Direct Numerical Simulation of Transitional and Turbulent flows in a square duct

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Abstract

Applications of duct flow are ubiquitous in oil and gas pipelines, heat exchangers, turbomachinery and nuclear engineering. The understanding of transition and turbulent flow in ducts is hailed as an important problem in industrial applications and scientific research. A non-circular duct with square cross-sectional geometry often shares interesting flow phenomena as compared to the pipe and channel flow. The in-depth perspective of the underlying dynamics of transition and turbulent flow in a square duct is still evolving and yet to be fully understood.

The overall aim of the thesis is to develop an optimized DNS solver and study the underlying dynamics of transitional and turbulent flow coherent motion in an infinite and finite length square duct. The DNS solver is optimized on an MPI parallel platform using a cubic (or 3D) domain decomposition technique, array operation, user-interface and parallel input/output. The parallel performance analysis of the optimized DNS solver on the multiprocessor computing system (PADUM supercomputer) shows 80% efficiency.

The DNS solver numerically investigates the transition and turbulent flow in an infinite length (or periodic boundary condition in streamwise direction) square duct. The thesis demonstrate the organized motion of the flow regimes below the frictional Reynolds number of the fully turbulent flow. The transitional flow is coined as "minimal and marginal" flows. The vortex-detection technique unveil hairpin vortices in fully and minimal turbulent flow in the square duct. Bursting of streaks is detected with variable interval time average, and the evolution of hairpin vortices has also been addressed. Turbulent intensities and energy spectra are reported and compared between the minimal, marginal and fully turbulent flow. The minimal turbulence in a square duct indicates

transitional turbulent flow characteristics like lesser occurrence of ejection and sweep, intermittent bursting events, and steeper variation of energy spectrum as compared to fully turbulent energy spectrum distribution.

The coherent structures are identified through the spatial and temporal analysis of Proper Orthogonal Decomposition (POD) modes. Analysis of two sets of POD data is performed. In obtaining the first set, POD is performed on the combined fluctuating velocity vector, while for the second set, only the fluctuating velocity along the y- or z-direction is used. It was found that the first two most energetic spatial POD modes are the streamwise-independent or non-propagating roll modes. The third and fourth most energetic modes are observed to be streamwise-dependent, propagating modes. The spatio-temporal analysis of POD modes confirms the presence of traveling waves in the square duct, and its average speed is also calculated. The POD of the second dataset showed only propagating modes, and no non-propagating modes were found. These propagating modes are also rotationally symmetric. It has been shown that there is an energy exchange between non-propagating modes and propagating modes. The flow dynamics of the first four reconstructed POD modes portray the self-sustaining turbulence mechanism in a square duct. The structures obtained from the first POD dataset reconstruction of 10% energy show well-organized hairpin vortices. Furthermore, the dataset reconstructed from modes containing 35% energy, gives detailed information on the coherent structures aligned along the wavy streamwise direction.

Laminar to turbulent flow transition in a finite length square duct has been carried out for the first time by imposing novel spatio-temporal finite amplitude inlet disturbance on the laminar flow. A short-duration narrow ring inlet disturbance is used, and it elucidates the most exciting dynamics of laminar to turbulence transition in a square duct. A short-duration inlet disturbance is imposed on the laminar flow at upper and lower transitional range bulk Reynolds number 2260 and 1540, respectively. The laminar flow at upper and lower transitional range Reynolds number is similar to marginal and minimal turbulent flow in a square duct. A disturbance applied on the upper transitional range laminar flow propagates downstream, giving puff (transition) and slug (turbulent) flow phenomena similar to pipe flow. However, at the lower transitional range, inlet disturbance shows only a puff-like structure. The mean secondary flow is obtained by the time and space average of the puff and slug region. The four vortex secondary flow is observed in a puff region with two vortex on each vertical wall, while conventional eight vortex is observed in the slug region. The transition (puff) flow coherent structures show the presence of dual-type hairpin structures. The dual-type coherent structures consist of conventional forward and non-convention reverse hairpin vortices. The high-speed streaks from the inlet disturbance play a role in the formation of the reverse hairpin. The turbulent kinetic energy indicates that the conventional -5/3 spectra for slug (turbulent) flow and -2 energy spectra for puff (transition) flow because of the flow's intermittency at the transition. We now confirm that the novel inlet disturbance through narrow ring captures laminar dynamics to turbulent transition.