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Morphology of laminar rheological flow in polygonal ducts

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Sayantan Sengupta (সায়ন্তন সেনগুপ্ত),[1,a] Arka Banerjee (অর্ক ব্যানার্জী),[1,2] and Shantanu Pramanik (শান্তনু প্রামাণিক)[1]

AFFILIATIONS

[1]Department of Mechanical Engineering, National Institute of Technology, Durgapur, West Bengal 713209, India
[2]Department of Mechanical Engineering, Dr. B. C. Roy Engineering College, Durgapur, West Bengal 713206, India

[a)]Author to whom correspondence should be addressed: ssengupta.me@nitdgp.ac.in

ABSTRACT

We numerically study the fluid dynamics of laminar, rheological flow in regular polygonal ducts. We demonstrate that the entry length for the flow development increases with a decrease in the number of sides m and an increase in flow behavior index n. Furthermore, we explore the impact of m and n on the major output parameters and propose simple correlations to predict entry length, the shape of the fully developed axial velocity profile and friction factor based on two newly introduced geometric parameters, viz., the factor of approach and integrity index. While it was well-known that turbulent flow through non-circular ducts typically induces Prandtl's secondary flow of the second kind, the present study reveals the occurrence of such secondary flow associated with the corner convexities of the primary velocity profile, even within the laminar regime. We capture a counter-rotating vortex pair at each corner of the polygonal duct as evidence of the secondary flow. A novel visualization method tracks the evolution of vortices diminishing downstream. The strength of the vortices reduces with the increase in the number of corners, as does the strength of secondary velocity. We demonstrate three distinct fluid dynamic regimes using the vortex line representation: the near-wall region, the inner core, and an intermediate region. The inner core and the intermediate region carry the signatures of potential and secondary flow regimes, respectively. These two regimes wipe out once the entire cross section becomes viscous-dominated, yielding a fully developed flow. Such development happens far from the duct's inlet for shear-thickening fluids.

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I. INTRODUCTION

Flow through non-circular cross sections is often investigated in the fluid dynamics of open channels, canals, and rivers.[1,2] However, it is equally important to understand the influence of non-circular cross sections on internal flows. Non-circular ducts are widely used in aerospace, biomedical, chemical, electronics, and nuclear industries.[3] Moreover, non-circular ducts are ubiquitous in many process applications, such as heat exchanger flows, water draining, ventilation and air conditioning systems, fluidized beds, and turbomachinery. Even though circular ducts are frequently used as heat exchangers, it is still necessary to use ducts with non-circular cross sections to achieve reasonable compactness (the ratio of surface area to volume). To improve the performance of heat exchangers, the designers often utilize different non-circular ducts, yielding greater compactness based on size and volume limits. For example, single and double-trapezoidal (hexagonal) ducts are used in lamella-type heat exchangers,[4] elliptical ducts are commonly used in industrial ventilation and air conditioning systems,[5] and rectangular ducts in plate heat exchangers. Literature shows that researchers have previously examined several non-circular duct shapes, such as semi-circular,[6] circular segments,[7] and double-sine[8] in many other applications. The present study considers regular polygonal cross sections for systematically introducing the impact of non-circularity in the analysis and a non-Newtonian fluid framework for the sake of generalization. We employ computational fluid dynamics (CFD) to examine the fluid dynamics of rheological flow in the polygonal ducts.

The transport of non-Newtonian fluids is pervasive in several process and chemical industries (e.g., the transport of chocolates, sauces, mayonnaise, jams, ice cream, cake mixes, and dairy products in the food industries; nail polish, lotions and creams, lipsticks, shampoos, shaving foams in cosmetics industries; paper pulp suspensions in paper manufacturing companies; printing inks in printing industries; creams, foams, suspensions in pharmaceutical companies; drilling muds, crude oils in petroleum industries). The non-Newtonian fluids can be broadly classified into viscoelastic and inelastic categories.[9,10] The viscoelastic category of non-Newtonian fluids exhibits a combination of viscous fluid and elastic solid attributes. The inelastic category