Numerical study of swirling, circular and annular, impinging jets with heat transfer

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Keywords: Impinging jets; Large Eddy Simulation

This paper deals with numerical simulations of swirling circular and annular impinging jets with heat transfer. Large Eddy Simulation (LES), based on higher order finite-differences on staggered Cartesian non-uniform grids, has been used. The current LES have the potential of dealing with transition as well as providing data on details of larger scale structures, statistical correlations and turbulent spectral content. On the other hand LES demands high temporal- and spatial-resolution, which in turns requires large computational resources. To obtain statistically stationary results, large number of samples may be required. This accentuate the need for computational resources even more.

The present LES model is a basic model without explicit Sub-Grid Scale (SGS) model. Instead, the numerical scheme accounts for the necessary amount of dissipation. By using the computational grid as filter, the cut-off wave-number depends directly on the grid spacing. Heat transfer has been modeled by a transport equation for a passive scalar.

The impinging jet has a nozzle-to-plate spacing, H/D, ranging from 0.5 to 2 nozzle diameters. The Reynolds number is between 10000 and 20000, based upon the mean axial nozzle velocity and the nozzle diameter. Different mean velocity profiles, swirl-rates (S) and disturbance levels have been applied at the velocity inlet.

FIG. 1: Isosurface for instantaneous scalar concentration in weakly swirling flow.

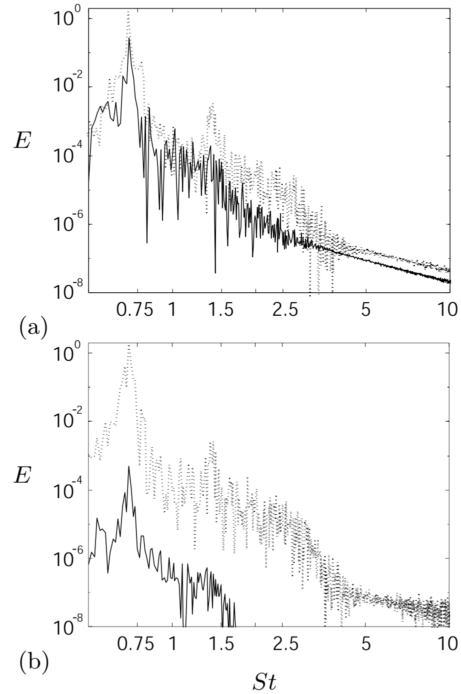

FIG. 2: Lower part of the frequency spectrum, for $S = 0$, on the jet axis. (a): u', (b): v'. (—): near the wall, (···): mid-distance to the wall.

The LES results clearly detect the transition process in the jet. The initial disturbances grow exponentially in size and eventually large scale primary vortices are formed. These vortices are convected downstream and initiate, counter rotating, secondary vortices. The secondary vortices have large influence on the wall jet and may cause local flow separation. Depending on the boundary conditions the downstream development becomes rather different and the characteristic frequencies, obtained by spectral analysis, both change in magnitude and energy content.

Budgets of the mean turbulent kinetic energy equation have been studied and dominant transport mechanisms have been identified. The LES data provide also directly the turbulent fluxes of the passive scalar. The data can be used to assess different models that are used within

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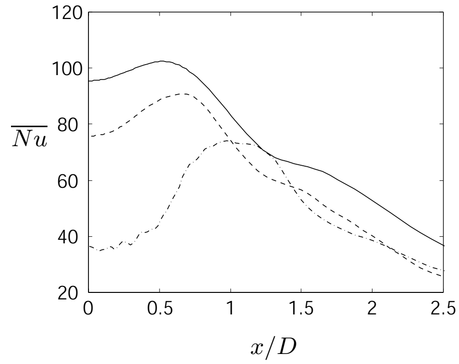

FIG. 3: Mean Nusselt number for $H/D = 2$. (—): $S = 0$, (- - -): $S = 0.5$, (- · -): $S = 1$.

the RANS frame-work. The effects of counter-gradient diffusion is seen clearly in the LES results. The influence on wall heat transfer and spatial temperature distribution have been analyzed. For high levels of swirl the heat transfer rates in the stagnation region is strongly obstructed by vortex breakdown. Comparison with RANS simulations and experimental data have been conducted. In large, the trends in both LES, RANS and experiments are rather similar. Details of the modeling of the turbulent fluxes reveal, however, the short-comings of some common models used in the RANS frame-work.

Fig. 1 shows an instantaneous three- dimensional scalar concentration field. Scalar concentration is used as it is informative in visualizations. The scalar follows the motion of the fluid and, therefore, it can be used to identify flow structures. The character of the instantaneous impinging jet is, as can be seen, irregular. From the nozzle and slightly downstream the flow seems to behave in a structured fashion only disturbed by oblique wavelike structures (a helical mode of a free jet). In the outer impingement region and downstream the flow become more and more disordered.

Fig. 2 depicts the frequency spectrum for u' in (a) and v' in (b) at two different points on the jet axis. The first evaluation point is at $y/D = 0.004$ and the second at $y/D = 1$. At $y/D = 1$ the fundamental frequency, St_f, is pronounced for both u' and v'. The Strouhal number of this frequency equals 1.4. For both velocity components there is a sub-harmonic, with Strouhal number equal to 0.7, present. This specific frequency, St_{PV}, characterizes the formation of primary vortices. The energy level of St_{PV} differs more than $\mathcal{O}(10^3)$ between the two points in (b), whereas in (a), the level is comparatively unchanged. This is so since, v' is being damped close to the wall, with a following redistribution of energy to u'. With swirl applied the characteristic frequencies increase and the spectrum becomes wider. For high rates of swirl the axial jet breaks down and a large recirculation region is formed, reaching as far downstream as $x/D = 1$. A direct consequence of this is that the Nusselt number becomes highly obstructed. This can be seen in Fig. 3, for $S = 1$. Consequently, when swirl is added there is a region, approximately limited to the stagnation region $|x/D = 1.25|$, in which the overall heat transfer decreases. Downstream of this region the influence from swirl decreases.

In this paper the fundamental characteristics of impinging jets are briefly covered. The influence from swirl, on formation of structures, statistics and heat transfer, is then studied in more detail. The paper ends with a brief study of various inflow boundary conditions, such as, mean velocity profile (solid-body rotation, fully developed pipe flow, annular jets) and disturbance level.

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