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Investigating heat transfer properties of tubular heat exchangers with a stochastic turbulence model

Pei-Yun Tsai*[1,2], Heiko Schmidt[1,2], and Marten Klein[1,2]

[1]Numerical Fluid and Gas Dynamics, BTU Cottbus-Senftenberg
[2]Scientific Computing Lab, Energy Innovation Center Cottbus

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Concentric coaxial pipe flows play an essential role in the engineering sector, in particular for tubular (pipe-in-pipe) heat exchangers. Heated concentric coaxial pipe flows have been studied numerically for feasible low Reynolds numbers to fundamentally investigate the dependence on the radius ratio [1] and thermal boundary conditions [2]. However, an accurate but economical approach to acquire robust predictions of both heat transfer and pressure loss in concentric coaxial pipe flows under fully developed (high Reynolds number) turbulent conditions has remained a challenge for state-of-the-art numerical methods and turbulence models. Reduced-order stochastic modeling, here by means of the so-called one-dimensional turbulence model [3] (ODT), is able to address this challenge as demonstrated previously [4, 5]. This is achieved by modeling turbulent eddies through a stochastically sampled sequence of physical mapping events. The computational domain is located in the radial interval ranging from the inner to outer cylinder walls, as shown in Figure 1(a). The temperature is modeled as a passive scalar subject to uniform heat flux boundary conditions. The model has been calibrated recently for concentric coaxial pipes for $Pr = 0.71$ [4]. For the calibrated model, the heat transfer, in terms of the Nusselt number, is shown as function of the radius ratio together with available reference data [1]. It is obtained that the Nusselt number at the inner cylinder, Nu_i, sharply increases as the radius ratio η decreases. The same behavior has also been captured in the low Prandtl number regime for $Pr = 0.025$. Still, a careful investigation of the flow's statistical features and scaling properties of the statistical moments of fluctuating flow profiles given the heat transfer has not been done in an extended parameter space. In this study, we investigate the turbulent flow in pressure-driven concentric coaxial pipes with momentum and passive scalar transfer using the ODT model to reach high Reynolds and low Prandtl numbers. It is discussed how wall-curvature effects influence the transfer properties and the turbulent boundary layer. This showcases the predictive capabilities and added value of this stochastic tool for reduced-order modeling of heat exchangers for advanced control of multi-energy grids.

*tsaipeiy@b-tu.de

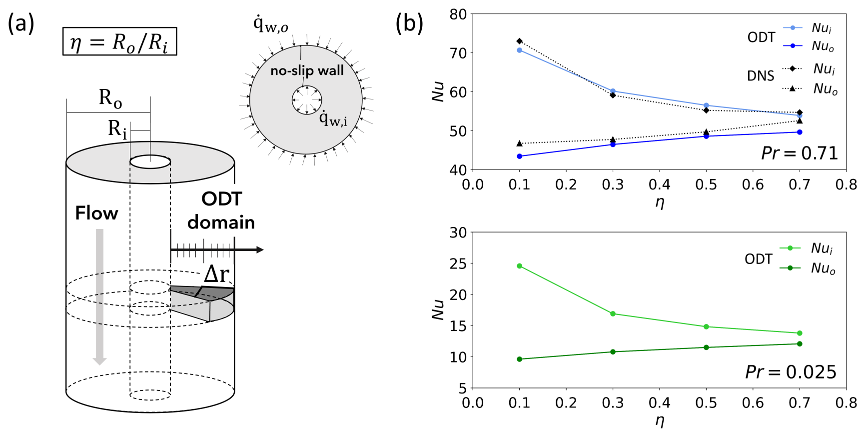

Figure 1: (a) Sketch of the annular pipe configuration. The wedge-like domain is used for ODT simulations. No-slip and uniform heat-flux boundary conditions are prescribed as indicated. (b) Nusselt number $Nu_{i,o}$ at the inner and outer cylinder for $Re_b = 17,700$ ($Re_\tau \approx 270$) as a function of the radius ratio η for air ($Pr = 0.71$, top) and mercury ($Pr = 0.025$, bottom), respectively. Reference data from [1].

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