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Measurement of the flow field characteristics in single and dual S-shape 90° bends using matched refractive index PIV

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ABSTRACT

The flow field in single and dual S-shape short radius 90° bends was measured using matched refractive index Particle Image Velocimetry (PIV) at Reynolds numbers of 40,000 and 70,000. The high velocity region in the first bend of the S-bend moves closer to the outer wall as it moves along the curvature than in the single bend. The flow then accelerates further along the inner wall of the second bend. The averaged in-plane components of the turbulence kinetic energy in the single bend and the first bend of the S-bend are similar, with an increase along the outer wall and downstream of the separation zone on the bend inner wall. The turbulence kinetic energy in the second bend was much higher than in the first bend of the S-bend. Counter rotating vortices develop in the first bend and propagates into the second bend. High velocity secondary flows are observed near the second bend inner wall at approximately 40° along the second bend.

1. Introduction

The flow in pipe bends has been studied since Dean [1] observed counter rotating vortices in a single 90° bend under laminar flow conditions. Similar features have been observed in sharp 90° bends under turbulent flow conditions [2,3]. The flow in bends is affected by centrifugal forces which drive the flow in the core region toward the outside radius. The pressure gradient in the cross section, due to this centrifugal force, drives the flow back along the walls toward the inner radius. The two mechanisms result in double counter rotating vortices within the cross section of the bend [2]. Meanwhile, the adverse pressure gradient along the inner radius may lead to flow reversal and separation from the wall. The dynamics of the double counter rotating vortices is highly sensitive to the upstream conditions. The flow separation on the bend inner wall near the outlet is reported to be transient and causes pressure fluctuations in the bend cross section [4]. Periodic changes in the strength of the counter rotating vortices downstream of a single bend has been observed [5–9] and reported to cause significant pressure fluctuations.

The flow dynamics in dual bends is even more complex due to the flow interactions within the two bends [10]. The flows through these bends are of interest because they can produce higher pressure losses and can promote heat or mass transfer in the bends [11–13] that is of importance in applications such as flow accelerated corrosion [14]. The flow dynamics in back-to-back bends arranged in U-, out of plane- and S-configurations have been investigated [10,15–22]. The turbulence level and pressure drop in the S configuration was highest when compared to the U- and out of plane-dual bend configurations under turbulent flow condition [15]. This could be due to the directional effects of the bend curvature on the flow in the first and second bend. In U-bends, the curvature in the first and second bend is in the same direction, and results in a reinforcement of the secondary flows in the second bend [20]. In S-bends, the curvature of the second bend would tend to drive the mean secondary flow in the opposite direction. In laminar flows through small angle bends, the secondary motions are suppressed in the initial part of the second bend and two pairs of counter rotating secondary motions were observed in the latter part and downstream of the second bend [10,17]. In larger angle bends, the secondary motions in the second bend may overcome those in the first bend [17]. This may not be the case in turbulent flows through bends. In this case, measurements in the pipe indicate that the secondary motions are unsteady [18]. The average turbulence level measured at different locations in the pipe downstream of the second bend of an S-bend decreased when the length of the pipe between the bends increased [18]. The maximum mass transfer that occurred downstream of the first bend also decreased when the distance between the bends increased [11], both of which indicate the presence of a second bend in close proximity to another has a significant impact on the flow through the bends.

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Nomenclature

D	nominal pipe diameter [m]
D_m	mass diffusivity for Hydrocal in water [m^2/s]
h	mass transfer coefficient [m/s]
r	local position in the pipe cross section [m]
R	pipe radius of curvature [m]
Re	Reynolds number $\rho \cdot U_o \cdot D/\mu$ [m]
u	total local flow velocity magnitude [m/s]
u'	fluctuating velocity component in x-direction [m/s]
v'	fluctuating velocity component in y-direction [m/s]
U_o	average bulk flow velocity in the upstream pipe [m]
X/D	streamwise dimensionless distance

Symbols

θ	bend cross sectional angle
Φ_1	bend angle of curvature (along first bend)
Φ_2	bend angle of curvature (along second bend)

The objective of the current study is to investigate the flow field within back to back 90° bends arranged in an S configuration. Measurements were performed for 90° bends with a radius of curvature r/D of 1.5 with zero separation distance between the bends for Reynolds numbers of 40,000 and 70,000. The flow field in acrylic test sections was measured with Particle Image Velocimetry by using a refractive index matched working fluid. The results for the back-to-back bends were compared to measurements in a single 90° bend at the same Reynolds numbers. The results show that the presence of the second bend had a significant effect on the trajectory of the mean flow through the bend.

2. Experimental facility and methodology

The measurements were performed in a 2.54 cm diameter flow loop shown schematically in Fig. 1(a). This facility has been used in previous mass transfer studies using water as the working fluid and is described in detail in [11]. Here, a 60% ratio of Sodium Iodide (NaI) to water by weight was used as the working fluid to match the refractive index to the acrylic test section [19]. The properties of the Sodium Iodide solution was obtained from [23]. The fluid is circulated from a 100 l reservoir through the test facility by a centrifugal pump. The flow rate is regulated by globe valves and measured by a turbine flow meter with an accuracy of ±1% of the flow reading. The flow is passed through a perforated plate followed by a honey-comb before entering a straight pipe with a length of 160 cm leading to the test section. The test section was manufactured from transparent acrylic with a cross sectional bend diameter of 2.54 cm and radius of curvature r/D of 1.5. The flow exited the test section to a 75 cm long straight pipe before being directed back to the reservoir. The fluid temperature was measured in the reservoir and controlled to within 25 ± 0.5 °C using a compensation cooling loop.

The velocity field is measured using a 2-dimensional Particle Image Velocimetry (PIV) system with a single PowerView 4MP 12 bit digital camera with a resolution of 2048 × 2048 pixels at a

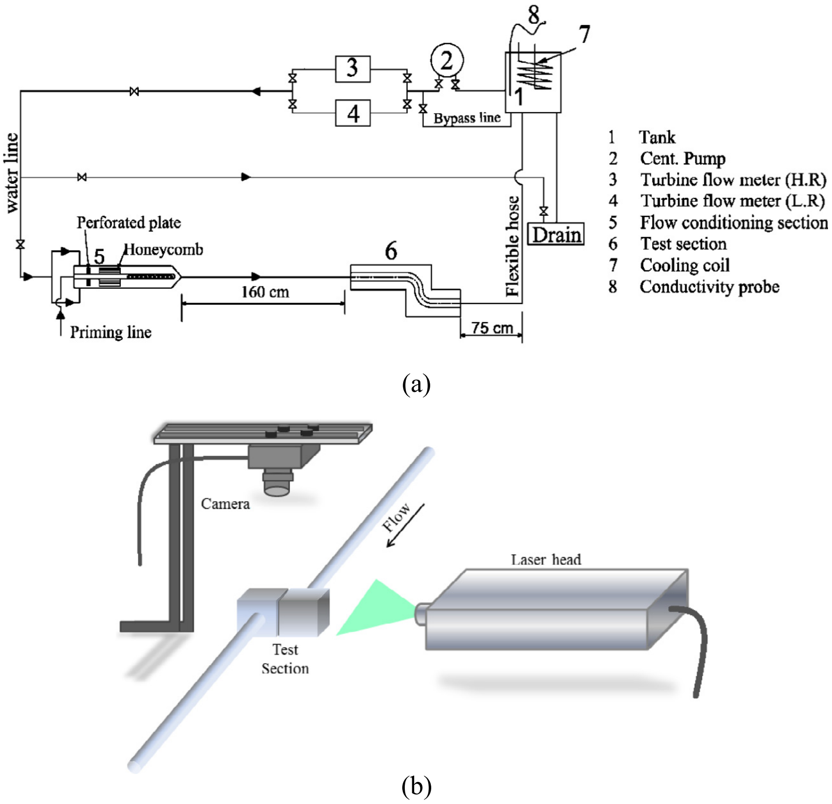

Fig. 1. Schematic of (a) flow loop and (b) the *PIV* setup.