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Study of heat transfer enhancement/suppression for molten salt flows in a large diameter circular pipe Part I: Benchmarking

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Abstract

Flow field and heat transfer measurement of turbulent pipe flow are carried out as a part of benchmark experiment for the flow and heat transfer measurement of electrically conducting fluid under magnetic field. The objective of this study is to clarify the effect of MHD force on the flow of molten salt simulant, potassium hydroxide-water solution in particular. At this first stage, water is used as working fluid to obtain reference data. The fully developed turbulent pipe flow at $Re = 5300$ is measured by using PIV technique and turbulent structure and turbulent statistics as well as averaged flow field are obtained. For heat transfer measurement, higher Reynolds number is chosen so as to reduce the effect of the buoyancy. For tests with water without the presence of the magnetic field, both heat transfer and flow field measurement results have good agreement with existing data and provide reference data of the apparatus.
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1. Introduction

The use of molten salt coolants, in particular fluorine–lithium–beryllium salt or FLiBe, has attractive features for liquid wall and liquid breeder blanket

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designs in fusion reactors [1]. The low electrical conductivity of such salts reduces the pressure drop associated with magneto-hydrodynamic forces to a nearly negligible level when compared to high conductivity liquid metals. But there are still many issues related to fluid mechanics and heat transfer in a blanket design using FLiBe. In particular, the low thermal conductivity and high viscosity of FLiBe make it a high Prandtl number medium—meaning heat transport from a heated wall into the core of the coolant flow is dominated by turbulent motion rather than thermal diffusion. Near wall flow structures are especially important because thermal boundary layer is much thinner than the momentum boundary layer. In the case where the thermal boundary layer lies within the viscous sub-layer, the heat transfer through the wall decreases considerably. This makes the investigation of the fluid mechanics and heat transfer of high Prandtl number fluid compared to low Prandtl number fluid very important from the design point of view in order to assess the applicability of FLiBe to high heat flux removal system as well as the prospect for heat transfer enhancement mechanisms. To understand the underlying science and phenomena of fluid mechanics and heat transfer of FLiBe, a series of experiments as part of the US–Japan Jupiter-II collaboration are in progress. A fluid flow facility utilizing water and water-based electrolytes as simulants for generic high Prandtl number, electrically conducting fluids like FLiBe has been constructed at UCLA. The approach involves flow field measurement and heat transfer experiments using these FLiBe simulants fluids along with modeling and analysis of fundamental phenomena of turbulence and heat transfer. Experimental results are compared to the simulations to provide fundamental insights for the design of FLiBe blankets. The current phase is preliminary experiment to obtain a reference data of the facility, water is used as working fluid. The results of heat transfer and flow field measurements are compared with the recent direct numerical simulation (DNS), as well as existing data [2] and correlations [3].

2. Experimental

The experimental setup consists of liquid loop with circular pipe test section, heaters, thermocouples and optical system for PIV measurement. Water flow is introduced into the horizontal pipe test section by a mechanical pump after passing through the heat exchanger, flow meter and honeycomb. Temperature of the fluid is monitored at both the inlet and the outlet. The test section is a smooth circular pipe made of SUS304 with 90 mm in diameter and 6.7 m in length, which corresponds to 74 times of the pipe diameter (D hereafter). This length is considered to be sufficient to obtain a fully developed turbulent flow. PIV measurement section is made of transparent plexiglass and is attached seamlessly to the end of the stainless steel pipe. Flow rate is controlled by variable frequency power controller and is measured by Karman vortex type flow meter which is calibrated by using velocity distribution measured by PIV. The Reynolds number covered by heat transfer experiment ranges from 5000 to 25,000 and PIV measurement is done at $Re = 5300$ so as to compare the available DNS data.

Dantec FlowMap 2000 PIV system which provides image storage and controls the synchronization of a camera and a laser is used for this experiment. Fig. 1 shows optical configuration of the PIV system. A laser sheet is supplied by NewWave mini Nd:YAG laser with its energy of 50 mJ per pulse and its repetition rate is 15 Hz double-pulsed. The laser sheet passes horizontally the half plane of the pipe and illuminates the seeding particles flowing with the water flow. The flow is seeded with polyamide particles whose relative density to water is 1.02 and diameter is 5 μm. The particles are small enough to follow the water flow and its relative density is close enough to that of the water to neglect the particle sedimentation due to the gravity force. The number density of the seeding particles is adjusted so that the particle images have several particles in the 16×8 pixels interrogation windows. Since a circular pipe is used, the image inside of the pipe is distorted by pipe curvature and the difference in index of refraction between air and fluid. To compensate the distortion, a square water jacket filled with the same fluid as in the main flow is attached to the test section. Particle images are captured by CCD camera with 768×484 pixels looking from the top of the pipe. The time interval is chosen to be 10 ms for pipe center and 5 ms for near wall. The camera records a pair of image at 15 Hz in frequency. For image analysis to produce velocity vector maps, FlowManager ver.3.70 software by Dantec is used and provides adaptive correlation technique. The adaptive correlation is based on the cross-

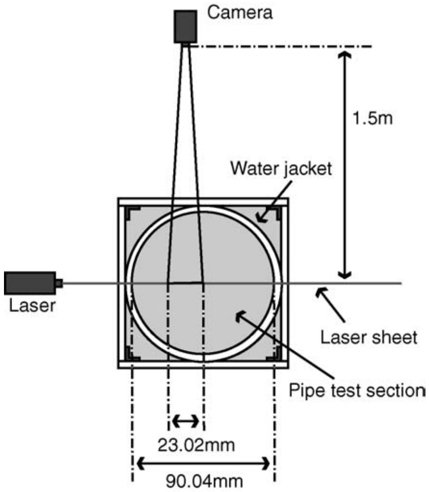

Fig. 1. Optical configuration for PIV measurement.

correlation technique, which is commonly used for PIV analysis[4]. The performance of the cross-correlation technique has been improved by using discrete offset [5] and iterative multi-grid approach [6]. Combined with the iterative approach, local median validation method is applied to remove spurious vectors [7] and a spatio-temporal gradient method to improve the accuracy for sub-pixel particle displacement [8] analysis. This method enables to achieve the accuracy of 0.01 pixels with small interrogation window.

For heat transfer experiment, heat flux is applied to the surface of the stainless steel pipe by nine parallel, identical (in power density) self adhesive nichrome tape heaters which covered the pipe surface from 15*D* to 70*D* downstream from the inlet. In order to perform constant heat flux experiments, it is important to ensure the uniform distribution of heat flux along the pipe and prevent localized heat flux concentration on the surface of the pipe. Therefore, tape heaters were carefully wrapped. Electric power is supplied to by circuit with transformer with output voltage of 480 V and maximum total current of 50 A. The entire pipe was covered with three layers of industrial insulation to prevent heat loss from the test section. Wall temperatures are measured by calibrated Cu-Constantan thermocouples affixed in wells (holes) at total of 36 points, which are drilled into the outer surface of the pipe so that the junctions of the thermocouples are located within 1 mm to the inner pipe surface. The location of thermocouples for wall temperature measurement is shown in Fig. 2. Since the thermocouples lie very close to the heating elements, the assembly of the thermocouples has considerably large effect on the uncertainty of the experiment. In order to estimate the uncertainty caused by local temperature distribution inside the pipe wall, 2-D model of the heater and pipe wall was created and temperature variation at the location of the thermocouple junction is analyzed by ANSYS. From this analysis, the wall temperature has $\pm 0.6\,^{\circ}$C of bias limit caused by heater geometry. Thermocouples are also installed at the inlet and outlet of the pipe after passing through the porous material to measure bulk mixing temperature.

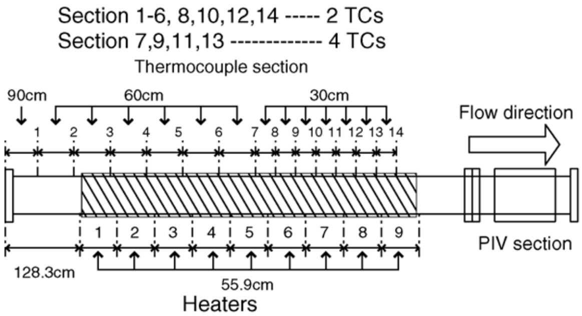

Fig. 2. Experimental test section for heat transfer and PIV measurement.

3. Result

3.1. PIV measurement

Since the PIV measures the average displacement of the particles in the small interrogation window, the fluctuation of the velocity tends to be smoothed. Therefore, RMS velocity averages and Reynolds stress could appear to be small when the smoothing by the nature of the PIV is significant. To avoid this effect, interrogation window has to be smaller than the smallest scale of the turbulence; Kolmogorov micro scale. Since the dynamic range of the velocity in PIV system is limited by the number of the CCD elements, decreasing the size of the interrogation window with higher magnification is accompanied by deterioration of the highest measurable velocity. This makes the turbulent measurement by PIV difficult.

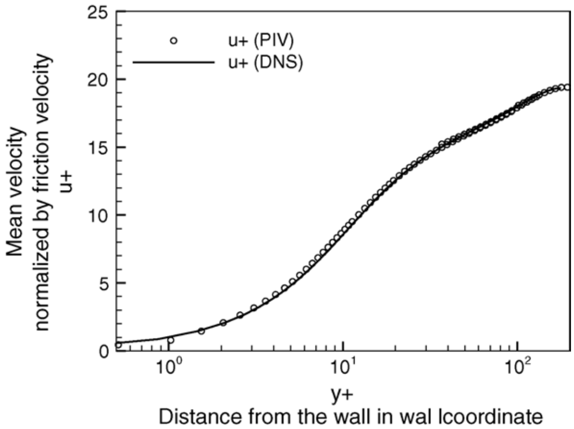

Fig. 3. Axial velocity profile at $Re = 5300$ scaled in wall coordinate.

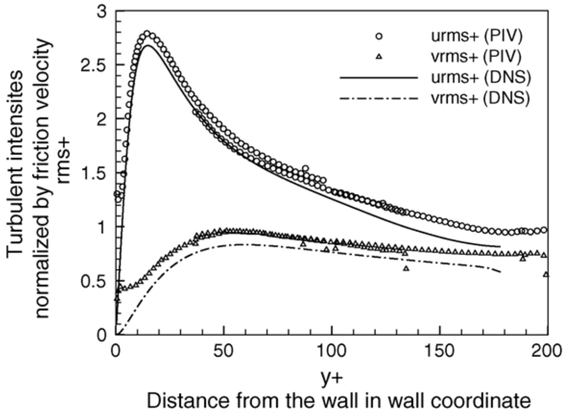

Fig. 4. Streamwise and radial components of turbulent intensities.

The mean velocity profile is shown in Fig. 3. The average is taken over 5000 instantaneous flow velocity. The mean velocity profile is converted into wall coordinates to obtain the universal velocity profile independent of Reynolds number, defined by $u_+ = U/u_\tau$, $y_+ = yu_\tau/\nu$, where y is the distance from the wall, u_τ the friction velocity defined by $u_\tau = \sqrt{\tau_w/\rho}$, and ν is the kinematic viscosity of the liquid. The experimental data is plotted along with the DNS (Direct Numerical Simulation) data by Satake et al. [9]. It is not possible to obtain accurate friction velocity from pressure drop, the friction velocity is calculated from the near wall velocity profile. Rough estimation of the friction velocity is given by Blasius' law (Eq. (1)) at first, then curve fitting method by McEligot [10] is used to determine the precise value

$$C_\mathrm{f} = \tau_w/(1/2)\rho U^2 = 0.079\, Re^{-0.25} \qquad (1)$$

The rms (root-mean-square) values of the fluctuation component of the velocities normalized by friction velocity, which are called turbulent intensities, are shown in Fig. 4 and compared with the DNS. In the core region ($y_+ > 120$) where the fluctuations are rather small, the PIV results show larger values than DNS. In this region, the magnitude of fluctuation may fall below the measurement accuracy due to so-called peak-locking effect [11]. The radial component of PIV has larger value in near wall region even though this must go to zero at the wall by theory. This is because the image is skewed by the curvature of the pipe and is elongated in radial direction even though the water jacket is attached to the test section in order to minimize the distortion. Therefore the distance from the wall on the image plane is not exactly equal to the distance in the physical space. Even so, both streamwise component (urms) and radial component (vrms) of the turbulent intensities obtained by PIV agree reasonably with DNS results.

The Reynolds shear stress distribution is shown in Fig. 5. Total shear stress of the fully developed statistically steady flow in the pipe must be linear and shown by the straight line of unit slope. This is because the gradient of the total shear stress must balance the pressure gradient along the axis. In the near wall region, the viscous stress plays dominant role and Reynolds stress goes to zero with $y_+ = 0$. On the other hand, the Reynolds stress plays dominant role and viscous stress is small in the core region. The region where

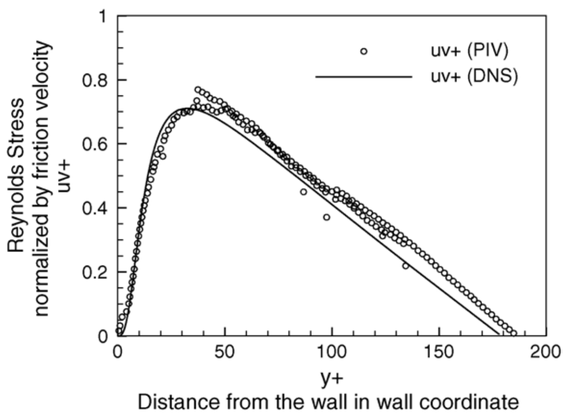

Fig. 5. Reynolds stress and total stress distribution.

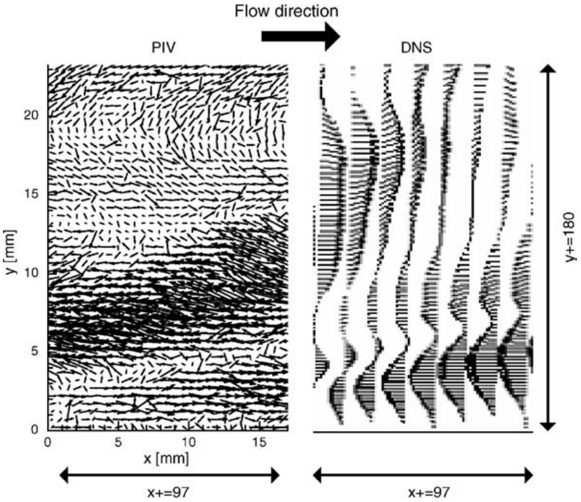

Fig. 6. Comparison of the vector maps of fluctuation velocity of DNS and PIV.

the Reynolds stress has peak value corresponds to the region where the turbulence is generated [12]. The Reynolds stress obtained by PIV experiment agrees very well with the DNS data. In general, the second order statistics are more sensitive to the measurement error. In fact, the agreement between the experiment and numerical simulation seems worse for second order statistics than for mean velocity. Considering the difficulty, however, the experimental data agrees very well with the simulation.

Fig. 6 shows the comparison between a vector map of one realization of the turbulent flow field by DNS and an instantaneous flow field measured by PIV. There are similar turbulent structures, near-wall shear layer structure, for example, seen in both figures.

3.2. Heat transfer

Local Nusselt number distribution along the pipe is measured for fully developed turbulent flow at $Re = 22{,}500$ and $Pr = 7.0$. Total heat flux applied is 5000 W/m^2. Nusselt number is defined by $Nu = qd/k(T_w - T_b)$, where q is heat flux applied on the pipe surface, T_b and T_w are estimated bulk mixing temperature and measured wall temperature, respectively. Heat flux is calculated from heating power, wall temperature

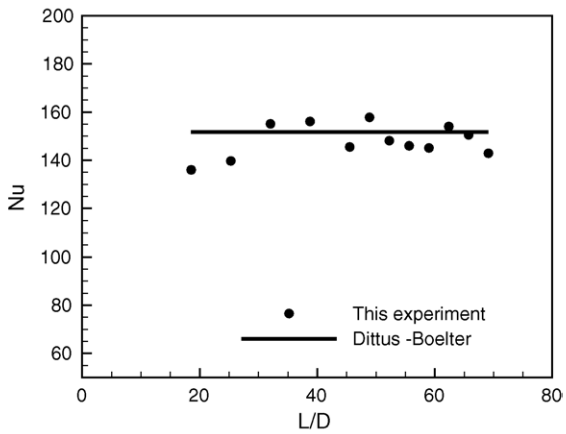

Fig. 7. Nusselt number distribution along the pipe.

is measured by thermocouples, and bulk temperature is estimated by Eq. (2) assuming that the heat loss is negligible and the temperature rises linearly along the heated section, where ΔT is total temperature rise along the pipe and x is downstream position of the measurement

$$T_b = T_{in} + \Delta T x/L \tag{2}$$

In order to ensure that the assumption is valid, the energy balance is examined by following procedure using Eq. (3). The inlet and outlet temperature is measured by thermocouples and the total temperature increase is compared with the calorimetric calculation. In Eq. (3), q is heat flux applied to the surface, A is surface area and $\dot{m}$ is mass flow rate

$$T_{out} - T_{in} = qA/C_p\dot{m} \tag{3}$$

Eq. (3) is satisfied with 6% through the measurements and ensures the energy balance. Comparison of the experimental result of Nusselt number distribution with empirical correlations [3] is shown in Fig. 7. The experimental result shows reasonable agreement with Dittus–Boelter equation within ±10% of uncertainty.

4. Summary and future plan

Flow measurement using PIV and heat transfer measurement have been carried out to study fully developed turbulent pipe flow as a preliminary research of thermo fluid properties of molten salt, FLiBe in particular. Flow condition of the experiment is Reynolds number 5300 based on the bulk mean velocity for PIV and $Re = 22{,}500$ for heat transfer experiment. Turbulent structure, mean flow property and turbulent statistics obtained by PIV technique are compared to the DNS (Direct Numerical Simulation) by Satake et al. and Nusselt number is compared with empirical correlations. The experimental results agree well with DNS and empirical correlation except for the near wall region where the images are distorted due to the curvature of the pipe. The mean flow profile shows very good agreement with DNS and the measurement error is less than 2% of the mean centerline velocity. Turbulent intensities and Reynolds stress profile agree well with DNS, which means that the fluctuation of the turbulent flow is well resolved by PIV. Nusselt number agrees with the empirical correlations within measurement uncertainty of 10%. Although there are some issues concerning the application of PIV for this experiment and the measurement accuracy of the heat transfer experiment, the result can be good benchmark of the experimental facility and will be used for a reference data for the flow and heat transfer measurement under the magnetic field in the near future.

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