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DNS STUDY OF TURBULENT FLOW THROUGH A CONCENTRIC PIPE FORMED BY AN OUTER SQUARE DUCT AND AN INNER CIRCULAR CYLINDER

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ABSTRACT

Turbulent flow through a concentric pipe has many practical engineering applications such as HVAC systems and heat exchangers. Direct numerical simulations (DNS) have been performed to study turbulent flow through a concentric pipe consisting of an outer square duct and an inner circular cylinder. A comparative study has been conducted for various hydraulic diameter ratios of the inner cylinder and outer square duct, i.e. d/D = 2/6, 3/6, and 4/6 for cases R1, R2 and R3 respectively. The friction Reynolds number is fixed at $Re_\tau = 2\delta u_\tau / \nu = 480$, where $\delta = D/2$ is the half duct height. The length is set to $L_z = 20\pi\delta$. The governing equations were solved using a spectral-element code called "Semtex", capable of conducting highly accurate DNS. The computational domain is decomposed using 3200, 3040, and 2880 quadrilateral elements in the cross-stream plane for cases R1, R2, and R3 respectively. These elements are further discretized using a 4^{th}-order Guass-Labatto-Legendre Lagrange polynomial before being expanded into 1024 Fourier modes in the axial direction (i.e., there are 53.2, 50.5 and 47.9 million nodes in cases R1, R2 and R3, respectively). To satisfy the demanding requirement of DNS on the grid resolution, the ratio of the grid size to the Kolmogorov length scale is kept at the order of unity. All DNS have been conducted using the GREX supercomputer of the University of Manitoba. The effects of the inner-to-outer duct width ratio on the fully developed flow are thoroughly studied through the analysis of the first- and second-order statistical moments of the velocity field, and a budget balance of the TKE transport equation. As a result of the unsymmetrical wall boundaries, secondary flows are induced that complicate the physics of the flow compared to a classical square duct. Secondary flows of Prandtl's second kind can be seen in the concave corners of the square duct, which become increasingly compressed as the ratio of the inner-to-outer wall increases. Through an analysis of the TKE contours, a dampening effect on turbulence is observed in the concave corners of the outer wall as the ratio of the inner-to-outer duct width increases. The budget balance indicates that from case R1 to R3, the production at the inner wall increases. Additionally, all terms of the budget balance collapse to zero at the concave corner. At the midpoint of the annular gap, the budget is balanced by the turbulent diffusion and dissipation, acting as the source and sink respectively.