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PIV Measurement of Isothermal Flow in the Moderator Circulation Test (MCT) Facility

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1. Introduction

One of the important design features of a CANDU reactor (a pressurize heavy water reactor) is the use of moderator as 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 local temperature 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. In the present work the test vessel is equipment 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. The pattern of preliminary measurement results are investigated to prepare the future plan of measurements as well as to see the feasibility of the PIV application to MCT.

2. Experimental method

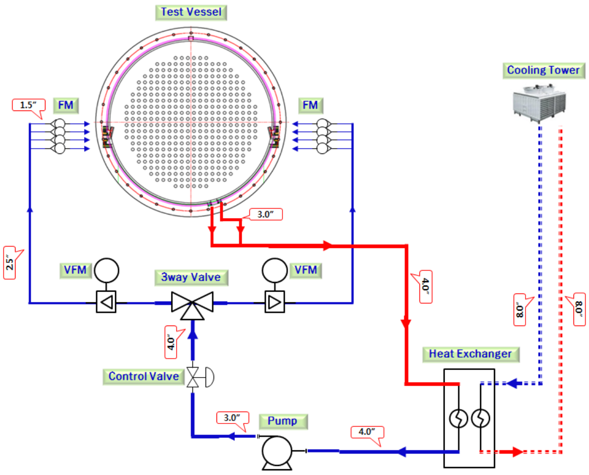
2.1 Test facility

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. The test vessel is equipment with 380 acrylic tubes (for non-heating test) or electric heaters simulating the horizontal fuel channels (for heating test). The electric heaters are designed to provide axial and radial power profiles representative of CANDU6 power profiles. An axial power profile is a symmetric cosine profile. A radial power profile is created by arranging the heaters in two concentric power zones, with an individual heat power ratio of 1.4 between the inner and the outer zones.

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 backward side of windows are made of one part of poly-carbonate sheet with 15 mm of thickness, which is sealed between two opposing stainless steel flanges (each 35 mm and 25 mm of 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.

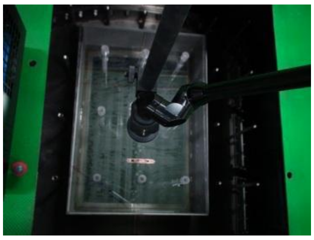
The velocity and temperature profiles in the test vessel are measured by the PIV and the LIF measurement systems, respectively. An access tank (950 mm × 650 mm) on top of the vessel allows the exposure of the laser beam as well as thermocouple measurements inside the vessel. The thermocouple rods are inserted in the 7 × 5 arrays of guide ports penetrating the upper part of the tank wall and the access tank. The thermocouple measurements can be used for auxiliary temperature measurements as well as calibration of the LIF measurements. 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. The inlet temperature is controlled by adjusting by-pass flow in the secondary side of the heat exchanger.

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.

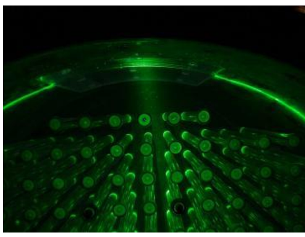
Figure 2 illustrates the PIV measurement system. The laser guiding arm in Fig. 2(a) was used to guide the laser beam to the target position and direction (top of the tank, downward). At the end of the guiding arm, combination of spherical and cylindrical lens are attached to make a thin light sheet on the x-y plane as shown in Fig. 2(b). 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 the restriction, additional experiments were conducted by placing the laser to side of the tank as shown in Fig. 3(b).



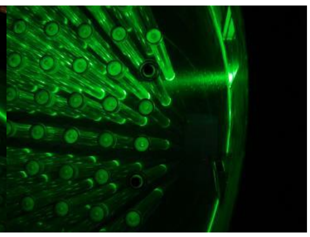
(a) Alignment of laser arm

(b) Overall view of laser sheet

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

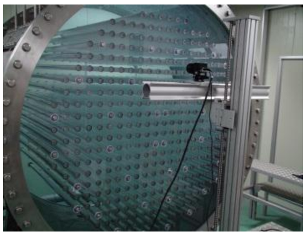


(a) Downward direction

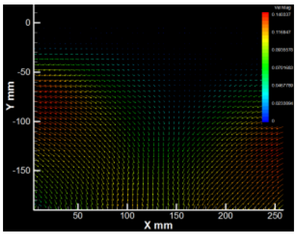


(b) To one side direction

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

In the PIV measurement the camera views the light sheet in front of the polycarbonate 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 200 correlation images in each test condition are collected and these images are processed by cross-correlation technique (Fig. 4(b)). Then the average of 200 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

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

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.

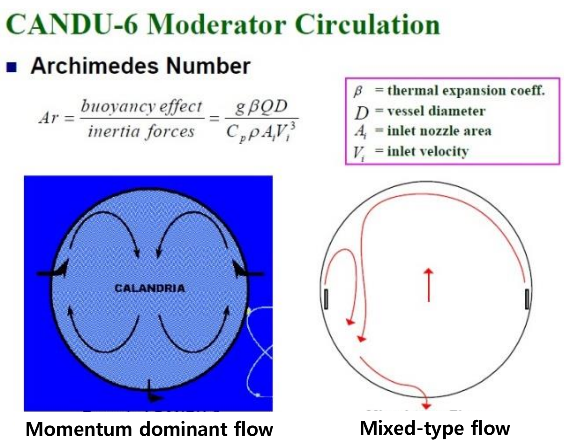


Fig. 5. Flow characteristics in the moderator tank

A downward flow vectors (-v) through the center of the tube columns are measured and the magnitude of the velocity in the center point of the unit cell is plotted in Fig. 6. The velocity distributions along the center line of the tank with different axial locations (z-direction) are compared. The measurement results clearly capture the decrease of velocity as it flows down toward bottom of the tank. The differences among velocity values for z = -295 mm, -30 mm, and 295 mm are small. However the velocity values for z = 295 mm are slightly lower than other two cases in the upper elevation (y>0) of tank. Since the case for z = 295 mm is measured the most far away from the CCD camera, the uncertainty of PIV measurements for this case should be investigated by repeating the test under same condition.

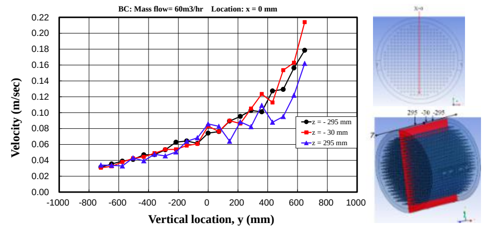


Fig. 6. Variation of downward velocity along the center line of tank for different Z-directions

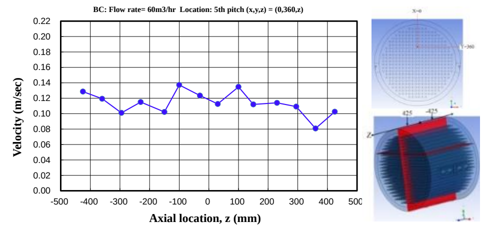


Fig. 7. Comparison of downward velocities for different Z-directions

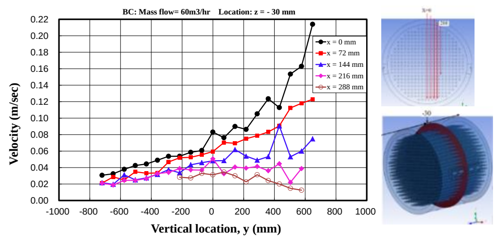


Fig. 8. Variation of downward velocity along the vertical line for different X-directions

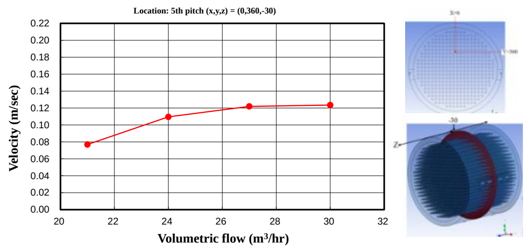
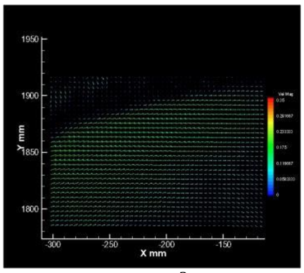
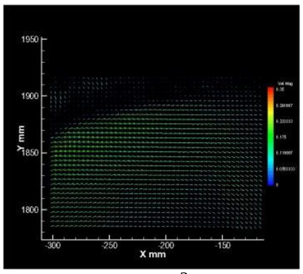


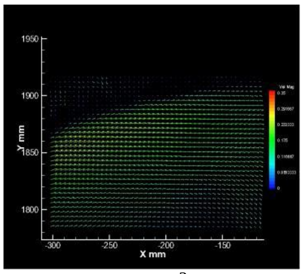
Fig. 9. Comparison of downward velocity for different inflow rate (half of total flow rate)



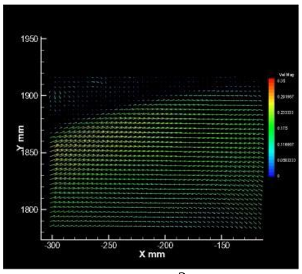
(a) 18 m^3/hr



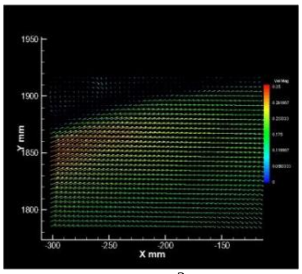
(b) 21 m^3/hr



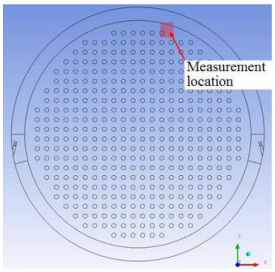
(c) 24 m^3/hr



(d) 27 m^3/hr



(e) 30 m^3/hr



(f) Measurement location

Fig. 10. 2D velocity profiles near the tank wall for different inflow rate

For the same 2D location, where x = 0 mm and y = 360 mm (on the x-y plane), the downward velocities for different z-locations (axial direction) are compared in Fig. 7. The most of velocity values are similar and within 17% of difference from 0.12 m/sec.

Variation of downward velocities along the vertical line for different x-directions (horizontal direction on the cross-sectional plane) is compared in Fig. 8. Since the downward flow is dominant along the center of the tube columns, the velocity is rapidly decreased as the measurement location is far from the center of tank.

The previous velocity measurements are performed for inlet flow rate of 30 m^3/hr from one side of inlet nozzles. To see the effect of the inlet flow rate to the internal velocity, other 3 cases for lower inflow rates are considered. The velocity is measured for the same location (x = 0 mm, y = 360 mm, z = -30 mm) as the inlet flow rate is reduced from the reference value (30 m3/hr) by 3 m^3/hr. The velocities for inlet flow rate of 21, 24, 27, and 30 m^3/hr are compared in Fig. 9. When the inlet flow rate becomes below the 27 m^3/hr, the velocity is clearly decreased.

The 2D velocity vectors near upper part of the tank wall are plotted in Fig. 10. The measurement regions are far away from the vertical center line by 3 times of pitch (Fig. 10(f)). The inlet jets from both sides of nozzles flow along the curvature of the tank wall and they collide each other at the center of the tank. It is clearly shown that the magnitude of vectors become larger as the inlet flow rate is increased. The velocity vector incoming from the left side of measurement window is slightly inclined in upward direction and it becomes inclined in downward direction passing through the right side of measurement window. If the measurement window is horizontally moved to the center of the tank, the vertical downward vector can be captured.

4. Conclusions

The 1/4 scale of moderator circulation test (MCT) facility has been installed to reproduce the moderator circulation behaviour in the CANDU6 calandria tank. In the present work the test vessel is equipment 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.

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.

More experimental works for the iso-thermal conditions as well as the heating conditions will be performed using PIV measurement in the future.

ACKNOWLEDGMENTS

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