grid and temperature profile along a cut of the fuel assembly outlet

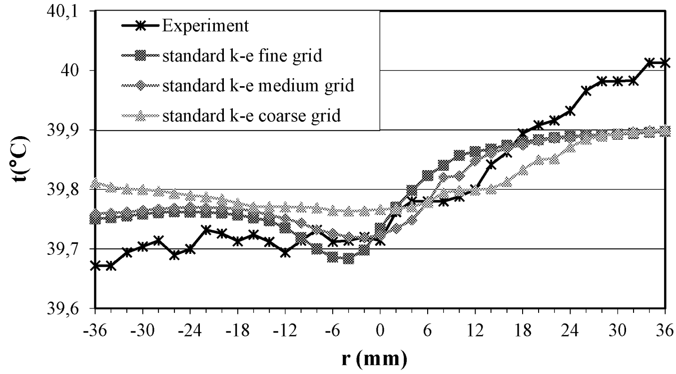

Fig.15: Meshing grid comparison with calculated temperature profiles in plane 3 of the fuel assembly outlet

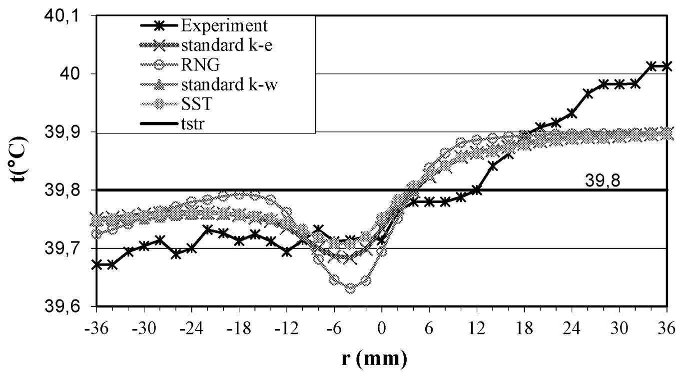

Fig.16: Turbulence model comparison with calculated temperature profiles in plane 3 of the fuel assembly

For better correspondence of the CFD simulations with the experiment, 4 mathematical turbulence models were tested – standard k-ε, RNG k-ε, standard k-ε and SST k-ε using the fine mesh (Fig. 16). The results show large variations at the center of the cross section, with the standard k-ε and SST k-ε models matching the measured data more closely than the RNG model, which showed a higher temperature drop at the center of the cross section. The greatest difference between the measured values is 0.34 °C, and the difference between the calculated temperature values of the SST model is 0.20 °C. The turbulence models were unable to match the temperature increase in the last phase of probe traversation where the difference between the measured and calculated values is 0.11 °C. The temperature difference between the SST and RNG turbulence models and the calculated mean temperature t_{str} at the position where the thermocouple is positioned in the reactor fuel assembly (Fig. 12, $r = -4$ mm), is 0.08 °C.

An analysis of the influence of the inlet boundary turbulence intensity shows no effect on the temperature profile in the fuel assembly outlet.

5. Conclusion

A physical experimental model of the fuel assembly of a VVER 440 nuclear power plant was reconstructed and installed in the laboratory of the Institute of Thermal Power Engineering of the Slovak University of Technology in Bratislava. The physical model was created to investigate coolant flow in the fuel assembly outlet.

In total, 37 measurements were analyzed to investigate temperature and velocity profiles of the coolant flow in plane 3 – the plane where the thermocouple in a nuclear reactor fuel assembly is placed. Analyses were made based on different mass water flow through a fuel assembly physical model, on temperature discontinuity generated by cold water flowing through tube triplets and the central tube in plane 1, and on the position of the mixing grid. The influence of the mixing grid position and the water flow through the fuel assembly physical model on temperature profiles in plane 3 approaches technical measurement uncertainty). The greatest influence on the inlet temperature discontinuity and on the temperature profiles in plane 3 is the cold water inlet through triplet tube γ and the central tube.

Results of validated CFD simulations and the experimental temperature data in plane 3 are in good accordance. Differences between the maximal and minimal temperatures in plane 3 obtained by experiment and with CFD are from 0.09 °C to 0.76 °C, and most values were around 0.2 °C. The analyzed turbulence models SST k-ε, with a mesh of 2,000,000 elements performed closest to the experimental temperature data. Inlet boundary turbulence intensity shows no effect on the temperature profile in the fuel assembly outlet.

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