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A Simplified CFD Model for Steady Transitional Flow in Narrow U-shaped Channels

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Abstract: In this paper, a simplified CFD model that facilitates rapid analysis of steady transitional flow in narrow U-shaped channels is proposed, formulated, and numerically implemented. A depth-averaging technique is used to reduce the original three-dimensional (3-D) Navier-Stokes (N-S) equations to two-dimensions (2-D) with a unique treatment of the viscous terms, which are expressed in terms of the local wall shear stress and computed through a use of the Colebrook correlation for transitional and turbulent flow in channels. Given slowly varying flow paths in the narrow channels, an integral of the 2-D N-S equations is approximated with a viscous Bernoulli equation. The resulting model is then solved with a finite-difference method, taking less than10 seconds using a modern PC desktop (Intel(R) Core TM2 Duo CPU, 2.4GHz).The numerical scheme is tested for smooth straight and U-shaped narrow channels, all within errors of 10%, as compared to experimental results. With its greatly reduced computational times, the proposed model is well suited for design analysis of compact heat exchangers with curved flow paths in narrow channels.

Keywords: Transitional flow, U-shaped channels, Depth-averaged Navier-Stokes equations

1 Introduction

Flow across narrow rectangular channels with curved (e.g., U-shaped) flow paths is encountered in many engineering applications, including compact heat exchangers, turbine internal channels, fuel cell plate processors, etc. Complexity is added for flow in curved channels owing to locally mixed flow regimes, especially when transitional flow is involved. Modern CFD packages may be able to simulate the 3-D transitional flow in curved channels, but it is often time consuming and the accuracy is not always guaranteed. However, by taking advantage of pressure driven flow in narrow (low aspect ratio) rectangular channels, the 3-D flow structure in channels can be simplified. This paper seeks a reduced model that is capable of quickly simulating flow in curved narrow channels, yet provides a useful and reliable answer for design and analysis of compact heat exchangers.

2 Problem Statement

A depth-averaging technique was proposed to reduce the steady 3-D N-S equations that describe the incompressible flow in a narrow (low aspect ratio, i.e., d<<L & W) rectangular channel as 2-D N-S equations:

$$Continuity:\nabla\vec{V}=0; Momentum: \rho(\vec{V}\cdot\nabla)\vec{V}=-\nabla P-\frac{\vec{\tau}_w}{d}$$

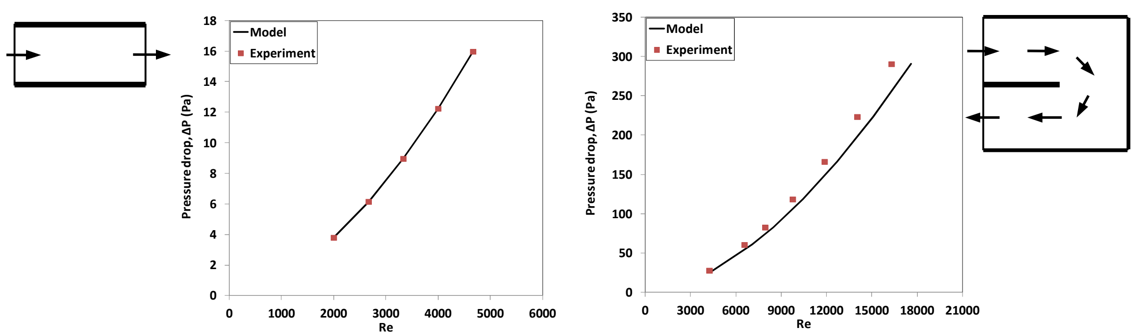
where, $\vec{V}$ is the depth-averaged velocity vector, $\vec{V}(u,v)$; P is the pressure and d is the half channel gap size; $\vec{\tau}_w$ is the local wall shear vector and its magnitude is given by $\tau_w = f\frac{\rho V^2}{8}$, in which f is the Darcy friction factor. For plain channel with known surface (equivalent sand grain) roughness, f can be computed using Colebrook correlation which offers a good estimation of frictional loss for transitional flow in channels/pipes.

Given slowly varying flow paths in the narrow channels, the steady energy equation can be derived in an approximate manner, which represents a "viscous Bernoulli equation" as:

$$\rho\frac{V^2}{2}+P+K(V)\Phi=const.$$

where, $K(V)=f\frac{\rho V}{8d}$ is a scalar coefficient, Φ is the velocity potential defined as $V=\nabla\Phi$. The reduced 2-D model automatically turns to 1-D if the flow path is not curved, i.e., in straight channels.

A finite difference numerical scheme based on potential flow theory was developed for the solution. The model has been tested for 1-D case for a smooth straight channel and 2-D case for a smooth U-shaped narrow channel, both within errors of 10% comparing to the experimental results, as illustrated in Figure 1. The computational time is within 10 seconds using a modern PC desktop (Intel(R) Core TM2 Duo CPU, 2.4GHz) for all the test cases.



(a) 1-D case **(b) 2-D case**

Figure 1 Comparison of model predictions with experimental results for: (a) a smooth straight channel (1-D case), and (b) a smooth U-shaped narrow(aspect ratio:1/29) channel (2-D case). Note: Re is the averaged value calculated at the channel entry section

3 Conclusion and Future Work

A simplified CFD model for the fast simulation of steady transitional flow in compact heat exchangers that have U-shaped flow path in narrow channels was presented. The model has been tested with experimental results for a smooth straight channel and a smooth U-shaped narrow channel, all within errors of 10%. The computational time was within 10 seconds using a modern PC desktop (Intel(R) Core TM2 Duo CPU, 2.4GHz). The preliminary results are very promising for a complete modeling of compact heat exchangers.