



Large Eddy Simulation of the Vortex Breakdown in Swirling Flow Using MPI Parallel Technique

Large Eddy Simulation 과 MPI 병렬 계산 기법을 이용한 스윙 유동에서의 Vortex Breakdown 에 관한 연구

O Hong-Gye Sung¹⁾, Vigor Yang²⁾
 오성홍계¹⁾, Vigor Yang²⁾

연소실 안으로 분출되는 스윙 유동의 vortex breakdown mechanism 에 대한 연구를 하였다. 3 차원 유한 체적기법과 Runge-Kutta 시간 적분법이 적용되었으며, 난류모델은 dynamic large eddy simulation (DLES)이 적용되었다. 계산 시간의 효율성과 기억용량을 효과적으로 사용하기 위하여 message passing interface (MPI) 병렬계산 기법이 적용되었다. 스윙 난류 유동에 있어서 vortex breakdown 거동을 가시적으로 표착 하였는데, 이는 스윙 유동에 의한 난류 응력 증대, 난류 생성/소산율 증대 및 혼합율 증대에 대한 실험적 근거를 뒷받침하는 매우 중요한 결과이다. 또한 평균 속도와 레이놀스 응력에 대한 계산 결과도 실험 결과와 비교하였다.

1. Introduction

Swirling flows are used extensively in engineering applications, in particular, for flame stability and mixing in the combustion of gas-turbine engines. The flowfields of current practical interest in combustor primary zone involve regions of highly turbulent swirling and recirculating flows. Such regions can promote rapid fuel/air mixing and enhance flame stabilization, which lead to improve combustion efficiency, better blow-off limits, and a reduction in the formation of particulate and gaseous pollutant.

Vortex breakdown is an important fluid phenomenon in swirling flows and has been widely researched since its discovery by Peckham & Atkinson[1] in an investigation of the flow over "Gothic" wings. The vortex breakdown produces swirl-stabilized combustion systems[2]. At the end of center recirculation zone, the central forced processing vortex core inducing pressure and velocity fluctuation like swirl instability develops [3]. As the degree of swirl increases, the distance between the fuel and the fuel front as well as the flame length decreases [4]. Also the corner recirculation zone shortens significantly, which may contribute the length of the combustor shorten [5].

The suppression of combustion inducing pressure oscillations and the extension of flammability limits are a major challenge in the design and development of high performance combustors. For both passive and active control of combustion, it is common critical issue to build upon the physical understanding of turbulent shear layer and combustion dynamics to guide the development of effective active/passive control technology as combustion characteristics are closely related to detailed fluid dynamic processes. Thus, the physical understanding of vortical structures in a turbulent swirl is the major concern in this study.

2. Theoretical Formulation

The Favre averaged governing equations based on the conservation of mass, momentum, and energy for a compressible gas can be expressed with subgrid closure terms[6-7].

2.1 Large eddy simulation

The compressible version of the dynamic Smagorinsky model (DSM) is employed in the present study. The assumption of the algebraic Smagorinsky type model is the equilibrium flow of turbulent energy cascade, and model coefficients are determined from isotropic turbulence decay. Moreover, the model coefficients are prescribed *a priori* and remain a

1) Tech-4-2, Agency for Defense Development

2) Mechanical Engineering Dept., The Pennsylvania State University

constant, which implies their inability to model correctly the unresolved subgrid stresses in different type of turbulent flow fields. The introduction of dynamic models circumvents this basic assumption in order to compute non-equilibrium flow by calculating the model coefficients directly (i.e., as a function of space and time during the simulation) thus providing the proper local amount of subgrid mixing and dissipation.

Another important idea in dynamic subgrid scale (SGS) modeling involves scale similarity, which assumes that the largest of the unresolved scales, which contain most of the SGS energy, have a similar structure to the smallest of the resolved scales [8]. Specific details of this algorithm are described in Ref 6-7.

2.2 Numerical Method

A three dimensional time-accurate scheme based on explicit Runge-Kutta time marching scheme and finite volume in space integration is used in this present work. Further efficiency is obtained by implementing an MPI (Message Passing Interface) parallel computing architecture with a multi-block technique. Pentium II 450 MHz processors are clustered for parallel computation. For this study, the computational domain was decomposed in a general fashion to almost evenly divide grid points among the processors. The computational domain is composed of 28 blocks are assigned to each processor (i.e. a total of 28 processors). Although the processors share the work, the solution is independent of the number of processors used. The grid points on each processor are updated to the next time step simultaneously. In order to calculate the spatial derivatives near the processor's domain boundaries, the information in the overlap regions on each side of the local domain must be obtained from neighboring processors. This communication overhead is directly proportional to the volume-to-surface ratio of that subdomain. As is well known, the scale-up depends upon the problem size, and the optimization of the number of processors needs to be determined. But the number of processors used, in reality, may be hardware-dependent to speed up calculation by considering both execution and waiting times because 3D LES code handles a huge grid size. For example, there are about 1 million grids in this study. It is difficult to coordinate a sufficient number of processors to address the lengthy waiting time and/or the limitations of processor availability.

3. Results and Discussion

An experimental test conducted by the propulsion laboratory in Airforce was chosen as a calculation model due to the availability of experimental data [11]. The experiments were conducted in the axisymmetric dump combustor model shown in Fig. 1. The working fluid was air pushed through the model by a centrifugal-type blower. The swirler with 12 circular arc inlet guide vanes was located 50.8mm upstream of the dump plane. The leading edge of each blade was designed to be tangential to the incoming flow and perpendicular to the centerline of the combustor. The combustion chamber consisted of a Plexiglas pipe, 152.5mm I.D. and 1850mm long. A laser Doppler velocimeter (LDV) was used to measure the three velocity components and some turbulence quantities in different swirl numbers. The centerline velocity in the inlet pipe is 19.2 m/s and the inlet Reynolds number is 1.25×10^5 , based on inlet radius. The swirl number in this experiment is defined as:

$$S = \frac{\int_{R_h}^{R_i} \bar{u} \bar{w} r^2 dr}{\int_{R_h}^{R_i} R \bar{u}^2 r dr} \quad (1)$$

where R represents the radius of a combustor and subscripts h and i means swirl hub and inlet pipe, respectively. \bar{u} and \bar{w} are the mean velocity of axial and swirl velocity, respectively. The swirl number is 0.5.

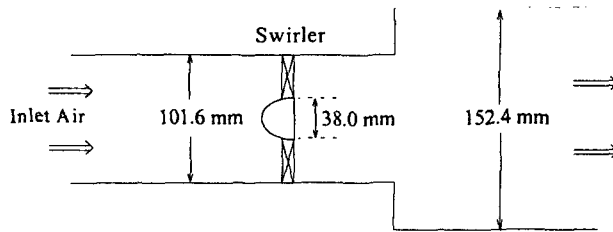


Fig. 1 Schematic of a model combustor with a swirl injector.

The computational domain consists of the inlet just after the swirler and the combustion chamber. The three-dimensional grid was generated by rotating the two-dimensional grid with respect to the combustor centerline, and the grid had $161 \times 75 \times 81$.

3.1 Comparison with Experimental Data

Comparisons of experiments and computational results are presented in this section, and the physical characteristics of swirling flow are discussed in the next section. The computational and experimental data of mean axial and mean azimuthal (swirl) component velocity are compared at several measurement locations in Fig. 2 and 3. The symbol represents the experimental data, while a line shows the computational results obtained by averaging the values during flow throughout at each axial location. The nomenclature, H , represents the height of the backward facing step of the combustion chamber.

Fig. 2 shows that the axis of maximum axial component velocity shifts from the center to the wall with downstream distance due to the Coriolis force of the swirling effect. Axial recirculations of a central toroidal zone and a corner zone result from the swirling effect, which are fairly captured (see Figs. 2b and 2c). Swirl directional velocities also show acceptable results, even though the swirl velocity near the corner seems to be under-predicted (see Fig. 3). But the experimental data at this corner seems to be over-measured because the axial velocities are very low speed at this location close to the sidewall of the combustor (see Fig. 2a).

Fig. 4 shows the comparison of turbulent kinetic energy. The turbulent kinetic energy near the center toroidal recirculation zone is much greater than that near the corner recirculation zone. This result represents the major benefit of swirling inlet flow because one of the most significant and useful phenomena of swirl components produces strong shear and high turbulence near the toroidal recirculation zone. The tendency to overpredict turbulent kinetic energy near the shear layer of the central recirculation zone may be related to the lack of accuracy of the subgrid turbulence model used or inaccurate measurements in high turbulent shear region. Although a few discrepancies can be seen, the overall agreement is acceptable in view of turbulence.

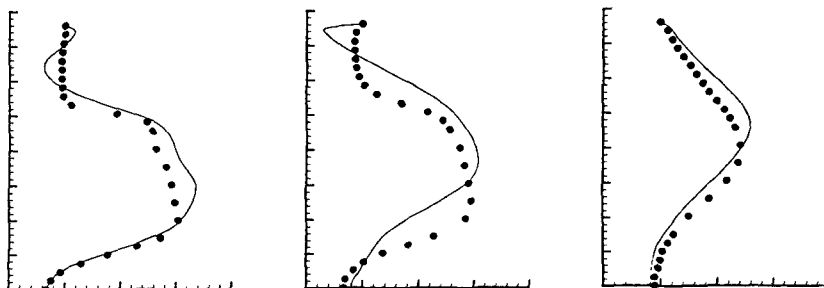


Fig. 2 Comparison of experimental and computational results of mean axial velocity at (a) $X/H = 0.38$ (b) $X/H = 2.0$ (c) $X/H = 4.0$ (line: computation; symbol: experiment).

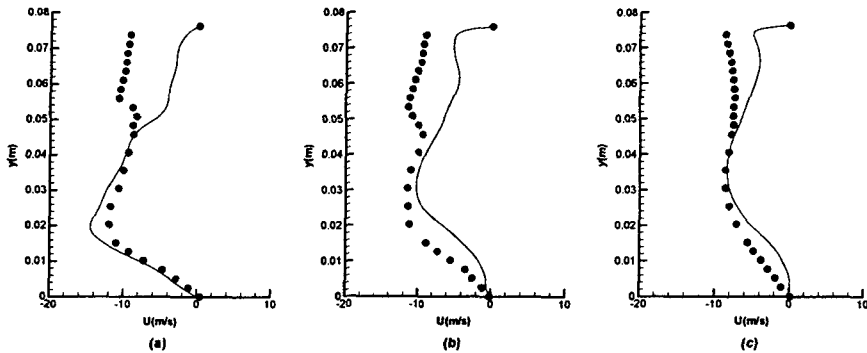


Fig. 3 Comparison of experimental and computational results of mean azimuthal velocity at (a) X/H=0.38 (b) X/H=2.0 (c) X/H=4.0 (line:computation; symbol:experiment).

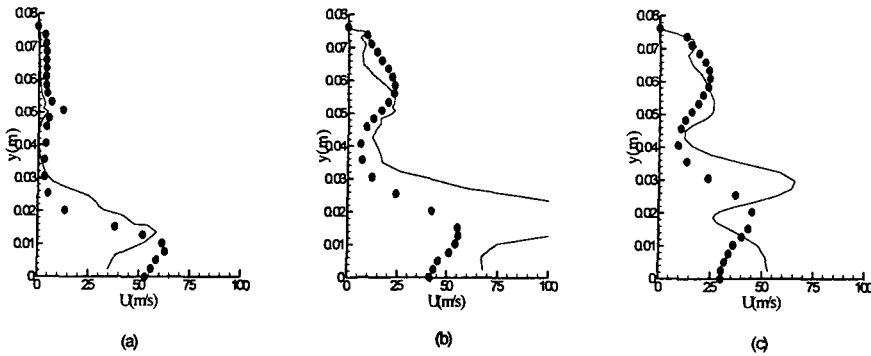


Fig. 4 Comparison of experimental and computational results of turbulent kinetic energy at (a) X/H=0.38 (b) X/H=2.0 (c) X/H=4.0 (line:computation; symbol:experiment).

3.2 Swirl Effects and Vortex Breakdown

The basic effect of a swirl results from the lateral momentum balance. For example, a high swirl significantly affects lateral pressure gradients given at any axial station from the lateral momentum balance, such as:

$$\frac{\partial p}{\partial r} = \frac{\rho w^2}{r} \quad (2)$$

The lateral pressure gradient increases the growth of the jet, resulting in reduction of combustion length. As the swirl velocities decay rapidly with downstream distance, the axial pressure gradient changes noticeably severely. Axial recirculation in the form of a central toroidal recirculation zone results eventually from the strong radial and axial pressure gradients.

Figure 5 shows a three-dimensional view of the iso-surfaces of instantaneous pressure fluctuations, presenting a portion of the dilatation effect of turbulent structures. The individual vortical structures are shedding with highly distorted and unstructured shapes. The structures grow with increasing axial distance, caused by the pairing of individual vortices. The somewhat organized structures seen upstream are stretched highly toward azimuthal direction near the vortex breakdown region, and then stretched again to axial direction as swirl velocity decrease. Thus, azimuthal coherence may break rapidly. These phenomena can be explained by observing the vorticity equation. Axial circulation intensity is decreased in the x-direction, which may induce the divergence of radial vorticity and stream surfaces to conserve the angular momentum. From this postulate, it is hoped that



some vorticity breakdown phenomena may be captured in the axial vorticity fields. As expected, process of vortices breakdown is vividly captured in the iso-surface field of the axial component of vorticity based on the mean flow field, as shown in Fig. 6. From Fig. 6, three important characteristics of swirling flow are visualized: diversity, decreasing strength of upstream vorticity, and vortex breakdown of turbulent swirling flow.

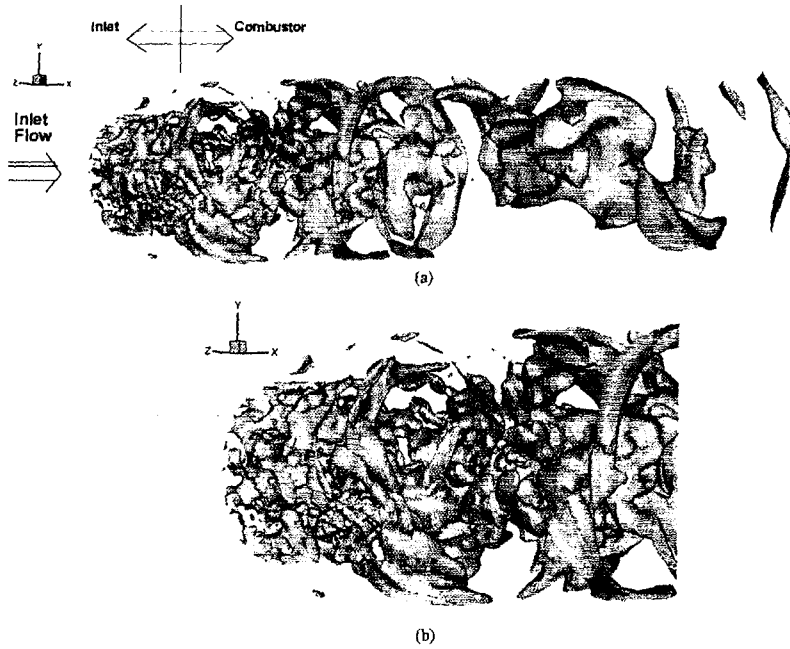


Fig. 5 Vortical structures visualized using iso-surfaces of instantaneous pressure fluctuations: entire domain (b) zoomed near the base of the combustor.



Iso-surfaces of axial vorticity component based on mean flowfield (red denotes -800 and blue denotes 800)

Fig. 6 Snapshot of iso-surface of axial vorticity component based on mean flowfield near the vorticity breakdown zone.



4. Conclusions

The swirling flow discharging into a combustion chamber was investigated using three-dimensional numerical analysis with an MPI (Message Passing Interface) parallel computing architecture. Large eddy simulation with dynamic subgrid scale (SGS) model gained and visualized some insight into some fundamental phenomena, focusing on the fluid dynamics aspects of the process, including turbulent behaviors and vortex breakdown, which are related to combustion stability, air/fuel mixing and pollutant formation. The results showed the significant effects of swirl, diversity, decreasing strength of upstream vorticity, and vortex breakdown of turbulent swirling flow, which is usually used to stabilize the flame in real combustion chamber. Mean velocities and Reynolds stresses are in good agreement with experimental results.

References

- [1] Peckham, D. H. & Atkinson, S. A., "Preliminary Results of Low Speed Wind Tunnel Tests on a Gothic Wing of Aspect Ratio 1.0", *Aeronautical Research Council CP 508*, 1957.
- [2] Lilley, D. G., "Swirl Flows in Combustion: a Review" *AIAA J.* 15, 1977, 1063-1077.
- [3] Rhode, D. L., Lilley, D. G. & McLaughlin, D. K., "Mean Flowfields in Axisymmetric Combustor Geometries with Swirl", *AIAA J.* 21, 1983, 593-600.
- [4] Dong, M. & Lilley, D. G., "Inlet Velocity Profile Effects on Turbulent Swirling Flow Predictions", *J. Propulsion Power* 10, 1994, 155-160.
- [5] So, R. M. C. & Ahmed, S. A., "Characteristics of Dump Combustor Flows", *Int. J. Heat Fluid Flow* 10, 1989, 66-74.
- [6] Sung, H-G, Hsieh, S.-H., and Yang, V., "Simulation of Flame Dynamics of a Premixed Swirl Injector in a Model Gas Turbine Engine", *AIAA 2000-0862, 38th Aerospace Science s Meeting & Exhibit*
- [7] Sung, H-G, Hsieh, S.-H., and Yang, V., "Combustion Dynamics of a Gas Turbine Swirl Stabilized Injector" *Twenty Eight International Symposium on Combustion*, 2000.
- [8] Germano, M., Piomelli U., Moin, P., and Cabot, W., "A Dynamic Subgrid-Scale Eddy Viscosity Model," *Phys. Fluid A* 3(7), 1991.
- [9] Favalaro, S. C., Nejad, A. S., Ahmed, S. A., Vanka, S. P. & Miller, T. J. 1989 An experimental and computational investigation of isothermal swirling flow in an axisymmetric dump combustor. *AIAA paper* 89-0620.