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Isothermal flow measurement using planar PIV in the 1/4 scaled model of CANDU reactor

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1. Introduction

The CANadian Deuterium Uranium (CANDU) reactor has a square array of horizontal fuel channels which are submerged in a pool of a heavy water moderator. Each fuel channel consists of two concentric tubes, a Pressure Tube (PT) inside a Calandria Tube (CT), and a gap that contains CO_2 insulating gas. One of the important design features of the moderator (heavy water) is a heat sink during some postulated accidents such as a large break Loss Of Coolant Accident (LOCA). If the moderator available subcooling at the onset of a large LOCA is greater than the subcooling requirements [1], a sustained calandria tube dryout is avoided. The subcooling requirements are determined from a set of experiments known as the fuel channel contact boiling experiments [2]. The difference between available subcooling and required subcooling is called subcooling margins. The local temperature of the moderator is a key parameter in determining the available subcooling.

To predict the flow field and local temperature distribution in the calandria, Korea Atomic Energy Research Institute (KAERI) started the experimental research on moderator circulation as one of a national R&D research programs from 2012. This research program includes the construction of the Moderator Circulation Test (MCT) facility [3], production of the validation data for self-reliant CFD tools, and development of optical measurement system using the Particle Image Velocimetry (PIV) [4] and Laser Induced Fluorescence (LIF) techniques. Small-scale 1/40 and 1/8 small-scale model tests were performed prior to installation of the main MCT facility to identify the potential problems of the flow visualization and measurement expected in the 1/4 scale MCT facility.

In the 1/40 scale test [5], a flow field was measured with a PIV measurement technique under an iso-thermal state, and the temperature field was visualized using a LIF technique. In this experiment, the key point was to illuminate the region of interest as uniformly as possible since the velocity and temperature fields in the shadow regions were distorted and unphysical.

In the 1/8 scale test [6], the flow patterns from the inlet nozzles to the top region of the tank were investigated using PIV measurement at two different positions of the inlet nozzle. For each position of laser beam exposure the measurement sections were divided to 7 groups to overcome the limitation of the laser power to cover the relatively large test section.

The MCT facility is the large-scale facility designed to reproduce the important characteristics of moderator circulation in a CANDU6 calandria under a range of operating conditions. It is reduced in a 1/4 scale and a moderator test vessel is built to the specifications of the CANDU6 reactor design, where a working fluid is sub-cooled water with atmospheric pressure. Previous studies were conducted with 380 acrylic pipes instead of the heater rods and a preliminary measurement of velocity field using PIV is performed under the iso-thermal test conditions. However, the acrylic pipes are easy to be deflected over time. The undesirable deflection of the acrylic pipes might affect the flow field. In the present work the test vessel is equipped with 380 heater rods replacing the acrylic pipes. Before we conduct the heating experiments, we performed the non-heating condition flow measurement to improve the accuracy of our result data.

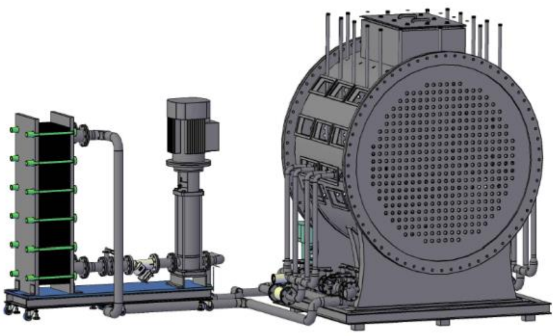
2. Experimental method

2.1 Test facility

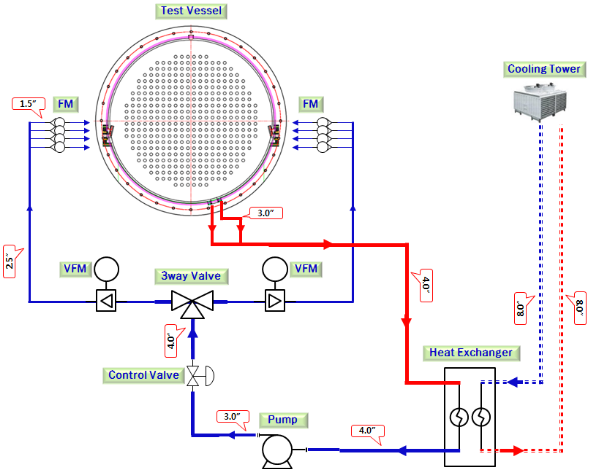
The MCT facility consists of the primary and secondary water circuit as the same as CANDU-6 moderator system. The primary circuit, as shown in Fig. 1(a), includes a moderator tank, a circulating pump, a heat exchanger, and intermediate pipe lines. The circulating pump enforces the cold water to enter the tank through eight nozzles, four nozzles at each side, and heated water exits from two outlet pipes at the bottom of the tank. When water flows through the heat exchanger tubes, primary hot water is cooled by the secondary side water circulating through the external cooling tower. Then cold water comes back to the inlet nozzles via a circulating pump.

The inner diameter and axial length of test vessel are 1900 mm and 1500 mm, respectively. Up to the previous studies, the horizontal fuel channels were simulated with 380 acrylic rods. The acrylic rods are not able to give a heating condition, and they are easy to deflect with time. Because of the deflection of the acrylic rods, the geometry of the flow path was changed with some portion of the spatial uncertainty. The test vessel is newly equipped with 380 electric heaters (stainless steel) instead of the acrylic tubes. The newly equipped stainless steel heater rods are straighter than previous deflected acrylic tubes. The electric heaters are designed to provide axial and radial power profiles representative of CANDU6 power profiles, but they are not operated during this experiment.

Tank walls with 5 mm of thickness and other support structures are made of SUS 304 stainless steel. Several transparent sections are incorporated into the vessel to facilitate flow visualization tests. The front and rear side of both ends of the tank are individually made of a poly-carbonate plate with 15 mm thickness. These plates are sealed by two stainless steel flanges (each of 35 mm and 25 mm thickness) with a silicone O-rings placed in-between. Eight view ports are installed to each side of the tank wall.



(a) Overview of the primary water circuit of MCT



(b) Pipe line configuration of MCT

Fig. 1. Geometric configuration of the MCT test facility

The MCT facility is thoroughly instrumented to provide data suitable for code validation. The test conditions are tightly controlled using a PC-based data acquisition and control system (DAS). The instrumentation can be divided into test vessel and loop instrumentation.

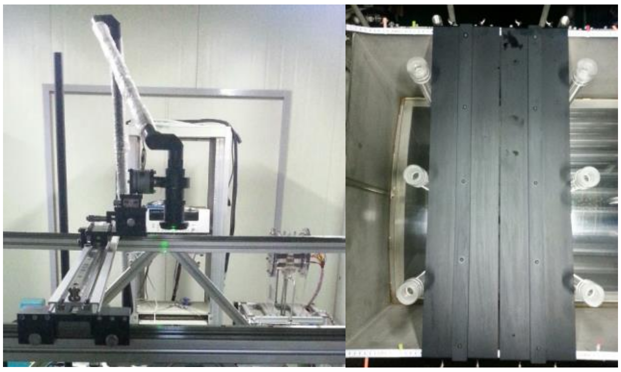
The velocity profiles in the test vessel are measured by the PIV measurement system. An access tank (950 mm × 650 mm) on top of the vessel allows the exposure of the laser beam as well as thermocouple measurements inside the vessel. The loop instrumentation consists of flow rate, temperature, and pressure measurements. The multi-stage centrifugal pump is used to circulate water in the primary loop and a total flow rate is adjusted by the inverter control. The flow rate to each side of inlet nozzles is measured by a vortex flow meter and the flow split to each side is automatically controlled by 3-way valve. The flow rates to individual inlet nozzles can be monitored and adjusted by rotameters. The inlet and outlet temperatures are measured by T-type thermocouples.

2.2 PIV measurement

The PIV measurement system consists of a TSI POWERVIEWTM Plus 2MP CCD camera and a Dual Nd-Yag. The double pulse laser was operated at 15 Hz with a 200 mJ/pulse. The laser beam was modified using spherical and cylindrical lens combination to form a thin light sheet on the x-y plane. 10 μm sized silver coated hollow spheres were used as a flow tracing particles. The 2MP CCD camera records scattering light from the tracer particles. INSIGHT^{TM} 4G software is used to control the image capture and perform the data analysis.

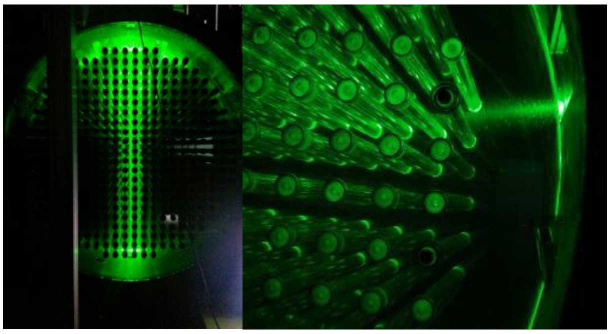
The PIV data analysis consists of cross-correlation to calculate the flow vectors with sequentially captured images which have discrete time difference (dt). The cross-correlation calculation was performed in each interrogation windows whose size is 32 x 32 pixels.

Figure 2 shows the PIV laser illumination system. The laser guiding arm in Fig. 2(a) was used to guide the laser beam to the target position and direction (top of the tank, downward). At the end of the guiding arm, combination of spherical and cylindrical lens are attached to make a thin light sheet in the x-y plane. The end of the guiding arm is attached to the linear motion and angle stage to accomplish the fine adjustment of the position and directing angle of the laser beam. The laser slit in Fig. 2(b) is also arranged on top of the Calandria tank to control the thickness of the laser sheet. The slit is also helpful to adjust the slit position using the gradation on a ruler which is attached on top of the tank. The thickness of the laser sheet is adjusted as 4 mm at slit position.



(a) Laser head adjustment (b) Laser slit

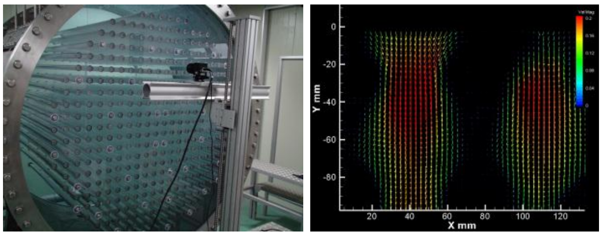
Fig. 2. Positioning of the measurement plane in the tank



(a) Downward direction

(b) To one side direction

Fig. 3. Illumination of leaser sheet in two different directions



(a) Camera mount with two axis traverse system

(b) Analysis of PIV images

Fig. 4. PIV image capture and vector generation

As the transparent window on top of the tank is not wide, the laser illumination from the top was limited to the center region. To overcome this limitation, additional experiments were conducted by placing the laser source to side of the tank as shown in Fig. 3(b).

In the PIV measurement the camera views the light sheet in front of the poly-carbonate plate of the tank. The camera mount with two axis (X-Y) traverse systems (Fig. 4(a)) ensures the target areas of the object plane in focus. The target images are captured by unit cell of square array while the camera is vertically traversed with a distance of pitch. Using Insight 4G, image acquisition, analysis and display software, image capture synchronization is controlled. In the sequence capture mode 1000 correlation images in each test condition are collected and these images are processed by cross-correlation technique (Fig. 4(b)). Then the average of 1000 vector files is computed by Tecplot software.

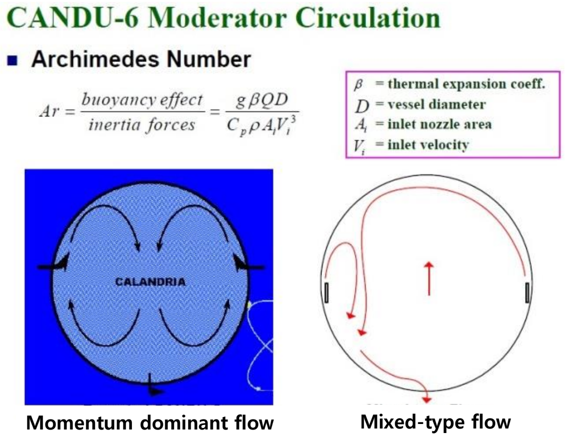
3. Results and analysis

From the scaling analysis [7] the flow pattern inside the moderator tank is determined depending on the ratio of the characteristic buoyancy to inertia forces, the non-dimensional Archimedes number (Ar), defined as

$$Ar = \frac{g\beta QD}{\rho C_p A u^3} \qquad (1)$$

where, Q is a heater power, D is a tank diameter, A is an inlet nozzle area, and u is an inlet velocity.

In the iso-thermal test for present work, where the flow is momentum dominant as shown in Fig. 5, the inlet jets penetrate to the top of the tank and produce a downward flow through the center of the tube columns towards the outlet nozzle and the flow fields are in symmetric distributions.



CANDU-6 Moderator Circulation

- **Archimedes Number**

$$Ar = \frac{buoyancy\ effect}{inertia\ forces} = \frac{g\beta QD}{C_p \rho A_i V_i^3}$$

β = thermal expansion coeff.
D = vessel diameter
A_i = inlet nozzle area
V_i = inlet velocity

Momentum dominant flow

Mixed-type flow

Fig. 5. Flow characteristics in the moderator tank

A downward flow vectors (-v) through the columns are measured and the magnitude of the velocity in the center point of the unit cell is plotted in Fig. 6. Distribution of downward velocity along the vertical lines for different x-directional locations (horizontal direction on the cross-sectional plane) are compared. The measurement results clearly show the decrease of velocity as it flows down toward bottom of the tank. The downward velocity profiles are significantly different in the y > 100 mm region of Fig. 6. The downward velocity profile at x = 0 mm is the highest among other positions, and it decreases as x-directional position is far away from the vertical centerline at x = 0 mm. For the case at x = 216 mm, there are negative velocities at y > 800 mm which means the upward velocity. This upward velocity is caused by the jet flow from the inlet nozzle at both sides. However, downward velocity profiles of y < 100 mm region are similar independent on the x-directional position. The reason why the velocity profiles are similar to each other at y < 100 mm region is that the upward inlet jet flow does not influence the lower region. As the downward flow of each x-directional position passes through the heater rods, the velocity is regularized.

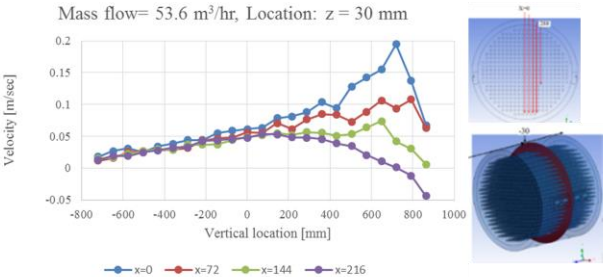
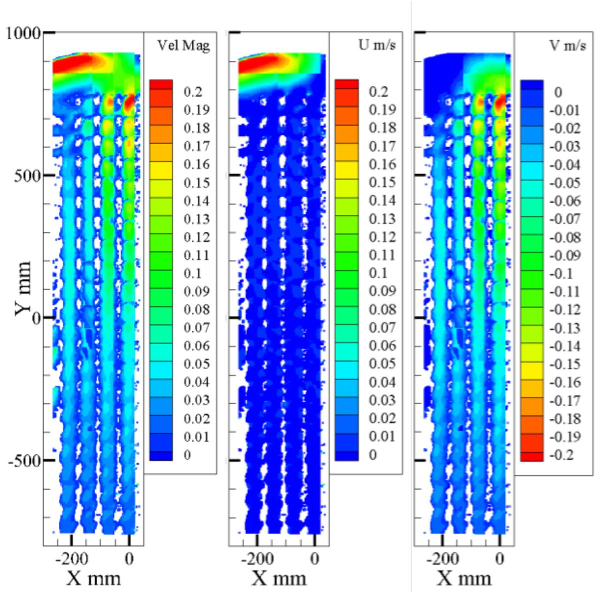


Fig. 6. Variation of downward velocity along the vertical line for different x-directions



(a) Velocity magnitude (b) x-directional velocity (c) y-directional velocity

Fig. 7. Overall velocity field plot

Because of the symmetric geometry and the non-heating conditions, momentum driven flow will be in a symmetric manner. Therefore, we conducted the flow measurements only for x < 0 region as shown in Fig. 7. For the non-heating tests Fig. 7 shows the overall velocity field fields by: (a) velocity magnitude, (b) x-directional velocity, and (c) y-directional downward velocity. There are obvious two regions where x-directional velocity or y-directional downward velocity is dominant. Top region of the fluid domain has high velocity which is induced by the inlet nozzle. Because the jet flow from the inlet nozzle moves along the circumference of the tank, x-directional velocity is dominant at top of the tank. However, the x-directional velocity at top-center region is low because of the symmetrical geometry. Jet flows from both side collides at top-center region and the fluid tends to flow downward. Therefore, we can see the high downward velocity from the top-center region. Middle region of the tank surrounded by the heater rods shows very low x-directional velocity and the relatively high y-directional downward velocity. Most portion of the velocity magnitude shown in Fig.7 (a) in the middle and low region are by the downward velocity (Fig. 7c).

From the present test results, we could observe that the jet flows generated due to the inlet flows go to top-center of the tank, impinge on each other, and form downward moving flows through the tube bank.

4. Conclusions

The 1/4 scale of moderator circulation test (MCT) facility has been installed to reproduce the moderator circulation behavior in the CANDU6 calandria tank. In the present work the test vessel is equipment with 380 heater rods replacing the acrylic tubes and a preliminary measurement of velocity field using PIV is performed under the non-heating test conditions.

The 2D velocity is measured on the cross-sectional plane normal to the axial direction of the tank. The PIV measurement results could capture the same flow pattern as that expected in the CANDU6 calandria tank under momentum dominant flow condition, where the inlet jets penetrate to the top of the tank and produce a downward flow through the center of the tube columns towards the outlet nozzle and the flow fields are in symmetric distributions.

The measurements of downward velocities are performed at different locations. The velocity is shown to be axially uniform. The velocity is rapidly decreased as the measurement location is far from the center of tank, since the downward flow is dominant along the center of the tube columns.

In the future we will conduct the flow measurements under the heating condition and compare those results with the CFD predictions.

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REFERENCES

[1] H.Z. Fan, R. Aboud, P. Neal and T. Nitheanandan, Enhancement of the Moderator Subcooling Margin using Glass-peened Calandria Tubes in CANDU Reactors, Proceedings of 30th Annual Conference of the Canadian Nuclear Society, May 31-Jun. 3, 2009, Calgary, Canada.

[2] G.E. Gillespie, An Experimental Investigation of Heat Transfer from a Reactor Fuel Channel: To Surrounding Water, Proceedings of 2nd Annual Conference of the Canadian Nuclear Society, Jun., 1981, Ottawa, Canada.

[3] H.T. Kim and B.W. Rhee, Scaled-down moderator circulation test facility at Korea Atomic Energy Research Institute, Science and Technology of Nuclear Installations Vol.2015, p. 1-11 2015. (to be published)

[4] C.D. Meinhart, S.T. Wereley and J.G. Saniago, A Pive Algorithm for Estimating Time-averaged Velocity Fields, Journal of Fluids Engineering Vol.122, p. 285-289, 2000.

[5] H.T. Kim, Measurement of Velocity and Temperature Profiles in the Scaled-down CANDU-6 Moderator Tank, Proceedings of the 21st International Conference on Nuclear Engineering, Jul. 29-Aug. 2, 2013, Chengdu, China.

[6] H.T. Kim, J.E. Cha, H. Seo and I.C. Bang, Measurement of Velocity and Temperature Profiles in the 1/40 Scaled-Down CANDU-6 Moderator Tank, Science and Technology of Nuclear Installations Vol.2015, p. 1-11 2015. (to be published)

[7] H.T. Kim, J.E. Cha, B.W. Rhee, and H-L. Choi, Preliminary CFD Analysis of the Moderator Circulation Test, 1st International Workshop on Advanced CANDU Technology, Nov. 29-30, 2012, Daejeon, Korea