Large-Scale Numerical Simulations on Mixing, Diffusion and Reaction in Complex Jet (Budgets of turbulent kinetic energy and Reynolds normal stresses in coaxial jets with and without swirl)

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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. As demonstrated by Mehta *et al.* (1991) for a single swirling jet and by Ribeiro & Whitelaw (1980) for the coaxial swirling jet, the swirling flows are responsible for the intensification of the Reynolds stresses and turbulent kinetic energy (TKE). This consequence of the swirl is an important point for the mixing enhancement. However, the reason of intensification of Reynolds stresses in coaxial jet due to the swirl has not been explored in detail. In this work, this is achieved by investigating the budgets of TKE and Reynolds normal stresses. Moreover, the analysis of budgets of TKE and Reynolds normal stresses for the coaxial swirling jet is rarely reported in the previous studies, and hence this study can form the basis for the turbulence modeling work. 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. A case of strong swirling strength is considered and compared with a case of no-swirl.

The governing equations solved in DNS are incompressible Navier-Stokes equation and continuity equation. 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 with strong swirl leads to the formation of an internal recirculation zone (IRZ). As expected, the Reynolds stresses and TKE are seen to be substantially increased in the strong swirling case as compared to non-swirling case. Following key observations were made from the budget analysis of TKE and Reynolds normal stresses:

- Due to swirl, the turbulent diffusion term in TKE budget became more active in the upstream region (around $x = 1.0D$, here D is the diameter of inner jet). This caused the energy level to increase in the central region of outer jet of swirling case.
- TKE in the region outside of IRZ was convected from highly energetic upstream region ($x = 0.3D$; $1.0D$) to the downstream region ($x = 3.0D$) in the swirling case, whereas the positive contribution by the convection term in non-swirling case seemed to be smaller.
- At $x = 1.0D$, the pressure-strain correlation term acted as energy sink for radial component of Reynolds normal stress at outer shear layer in the swirling case contrary to the non-swirling case.
- The analysis of production terms of Reynolds normal stresses at $x = 1.0D$ (where the great difference in Reynolds normal stresses is observed between two cases) showed that in addition to the higher production for the streamwise component of normal stress, the significant production was observed for the other components with the introduction of swirl. This was because with the introduction of swirl, the terms having streamwise gradient of mean velocity also contributed to the production in addition to the terms with the radial gradient of mean velocity. In the region upstream of central stagnation point of swirling case, a distinctive negative production at inner shear layer was observed for the radial component of normal stress, which was the consequence of positive radial gradient of mean radial velocity in the region caused by the spreading of jets.

Mehta, R. D., Wood, D. H. & Clausen, P. D. 1991 *Phys. Fluid A-Fluid* **3** (11), 2716-2724.
Ribeiro, M. M. & Whitelaw, J. H. 1980 *J. Fluid Mech.* **96** (4), 769-795.