Large-Scale Numerical Simulations on Mixing, Diffusion and Reaction in Complex Jet (Direct Numerical Simulation of Turbulent Swirling Jet Flows)

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The industrial applicability of swirling jets ranges from the combustion devices to the heat exchangers. An ideal industrial burner, in particular, needs the abilities of efficient mixing of fuel with the oxidant, preventing combustion flame from blowing out and reusing heated products of combustion to improve efficiency. Swirling jet fulfills these characteristics. However, many questions related to the flow structures and mixing mechanism are yet to be addressed and hence an effort is made in the present study to contribute to address some of those. The direct numerical simulation (DNS) is used to study the single-phase, unconfined coaxial jets under the influence of swirl introduced in the outer jet. Two cases of different swirling strengths are considered and compared with a case of no-swirl.

The governing equations solved in DNS are incompressible Navier-Stokes equation and continuity equation. The scalar transport equations are also solved separately for passive scalars originating through two jets. The inlet conditions required for DNS are produced in OpenFOAM by simulating the nozzles. OpenFOAM and DNS simulations are carried out on CX400/270 and FX100 of Nagoya University's HPC facility respectively. The instantaneous velocity data at the nozzle exit is saved separately and later given to DNS as inlet condition. The basic statistics obtained in numerical study are verified with the experimental measurements and found to be satisfactory.

The case of intermediate swirling strength shows a faster centerline decay as well as the radial spread of mean streamwise velocity in the downstream region as compared to the non-swirling case. The case with a strongly swirling strength leads to the formation of an internal recirculation zone. Mean scalar distributions show the better spreading rate of scalars for the intermediate swirl case as compared to the non-swirling case, whereas the strongly swirling case experiences it from far upstream as compared other two cases. This is confirmed by entropy, a measure of diffusion of scalars. Moreover, the ambient fluid reaches the centerline earlier with the introduction of swirl, which is the result of an increase in entrainment rate due to swirl. The enhanced presence of ambient fluid is observed to be influencing the scalar fluctuations. The positive correlation between scalar fluctuations is evident at the further upstream region in the intermediate swirling case as compared to non-swirling one, which is enabled due to the presence of ambient fluid. However, in strongly swirling case, this process takes place at remarkably far upstream due to an additional effort by the internal recirculation zone.

Spectral proper orthogonal decomposition (SPOD)[1] is employed to better understand the physically important structures or modes in the strongly swirling case. The upstream region witnesses the counter-rotating vortices in pairs in the dominant modes, which are also observed to be contributing to the Reynolds normal stresses to a larger extent. However, these structures vanish subsequently in the downstream region. The extension[2] of this method to the scalars suggests that there exist separate structures in the inner and outer shear layers. The counter-rotating vortices are also observed to have a considerable contribution to the turbulent radial fluxes of the scalars.

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[1] M. Sieber, C. O. Paschereit, K. Oberleithner, Spectral proper orthogonal decomposition, Journal of Fluid Mechanics 792 (2016) 798-828.
[2] J. Borée, Extended proper orthogonal decomposition: a tool to analyse correlated events in turbulent flows, Experiments in Fluids 35.2 (2003) 188-192.