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主 論 文 の 要 旨

論文題目　**Numerical investigation of momentum and scalar transport in turbulent unconfined coaxial swirling jet**
(乱流開放型同軸旋回噴流における運動量とスカラ輸送の数値的研究)

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論 文 内 容 の 要 旨

Swirling flows are widely used in many engineering applications, such as industrial burners, combustion engines, and heat exchangers. As far as the industrial burners are concerned, it is desired to have the reduced length of combustion flame as well as to increase the efficiency by reusing the unburned fuel and the burned products of combustion containing high heat energy. The jet with swirling motion fulfills these characteristics by enhancing the mixing between fuel and oxidant jet, and recirculating the burned/unburned products of combustion in order to ignite the incoming mixture, which make the swirling jet an essential constituent of burners and thus gain the attention of many researchers.

Although there are some advances in the understanding of swirling jet, there are some questions which are yet to be addressed:

- The introduction of swirl intensifies all the six independent components of Reynolds stresses. This feature of increase in the Reynolds stresses along with their spread is vital for the mixing enhancement. However, the reasons for this change in Reynolds stresses, and hence the turbulent kinetic energy (TKE) in coaxial swirling jet have not been thoroughly explored yet.
- Passive scalars have been widely used to demonstrate mixing in various jet flows.

However, in the past studies, the injection of passive scalars through only one of the two jets of coaxial swirling jet limited the investigations aiming at the mixing features. Simultaneous injection of passive scalars through both the jets of coaxial jet would provide more insight into mixing characteristics.

- Over the years, various techniques of modal decomposition have been developed to better understand the physically important structures or modes in the swirling jet. Some studies have focused on the visualization of coherent structures using these techniques for the configuration of single swirling jet only, but that for the coaxial swirling jet is scarcely investigated.

This thesis focuses on the above topics and attempts to enhance the knowledge in the field of coaxial swirling jet. In this thesis, direct numerical simulation (DNS) is used to study the single-phase, unconfined coaxial jet under the influence of swirl introduced in the outer jet (OJ). Two cases with coaxial jet with varying swirling strengths (Swirl number, Sw = 0.5 and 1.8) are investigated and compared to a non-swirling case (Sw=0).

In Chapter 1, the research background and motivation of the study are briefly introduced.

In Chapter 2, the numerical methodology and flow conditions used for the investigation are explained. In order to better the inlet boundary condition, which is crucial in case of swirling jet, the separate simulations using OpenFOAM software are performed for the nozzles, and the data of instantaneous velocity components at the nozzle exit is mapped onto the DNS computational grid. The DNS program is written in FORTRAN programming language.

In Chapter 3, the numerical results are verified with the experimental measurements and seem to be satisfactory. The results of momentum transport are presented and the following conclusions are drawn.

- In the intermediate swirl case (i.e., Sw=0.5), a contrasting acceleration after a brief decay in streamwise velocity is observed in the upstream region due to the negative pressure gradient. However, the downstream region exhibits a centerline decay and radial spread of streamwise velocity. The rates of centerline decay and spread of jet are further enhanced with the increment in swirling strength (i.e., case Sw=1.8), which eventually forms the internal recirculation zone (IRZ) or partially-penetrated vortex breakdown bubble.

- As a result of swirl, the Reynolds stresses and TKE are observed to be intensified. Analysis of budgets of TKE and Reynolds normal stresses are carried out for cases *Sw*=0 and *Sw*=1.8, and the following key conclusions are made.
    - Turbulent diffusion term causes the TKE level to increase in the central region of OJ of swirling case.
    - TKE in the region outside of IRZ is convected from the highly energetic upstream region (*x*=0.3*D*, 1.0*D*) to the downstream region (*x*=3.0*D*) in the swirling case. However, the positive contribution by the convection term in non-swirling case is small.
    - The pressure-strain correlation term distinctively acts as an energy sink at *x*=1.0*D* for the radial component of Reynolds normal stress at the outer shear layer in the swirling case contrary to the non-swirling case.
    - Production of Reynolds normal stresses is enhanced due to the swirl as the terms having streamwise gradient of mean velocity also contribute to the production in addition to the terms with the radial gradient of mean velocity.

In Chapter 4, the separate passive scalars are injected simultaneously through each jet of the coaxial jet to study the mixing between two jet fluids. The conclusions based on this study are summarized as follows.

- The intermediate swirling case exhibits a slower decay of the mean inner jet (IJ) scalar and slower inward growth of the mean OJ scalar due to the acceleration in the upstream central region compared to the non-swirling case. However, the downstream region exhibits a wider spread of scalars, which is confirmed by quantifying the diffusion of scalars based on entropy.
- The occurrence of an IRZ in strongly swirling case leads to a dramatically improved spreading rate of mean scalars, which is also confirmed based on entropy evolution. This spreading is more prominent in this case than in the other two cases.
- Turbulent azimuthal flux is observed distinctively stronger in the swirling cases compared to the non-swirling case, in which this flux is negligible.
- Positive segregation parameter signifying better mixing characteristics is observed at far upstream in the strongly swirling case as compared to the other two cases. Furthermore, the maximum negative magnitude of the segregation parameter, which represents the degree of "unmixedness", is lower in the strongly swirling case compared to the other two cases.
- The joint probability density function of the scalar fluctuations at the leading centerline stagnation point in the strongly swirling case contains two peaks, which

indicates the flapping between IJ and OJ scalars caused by the oscillation of the stagnation point.

In Chapter 5, spectral proper orthogonal decomposition (SPOD) analysis is carried out at 2D planes to investigate the coherent structures present in the flow for the case of strong swirl (i.e., case Sw=1.8). The analysis is extended to the transport of two passive scalars. The following conclusions are made from the findings.

- At the cross-stream section present in the upstream region of central stagnation point, first two and succeeding two spatial modes of velocity field reveal three and four pairs of counter-rotating vortical structures, respectively, and these vortical structures are centered at the inner shear layer.
- In the same upstream region of central stagnation point, spatial modes of scalars also exhibit three and four pairs of the alternate positive-negative organized lobe-like structures in the inner shear layer for the first two and succeeding two modes, respectively. However, different structures are appeared in the spatial modes of OJ scalars in the outer shear layer.
- The first four modes are appeared to have a higher contribution in the root-mean-squared (RMS) velocities, RMS scalar fluctuations and radial turbulent fluxes of scalars. However, this contribution is asymmetric about the axis.

In Chapter 6, the main conclusions of the present thesis are summarized, and some prospects about the future study are also introduced and discussed.

The results of this work can be useful for understanding and designing practical combustors, which often have swirling flows. Based on the observation in the intermediate swirling case that the flow is accelerated in the upstream region, it can be said that the swirling coaxial jet does not always ensure the decay of jet and hence the spread, and this observation needs to be considered while designing the combustors. Another significance of this study is that the budget analysis of TKE and Reynolds normal stresses may provide a useful basis for turbulence modeling work.