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Dean instability and secondary flow structure in curved rectangular ducts

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ABSTRACT

The pressure driven, fully developed turbulent flow of incompressible viscous fluid (water) in 120° curved ducts of rectangular cross-section is investigated experimentally and numerically. Three different types of curved duct (A-CL, B-SL and C-IL) with continuously varying curvature conform to blade profile as the inner and outer curvature walls to simplify and guide the impeller design of pumps. After validating the numerical method against Particle Image Velocimetry (PIV) measurements, the flow development in the ducts is analyzed in detail by Computational Fluid Dynamics (CFD) for a wide range of Reynolds numbers ($Re = 2.4 \times 10^4$–1.4×10^5) and aspect ratios ($Ar > 1.0$, $=1.0$ and <1.0). The results clearly depict the existence of multiple Dean vortices along the duct: while the axial velocity profile is more related to an inner Dean vortex (called split base vortex), the wall pressure is more influenced by the Dean vortex attached to the inner curvature wall (called ICW Dean vortex). The induced multiple Dean vortices and the secondary flow patterns in the duct cannot be faithfully predicted by using traditional techniques. Therefore, a new criterion based on the vortex core velocities is proposed. With this approach, the effects of *Re, Cr* and *Ar* on the Dean instabilities in curved ducts are carefully studied. Decreasing *Re* promotes the generation of Dean vortices closer to the duct inlet, a trend that is as opposed to laminar flow. In addition, a new pair of vortices called entrainment Dean vortex occurs near the outlet of the curved duct with $Ar = 1.0$, which has not been previously reported in the literature.

1. Introduction

Curved ducts (or channels) are omnipresent in hydraulic systems. A common example is the spiral channel of a pump volute and flow passage in an impeller. These types of flow are usually simplified as flow in a curved duct of rectangular cross-section, and have been extensively investigated to guide fluid machinery designs (Boyle et al., 1989; Tsujita and Mizuki, 2003; Michael and Chris, 2010). Unlike a typical curved duct with constant curvature, the curvature in the flow passage of fluid machinery varies continuously along the flow direction.

Due to the presence of centrifugal force and pressure gradient, the flow in a curved duct is characterized by a pair of counter-rotating secondary vortices which is known as the Dean vortices (Dean, 1927, 1928). For this flow, the governing parameter is Dean number (De), which is defined as

$$De = \frac{u_b D_h}{\nu}\sqrt{\frac{D_h}{R_c}} = \mathrm{Re}Cr^{1/2} \quad (1)$$

where u_b is the bulk velocity, ν is the kinematic viscosity of fluid, $D_h (= 2ab/(a + b)$, where a and b are the height and width of duct, respectively) is the hydraulic diameter, R_c is the mean radius of curvature, Re is the Reynolds number based on the bulk velocity and the hydraulic diameter, and Cr is the curvature ratio.

According to Eq. (1), Dean number may be interpreted as the ratio of inertial or centrifugal force to viscous force, or as Reynolds number modified by the path curvature. It depends on 2 dimensionless parameters, i.e., the curvature ratio Cr and the aspect ratio Ar ($=a/b$). Fellouah et al. (2006a, b, 2010) investigated both Newtonian and non-Newtonian fluid flow in 180° curved channels with $5.5 \le Cr \le 20$ and $0.5 \le Ar \le 12$ in the laminar regime (De < 500). Chu et al. (2010) studied the flow in curved rectangular microchannels with $0.5 \le Ar \le 1$ and $0.035 \le Cr \le 0.04$ for Re ranging from 80 to 876, and Guo et al. (2011) investigated the laminar flow ($100 < Re < 900$) in curved rectangular channels with $0.0067 \le Cr \le 0.0356$ and $0.5 \le Ar \le 1$. Later, Chandratilleke and Nursubyakto (2003) presented a numerical study in externally heated curved rectangular ducts with $1 \le Ar \le 8$ for De ranging from 20 to 500. More recently, Chandratilleke et al. (2012) proposed an improved model based on 3-dimensional (3D) vortex structures to capture the onset of Dean instability in curved rectangular ducts with $1 \le Ar \le 6$ and $4 \le Cr \le 5$.

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Nomenclature

a	height of duct cross-section	Re	Reynolds number based on the axial bulk velocity and hydraulic diameter ($=u_bD_h/\nu$)
Ar	aspect ratio ($=a/b$)	u_a	axial velocity
b	width of duct cross-section	u_b	bulk velocity in axial direction
Cr	curvature ratio ($=D_h/R_c$)	u_R	secondary velocity in radial (R) direction
De	Dean number ($=\mathrm{Re}Cr^{1/2}$)	u^*	normalized axial velocity ($=u_a/u_b$)
De_{crit}	critical Dean number for the onset of Dean vortex	u, v, w	velocity component in x, y, z direction
D_h	hydraulic diameter ($=2ab/(a+b)$)	x, y, z	coordinate system
R	radius of curvature	θ, r	polar coordinate system
R^*	normalized radius of curvature ($=(R-R_{ICW})/b$)	R, s	coordinate system in cross-section
R_c	mean curvature radius ($=R_{ICW}+b/2$)	ρ	density of fluid
		ν	kinematic viscosity of fluid

Ko and Wu (2009) investigated secondary flow instability induced by turbulent forced convection in curved rectangular ducts with $Ar = 0.25$, 1 and 4. It is noted that the aforementioned studies focused on curved ducts with constant curvature and aspect ratio. On the other hand, Bhunia and Chen (2009) investigated laminar air flow in a curved rectangular channel with variable cross-sectional area by varying b while keeping the radius of concave wall (R_{ICW}) constant. Li et al. (2016) studied turbulent liquid flow ($24{,}000 < Re < 140{,}000$) and investigated the influence of Cr in curved rectangular ducts with constant cross-section width (b) but continuously varying curvature (R_{ICW}). Both studies depicted the existence of multiple Dean vortices in the duct.

One may establish the quantitative criterion for capturing the onset of Dean instability (i.e., determination of the critical Dean number De_{crit} for the occurrence of Dean vortex) using several approaches. The first approach is flow visualization, which was used in Bara et al. (1992) to investigate the laminar flow development in a curved duct with $Cr = 15.1$ and $Ar = 1.0$, and found $De_{crit} = 137$. Fellouah et al. (2006a, b, 2010) showed that flow visualization is an approximative approach and thus proposed an alternative method based on the radial gradient of the axial velocity. However, Chandratilleke et al. (2012) suggested that the change of axial velocity in radial direction is not fundamentally linked with secondary vortex generation, and proved that Fellouah et al. (2006) had failed in detecting the Dean instability around De = 100. Therefore, Chandratilleke et al. (2012) developed another technique, i.e. the adverse pressure gradient at the outer duct wall and assigned normalized helicity threshold. Nadim and Chandratilleke (2014) compared the two techniques in a two phase flow and found that the helicity threshold technique is more appropriate. However, it is noteworthy that all these approaches were proposed and tested for laminar flow, and may not be applicable in turbulent flow. In addition, these approaches were proposed to for the detection of the basic type of Dean vortex, yet their applicability for different types of Dean vortex has not been verified. This motivates the present study to elucidate the onset of Dean instability and the characteristics of multiple Dean vortices for turbulent flow in curved ducts. Specially designed ducts with variable curvature are used to simulate the flow passage in the impeller of centrifugal pumps. The present study is an extension of our earlier study (Li et al., 2016), in which the overall flow development in those ducts was presented.

2. Duct model and experiment setup

2.1. Design and fabrication of curved ducts

Fig. 1(a) shows the schematic diagram and coordinate system of the curved rectangular duct with a uniform cross-section (width b and height a). The model consists of the curved duct (which spans from the polar angle $\theta = 0^\circ$ at the inlet to $\theta = 120^\circ$ at the outlet) fitted with 980-mm-long straight inlet and outlet. Here, the curvature ratio (Cr) and aspect ratio (Ar) are defined as

$$Cr = \frac{D_h}{R_c} = \frac{D_h}{R_{ICW} + b/2} \tag{2}$$

$$Ar = \frac{a}{b} \tag{3}$$

where R_{ICW} is the radius of inner curvature wall (ICW).

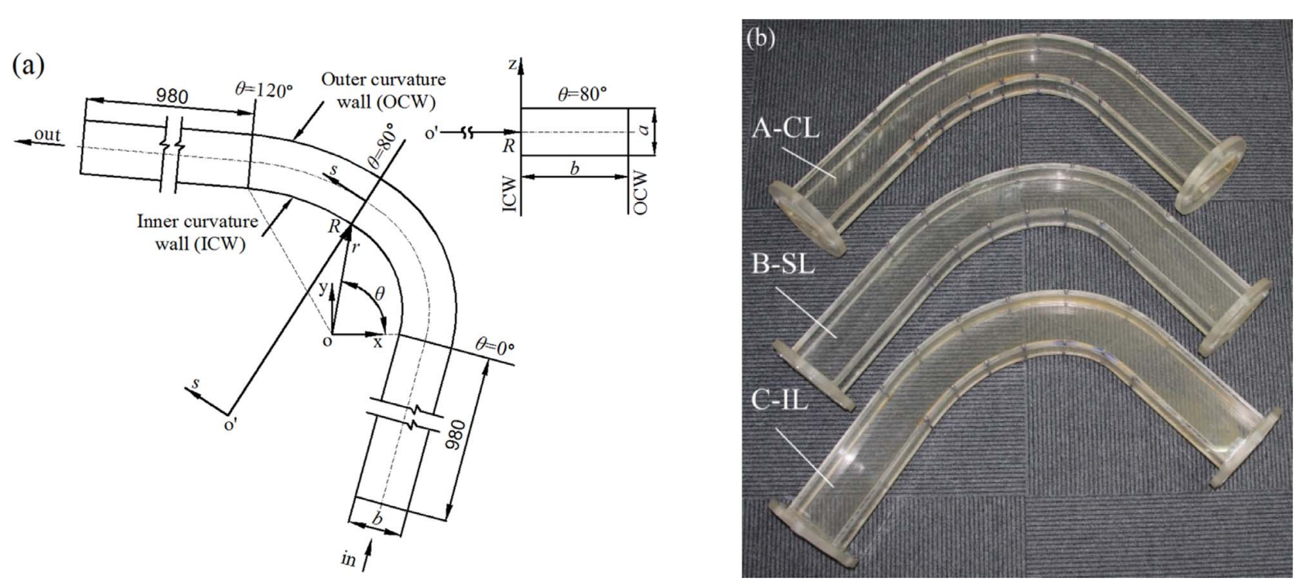

Fig. 1. (a) Schematic of curved duct model; (b) photograph of the physical models with $Ar = 0.4$.

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