Experimental Study on Local Flow Structure and Turbulence Quantities in a Heated Rectangular Riser of Air-cooled Reactor Cavity Cooling System

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1. Introduction

Very High Temperature gas-cooled Reactor (VHTR) is one of the concepts of GEN-IV reactor, and Reactor Cavity Cooling System (RCCS) is a passive cooling system of VHTR, which uses natural circulation to remove decay heat emitted from the reactor vessel in normal and emergency operation conditions [1]. Korea Atomic Energy Research Institute (KAERI) designed air-cooled RCCS [2], and it incorporates rectangular riser channels, which uses chimney effect for natural circulation of outside air, surrounding the reactor vessel for decay heat removal. Therefore, the performance of RCCS should be predicted precisely to ensure the safety of the reactor vessel of VHTR.

Several researches on the performance of RCCS have been conducted with reduced-scale experiment facilities, at KAERI, Argonne National Laboratory (ANL), University of Wisconsin, and some verification observed heat transfer deterioration in some experimental conditions whose flow rate are relatively low [2, 3, 4]. At Seoul National University, a separate effect test facility, Riser Heat transfer Experiment Facility (RHEF), was constructed, and convective heat transfer phenomena inside a single RCCS riser was investigated [5]. From the experiment results of RHEF, heat transfer deterioration in mixed convection conditions was identified [5] whose heat transfer mechanism is complicated due to thermo-physical properties variation [6]. However, mixed convection heat transfer has not been sufficiently investigated due to the lack of experimental researches, especially in a rectangular duct.

In this study, an airflow visualization experiment facility, which has four-side wall heated rectangular test section, was constructed by the half scales of the test section of RHEF. By measuring local flow structure and turbulence quantities with PIV method, convective heat transfer phenomena inside the rectangular riser was identified in turbulent forced convection conditions, and the effect of buoyant force on the measurement variables was investigated by comparing the experimental data with and without heating. In the end, plan for further experimental investigation and heat transfer quantification strategy for turbulence model assessment were introduced.

2. Airflow Visualization Experiment

2.1 Apparatus

Fig. 1 shows the schematics of airflow visualization experiment facility and the design of its test section [7]. The test section has 1 m of adiabatic entrance region for flow development and 2 m of heating region, and the width and depth of inner test section are 120 mm and 20 mm, respectively, which are the half scales of those of the prototype RCCS riser and RHEF [7]. The test section consists of transparent heat-resistant glass to capture airflow inside the riser with PIV method, and for transparent resistive heating on the test section, FTO (Fluorine doped Tin Oxide), transparent conducting material, was coated on the inner surface of the test section.

DEHS (Di-Ethyl-Hexyl-Sebacat), which is non-toxic and volatile oil, was injected to the test section as seed particles of 1 μm droplet size for PIV method. DEHS aerosol was injected into the lower plenum before the adiabatic entry region, and the flow distribution is mixed up and flattened with reduced turbulence intensity passing through perforated screens and honeycomb structure [8, 9].

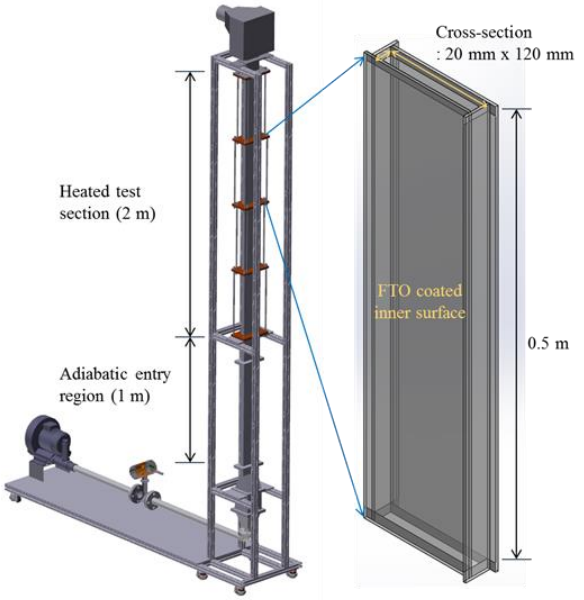

Fig. 1. The schematics of airflow visualization experiment facility and its design of the test section.

2.2 Measurement Instrumentation

To visualize airflow in the heated rectangular test section, PIV method was adopted in this study. A continuous planar laser and a high-speed camera were equipped on 2-axis traverse systems to capture the velocity fields changing the measurement locations and direction. Velocity fields were measured at about 1.4 m-height from the entrance of the heating region, and Fig. 2 shows the measurement locations of velocity fields and system coordinate. To obtain time-averaged measurement variables, airflow were captured for 60 seconds and total 1500 velocity vector fields were obtained by PIV analysis. To enhance the detectability of PIV analysis, background subtraction process was conducted, which can eliminate background noise and refraction of a laser at the glass surface.

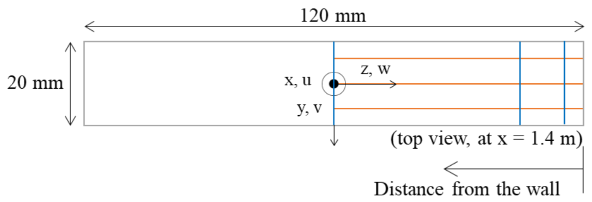

Fig. 2. Measurement locations of velocity fields and system coordinate in the experiment.

2.3 Experimental Conditions

In this study, local flow structure and turbulence quantities in forced convection heat transfer conditions were measured, and to identify the effect of buoyant force on the turbulence quantities and heat transfer phenomena, experiment was also conducted in adiabatic conditions without resistive heating. Experiment was conducted in four different conditions and it is described in Table I. For each of the heating conditions, total 558W was imposed on the test section, and to characterize the heating conditions, the Richardson number ($Ri \equiv Gr_z/Re_z^2$) is used, which represents the strength of the buoyancy force relative to the strength of the forced convection. If the Richardson number is much less than unity, the effect of buoyant force is regarded as negligible, and if the Richardson number is of order unity, the flow is regarded as mixed convection condition, whose heat transfer mechanism is complicated due to the thermo-physical property variations [10, 6].

Table I: Experimental Conditions

	Case No.	Inlet Re	Ri (x = 1.4 m)
Adiabatic conditions	Case 1	5500	-
	Case 2	7700	-
Heating conditions	Case 3	5500	0.28
	Case 4	7700	0.12

3. Results of Visualization Experiment

3.1 Local Flow Structure

Fig. 3 shows time-averaged vertical velocity distributions inside the test section (x = 1.4 m) in Case 1 and Case 3. It is confirmed that the experimental results of Case 2 and Case 4 have no significant differences with Case 1 and Case 3, respectively, because of the similarity of turbulent flow when they are normalized by each inlet average velocity value. In Fig. 3, the average velocity in Case 3 increased compared with Case 1 due to the thermal expansion of airflow, but overall velocity distributions were not that changed at each of the measurement locations despite wall heating as described in Fig. 4, which shows normalized primary velocity profiles of Case 1 and 3 at the mid-plane (y = 0 mm) and at the half line (z = 0 mm) of the test section measured from the different directions. It is identified that the velocity values at the center of the test section from two different directions have equivalent values.

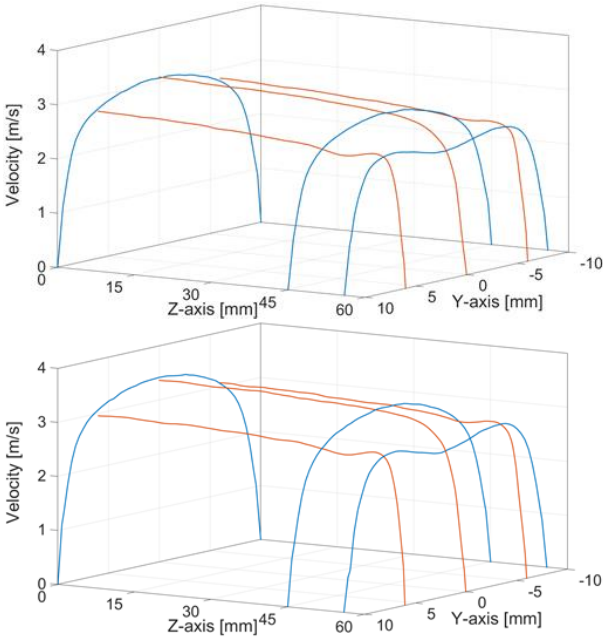

Fig. 3. Vertical velocity components of the obtained local flow structure at x = 1.4 m in Case 1 (up) and Case 3 (down).

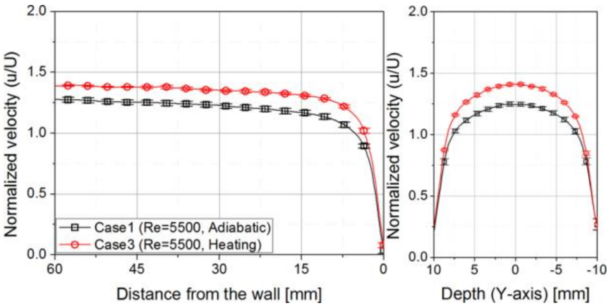

Fig. 4. Vertical component velocity profiles at the mid-plane (y = 0 mm, left) and the half line (z = 0 mm, right) of the test section in Case 1 and 3.

In Fig. 3, at the corner of the test section, increase of velocity was observed, which implies the existence of secondary flows. Fig. 5 presents normalized horizontal velocity profiles from the wide side and from the narrow side in Case 1 and 3. In case of turbulent flow conditions in a non-circular geometry, secondary flows are formed at the corner of the test section, and its maximum magnitude was about 1.5% of the centerline velocity in previous researches [11]. Also, in this experiment, horizontal velocity distributions were observed near the corner of the test section.

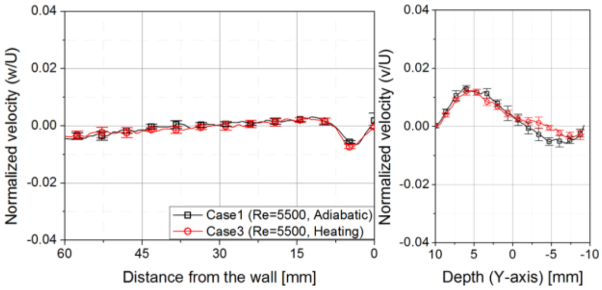

Fig. 5. Horizontal component velocity profiles from the wide side (y = 0 mm, left) and from the narrow side (z = 56 mm, right) of the test section in Case 1 and 3.

3.2 Turbulence quantities

Fig. 6 shows Reynolds shear stress distribution at different measurement locations in Case 3. u'w' distributions were obtained from the wide side and u'v' distributions were obtained from the narrow side. u'w' distributions have increase of the absolute values at the near-wall region of narrow side, while u'v' distributions show symmetric distribution all over the test section. It is known that the distribution of Reynolds shear stress are related to the distribution of secondary flows [11]. However, in this study, the effect of buoyant force on the Reynolds shear stress were not observed between the experimental cases with and without heating.

At the mid-plane, due to the symmetric distribution of u'v' Reynolds shear stress, it can be said that u' and v' is independent along the mid-plane, and it is confirmed that the horizontal velocity fluctuation distributions, v', have uniform values along the mid-plane. If it is assumed that v' is independent with u' and w' at the mid-plane, turbulent kinetic energy distribution along the mid-plane can be obtained from this visualization experiment as presented in Fig. 7. Turbulent kinetic energy distribution shows steep increase of the distribution at the near-wall region. These experimental data for turbulent quantities can be utilized to assess prediction capability of turbulence models in heated rectangular riser duct.

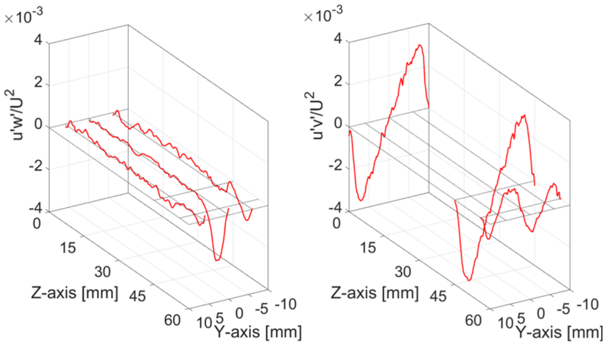

Fig. 6. Reynolds shear stress distributions captured from the wide side (left) and the narrow side (right) at different measurement locations in Case 3.

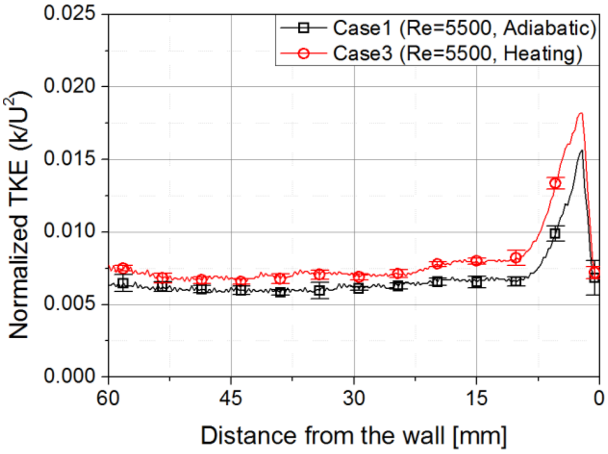

Fig. 7. Normalized turbulent kinetic energy distribution at the mid-plane of the test section in Case 1 and 3.

3. Conclusions and Future Works

To investigate the heat transfer phenomena in RCCS riser duct, air flow visualization experiment were conducted and local flow structure and turbulence quantities were measured inside the rectangular riser duct in forced convective heat transfer conditions. The existence of secondary flows were observed at the corner of the rectangular test section, and the distributions of Reynolds shear stress and turbulent kinetic energy were identified. But no significant effect of wall heating on the measurement variables was observed in this experimental cases.

To investigate the heat transfer deterioration in mixed convection conditions, further experiments will be conducted in various heating conditions. And by obtaining temperature boundary condition of the test section of visualization experiment facility, CFD analysis will be conducted in identical conditions with visualization experiment. By comparing the results from the experiment and CFD calculations, prediction capabilities of turbulence models in various heating conditions will be assessed and optimum model for the prediction of RCCS performance will be selected.

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