Measurement of velocity field in pipe with classic twisted tape using matching refractive index technique

Min Seop Song, So Hyun Park, Eung Soo Kim*
Department of Nuclear Engineering, Seoul National University, 559 Gwanak-ro, Gwanak-gu, Seoul, South Korea
**Corresponding author: kes7741@snu.ac.kr*

1. Introduction

The twisted tape is a passive equipment enhancing the heat transfer capability of a heat exchanger. Several literatures [1] reported that a twisted tape increases turbulent intensity and induces swirl flow to improve the heat transfer efficiency. Previously, many researchers conducted experiments and numerical simulations to measure or predict a Nusselt number or a friction factor in a pipe with a twisted tape ([2], [3], [4]) while some other studies focused on the heat transfer performance enhancement using various twisted tape configurations ([1], [5]). However, since the optical access to the inner space of a pipe with a twisted tape was limited, the detailed flow field data were not obtainable so far. Thus, researchers mainly relied on the numerical simulations to obtain the data of the flow field.

In this study, a 3D printing technique was used to manufacture a transparent test section for optical access. And also, a noble refractive index matching technique was used to eliminate optical distortion. This two combined techniques enabled to measure the velocity profile with Particle Image Velocimetry (PIV). The measured velocity field data can be used either to understand the fundamental flow characteristics around a twisted tape or to validate turbulence models in Computational Fluid Dynamics (CFD). In this study, the flow field in the test-section was measured for various flow conditions and it was finally compared with numerically calculated data.

2. Experimental Setup

2.1 Flow Visualization Loop

An overall configuration of the experimental loop is presented in Figure 1. It is composed of a test section for flow visualization, a pump, a Coriolis flowmeter, and a tank.

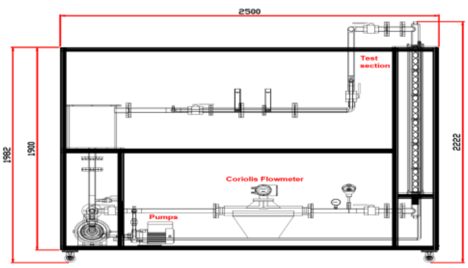

Fig. 1. Flow visualization loop

2.2 Test Section

A 3D printer using a Stereolithography method, RM-6000 of CMET, was used to make a test section. The shape of the test section was a single pipe containing a twisted tape along the flow direction. The material of the model was TSR-829, an epoxy resin. The layer thickness was 0.05mm in z-direction. Figure 2 shows both the CAD drawing and the 3D printed model of the test section. Among various twisted tape configurations, the most classic twisted tape which has the same scale of a diameter of the pipe and a height of the tape as 38mm was selected. The thickness of the tape was 2mm and the twist ratio was 3 (Y/D). Total length of 1368mm test section was made to achieve sufficient development length.

The 3-D printed models were fabricated to have the additive layers aligned to the camera with a 45 degree angle. Denis Butscher et al reported that the optimal particle image was captured when the laser plane illuminated or laser light reflected from the particle was not parallel to layer [6]. The image of particle was elongated when it was parallel to the layer. The refractive index of this model was 1.514 for the ray of wavelength of 532nm, which is the wavelength of Nd: Yag laser [7].

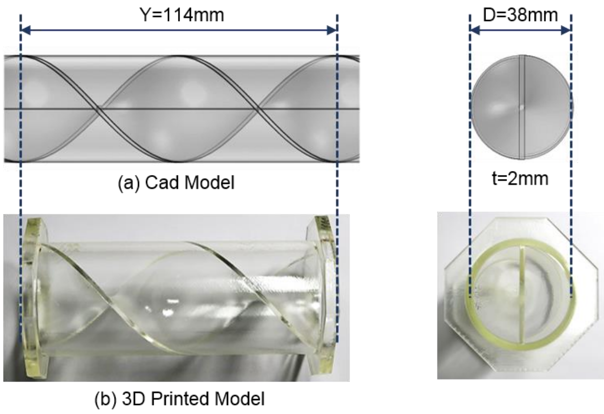

Fig. 2. Geometry of test section

2.3 Working Fluid

A working fluid was made by mixing light mineral oil and anise seed oil. Anise seed oil is a type of herb oil extracted from anise seed. Advantage of this oil is its high refractive index, 1.555. While mineral oil has lower refractive index than that of anise seed oil, it can be well mixed with anise seed oil. Therefore mineral oil is used with the purpose of adjusting the refractive index of the working fluid. Anise seed oil and mineral oil was mixed in the proportion of 59.8:40:2 to achieve the refractive index of 1.514, which is the refractive index of the 3-D printed model. The density of this oil was 915 kg/m3, measured from the Coriolis flowmeter. The viscosity was calculated as 0.0028683kg/ms by the correlation [6].

2.4 Matching Refractive Index

The test section was placed in a rectangular channel of glass. And to minimize the optical distortion, the inner space and the outer space of the model were filled with mixed oil. Figure 3 represents the comparative images of the test section in the presence of working fluid. The dotted image behind the test section was shown without distortion at matched refractive index condition.

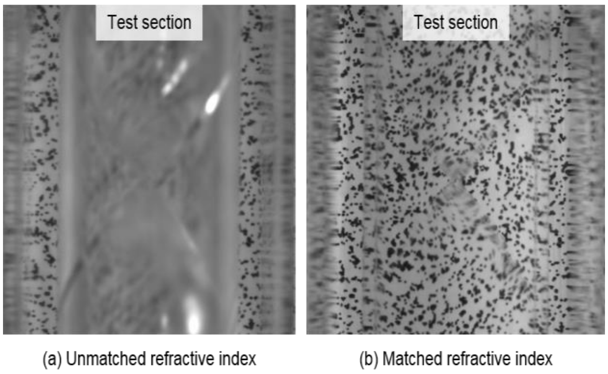

Fig. 3. Dotted image behind the test section with working fluid filled and unfilled

2.4 Particle image velocimetry system

The measurement of the flow field was performed by a particle image velocimetry (PIV) system of ILA, Germany. The particle image velocimetry measures 2 dimensional or 3 dimensional velocity field from particle images captured by the double head 532nm Nd:Yag laser and CCD camera of 2 megapixel with 14bit dynamic range[8]. The synchronizer were included to control the signal of laser and camera.

2.5 Experiment condition

Velocity field measurement was performed in the range of Reynolds number from 1370 to 9591. Table 1 shows the flow rate conditions. A hydraulic diameter was 0.0229m. According to the average velocity calculated from Reynolds number, the time distance between laser sheets was calculated. It was intended that particles move about 5 pixels in the time distance. The expected distance of the particles crossing laser sheet was calculated as 0.2 mm which is much shorter than the thickness of the laser sheet of 1 mm.

Table 1. Flow rate and time distance of cases

Mass flow Rate (kg/min)	Re	Average Velocity (m/s)	Time Distance (us)
5	1370	0.188	1314
15	4110	0.563	438
25	6851	0.938	266
35	9591	1.313	190

2.6 PIV measurement

Silver coated hollow glass spheres with a diameter of 15um were used as seed particles. The size of particle was about 2~3 pixels in the recorded images. A resolution of the camera was 1600 by 1200 pixels and the field of view was 80mm x 60mm. The ratio between the actual pixel size and the field of view was 0.15. The field of view was located at the 228mm above the bottom. The measurement planes and the field of view is depicted in the Figure 4. The measurement planes were at the first center of the test section and it moved by 6mm forward. Standard cross-correlation was applied with the interrogation window size of 32 pixels. Total 177 image pairs were calculated and averaged.

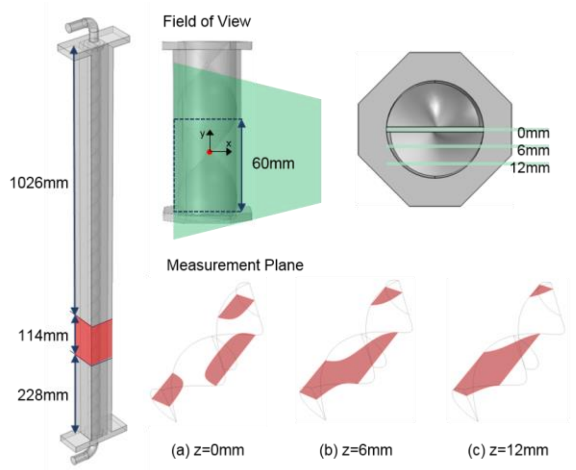

Fig. 4. PIV measurement planes

2.7 CFD simulation

COMSOL, a multi-physics code, was used to calculate the flow field numerically. As the test section was made from the computer aided designed files, the CAD file of the twisted tape was also used for the simulation. Using that CAD file, the inner flow path of the pipe was extracted. A standard k-e turbulence model was adopted in the simulation. As the geometry of inlet

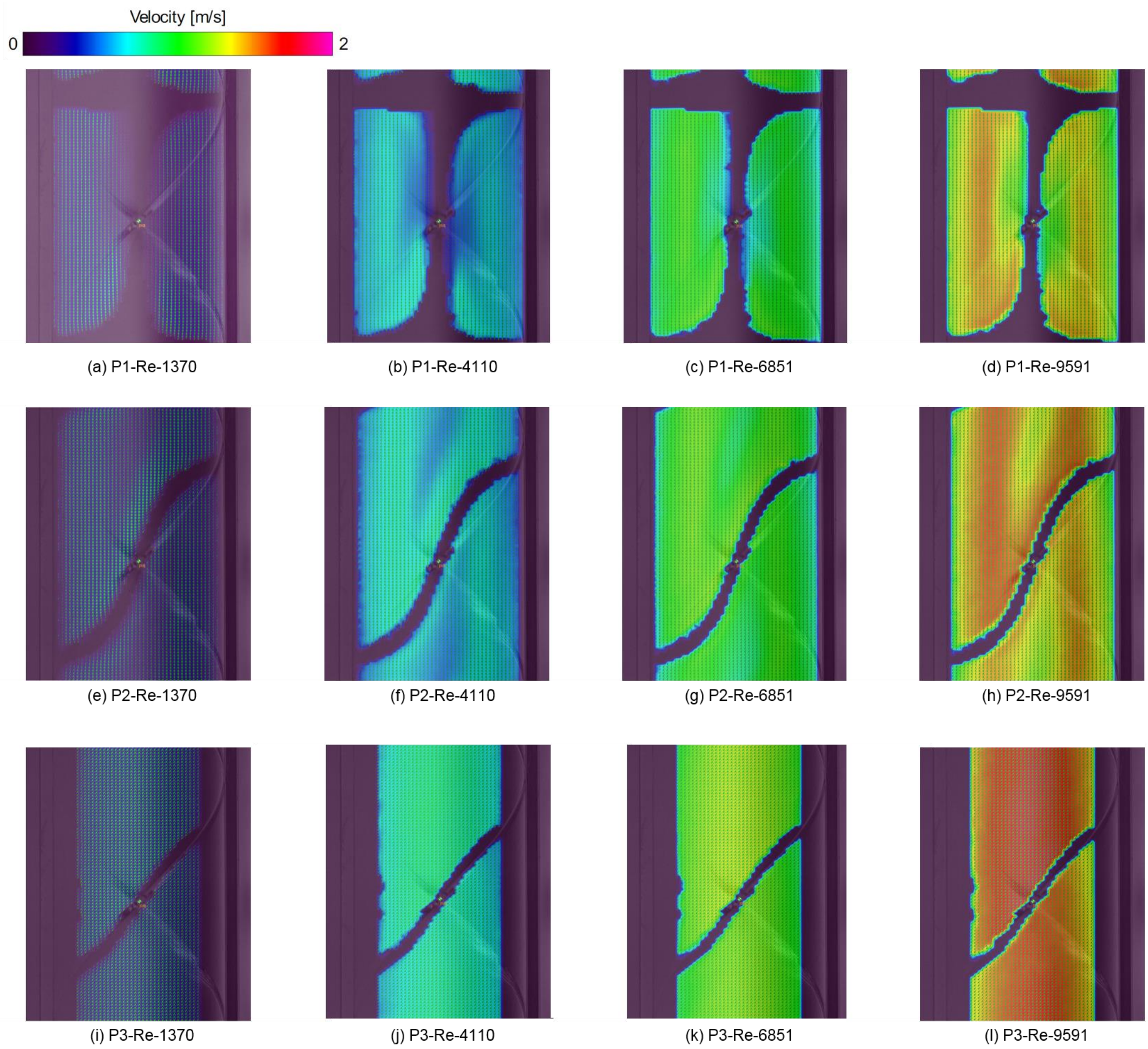

Fig. 5. Average velocity vector fields

and outlet are identical, the same average velocity was used for the boundary condition.

3. Result and Discussion

Figure 5 shows the average velocity vector fields and contour of magnitude. Unsolved regions is the place that the tape exist. Results shows that magnitude of velocity is higher far from the wall and the magnitude of velocity was even at the plane3.

The PIV data were compared with the CFD results at the line of y=0. Figure 6 represents the comparative graph between the CFD and the PIV at the different measurement planes. The x axis represents the distance from the origin in x-direction. The y axis represents the velocity magnitude of 2 components of velocity. Velocity component u, v in PIV and u, w in CFD was

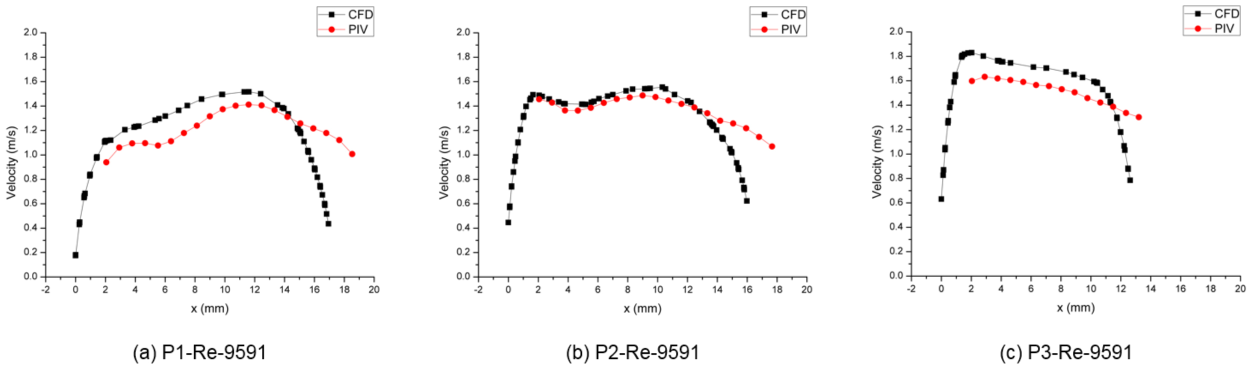

Fig. 6. Magnitude of velocity from CFD and PIV at y=0

selected to calculate the magnitude of velocity. Overall, the velocity magnitude of the CFD were predicted to be higher than the PIV data. The relative error between the CFD and PIV data was the smallest in the plane 2 within 3.2%. The graph for the different Reynolds numbers showed the same tendency.

Assuming that the velocity magnitude of the PIV data reflects the real velocity field, it can be concluded that the CFD results a little bit overestimated the velocity. This difference could be originated from (1) the difference between the real viscosity and the calculated value, (2) insufficient mesh quality and (3) imperfect turbulent parameter quantities. However, capability of the CFD to predict the velocity in the region adjacent wall was much better than the PIV data. Due to the cross-correlation algorithm, a velocity measurement at the wall was very limited. Therefore, additional measurement techniques such as the laser doppler velocimetry (LDV) are currently under considerations for further tasks in order to obtain the velocity near the wall.

4. Conclusions

Velocity fields in a pipe with a classic twisted tape was measured using a particle image velocimetry (PIV) system. To obtain undistorted particle images, a noble optical technique, refractive index matching, was used and it was proved that high-quality image can be obtained from this experimental equipment. The velocity data from the PIV was compared with the CFD simulations. The results show that the velocity field calculated using a standard k-e model estimates the velocity somewhat higher than the experimental data. However, further numerical studies are needed to make a conclusion at this stage.

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