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MODELING OF FLOW IN NUCLEAR REACTOR FUEL CELL OUTLET

MODELOVANIE PRÚDENIA VO VÝSTUPNEJ ČASTI PALIVOVEJ KAZETY JADROVÉHO REAKTORA

Abstract

Safe and effective load of nuclear reactor fuel cells demands qualitative and quantitative analysis of relations between coolant temperature in fuel cell outlet temperature measured by thermocouple and middle temperature of coolant in thermocouple plane position. In laboratory at Insitute of thermal power engineering of the Slovak University of Technology in Bratislava was installed an experimental physical fuel cell model of VVER 440 nuclear power plant with V 213 nuclear reactors. Objective of measurements on physical model was temperature and velocity profiles analysis in the fuel cell outlet. In this paper the measured temperature and velocity profiles are compared with the results of CFD simulation of fuel cell physical model coolant flow.

Abstrakt

Pre bezpečné a efektívne zaťažovanie palivových kaziet jadrového reaktora treba kvalitatívne a kvantitatívne analyzovať súvis medzi teplotou chladiva na výstupe z palivovej kazety meranou termočlánkom a strednou teplotou teplotového poľa chladiva v rovine umiestnenia termočlánku. V laboratóriu Ústavu tepelnej energetiky Strojníckej fakulty STU v Bratislave sa realizovalo experimentálne zariadenie s fyzikálnym modelom palivovej kazety reaktora V 213 jadrovej elektrárne VVER 440. Cieľom meraní uskutočnených na fyzikálnym modeli palivovej kazety bola analýza teplotových a rýchlostných polí vo výstupnej časti palivovej kazety. V príspevku sú porovnané výsledky meraní teplotových a rýchlostných polí vo výstupnej časti fyzikálneho modelu palivovej kazety a výsledky počítačovej CFD simulácie prúdenia vody v tomto modeli.

1 INTRODUCTION

Fuel cells power of pressurized water reactors VVER-440/213 is limited by design values of: fuel cell, fuel rod and linear fuel rod power load. Fuel assemblies manufacturer made constructional changes which have distinctive influence in the flow relations in fuel cells of active zone. That is limitation of coolant flow in active zone of nuclear reactor, rate of flow and temperature through every single part as well. Safety and economic criteria for nuclear power plant service depend on active zone fuel cell load.

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It is important to know power of each single fuel cell because of safety. During fuel cell overload the protective coating could be disturbed which inflicts radioactive products emission to coolant flow. Monitoring of active zone and its neutron-physical parameters is ensured by in-reactor control system.

2 COOLANT FLOW IN FUEL CELL OUTLET

Coolant in nuclear reactor VVER 440 fuel cell is flowing along 126 fuel rods. Due fuel cell properties and cell position in reactor there is possibility of uneven heat production and transfer in fuel rods which may cause incorrect measurement of temperature by thermocouple in the fuel cell outlet. This inaccuracy is eliminated by reducing of fuel rods load but it leads to reactor power decreasing. Considering this fact in fuel cell is built in a mixing grid designed to flatten coolant temperature profile. Coolant is flowing through outlet of fuel cell which change flow cross- section area and shape from hexagonal to circular. Next flattening of coolant temperature array is caused by catcher. Coolant temperature in the fuel cell outlet is measured by thermocouple in fuel cell axis and positioned 300mm up by fuel rods ending (plane 2). Measurements are provided in one point. Safe and effective load of nuclear reactor fuel cells demands qualitative and quantitavive analysis of relations between coolant temperature in fuel cell outlet measured by thermocouple and middle temperature of coolant temperature profile in thermocouple plane position.

In nuclear reactor VVER-440/V213 fuel cell in operation flowin 26,64 kg.s^{-1} of cooling water. Coolant flowing with 300°C in fuel rods bundle is characterized by Reynolds number value 2,65.10^{5} and in fuel cell outlet (thermocouple position, plane 2) the value of Reynolds number is 5,11.10^{6} . Reynolds number values $Re = 2{,}65.10^{5}$ and friction coefficient $\lambda=0{,}063$ for real fuel cell are located in automodelling r range of flow.

3 FUEL CELL PHYSICAL MODEL

In laboratory at Insitute of thermal power engineering was built up an experimental physical fuel cell model of VVER 440 nuclear power plant with V 213 nuclear reactor. Objective of measurements on physical model was temperature and velocity profiles analysis in the fuel cell outlet. Physical model is made in scale 1:1,125.

In fuel cell physical model is possible to work with coolant temperature up to 80°C. It is caused by used material in fuel cell model construction and manner of water heating in accumulative vessel. During measurements coolant flow was starting at 4,9 kg.s^{-1} up to 11,1 kg.s^{-1}.

Temperature and velocity profiles measurements on fuel cell physical model are realized close to automodel rage of flow, when friction coefficient is almost constant. At flow 11,00 kg.s^{-1} and temperature 37,51 °C Reynolds number characterized coolant flow in fuel rod bundle is $Re = 2{,}74.10^{4}$ and coefficient of friction $\lambda=0{,}039$. Considering the temperature of water 80°C Reynolds number raise to $Re = 3{,}45.10^{4}$ and friction coefficient is $\lambda=0{,}038$.

Compliance between measurements results on physical model and real coolant flow in fuel cell outlet is acquired with dimension and physical similarity.

4 MEASUREMENTS ON FUEL CELL PHYSICAL MODEL

In the fuel cell physical model is not possible to simulate real power distribution along a single rod as it is in real fuel cell of nuclear reactor. Temperature discontinuity is modeled by mixing heated (primary) water that is flowing along fuel rods bundle with cool (secondary) water flowing from one of the tube triplet α, β, γ and/or central tube (fig.1a). Temperature and velocity profiles are measured with combined probes C1 a D1 located in plane 1 in zone between rod bundle ending and mixing grid. In plane 2, where in real fuel cell is located thermocouple for measuring outlet water temperature are installed traversers for combined probes E2 and F2 movement for temperature and velocity profile measurements (fig.1b).

14 measurements were realized on physical model with three different flow rates and five variants of isokinetic secondary water distribution to fuel cell model. In this paper is closer look on measurement M R1,2_11_2, which has flow 10,86 kg.s^{-1} of water and secondary water was distributed by α tubes triplet located nearest to fuel cell axis. Temperature profiles in plane 1 and 2 are showed in fig.2a and fig.2b.

Temperature *t C1* measured by C1 probe is negligible affected by distributed cold water (temperature differences 0,25°C, fig. 2a). Temperature profile *t D1* measured by probe D1 shows temperature drop 2,67 °C in second part of traversing distance. Relatively extensive part affected by water flow can be explained as intensive mixing of water behind central tube.

Measured temperature values *t E2, t F2* in plane 2 start from 37,39 °C up to 37,69 °C, difference is 0,30 °C (fig. 2b). By temperature and velocity profiles integration the middle temperature of the coolant $t_{str\ 2}$ = 37,57 °C is calculated in the plane 2 where thermocouple is located.

5 CFD MODELING OF FLOW IN FUEL CELL PHYSICAL MODEL

For water flowing analysis in fuel cell physical model outlet with CFD unstructured tetrahedral grid with 638 000 control volumes was used.

Starting conditions for Fluent software are values from measurements on fuel cell physical model. Boundary conditions: standard *k-ε* turbulent model, standard wall function, results setup – segregated, energy equation turned on, inlet ordered as velocity, outlet ordered as pressure, medium is water.

Result for measurements M R1,2_11_2 is CFD R1,2_11_2 simulation. Coolant temperature in plane 1 is 33,76 ˚C to 37,57 ˚C (fig. 3a). Coolant temperature range right behind mixing grid starts at 34,43˚C up to 37,57˚C. Coolant in plane 2 (thermocouple position plane, fig. 3b) has temperature from 37,20 ˚C to 37,57 ˚C, difference is 0,37 °C.

6 RESULTS COMPARISON OF TEMPERATURE PROFILES MEASUREMENTS WITH CFD SIMULATION OF COOLANT FLOW IN PHYSICAL MODEL FUEL CELL

Differences values of water temperature Δt_{R1} in plane R1 and Δt_{R2} in plane R2 are shown in fig.4, which are calculated for plane Ri from difference $\Delta t_{Ri,exp}$ maximal and minimal water temperature known from measurements on physical model and difference $\Delta t_{Ri,\ CFD}$ maximal and minimal water temperature by CFD simulation of fuel cell model:

$$\Delta t_{Ri} = |\ \Delta t_{Ri,\ exp} - \Delta t_{Ri,\ CFD}\ | = |\ (t_{Ri,\ exp\ max} - t_{Ri,\ exp\ min}) - (t_{Ri,\ CFD\ max} - t_{Ri,\ CFD\ min})\ | \qquad (1)$$

For eight compared results of temperature profiles measurements in model outlet and CFD simulation the water temperature difference values Δt_{R1} in plane 1 starts from 0,42 °C up to 2,49 °C and in plane 2 Δt_{R2} 0,05 °C to 0,27 °C.

Regarding to small differences between physical model measurements results of temperature and velocity profiles in planes 1, 2 and ĆFD simulations of coolant flow in fuel cell model outlet, it is possible to state that with properly defined starting and boundary conditions a CFD simulation provides comparable results to measurements on physical model fuel cell.

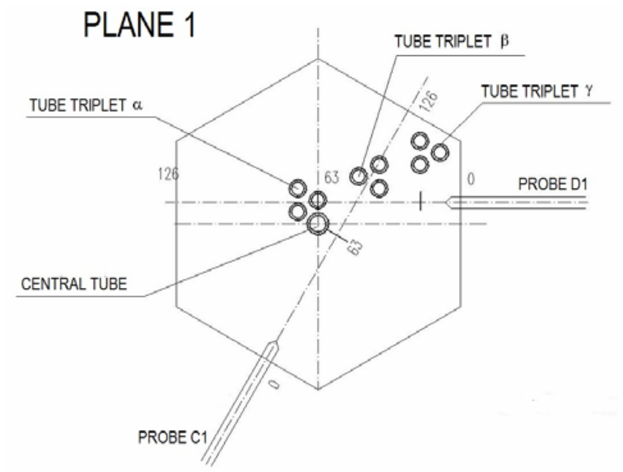

Fig. 1a Location of combined probes C1 and D1 in plane 1 of fuel cell model

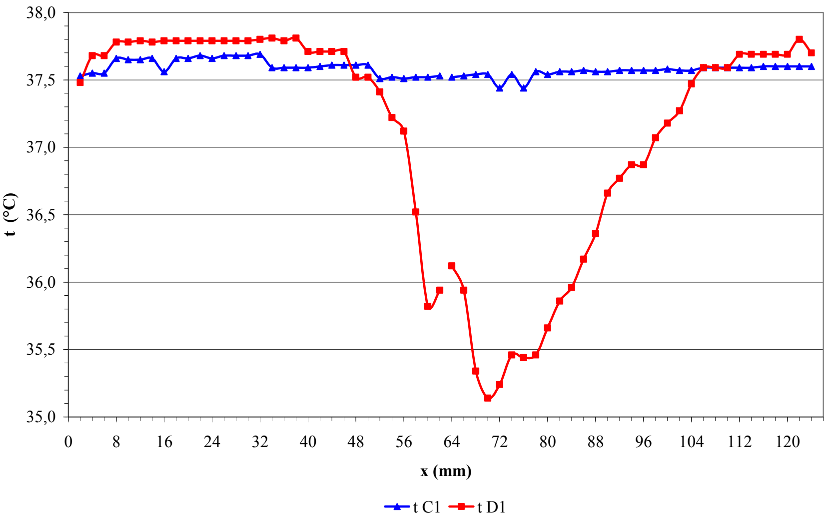

Fig. 2a Measurement M R1,2_11_2 – temperature profiles in plane 1

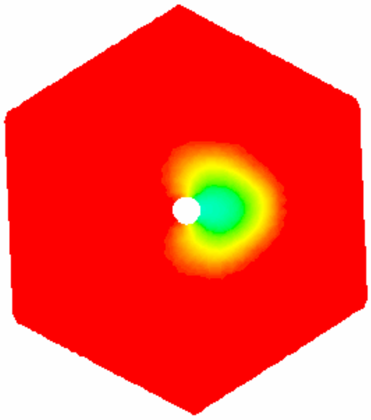

Fig. 3a Coolant temperature profiles in plane 1 for CFD R1,2_11_2 variant

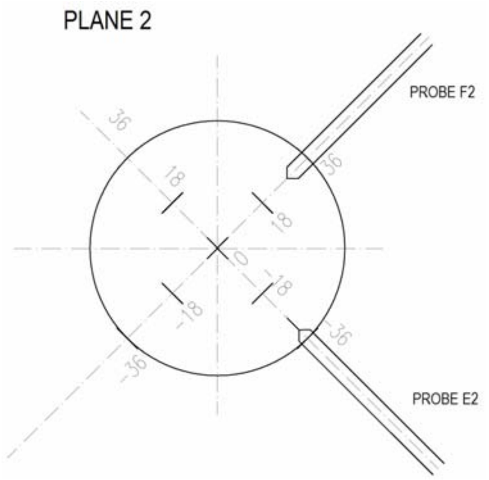

Fig. 1b Location of combined probes E2, F2 in plane 2 of fuel cell model

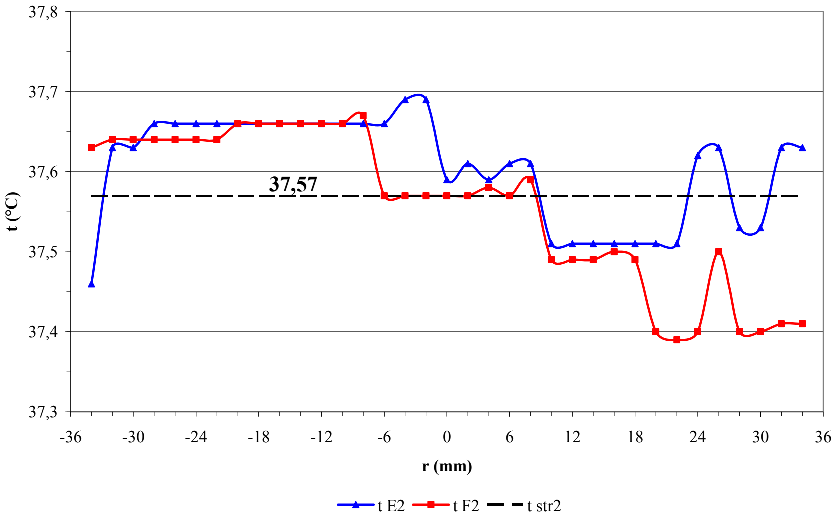

Fig. 2b Measurement M R1,2_11_2 – temperature profiles in plane 2

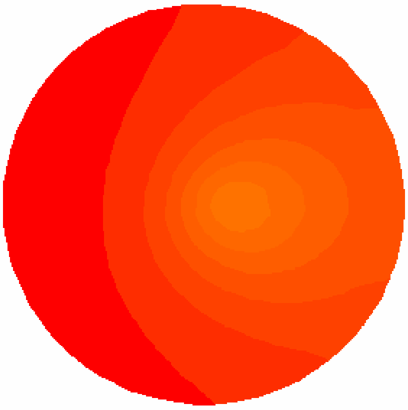

Fig. 3b Coolant temperature profiles in plane 2 for CFD R1,2_11_2 variant

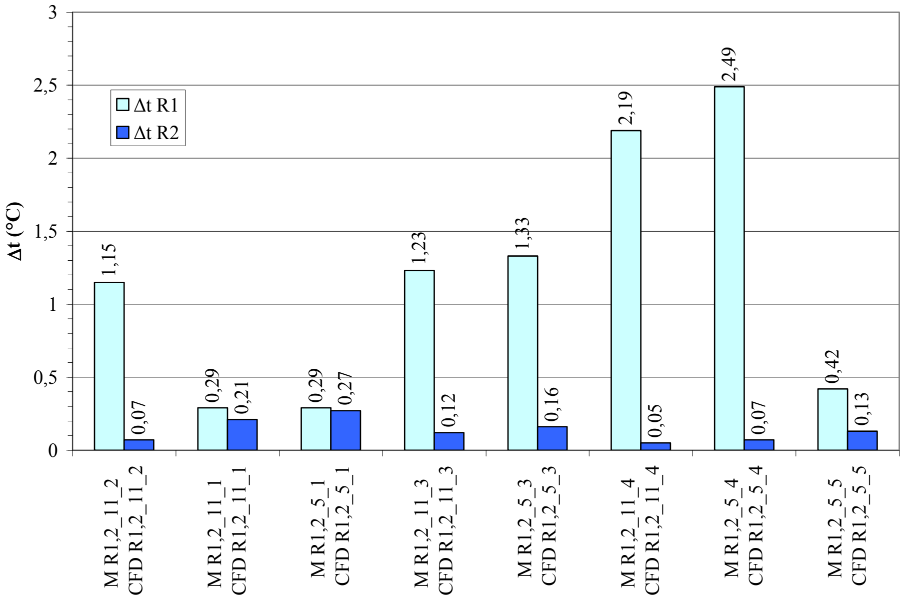

Fig. 4 Water temperature differences Δt_{R1} and Δt_{R2} in planes R1 and R2 measured temperature profiles compared to CFD simulation of flow

7 CONCLUSION

For realized measurement variants on physical model were realised for CFD coolant flow simulations in physical model fuel cell outlet. Considering measured results, appropriate manner of turbulence modeling and grid generation was chosen. CFD simulation of coolant flow gives satisfactory accordance with results of temperature and velocity measurements at the physical model outlet. Measured temperature and velocity profiles in the plane 1 can be replaced in CFD simulations by calculated distribution of power in fuel rods and thus analyses of coolant flow in fuel cell nuclear reactor VVER 440.

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