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EFFECT OF SCALING ON THE THERMALHYDRAULICS OF THE MODERATOR OF A CANDU REACTOR

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ABSTRACT

Three dimensional numerical simulations are conducted on the CANDU Moderator Test Facility (MTF) and the actual size CANDU reactor. Moderator test facility is ¼ scale of the actual reactor. The heat input and other operating conditions are scaled down from the real reactor to the MTF using constant Archimedes number (as considered in MTF experiments performed by Atomic Energy of Canada Ltd.). The heat generations inside both tanks are applied through volumetric heating. In this method, heat is added to the fluid throughout the volume as it occurs in real reactor through fission heat generation and gamma rays from radioactive materials.

The temperatures in actual reactor simulation are about 10 ^{o}C greater than in MTF simulations. The separation between high and low temperature zones are more visible in real reactor simulation comparing to MTF simulation. The result indicates that the MTF has better mixing and weaker buoyancy forces comparing to real reactor. The velocity distribution in both cases seems similar with impingement point for inlet jets in both cases at the right hand side of the tank. Although the velocities are considerably higher (about 40%) in the case of real reactor, but as we go toward inner core of the tanks, the velocities are similar and very low. Several points inside the tank are monitored for their temperature and velocity with time. The results for these points show fluctuations in both temperature and velocity inside the tank. The fluctuations frequency seems higher in the case of real reactor while the amplitude of fluctuations is smaller in real reactor in most of the points. Here, in this research we have shown that Archimedes number alone cannot be a good scaling parameter (as used in MTF experiments) and it should be used along with Rayleigh number for scaling purposes.

Key Words: Thermal hydraulics, Moderator Test Facility, Temperature Fluctuations, Surface Heating, Volumetric Heating, Scaling.

1. INTRODUCTION

Canadian Deuterium Uranium *(CANDU)* nuclear reactor is a Pressurized Heavy Water Reactor *(PHWR)* which uses a moderator tank to moderate the water temperature. A neutron moderator is a medium that reduces the speed of fast neutrons, thereby turning them into thermal neutrons capable of sustaining a nuclear chain reaction involving uranium-235. The moderator system in a CANDU reactor is a low-pressure system that is separate from the primary heat transport system. Heavy water is used both as the moderator and as the primary heat transport fluid. CANDU power reactor is comprised of several hundred horizontal fuel channels in a large cylindrical Calandria vessel. Each fuel channel consists of an internal pressure tube *(containing the fuel and the hot pressurized heavy water primary coolant)*, and an external Calandria tube separated from the pressure tube by an insulating gas filled annulus. The Calandria vessel contains cool low-pressure heavy-water moderator that surrounds each fuel channel. Twelve bundles sit end-to-end within the pressure tube, roughly six meters long, through which pressurized heavy-water coolant is circulated [2].

The specific studies on thermal hydraulics in CANDU reactors or in general term, pressurized heavy water reactors are very limited in the open literature. This is due to the fact that CANDU reactors are relatively new *(since 1970s)* and also due to limitation on accessibility to existing studies due to sensitivity of the issue. These studies can be categorized mainly to experimental and numerical studies which some of them will be mentioned here.

Koroyannaski et al [3] experimentally examined the flow phenomena formed by inlet flows and internal heating of a fluid in a Calandria cylindrical vessel of SPEL (Sheridan Park Engineering Laboratory) experimental facility. They observed three flow patterns inside test vessel and their occurrence was dependent on the flow rate and heat load. Austman et al. [4] measured the moderator temperature by inserting thermocouples through a shut-off rod *(SOR)* guide tube in operating CANDU reactors at Bruce A and Pickering. Huget et al. [5] and [6] conducted 2-dimensional moderator circulation tests at a 1/4-scaled facility in the Stern Laboratories Inc. *(SLI)* in Canada.
Khartabil et al. [7] conducted three-dimensional moderator circulation tests in the moderator test facility *(MTF)* in the Chalk River Laboratories of Atomic Energy of Canada Limited *(AECL)*. Along with separate phenomena tests related to the CANDU moderator circulation, such as a hydraulic resistance through tube bundles, velocity profiles at an inlet diffuser, flow development along a curved wall, and the turbulence generation by temperature differences was measured. He also [8, 9] experimentally studied the moderator tank and recorded its temperature in many points during the operation using fixed thermocouples. He was able to create temperature maps on moderator cross section plane. In order to perform the experiment, a scaled Calandria vessel was designed and tested. The CANDU Moderator Test Facility *(MTF)* is a ¼ scale CANDU Calandria, with 480 heaters that simulate 480 fuel channels. It is specifically designed to study moderator circulation at scaled conditions that are representative of CANDU reactors. The MTF was operated at various operating conditions that simulate moderator circulation in CANDU reactors and temperatures were recorded. This study is initiated by these tests in order to numerically simulate the same tank to have more in depth analysis and extract data which are impossible to obtain using experimental devices.

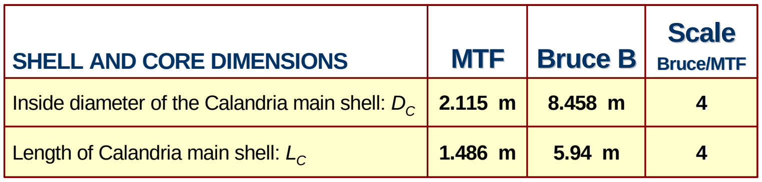
The real time data recording at various locations inside the MTF tank have shown some level of fluctuations in the moderator experimental temperatures. Fluctuations in moderator temperatures are believed to be due to the flow turbulence resulting from the interplay of local momentum and buoyancy forces, inlet nozzle jet impingements, and the flow passing through the tube bundle. The magnitude of the temperature fluctuations measured in the three-dimensional moderator test facility *(3D-MTF)* depends on the test conditions and on the location in the core.

In this study, two different set of simulations are performed for both actual size reactor and MTF and the result for temperature and velocity distributions and fluctuation plots are compared to investigate the nature of the flow inside the moderator. The results for both simulations are compared with each other to study the effects of scaling on the results and find out if proper scaling methods have been employed to model the real reactor in MTF facility.

2. NUMERICAL SETUP

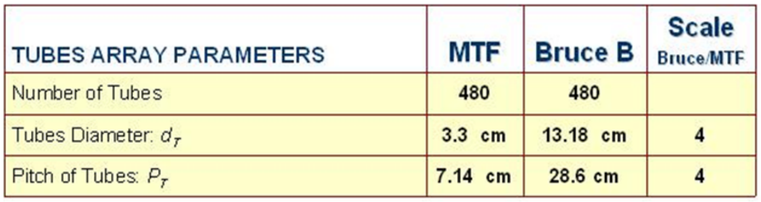
The MTF tank is a ¼ scale of Bruce B Calandria tank, as their main dimensions are shown in Table I and Table II. The MTF and Bruce tanks and their inlet nozzles are also shown from various views in figure 1.

Table I. MTF and Bruce B Shell and Core Dimensions



SHELL AND CORE DIMENSIONS	MTF	Bruce B	Scale Bruce/MTF
Inside diameter of the Calandria main shell: D_C	2.115 m	8.458 m	4
Length of Calandria main shell: L_C	1.486 m	5.94 m	4

Table II. MTF and Bruce B Tubes Array Dimensions



TUBES ARRAY PARAMETERS	MTF	Bruce B	Scale Bruce/MTF
Number of Tubes	480	480	
Tubes Diameter: d_T	3.3 cm	13.18 cm	4
Pitch of Tubes: P_T	7.14 cm	28.6 cm	4

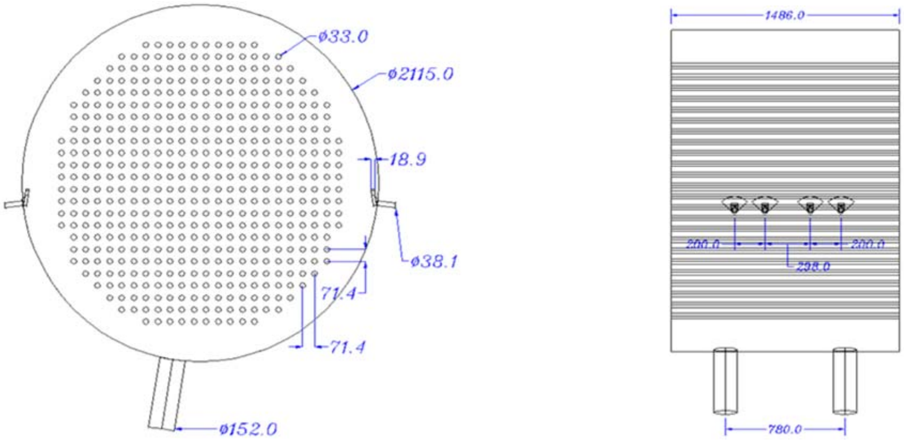


Figure 1. The schematic drawing of the MTF tank (all dimensions are in mm).

During the normal operation of CANDU reactor, the cold moderator water enters the tank through eight nozzles, four nozzles at each side, and heated fluid exits from two outlet pipes at the bottom of the tank. Throughout the operation, two major flow characteristics are identified inside the tank: Buoyancy driven fluid flows formed by the internal heating, and momentum driven fluid flows by the jet flows through the inlet nozzles, respectively. The flow behavior depends on the operating conditions, such as, moderator mass flow rate and its temperature, and the rate of heat influx to the moderator. The operating conditions for the MTF and Bruce B used in the simulations are listed in Table III.

Table III. MTF and Bruce B operating conditions.

NOMINAL CONDITIONS	MTF	Bruce B, 50% FP
Power (kW)	**1,090**	**64,500**
Average heat source	**14.74** kW/m^2	**277** kW/m^3
Moderator mass flow rate (kg/s)	**22.9**	**948.0**
Number of nozzles	**8**	**8**
Number of outlets	**2**	**2**
Inlet Temperature (ºC)	**40.1**	**44.8**
Outlet Temperature (ºC)	**51.5**	**61.0**
Temperature difference (ºC): ΔT	**11.4**	**16.2**

In the actual Calandria vessel of a CANDU reactor, the cold fluid is heated by direct heating of neutrons, decay heat from fission products, and/or gamma rays in the vessel. In numerical simulation this method is represented through heat sources inside the tank. The tank volume is divided into 6 zones and each zone has its own volumetric heat source.

An unstructured non-uniform tetrahedral mesh was used to construct meshes in the full MTF and Bruce tanks. A total of 3,200,000 meshes were generated using the commercial software Gambit and the solution domain is divided into 20 partitions for parallel processing. Fluent V.12 has been employed to perform the simulations. Fluent solves the governing integral equations for the conservation of mass, momentum, energy, and turbulence where the fluid is assumed to be incompressible and single-phase and the flow is considered to be time dependent and turbulent.

3. RESULTS

Figure 2 shows the temperature distribution inside the moderator tank for both MTF and the actual reactor tank. It presents a plane which passes through two inlet nozzles and one outlet. This is one of the most important planes inside the tank since it shows the interaction between inlet jets, bulk fluid inside the tank, and the exit flow.

Temperature contours are shown for two different times. The first one is the initial phase at t = 20 s and the second one is for t = 150 s which is considered the end of the simulation. The upper row corresponds to MTF simulation and the lower row is the result of actual moderator simulation. Two inlet nozzles are visible at two sides of the outer wall with low temperature of 40 ^{o}C. The highest temperature observed for MTF is around 55 ^{o}C at the opposite side of the impingement location while the high temperatures are near 73 ^{o}C at almost the same location as MTF for the actual reactor. This is close to 35% variation in maximum temperature between to cases. The average temperature in bulk flow in the case of MTF is close to 55 ^{o}C while in the case of actual reactor it increases by 18% to 65 ^{o}C. The location of the hot zone is almost the same in both cases as the impingement point for inlet jets are located on the top right hand side of the tank.

The temperature distribution is more homogenous in the case of MTF and less segregation can be observed between high and low temperature zones. This can be the result of better mixing of hot and cold flows in the case of MTF comparing to the actual reactor. The competing forces here are the momentum of the inlet jets and the buoyancy force due to temperature difference inside the tank. Since the method of heat generation is the same for both MTF and the actual reactor, this significant variation in temperature distribution can be attributed to the scaling method employed in modeling the actual reactor.

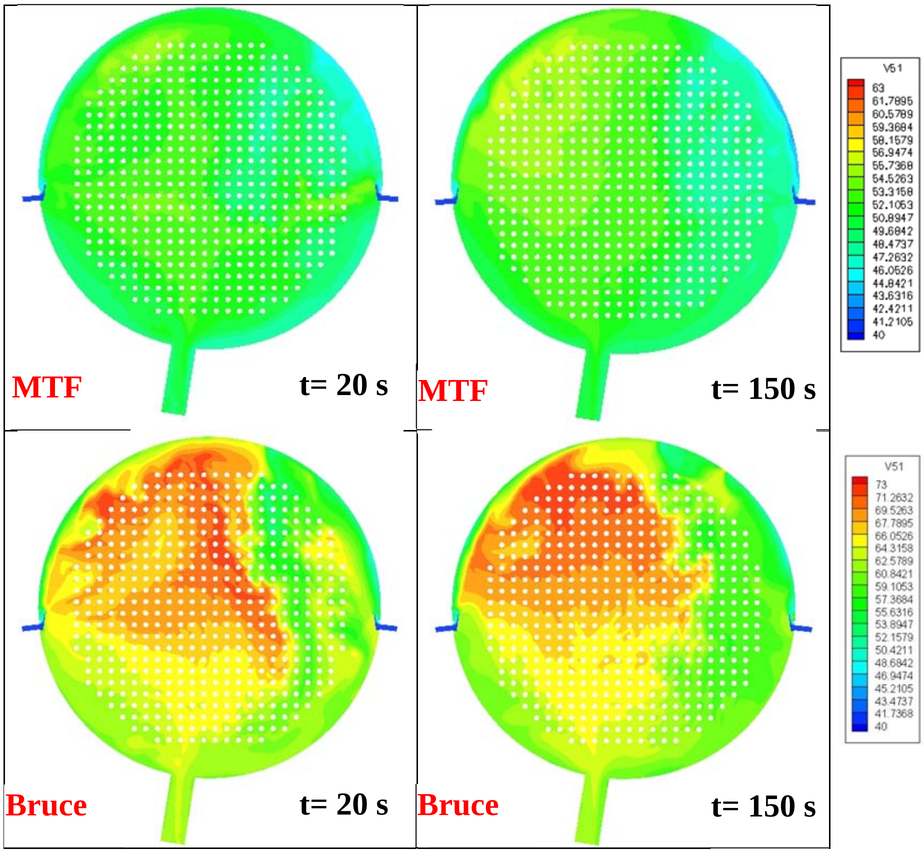


Figure 2. Temperature contours in various times for Bruce and MTF.

Figure 3 shows the velocity contours for the same plane as figure 2 at the same instances. The impingement point is located at the top right hand side of the tank for both cases. Thee velocities are nearly 45% higher in the case of the actual reactor with velocities as high as 1.3 m/s comparing to only 0.9 m/s for the MTF. After two inlet jets impinge on each other a secondary jet is formed which passes through the tube bundles and goes toward the exit pipe. The velocity distributions show that the secondary jet penetrates more in the case of actual reactor comparing to the MTF simulation.

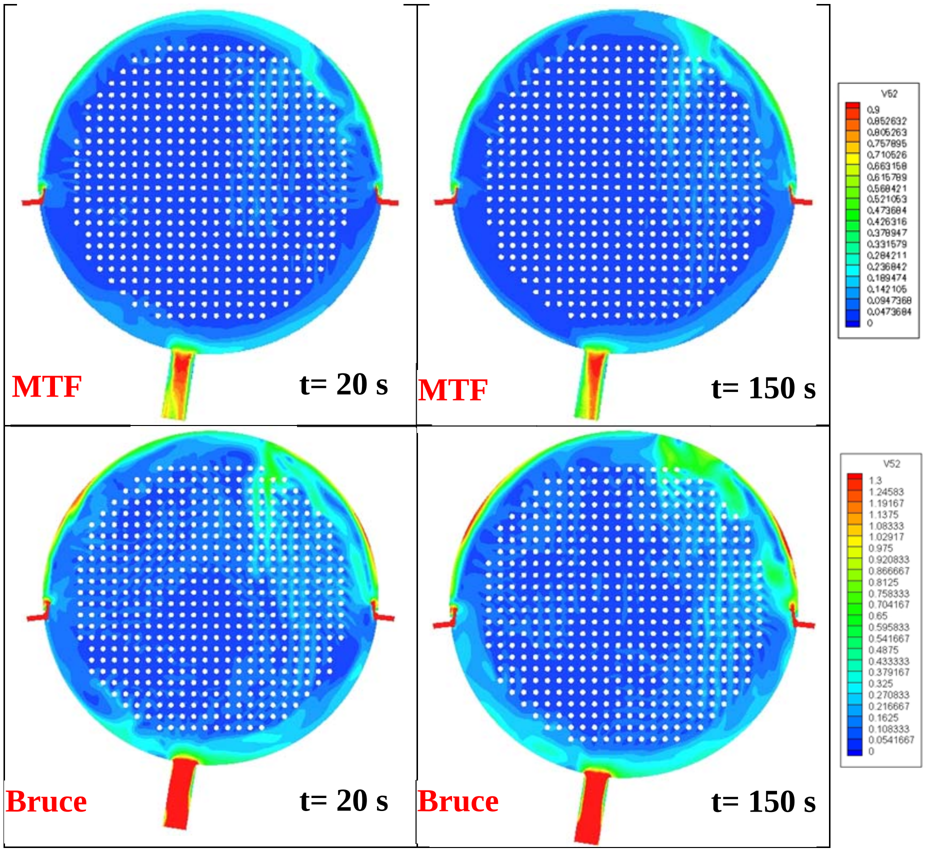


Figure 3. Velocity contours in various times for Bruce and MTF.

Several points inside the tank have been monitored throughout the simulation for their temperature and velocity. The results for these points are used to analyze fluctuations inside the tank. One point is chosen here for comparison purposes. It is located at the middle of the tank close to the interaction between hot and cold zone.

Considering all monitored points, no general trend can be identified for the frequency and amplitude of temperature and velocity fluctuations. But in most points as shown in figure 4, in the case of the actual reactor the frequency is higher and amplitude is lower comparing to the MTF simulation. The higher frequency can be attributed to more temperature gradient visible in the case of the real reactor. Since the real reactor observes more segregation between high and low temperature, the interaction between these two flows are more intense and results in higher frequency fluctuations in temperature.

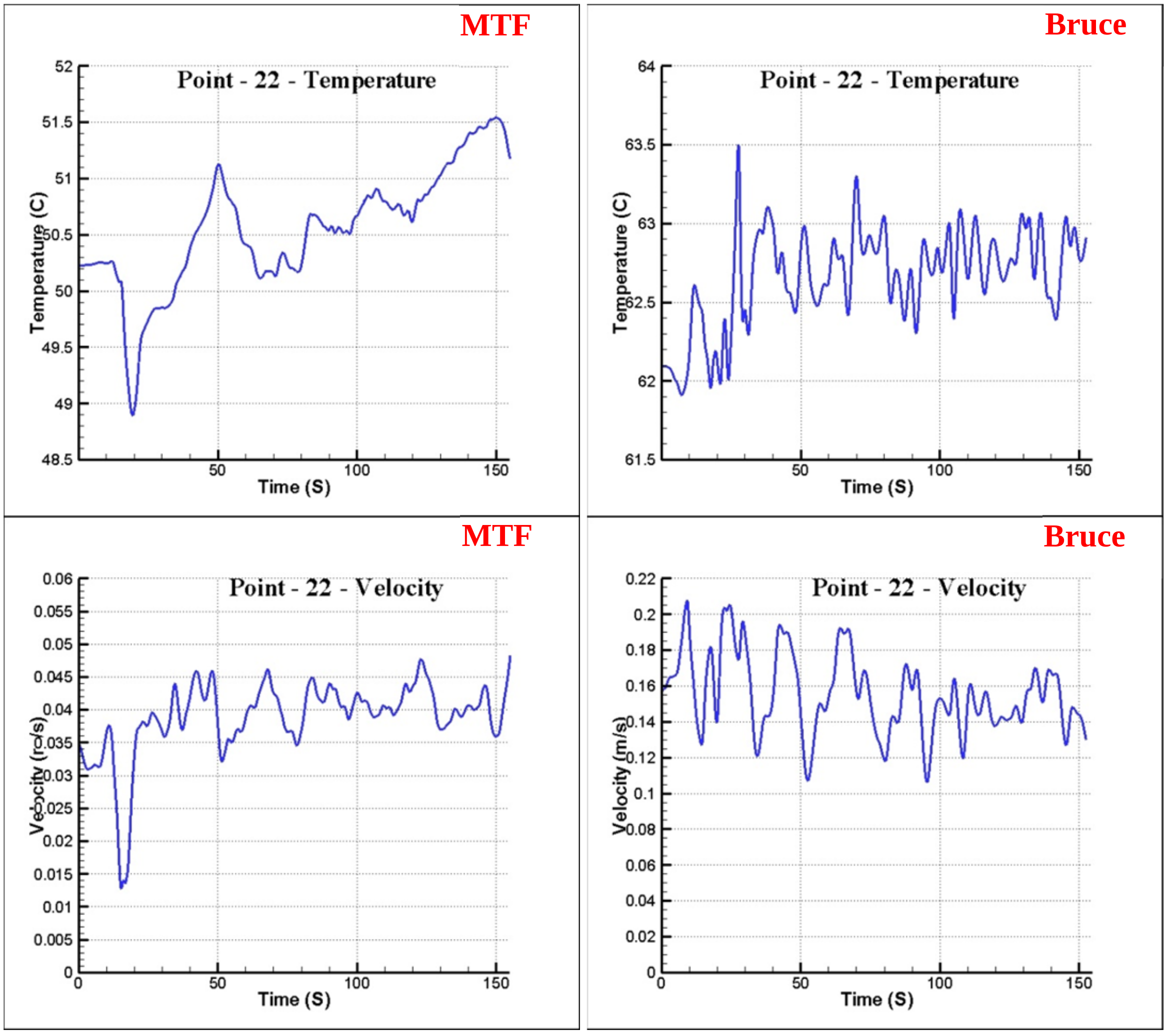


Figure 4. Temperature and velocity fluctuations plot for Bruce and MTF.

Based on the results presented, it can be concluded that the flow inside the tank is dominated by two forces: momentum and buoyancy. The first is due to the inlet jets and the latter one comes from density variation (due to temperature gradient) inside the tank. Momentum causes the bulk flow motion from the inlets to the outlets and buoyancy causes the formation of hot zone on the top left corner of the tank.

In order to be able to quantify the phenomena, two non-dimensional numbers are considered in the open literature for similar cases. These numbers are Archimedes and Rayleigh numbers. The definitions for these numbers are as follow:

$$Ar = \frac{Gr}{Re^2} = \frac{\frac{buoyancy}{viscous}}{\frac{momentum}{viscous}} = \frac{buoyancy}{momentum} = \frac{g\beta\Delta TD}{V^2} \qquad (1)$$

$$Ra = GrPr = \frac{(buoyancy)(convection)}{(momentum)(conduction)} = \frac{g\beta\Delta T D^3}{\alpha \upsilon} \tag{2}$$

Where g is the acceleration of gravity, V is the inlet average velocity, β is the thermal expansion coefficient, α is thermal diffusivity, $\Delta T = T_{out} - T_{in}$, υ is kinematic viscosity, and D is the tank diameter. Archimedes number shows the ratio between buoyancy and momentum forces which are the main competing forces here and the Rayleigh number adds to this ratio the effect of heating method inside the tank. Khartabil et. al. [7] used Archimedes number as the basis of their experiments. They wanted to scale down their experiment tank 4 times smaller in each direction comparing to the actual reactor (64 times smaller in volume). They assumed constant Archimedes number for both cases and then scaled down both the volume and the heat input by a factor of 64.

Comparing the simulation results for the actual reactor and the scaled down MTF model shows that the differences between the two are noticeable and can be attributed to the method of scaling. The temperature distributions, maximum and minimum temperatures, velocity distributions, and the fluctuations frequency and amplitude vary in the two cases in a way that cannot be ignored or being associated with numerical errors. Table IV shows the comparison between Archimedes, Rayleigh, and Grashof numbers for MTF and the actual reactor. It is clear that although the Archimedes numbers match, but the Rayleigh numbers vary by 2 orders of magnitude. This can be the main reason behind the differences observed between two cases which are supposed to present each other with an acceptable accuracy.

Table III. MTF and Bruce B operating conditions.

	Ar	Ra	Gr
MTF	0.1027	3.6×10^{12}	1186.7×10^{8}
Bruce	0.1131	4.6×10^{14}	9060.65×10^{8}

The main issue which triggered the experimental and numerical investigation of the moderator tank was the fluctuation observed in temperature and velocity inside the tank. The result presented here, clearly shows that the fluctuation for the same points inside the MTF and the actual tank are noticeably different. Although one may expect to see different fluctuations at the same point (since the nature of the fluctuations is random and unpredictable), but their frequency and amplitude and also the average quantity should be similar which is not the case in comparing several points between the two cases.

There are several papers [10, 11, 12] which suggest that the fluctuations inside the tank have direct relation with Rayleigh number. In fact, they suggest that Rayleigh number is the determining factor for the fluctuations and higher than a critical Rayleigh number the fluctuations are initiated. For example cheng et. al. [10] suggests that for air convective flow inside a bottom heated cylinder, flow is chaotic for Rayleigh number higher than 10^5. All other papers also suggest similar ranges for the initiation of fluctuation and chaotic flow. The Rayleigh number for our specific case is much higher than critical Rayleigh number and we are well inside the chaotic zone which will cause unsteady fluctuations in temperature and velocity. As a result, Rayleigh number becomes an important part of our conditions and should be considered in scaling procedure from the actual reactor moderator to the MTF tank.

4. CONCLUSIONS

Three dimensional, unsteady simulations are performed for both the actual moderator tank of a CANDU reactor and a scaled down version called MTF (Moderator Test Facility). MTF is built by AECL (Atomic Energy of Canada Limited) and is used to investigate the flow pattern inside the moderator tank. The result for temperature and velocity distributions and fluctuations are compared for both cases and similarities and differences are pointed out. The scaling procedure from the actual reactor to the MTF is discussed. The important non-dimensional numbers are introduced and the effect of each number is explained.

The study showed that noticeable differences exist between the actual reactor results and the MTF results. It was concluded that these variations may be due to the scaling procedure which only has considered constant Archimedes number. This study suggested that the Rayleigh number should be used along with Archimedes number in scaling since the Rayleigh number is the determining quantity in temperature and velocity fluctuations inside the tank.

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