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Thermal-Hydraulic Analysis of TEPLATOR Moderator Cooling System

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ABSTRACT

The heavy water reactor concept TEPLATOR contains separate independent systems for the primary coolant and the moderator. The present study analyses the low-pressure moderator cooling system of TEPLATOR during full-power operation. The moderator is heated from neutron thermalization, gamma rays' absorption, fission product decay and decay of activation products. Additionally, heat transfer from the coolant channels has to be taken in the analyses of the moderator cooling system. Preliminary thermal-hydraulic analyses of the cooling system are supplemented by CFD simulations of heat and fluid flow in the moderator vessel, emphasizing flow type regimes. Results from CFD simulations will be further assessed to evaluate and optimize the moderator cooling system with particular attention to inlets and outlets locations.

1 INTRODUCTION

Heavy water moderator is used in the Small Modular Reactor (SMR) concept TEPLATOR [1-3] to moderate fast neutrons produced by fission. The moderator is separate from the primary coolant cycle and its temperature has to be maintained in certain limits during the operation. The moderator is heated from heat transfer from pressure channels and radiation heating in the moderator itself. Similarly, as in CANDU reactors, the radiation heating is 5% of the heat energy produced in the reactor [4,5].

The moderator cooling system plays a significant role during the reactor operation and its performance directly influences the performance of the reactor through the moderator temperature distribution [6]. Several studies focused on moderator flow in a small-scale moderator vessel of CANDU reactors [7-10]. A study performed in the advanced reactor concept with a passive moderator cooling system investigated an influence of a flow type on the temperature distribution [11].

The TEPLATOR moderator cooling system is designed to keep the moderator temperate below saturation for all operation regimes [12]. If the moderator cooling system fails, the reactor will be shutdown and the moderator will be drained into a dump tank where the residual heat is removed using a passive cooling system.

The present paper focuses on analysing heat and fluid flow in the moderator's vessel using CFD simulations. The simulations are performed for several mass flow rates to study the influence of flow type on the moderator temperature distribution.

2 PROBLEM FORMULATION

The dominant source of heat in the moderator is radiation heating [5]. The total heat generated in the moderator is 1.7 MW. The heat transfer from the pressure channels to the moderator is just 5 % of the total heat in the moderator.

A primary investigation of the moderator cooling system is focused on the influence of the mass flow rate on the mean and maximum temperature of the moderator. The mass flow rate defines the size of moderator heat exchangers and the amount of heavy water in the cooling system. Three mass flow rates were chosen for the investigation, 22.5, 45 and 90 kg/s.

Temperature distribution in the moderator depends on a flow regime in the moderator's vessel. The flow regime in the moderator's vessel can be determined using the Richardson number [9-11]. The Richardson number is calculated as

$$Ri = \frac{g\beta\dot{Q}_{tot}H}{c_p\rho AU^3} \quad (1)$$

where g is the acceleration of gravity, β is the thermal expansion coefficient, Q Q_{tot} is the total heat power in the moderator, H is the height of the moderator vessel, c_p is the isobaric heat capacity, ρ is the moderator density, A is the total cross-section area of inlet nozzles, U is the inlet velocity.

Previously determined flow regimes in CANDU 6 reactors [9]:

- Buoyancy dominated flow Ri>0.12.
- Inertia dominated flow Ri<0.04.
- Mixed-type flow 0.04<Ri<0.12.

Buoyancy-dominated flow has been identified as the regime with the highest temperature difference of moderator. The mixed-type regime is an unstable regime where buoyant and inertia forces interact with each other and create flow instabilities. The inertia-dominated regime is a stable regime with the lowest temperature stratification in the moderator's vessel. Calculated Richardson numbers for TEPLATOR are in Table 1. Two cases (MF-45 and MF-90) belong in the inertia-dominated flow regime and MF-22 is in the buoyant flow regime.

Table 1: Tested case variants.

Case	Mass flow rate	Ri	Re_{pipe}	ΔT
MF-22	22.5 kg/s	0.2620	87 000	17.8 K
MF-45	45 kg/s	0.0327	174 000	8.8 K
MF-90	90 kg/s	0.0041	347 000	4.4 K

The TEPLATOR moderator cooling system contains six inlet and two outlet nozzles distributed in the outer region of the moderator's vessel. The computational domain of the moderator's vessel is shown in Fig. 1 left.

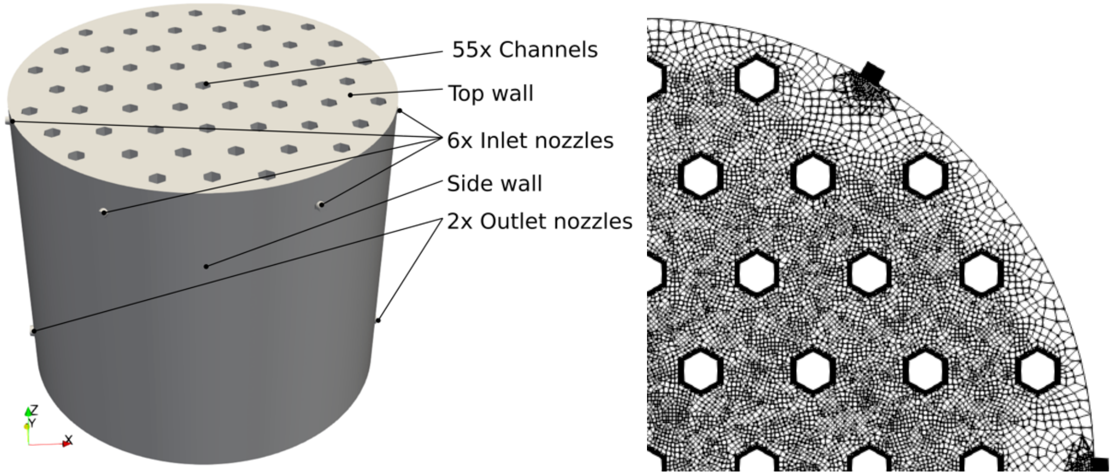

Figure 1: Computational domain of the moderator vessel (left), cross-section of computational grid in the location of inlet nozzles (right).

3 NUMERICAL MODEL

The CFD thermal-hydraulic calculations were conducted in the open-source package OpenFOAM v2106 [13]. The computational domain contains the moderator vessel with inlet and outlet nozzles (see Fig. 1 right). The computational grid of the moderator's vessel was generated in GMSH [14] and nozzles were created using blockMesh (meshing utility in OpenFOAM). The final grid was assembled using mergeMeshes and stitchMesh OpenFOAM utilities. Three computational grids were generated with 2.5, 3.7 and 4.9 mil. of hexahedral cells. A constant velocity profile was applied to the nozzle inlets and constant pressure was applied for the outlet nozzles. Walls were treated as adiabatic except for the pressure channel walls, where a corresponding heat flux was applied.

The volumetric heat flux from radiation heating was treated as a constant field for the initialization process and later as a spatially varying heat source based on results from Monte Carlo simulations [5,15].

The RANS turbulent model k-ω SST [16] was used in the present study and the computational grid contained fine near-wall resolution to predict heat transfer from pressure channels correctly [17,18].

4 RESULTS

A summary of results from conducted simulations is in Table 2, where mean, maximum and outlet moderator temperatures are shown. An increase in mass flow rate resulted in a lower mean moderator temperature in the moderator's vessel. The maximum temperatures are sufficiently low and far from saturation. The reserve is almost 30 K for the low mass flow rate case MF-22.

Table 2: Mean, maximum and outlet moderator temperatures.

Case	Mean moderator temperature	Maximum moderator temperature	Outlet moderator temperature
MF-22	331.7 K	345 K	330.7 K
MF-45	322.3 K	337 K	321.7 K
MF-90	317.7 K	333 K	317.4 K

Moderator temperature distributions are shown in Figs 3-6. The inertia-dominated flow regime (Case MF-90) resulted in a lower thermal stratification in comparison with other cases. Results from the buoyant-dominated flow regime (Case MF-22) show a plume with higher temperatures located in the upper part of the moderator's vessel. The inlet jets could not penetrate the whole bundle, resulting in higher temperatures in the vessel's center. The case MF-45 evinced some non-uniform patterns, and it seems that this case is at the edge of the mixed-type flow regime. However, a further investigation should be done to correctly analyze this particular flow behavior.

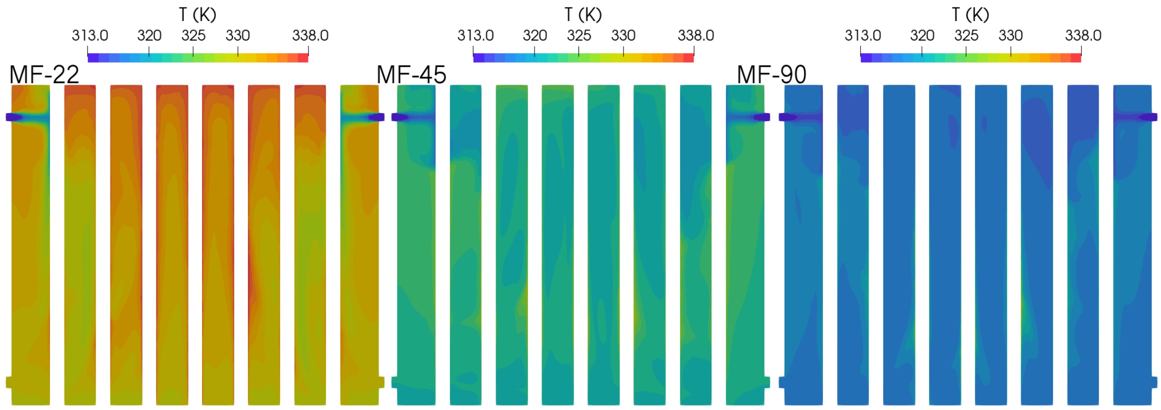

Figure 3: Contours of temperature at the plane xz.

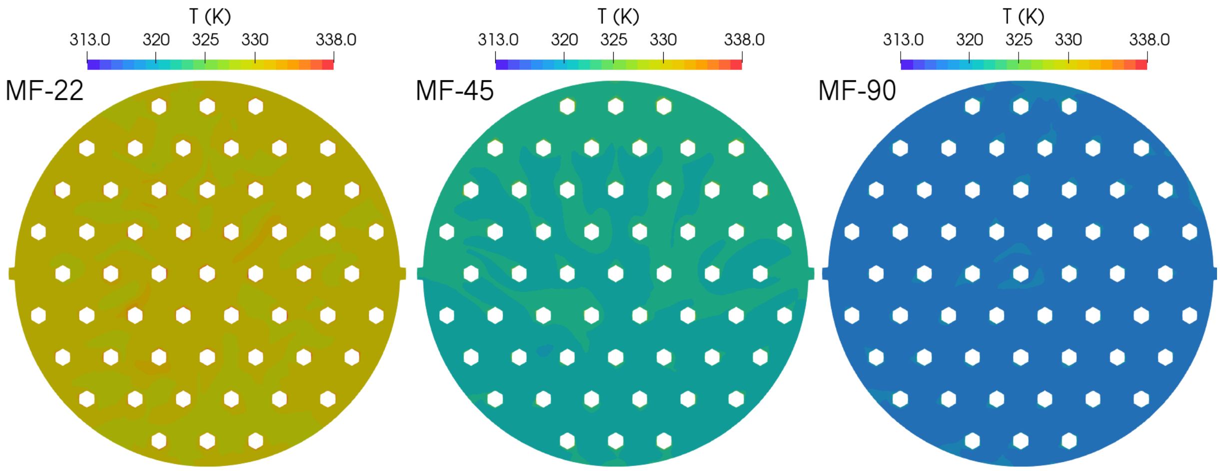

Figure 4: Contours of temperature at the plane xy, z=0.2.

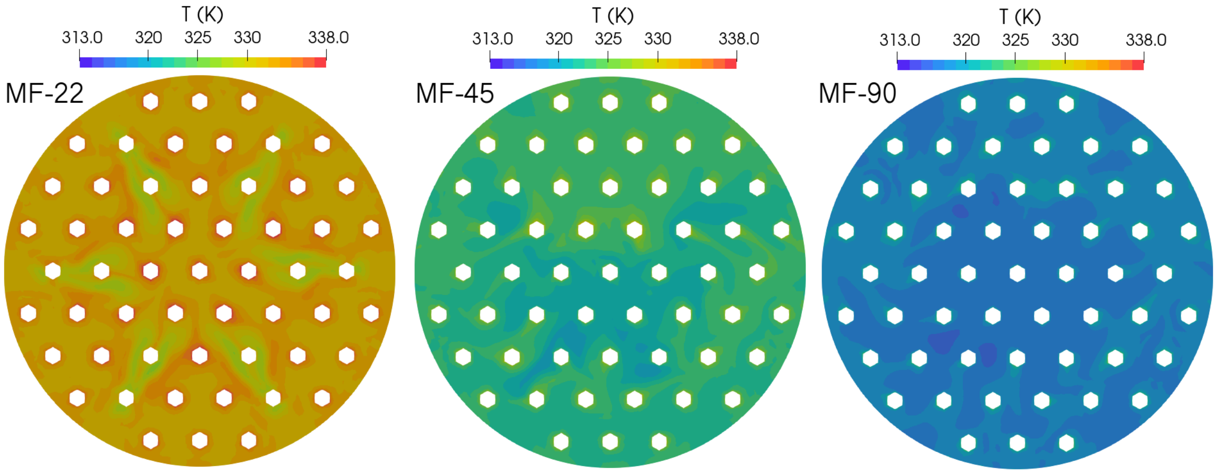

Figure 5: Contours of temperature at the plane xy, z=1.39.

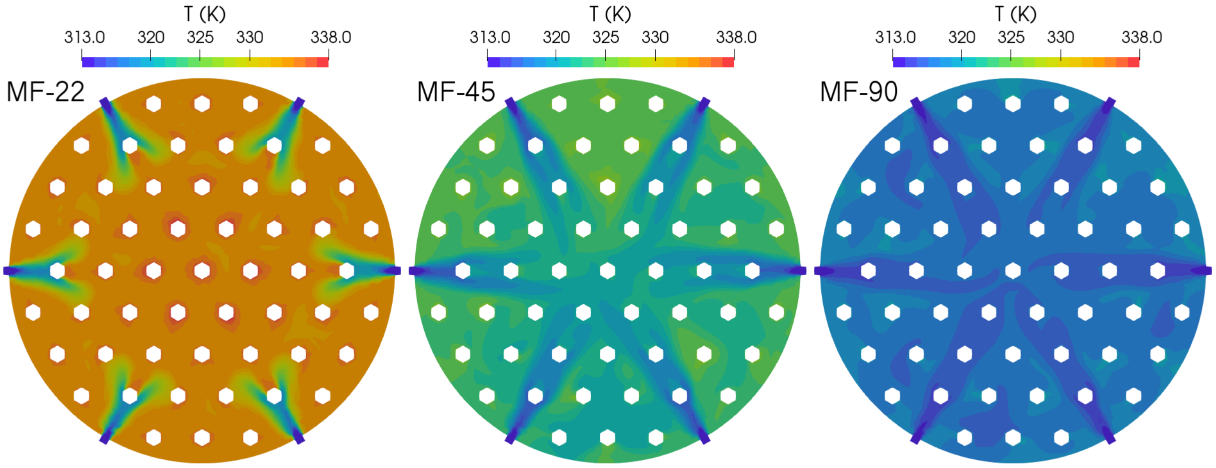

Figure 6: Contours of temperature at the plane xy, z=2.5.

The velocity field shown in Fig. 7 and streamlines in Fig. 8 indicate that for the low mass flow rate case, the inlet jets dissipate too quickly, and they are not able to penetrate the vessel core. This relates to the buoyancy-dominated flow with the stratified temperature profile as a high heat power is near the center fuel assemblies, which results in high buoyant forces [10]. Results from the case MF-90 show that inlet jets had sufficient inertia to penetrate the vessel core, resulting in better mixing than the case MF-22. The mid-mass flow rate case MF-45 shows a good mixing, as the high mass flow rate case.

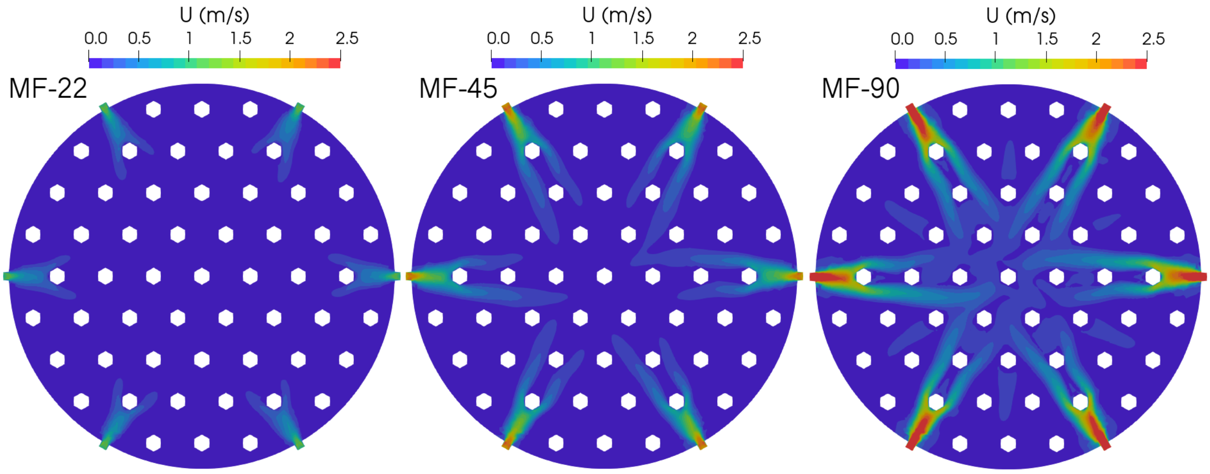

Figure 7: Contours of velocity magnitude at the plane xy, z=2.5.

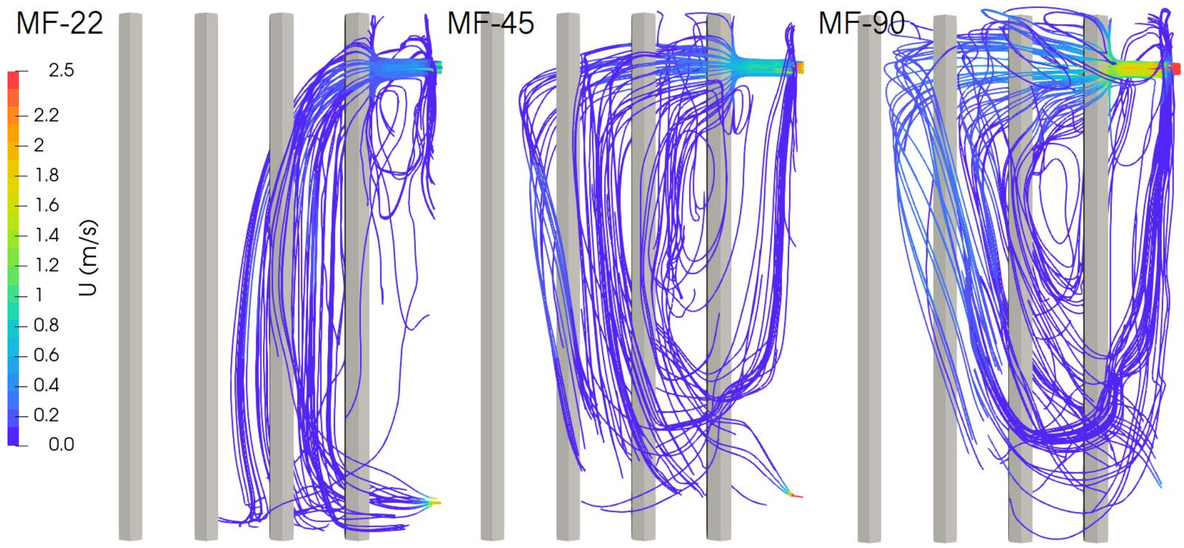

Figure 8: Streamlines of one inlet nozzle coloured by velocity magnitude.

5 CONCLUSIONS

The present study focused on the evaluation of the moderator cooling system in terms of temperature distribution in the moderator's vessel. Predicted results confirm predefined regimes based on the Richardson number. The inertia-dominated flow regime, the case MF-90, showed well-mixed fluid flow with low-temperature differences in the moderator's vessel. The buoyancy-dominated flow regime (MF-22) evinced a stratified temperature field with high temperatures near the center channels and at the top of the vessel. The case MF-45 was identified as a possible transition flow regime from the inertia dominated to the mixed type as some unsteady, randomly distributed temperature patterns were seen near the bottom of the vessel.

Future work in thermal-hydraulic analyses of the TEPLATOR moderator flow will focus on a reactivity change from temperature feedback.

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