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Computational Analysis of Rheological Secondary Flow in a Pipe-Manifold Containing In-Plane Double Bends

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ABSTRACT

Non-Newtonian fluid flow in pipe bends is inevitable in industrial applications. Previous researchers have extensively explored Newtonian flow through curved ducts. However, the non-Newtonian counterpart gets little attention. We study the turbulent flow of shear-dependent fluids obeying the Power-Law model in a pipe manifold containing an in-plane double bend. Ostwald–de Waele's power law is used to model the fluid's rheology. We utilize computational fluid dynamics (CFD) to solve Reynolds-averaged Navier–Stokes (RANS) equations with the k-ε turbulence model. We validate our numerical results with previous experimental results. The in-plane double bend perturbs the flow in the pipe manifold to develop a Prandtl's secondary flow of the first kind. A fully developed flow at the bend upstream is disturbed due to the bend's curvature and regains its fully developed characteristics upon a certain downstream length after the exit of the bend. We study the rheological characteristics of the secondary flow within the bend and the evolution of fluid flow at the bend downstream. We demonstrate that the centrifugal force-dominated secondary flow increases with a decrease of the non-Newtonian power-law index. We capture the camel's-back-shaped velocity profiles within the bend due to accelerating-decelerating flow. The study reveals that the average flow velocity increases along the bend with a corresponding pressure head loss. We quantify this velocity rise by a newly introduced non-dimensional number, viz. enhancement ratio. The double bend's enhancement ratio decreases with an increase in n.

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1. INTRODUCTION

Bent pipes are unavoidable in industries like gas and oil, food processing, paper manufacturing, and heat & energy sectors like nuclear power plants, solar thermal systems etc. The evolution of cross-stream flow inside a skewed pipe, i.e. Prandtl's secondary flow of the first kind, has been a matter of concern for years (Bradshaw et al., 1987; Lai et al., 1991; Kalpakli et al., 2016). Additional losses are incurred in the pressure head due to the presence of bends in ducts (Ito 1960), which is a matter of concern for engineers to optimize energy consumption. This loss is due to the disturbances created by cross-stream flow, which is greatly affected by both the Reynolds number (Re) and curvature ratio (Berger et al., 1983; Ito 1987). The curvature ratio is a geometrical parameter, defined as the ratio of bend radius to the inner radius of the pipe, i.e. R_c/R. A non-dimensional number called Dean number (De) defined as, $De \equiv Re\sqrt{R_c/R}$; is often used to characterize the effect of Re and (R_c/R) on flow inside curved pipes in a combined manner. On the contrary, analyzing the individual effect of Re and R_c/R is a good practice in many cases, such as turbulent flows (Cieślicki & Piechna, 2012; Canton et al., 2016). Prandtl's secondary flow of the first kind is always a centrifugal-force dominated flow, resulting in a local pressure gradient (Barua 1963) which causes the mid-plane fluid particles to move towards the outer core of the pipe along with the formation of a pair of counter-rotating Dean vortices (Dean, 1927).

Effective space utilization is a matter of concern in industries, attracting engineers towards layout complexity while designing a system. To avoid long-distance straight pipes, often bends and bend-combinations are employed. Successive bends or bend combinations may be either in-