1/8 척도 CANDU6 감속재 순환 유동 실험에 대한 PIV 속도장 측정

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PIV Measurement of Velocity Profile in the 1/8 Scale CANDU6 Moderator Circulation Test

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Abstract. The Korea Atomic Energy Research Institute (KAERI) has a scaled-down moderator test program to simulate the CANDU6 moderator circulation phenomena during steady state operation and accident conditions. In the present work a preliminary experiment using a 1/8 scaled-down moderator tank has been performed to identify the potential problems of the flow visualization and measurement in the scaled-down moderator test facility. With a transparent moderator tank model, a velocity field is measured with a Particle Image Velocimetry (PIV) technique under an isothermal state. The flow patterns from the inlet nozzles to the top region of the tank are investigated using PIV for a 1/8 scale moderator tank.

Key Words: PIV, 유동가시화, 속도장 측정, 중수로(CANDU6), 감속재 순환유동, 감속재 순환실험 장치 (MCT), 과냉각여유도(subcooling margin)

1. Introduction

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 fuel channel contact boiling experiments [2]. The difference between the available subcooling and required subcooling is called the subcooling margin.

The local temperature of the moderator is a key parameter in determining the available subcooling. To predict the local temperature in the calandria, numerous experimental and numerical researches have been

carried out.

Koroyannaski et al. [3] experimentally investigated the flow phenomena generated by the inlet jet and internal heating of a fluid in a calandria-like cylindrical vessel of SPEL (Sheridan Park Engineering Laboratory). These experimental results give an intuitional observation on the relationship between the moderator circulation pattern and the inlet flow rate and heat load.

Huget et al. [4] performed experimental and numerical investigations of the moderator circulation test in a two-dimensional (2-D) slice-type facility at Stern Laboratories, Inc. in Canada. It was a useful intermediate step to a complicated three-dimensional (3-D) test and provided preliminary information on the

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moderator circulation flow patterns, and assisted in the tuning instrumentation, data recording, and data analysis techniques needed for the massive data collected in the 3-D test.

The experimental programs at Chalk River Laboratories in Canada comprised a number of single-effect and integral-effect tests. The separate-effect and component experiments, performed in specially designed test sections and test loop configurations, include a round jet development test, moderator inlet diffuser characterization, tube bank pressure loss experiments, wall jet development studies, and buoyant jet experiments. Khatabil et al. [5] conducted a 3-D moderator circulation test in the main Moderator Test Facility (MTF). The temperature measurements in the MTF provided the local temperature at more than 300 locations in the test facility. In addition to the temperature measurements, the MTF tests also included 3-D velocity and turbulence measurements using Laser Doppler Anemometry (LDA) instrumentation. The MTF test program provided data for validation of the Computational Fluid Dynamics (CFD) code, MODTURC_CLAS [6], which is employed by the CANDU industry to predict the moderator flow and temperature distributions in a range of CANDU moderator designs.

The Korea Atomic Energy Research Institute (KAERI) started experimental research on moderator circulation as one of the national R&D research programs from 2012. This research program includes the construction of the Moderator Circulation Test (MCT) facility [7], the production of validation data for self-reliant CFD tools, and the development of an optical measurement system using the Particle Image Velocimetry (PIV) and Laser Induced Fluorescence (LIF) techniques.

In the present work, a preliminary experiment using a 1/8 scaled-down moderator tank [8] has been performed to identify the potential problems of the flow visualization and measurement in the large-scale moderator test facility (MCT). A PIV technique is used to measure the velocity distributions in the scaled moderator tank to secure the experimental data for

developing a three-dimensional CFD code for CANDU6 moderator circulation. Ultimately, it will make a guideline for developing a safety analysis code simulating a CANDU6 moderator tank by providing experimental data for its validation. In particular, the flow patterns from the inlet nozzles to the top region of the tank are investigated using PIV for a 1/8 scale moderator tank.

2. 1/8 Scale Moderator Test Facility

A schematic diagram of the 1/8 scaled-down moderator facility is shown in Fig. 1. The scaled-down moderator tank is a slice type of calandria, only modeling a quarter of the axial configuration of the prototype, since one nozzle instead of four nozzles is installed at both sides of the tank. The inner diameter and axial length of the tank are 0.98 m and 0.2 m, respectively. Light water (H_2O) is used instead of heavy water (D_2O) in the scaled-down moderator facility, and is circulated by a pump with a maximum capacity of 55 LPM. The locations of two inlet nozzles and one outlet nozzle are based on the actual configuration of the CANDU6 moderator tank. The flow passage angles from the vertical center line for the inlet nozzle and outlet nozzle are 14° and 16.19° , respectively. The pump inverter and gate valves are installed to regulate the volumetric flow rate. A rotameter is installed in front of each inlet nozzle to measure the volumetric inlet flow rate. The tank consists of transparent acrylic walls for flow visualization. Fig. 2(a) shows the cross section of the scaled-down moderator tank and configuration of the inlet nozzles. A total of 380 acrylic tubes are installed as flow obstacles within the tank to simulate a matrix of calandria tubes. These acrylic tubes are 18 mm in outer diameter and 37 mm in lattice pitch. The inlet nozzle has four jet orifices, and the left and right sides of the nozzle are symmetric, as shown in Fig. 2(b). Each jet orifice has a rectangular shape with a 24 mm width and 9.8 mm height.

The working fluid containing the PIV particles flows into the tank through two inlet nozzles and comes out of one outlet nozzle. The two inlet flow rates are

balanced against each other. The total volumetric flow rate for the nominal condition is 50 LPM. The volumetric flow rate in the moderator circulation loop is controlled by a pump inverter and measured by a rotameter. The temperature of the working fluid is constant at 25°C.

Fig. 1. 1/8 scale moderator test facility

Fig. 2. Geometric configuration of the 1/8 scale moderator test facility

3. PIV System

Velocity measurements were carried out using a two-dimensional PIV system commercially available. Pairs of sequential digital images are used in PIV system for acquiring the direction and magnitude of the fluid flow. Displacement of the tracer particles in the second image, relative to the position of the particles in the first image, is a measure of the motion of the fluid, and thus the velocity field can be calculated. Fig. 3 illustrates the PIV system arranged for the scaled moderator tank. The Nd:YAG double cavity laser and an optical lens produce the illumination light sheet inside the test facility, and the laser has a maximum output power of 65 mJ with a wave length of 532 nm. The light coming from the laser makes the measurement

section in the field, and the charge-coupled device (CCD) camera traces the movements of the tracer particles that are interacting with the laser in terms of reflection. The CCD camera uses a dual frame technique corresponding to a resolution of 2048 pixels $\times$ 2048 pixels, and 1 GB on-board memory is used for the data processing. The CCD with a frame speed of 14 frames per second and 100 frames per sequence was used for the PIV experiments. The Nd:YAG double cavity and CCD camera each stand on a tripod that allows the devices to move easily for analyzing a certain area. The time step, which is a suitable pulse separation value, is set to 2500 μ s to obtain an average particle movement of 5 pixels. In the PIV experiments, glass hollow spheres with a diameter range of between 9 and 13 μ m are used as seeding particles. To track the particle movements, a 532 nm band pass filter with a bandwidth of 10 nm is mounted on the CCD camera. In the present work, PIV images were analyzed using a cross-correlation interrogation algorithm. In particular, for the progression of vector processing, a constant interrogation window size is not used because such a constant window size of 32 pixels $\times$ 32 pixels, for example, can capture certain displacement gradients, but cannot follow gradients smaller than the spatial resolution. To obtain significant improvement in accuracy and spatial resolution, it is selected to automatically change based on the Gaussian weighting function, which finds the optimized one locally according to the local seeding density and flow gradients because the flow pattern in the scaled moderator tank is very dynamically changed, which is called adaptive PIV. The overlap area among neighboring interrogation windows is set at 50% to increase the sampling data. A variable shape is determined as the following method.

The method of automatic change in the interrogation window is increasing the size of the window in the direction of larger flow structures indicated by a smaller velocity gradient, keeping the same overall size of the window by enlarging the window in the perpendicular direction [9].

Fig. 3. Experimental set up for PIV system to the scaled moderator tank

4. Results of PIV Measurement

Fourteen images of the velocity distributions at each measurement section are obtained by the PIV systems. The measurement sections from the inlet nozzle to the top region of the moderator tank are divided into 7 groups for each jet orifice owing to too large a size of the tank compared to the power of the current laser and the resolution of the CCD camera. Fig. 4(a) shows the PIV analysis areas with a cross-section view (x-y axis) of the facility, and Fig. 4(b) illustrates position 7 of the laser installation along with the inlet nozzle (y-z axis). As shown in Fig. 2(b), there are 4 jet orifices in each inlet nozzle. The centerline of the 1st and 2nd jet orifices is investigated to analyze the velocity distribution because the jet orifices have a symmetric structure along with the middle of the inlet nozzle, which means there are the same velocity distribution patterns between the combination of the 1st and 4th jet orifices and one of the 2nd and 3rd jet orifices. The velocity profiles around the fuel channels cannot be obtained owing to the difference in the refractive index between the working fluid and the acrylic materials. The difference refractive value results in a laser distortion that interrupts the laser sheet formation [10]. The 7 PIV results for one inlet nozzle are combined with the one image result using Tecplot software to obtain the overall velocity distributions. Therefore, two kinds of overall velocity fields are investigated.

Fig. 4. Measurement locations

The calibration plate is used to obtain the exact scale of the CCD camera for an accurate analysis of the vector values. The measurement section area of each PIV image is about $0.15 \text{ m} \times 0.15 \text{ m}$, which means that a $1 \text{ pixel} \times 1 \text{ pixel}$ CCD camera can afford an area of $73 \mu\text{m} \times 73 \mu\text{m}$ for the image processing corresponding to a $73 \mu\text{m}/\text{pixel}$ spatial resolution. To obtain the vector fields, 100 images are averaged for each measurement section. To obtain 100 images with a CCD camera, it takes 7.1 s, which is enough time to simulate the steady-state flow patterns in the experimental facility.

The volumetric flow rate for the one inlet nozzle is 25 LPM, which corresponds to a $442.5 \text{ kg/m}^2\text{-s}$ mass flux. Fig. 5 shows the results of the vector fields with PIV experiments for the 1st, 2nd, and 3rd locations, as described in Fig. 4(a). The red line indicates the scaled moderator tank wall, and the white circles are the fuel channels installed with acrylic tubes. Figures 5 (a), (c), and (e) are the results of the 1st jet orifice, while Figures 5 (b), (d), and (f) are the vector distributions of the 2nd jet orifice. The same legend for each location is set to compare the 1st and 2nd jet orifices accurately. Figures 5(a) and (b) show the position of the inlet nozzle where the maximum upward velocity along with the tank wall is formed. Using the PIV system, the maximum velocities of Figures 5(a) and (b) are measured as 0.319 m/s and 0.416 m/s, respectively. The main differences in the maximum velocities between the 1st jet orifice and 2nd jet orifice are due to the PIV observation error and the flow distribution on each jet orifice. Owing to the high

velocity compared with the surroundings, the flow pattern right after the jet orifice cannot be analyzed. Another reason is that the working fluid can be focused on a certain point of the jet orifices, which are not equally distributed. Yoon [11] simulated using the CFD code to analyze the outlet flows from the inlet nozzle of the CANDU6 moderator system. The results showed that the outlet flow in terms of the flow rate was not equally spaced for each jet orifice area because a reverse flow at the centerlines on the jet orifices was developed. The reverse flow caused an unpredictable low mass flow rate and turbulence parameters.

The maximum velocities of Figures 5(c), (d), (e), and (f) are 0.263 m/s, 0.262 m/s, 0.199 m/s, and 0.161 m/s, respectively. The upward flow exists along with the wall surface, and a downward flow is observed except for the wall surface regions. It seems that the flow does not create the boundary region between the upward flow and the downward flow. Because the results of the velocity distributions are averaged for 100 images, an instantaneous turbulence flow cannot be acquired and thus the boundary seems to be a non-flow region.

Fig. 6 indicates the averaged velocity fields from the 4th to 7th positions, as shown in Fig. 4(a). The images in the left side are the result of the 1st jet orifice, while images of the right side indicate the 2nd jet orifice. The maximum velocities from Figures 6(a) to (h) are 0.175 m/s, 0.139 m/s, 0.175 m/s, 0.131 m/s, 0.150 m/s, 0.126 m/s, 0.121 m/s, and 0.093 m/s, respectively. There is a tendency for the flow rate for the 1st jet orifice to be faster than the 2nd jet orifice. The average velocity including the maximum speed of the 1st jet orifice is faster than that of the 2nd jet orifice. From this result, we can see that the inlet flow of 25 LPM does not equally spread out toward the four jet orifices from the inlet nozzle. The velocity fields at the top region of the scaled moderator tank cannot be measured because there are no movements of the particles. This means that the flow pattern for the top of the moderator tank is suspended.

Fig. 7 shows the combined vector distributions from the 1st to 7th regions for the 1st and 2nd jet orifices. A faster velocity is used for the overlapping position to obtain the vector distributions. The flow of the 1st jet orifice is faster than that of the 2nd jet orifice, as shown in Figures 7(a) and (b). The vector fields surrounding the horizontal rods made of acrylic tubes are not accurate because a laser distortion is created such that the laser sheet cannot penetrate the inside of the tank.

Fig. 5. The velocity fields of the PIV results from 1st to 3rd positions

Fig. 6. The velocity fields of the PIV results from 4th to 7th positions

5. Conclusions

In the present work, the velocity profile in a scaled-down CANDU6 moderator tank is measured using PIV at two different positions of a laser sheet, which are at the 1st and 2nd jet orifices of the inlet nozzle. For each position of the laser beam exposure, the measurement sections are divided into 7 groups to overcome the limitation of the laser power to

cover the relatively large test section.

There is a tendency for the flow rate of the 1st jet orifice to be faster than the 2nd jet orifice. The average velocity including the maximum speed of the 1st jet orifice is faster than that of the 2nd jet orifice. From this result, we can see that the inlet flow of 25 LPM does not equally spread out toward the four jet orifices from the inlet nozzle. Since the inlet jet penetration is dependent on the inlet velocity, the flow split among the jet orifices should be investigated in future work.

There was a light distortion surrounding the horizontal rods made of acrylic owing to the difference in refraction index between the structure and the working fluid. The same refractive index of water such as fluorinated ethylene propylene (FEP) material can be recommended to obtain the exact vector fields inside the tank.

Fig. 7. The overall velocity profiles of PIV measurement

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