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Convective Cooling in a Pool-type Research Reactor

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Abstract. A reactor produces heat arising from fission reactions in the nuclear core. In the Missouri University of Science and Technology research reactor (MSTR), this heat is removed by natural convection where the coolant/moderator is demineralised water. Heat energy is transferred from the core into the coolant, and the heated water eventually evaporates from the open pool surface. A secondary cooling system was installed to actively remove excess heat arising from prolonged reactor operations. The nuclear core consists of uranium silicide aluminium dispersion fuel (U_3Si_2Al) in the form of rectangular plates. Gaps between the plates allow coolant to pass through and carry away heat. A study was carried out to map out heat flow as well as to predict the system's performance via STAR-CCM+ simulation. The core was approximated as porous media with porosity of 0.7027. The reactor is rated 200kW and total heat density is approximately 1.07+E7 Wm^{-3}. An MSTR model consisting of 20% of MSTR's nuclear core in a third of the reactor pool was developed. At 35% pump capacity, the simulation results for the MSTR model showed that water is drawn out of the pool at a rate 1.28 kg s^{-1} from the 4" pipe, and predicted pool surface temperature not exceeding 30˚C.

INTRODUCTION

Computational fluid dynamics (CFD) codes has emerged as a safety analysis tool for understanding nuclear reactor behavior. The code allows in-depth analysis of local temperature and flow fields around fuel geometries as well as flow in reactor coolant system [1][2][3][4][5]. While the predictive capabilities of such codes provide 3D view of thermal flow changes, the certainty of such prediction relies on reactor data that essentially provide code validation.

The Missouri University of Science and Technology Reactor (MSTR) is a 200kW research reactor, and have been in operation since 1961 [6]. Several studies were carried out to prepare for a reactor uprate, and neutronic and thermal-fluid models were developed for this purpose [7][8][9]. In this work, both experimental work and computational calculations were performed to study thermal flow in the MSTR. CFD models were developed and provided analysis of the natural convection cooling of the MSTR core. Results from experimental works described the thermal flow evolution in the core area.

REACTOR DESCRIPTION

The MSTR is fuelled with plate-type fuel, U_3Si_2-Al, at 19.75 wt% U-235 enrichment [6]. The reactor core consists of fifteen fuel elements, four control rods and two irradiation fuel elements. A standard fuel element has 18 fuel plates and a control rod fuel element consists of 10 fuel plates (Figure 1). The irradiation fuel element contains 9 fuel plates. The "fuel meat" dimension is approximately 0.05cm x 6.10cm x 60.96cm. The gap between plates is 0.315cm. In all fuel elements, the plates are encased in an aluminum sleeve, which allows water (coolant) to flow through the gaps between the plates to remove the heat generated from fission. The reactor pool has a rectangular shape with dimensions approximately 5.79 m long, 2.74 m wide and 8.23 m deep. It contains about 113.56 kiloliters of highly purified water. Pool walls are made of ordinary reinforced concrete. The core cooling is by natural

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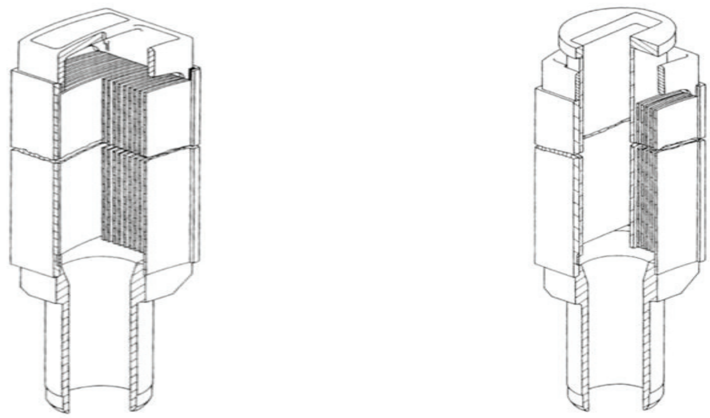
convection, and the heated pool water evaporates into the reactor space. The specific configuration of the MSTR core in this study is 120W, where the fuel elements and control rod fuel element are arranged in a 9 x 5 grid (Fig. 2). There are a total of 310 fuel plates and approximately 295 channels through which coolant flows.



(a) (b)

FIGURE 1. (a) Standard Fuel Element and (b) Control Rod Fuel Element.

TEMPERATURE MEASUREMENT

In this work, three locations in the MSTR core were selected for monitoring temperature changes at 100kW and 200kW. A thermocouple tree (TC-tree) consisting of 17 Type K thermocouples attached to a half-inch PVC pipe was extended into the MSTR pool. The pipe is approximately 8 meters long, and wires connected to the thermocouples are securely wrapped around the pipe. The thermocouple is arranged so that it is one feet apart from each other for thermocouple #1 to #8 and two feet apart for thermocouples #9 to #17. Averaged temperature readouts are taken from FLUKE 54 II Thermometer readers. At the end of the pipe, there is a notch that is used to set it on the fuel element or the grid plate. From the measurements, vertical temperature distributions were obtained. Two locations, C9 and D3, were selected at the periphery of the core and the location F14 is above the center of the core (Fig. 2). The three locations selected represent three points along an approximate middle cross-section of the core; C9 and D3 are easily accessible locations at the core periphery, and F14 is in the core center where the flux is highest.

MODEL DESCRIPTION

A simplified model of the MSTR was developed for CFD analysis [10]. The model consist of one third of the reactor pool, three fuel elements (1.86E+6 Wm^{-3}), an eductor , a 4” pipe inlet with cone-shaped 6” opening, and a fuel storage area (Fig. 3). The inlet serves to remove heated water from the pool into a heat exchanger system. The cooled water is returned to the pool through an eductor that is attached to a pipe which is angled 30° downward from bulkhead wall. MSTR’s heat flux has a cosine shape [7] and this flux was applied on the fuel surfaces. The fuel region was defined as porous region with porosity of 0.7027 [9, 11]. Temperature of the reactor walls were at 294K to correspond with the wall temperature at the start of reactor power up. The walls and the bulkhead surface were maintained at 294K as their locations are far enough from the core that they are not highly affected by the core heat. Top of the pool was set to be adiabatic; evaporation mode is neglected. The model does not consider conjugate or radiation heat transfer.

RESULTS AND DISCUSSION

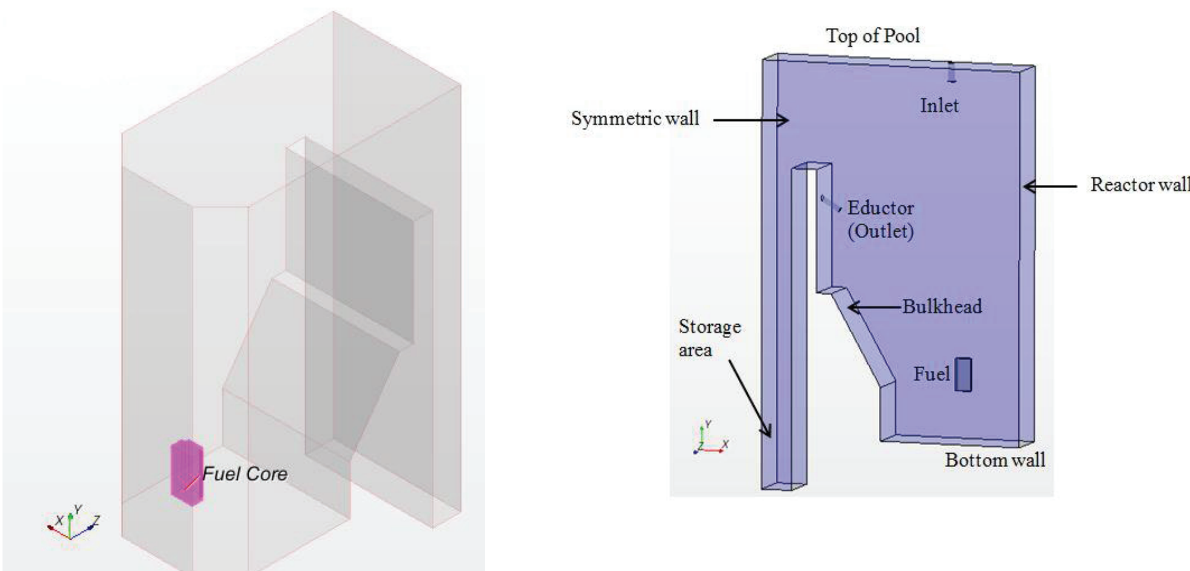
MSTR Thermal Flow

The TC-tree was lowered into the pool at locations D3, F14 and C9 (Figure 2). Temperature measurements were recorded, and were plotted against elevation to show coolant temperature variation in the vertical direction. To obtain an accurate temperature distribution at both D3 and C9 positions, the TC-tree was aligned as closely as possible to fuel elements F4 and F2 respectively. This alignment is made so that the temperature changes along the vertical fuel plate can be captured. At position F14, the TC-tree was placed right above the core to obtain heat plume measurements. Two sets of thermocouple are permanently fixed at the bottom and at the top of the pool, and pool temperatures are continuously monitored during reactor operation. Temperature of the pool during power up is different than at the end of the temperature measurements. Measurement values recorded by the TC-tree are corrected according to the pool temperature at the time of reading.

	1	2	3	4	5	6	7	8	9
A									
B						Source			
C					C4	F5	F1	F17	
D				F4	F8	F14	C1	F10	F2
E				F9	C3	F12	C2	F7	F3
F				CRT	F15	HC	F13	BRT	F6

(a) (b)

FIGURE 1. MSTR 120W Core configuration
(F:Fuel elements, C:Control rods, CRT/BRT: Cadmium/Bare Rabbit Tube, HC: Hot Cell).



(a) (b)

FIGURE 2. MSTR Model (a) Fluid region of the entire pool and complete fuel elements (b) A third of pool and 20% fuel**.**

In the core map, location F14 is approximately the center of the MSTR core. Location C9 is a position bordered by fuels F17 and F2. Location D3 is in the periphery of the core and is adjacent to fuel F4. The coolant temperature rise in F14 is the largest, followed by temperatures in locations C9 and D3. These temperature distributions showed the expected trends, whereby the highest temperature corresponds to the center of the core where the highest flux is located. At C9, the fuels F17 and F2 contributes to a higher temperature rise compared to peripheral temperatures at location D3. Reactivity variation exist between standard fuel element at the center of core (2.5% $\Delta k/k$ to 5.6% Δ k/k) and standard fuel element at the core periphery (0.5% $\Delta k/k$ to 1.5% $\Delta k/k$) and these variation contributes to the temperature trends as well. The F14 data showed that there is a 14K temperature drop from 317K (44°C) to 303K (30°C). This drop is seen from the top of the core to a distance 1.2 meters away from the core top. At 3.5 meters above F14, the coolant temperature was recorded to be between 298K (25°C) and 300K (27°C). The data suggest that the upward convective flow is strongest at F14, and coolant mixing starts approximately 1.5 meters away from the top of the core. As the heat flow from F14 slows-down, the coolant temperature increases between 300K (27°C) and 303K (30°C) in locations C9 and D3.

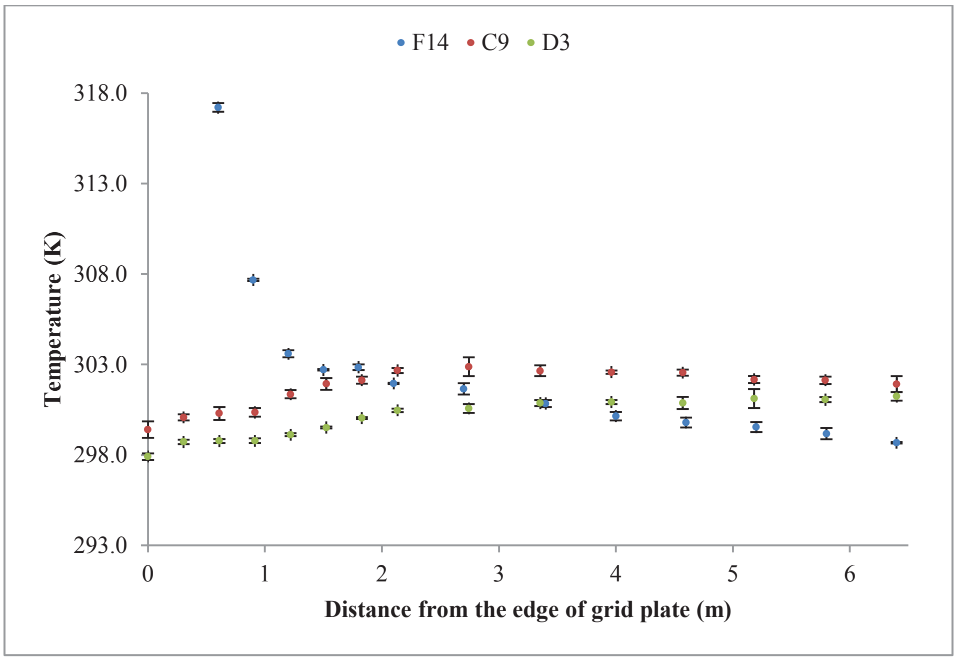


FIGURE 3. Temperature measurement at locations D3, C9 and F14.

Figure 5 shows the F14 temperature distributions at three power levels at 200kW, 100kW and 10kW. The highest temperature recorded is at the position closest to the core; at 200kW, 100kW, 10kW the values are approximately 317K (44°C), 311K (38°C) and 300K (27°C) respectively. The heat dissipates, and coolant temperature starts to come to equilibrium at about 4.5 meters above the core. Measurement uncertainty from the thermocouples is ± 2.2°C or 0.75% above 0°C. Each reading from the thermocouple is taken in a 1-minute average. Experimental statistical methods were applied to obtain error bars in Figs. 4 and 5. Part of this experimental result was used to provide validation for the MSTR model [9].

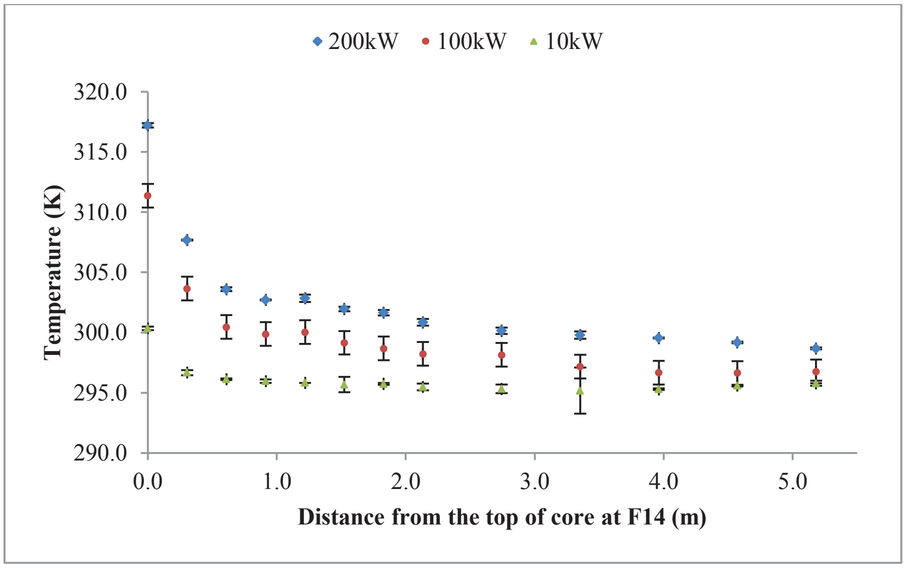
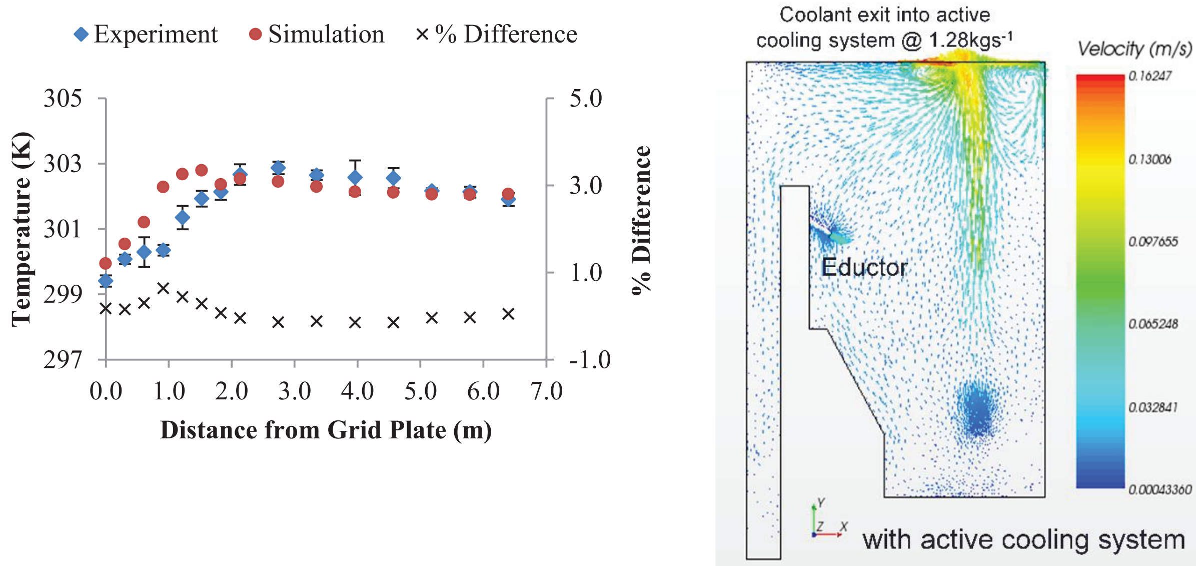


FIGURE 4. Temperature distribution at the core center (F14 location).

CFD Result

Through CFD analysis, users are not only able to visualize the thermal flow in the reactor, but also obtain predictions about the bulk heat removal in various reactor operating conditions.

Figure 6(a) shows the temperatures at location C9 where in this case only natural convection is at work for heat removal. The graph shows a gradual temperature increase in the coolant adjacent to fuel element F2 and F17. The approximate length of the fuel is 0.61m. At 0.6m distance above the core, the coolant temperature begins to come into equilibrium with the bulk pool temperature. Compared with the simulation results, the model predicts a higher temperature rise up to 1.8m and then follows the experimental data trend above 1.8m. The higher rise is due to the model not incorporating the mechanical assembly of the fuel core, which influences flow at the core area. The average temperature difference between simulated result and experimental data is approximately 2K. Figure 6(b) shows the velocity field for the MSTR operated at 200kW. Cool water is discharged at a constant rate 0.4536 kgs^{-1} into the pool through the eductor, and is mixed with the bulk pool water. Heated water is drawn to the inlet where the mass flow rate was predicted to be 1.28kgs^{-1}. According to reactor records, previous pool cooling rate was 2°F per 48 hours, however, the active cooling system allows 1.5 hour to cool the 30,000 gallon pool down from 31°C to 20°C [12].



(a) (b)

FIGURE 6. Simulation results at 200kW (a) Temperatures at C9 (b) Cross-sectional view of the MSTR showing the velocity field.

SUMMARY

This work was done to map out heat flow in the Missouri S&T reactor both experimentally and via computer simulation. The temperature data showed the values at three different locations in the pool for both reactor powers 200kW and 100kW. From CFD analysis, both temperature and flow field of the coolant/moderator was predicted. The results provided MSTR users the ability to analyze thermal flow as well as the tools to predict future operating conditions of the reactor.

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