Basis Mode of Turbulent Flame in a Swirl-Stabilized Gas Turbine using LES and POD

Hong-Gye Sung
Tech-4-2
Agency for Defense Development
Taejon, Korea

Vigor Yang
Department of Mechanical Engineering
The Pennsylvania State University
University Park, U.S.A.

ABSTRACT

Unsteady numerical study has been conducted on combustion dynamics of a lean-premixed swirl-stabilized gas turbine swirl injector. A three-dimensional computation method utilizing the message passing interface (MPI) parallel architecture, large eddy simulation(LES), and proper orthogonal decomposition (POD) technique was applied. The unsteady turbulent flame dynamics are simulated so that the turbulent flame structure can be characterized in detail. It was observed that some fuel lumps escape from the primary combustion zone, and move downstream and consequently produce hot spots. Those flame dynamics coincides with experimental data. In addition, basis modes of the unsteady turbulent flame are characterized using proper orthogonal decomposition (POD) analysis. The flame structure based on odd basis modes is apparently larger than that of even ones. The flame structure can be extracted from the summation of the basis modes and eigenvectors at any moment.

Keywords : computational combustion dynamics, turbulent flame, swirling flow, LES, POD

INTRODUCTION

Gas turbines have traditionally used a diffusion-style combustor to supply reactants to the primary combustion region of the combustor. This produces a stable flame in the primary zone because combustion occurs at near stoichiometric conditions, with reactants consumed at a rate controlled by the mixing of the fuel and air streams. Subsequent mixing with secondary and tertiary air streams reduces the gas temperature to the desired turbine inlet temperature. The diffusion combustor has another advantage in that fuel and air

are mixed inside the combustor, thereby preventing flashback [1]. But tighter regulation of NOx emissions favors the use of lean premixed (LPM) combustion. By premixing fuel and air upstream of the reaction region, LPM combustors avoid locally stoichiometric combustion, thus eliminates the high temperature which may produce thermal NOx. Recently it was reported that oscillating combustion has emerged as a common problem in LPM combustor design. Oscillations occur when variations in heat release periodically couple to acoustic modes in a combustion chamber, producing significant pressure oscillations. These oscillations must be controlled because the resulting vibration can shorten the lifetime of engine. To actively control oscillation problems, it is helpful to understand the flame structure and its basis modes.

Most LPM systems stabilize the flame with recirculation developed by swirling flow. Vortex shedding from a step-stabilized flame can produce oscillations in the combustor, but there is no comparable understanding for swirl-stabilized flames. Thus, one of main focuses of this study was on characterizing the flame structure oscillated via simulation of turbulent flame in a model combustor.

THEORETICAL FORMULATION

The Favre averaged governing equations based on the conservation of mass, momentum, energy, and species concentration for a compressible, chemically reacting gas can be expressed with subgrid closure terms[2].

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 isotopic turbulence decay. Moreover, the model coefficients are prescribed a priori and remain a 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 [3]. Another important idea in 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 [4].

Numerical Method

A three dimensional time-accurate scheme based on semi-implicit Runge-Kutta time marching scheme and finite volume in space integration is used in this present work. One of the concerns in handling the chemical reacting term is the stiffness of the equations, since chemical processes have a wide range of time scales which are much smaller than the flow ones. As a result, if explicit methods are used to integrate the stiff governing equations, the computations will become inefficient, because the time step sizes directed by the stability requirements are much smaller than those required by the accuracy considerations. To overcome the stiffness problem, the additive semi-implicit method is introduced [5], which additively splits the governing equations into stiff and non-stiff terms. The stiff terms are treated implicitly, while the non-stiff

ones are treated explicitly. To advance simultaneous high-order temporal accuracy and good stability properties, additive semi- implicit RK formulations have been developed by Zhong [6].

Further efficiency is obtained by implementing an MPI (Message Passing Interface) parallel computing architecture with a multiblock technique. For this study, the computational domain was decomposed in a general fashion to almost evenly divide grid points among the processors for parallel computation. The computational domain is composed of 102 blocks assigned to each processor (i.e. a total of 102 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.

RESULTS AND DISCUSSION

The model gas turbine combustor consists of a single-swirl injector, a combustion chamber, and a nozzle as shown in Figure 1 [7]. The swirler has eight straight, flat vanes with a 45-degree swirl angle. The inside diameter of the combustion chamber is 45 mm with an aspect ratio, A_{inlet}/A_c, of 0.16 and a length of 207 mm. The nozzle with a 30-degree converging angle acoustically isolates the combustion chamber from its downstream conditions when it becomes chocked. The estimated swirl number, S, based on swirler geometry is 0.69 for a 45-degree swirler.

The computational domain consists of a coaxial injector and a combustion chamber without a nozzle. The three-dimensional grid was generated by rotating the two-dimensional grid with respect to the combustor centerline, and the grid had 135×110×81. Of the 135 axial grid points, 25 are used to cover the inlet section (upstream of the expansion). The basic scales of combustor in computational domain are the same as those in the experimental facilities, but the nozzle is not includede to save the total number of grid points for economic computation. Thus, the boundary conditions should be carefully applied without contaminating the experiment' s conditions. According to the experiment, this model combustor shows a dominant 1L mode with its harmonics, which implies a node point of acoustic wave at the middle of the chamber. Thus, it is notable that the computational chamber length is chosen to be half of the experimental chamber length, with the boundary conditions of a constant back-pressure on the exit surface.

In this study, the equivalence ratio 0.6, pressure 4 atm., and inlet temperature 670 K (assuming perfect premixed state) were chosen as the simulation base line.

Flame Dynamics

Fig. 2 shows the temperature contours near the primary combustion zone in the x-y plane, while Fig. 3 shows the temperature contours in the primary combustion zone on the y-z plane, to animate the flame evolution. The hot gas product penetrates to the corner of the combustor so that chemical reacting takes place on both sides of the fuel. Generally, the shape of the flame front looks like a peninsula, with some fuel lumps escaping the primary

combustion zone at certain moments. The isolated fuel lumps move further downstream and eventually die out with accompanying hot spots, which results in irregular local heat release. The hot spot appears to aggravate the combustion instability and therefore undesirable thermal prompt NO_x formation. Fig.4 compares the heat release rate of the computational results and the CH* images of the experimental data. Flame size and shape compare well to each other, and almost chemical reactions take place near the dump plane of the combustion chamber. From both experiment data and computational results, it can be observed that fuel lumps are escaping from a primary combustion zone at $2\pi/3$, thus decreasing flame size. The flame also stretched after π. Those flame dynamics coincide with each other

Modal Analysis

As shown in previous sections, a turbulent flame in swirling environments is so complex that any analytical model may not diagnose swirling turbulent combustion properly -- especially in confined geometry -- even though the characterization of it is a milestone in current and future research work to actively control combustion instability. One of the primary motivations of this section is to identify those features of swirling turbulent flame structures based on the computational results of this study described in the previous section. To this end, we introduce modal signal processing of Proper Orthogonal Decomposition (POD) method [8,9]. Physically, the POD has been applied with a considerable success to a wide variety of areas, ranging from free shear flows [10] to flames [11]. The POD has also been applied to a turbulent channel flow, and a numerical validation of low-dimensional models based on the POD has already been established [12,13].

In this study, POD was applied to characterize the basic mode of heat release patterns in turbulent swirling combustion. First, we constructed the array of inner products based on the three-dimensional heat release data, then got an optimal set of trial functions with corresponding eigenvalues. Table 1 shows the eigenvalues with the associated energy corresponding to heat release, from which approximately 90% of the energy is captured in the first thirteen modes. It is a relatively wide range of eigenvalues to resolve effective heat release energy (e.g., first nine modes are required in case of velocity structure) because the heat release rate varies by a huge gradient on the flame edge (i.e., the variation from *10E+1* to *10E+7*). Based on POD analysis, the basis modes of flame structure are determined (see Fig. 5). The flame structure can be extracted from the summation of the basis modes and eigenvectors at any moment. This information will be useful to anyone interested in active control of flame, since we can anticipate flame structure at any time, as well as generate an instantaneous flame structure very quickly.

CONCLUSIONS

The swirl-stabilized gas turbine engine of chemically reacting case was investigated using three-dimensional numerical analysis with an MPI (Message Passing Interface) parallel computing architecture. The conservation equations, including finite chemical reaction rate and dynamic large eddy turbulent simulation, were solved by finite volume numerical scheme in space and implicit Runge-Kutta time marching technique.

The instance of a chemical reaction, with lean premixed combustor, equivalence ratio 0.6 with high swirl rate (swirl number 0.69) was analyzed by evaluating of a fluctuating flame behavior and unsteady heat release. The unsteady flame with burning on a double-side surface of a fuel stream is reduced as fuel lumps escape from the primary combustion zone at about 120 degrees of pressure fluctuation in the combustion chamber, and then growing/stretching back to the original shape. This behavior corresponds to previous experiments governed dominantly by 1L mode of acoustic waves in combustor.

Even though the unsteady flame is so complicated, the basis modes of the flame are obtained by the means of POD. According to the evaluation of POD, several modes (e.g., 10 modes) can precisely and quickly regenerate the flame structure at any moments of interest. The modal analysis results may also be useful for further active control research.

REFERENCES

1. Richards, G. A. (1996), "Gas Turbine Combustion Instability," *Technical Meeting of the Central State Section of the Combustion Institute*, May 5-7, St. Louis MD.
2. 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*
3. Germano, M., Piomelli U., Moin, P., and Cabot, W. (1991), "A Dynamic Subgrid-Scale Eddy Viscosity Model," *Phys. Fluid* A 3(7).
4. Moin, P. (1997), "Progress in Large Eddy Simulation of Turbulent Flows," *AIAA Paper*, 97-.
5. Chiu, C. E. and Zhong, X. (1996), "Numerical Simulation of Transient Hypersonic Flow Using the Essentially Non oscillatory Schemes," *AIAA Journal* Vol. 34, No. 4, pp. 655-661.
6. Zhong, X. (1996), "Additive Semi-Implicit Runge-Kutta Method for Computing High- Speed Nonequilibrium Reactive Flows," *J. Computational Physics*, 128, pp. 19-31.
7. Seo, S. (1999), Combustion Instability Studies in Model Gas Turbine Combustors, *Ph.D. Thesis*, The Pennsylvania State University, University Park, PA.
8. Sirovich, L. E., (1987), "Turbulence and the Dynamics of Coherent Structures. Part I: Coherent Structures," *Q. Appl. Math.*, XLV: 561-571.
9. Sirovich, L. E. and Everson, R., (1992), "Management and Analysis of Large Scientific Datasets," *Int. J. Supercomputer Applications*, 6: 50.
10. Sirovich, L. E., Kirby, M. and Winter, M., (1990), "An Eigenfunction Approach to Large Scale Transitional Structures in Jet Flows," *Phys. Fluids*, 2 pp. 127-135.
11. Torniainen, E. D., Hinz, A., and Gouldin, F. C., (1997), "Tomographic Aanalysis of Unsteady, Reacting Flows," *AIAA* 97-0257.
12. Podvin, B. & Lumley, J. L., (1998), "A low-dimensional approach for the minimal flow unit," *J.Fluid Mech.*, 362:121-155.
13. Berkooz, G., Holmes, P., and Lumley, J. L.(1993), "The Proper Orthogonal Decomposition in The Analysis of Turbulent Flows," *Ann. Rev. Fluid Mech.*, 25: 539-575.

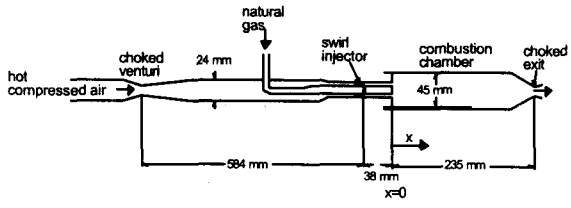

Fig.1. Schemetics of a model gas turbine combustor

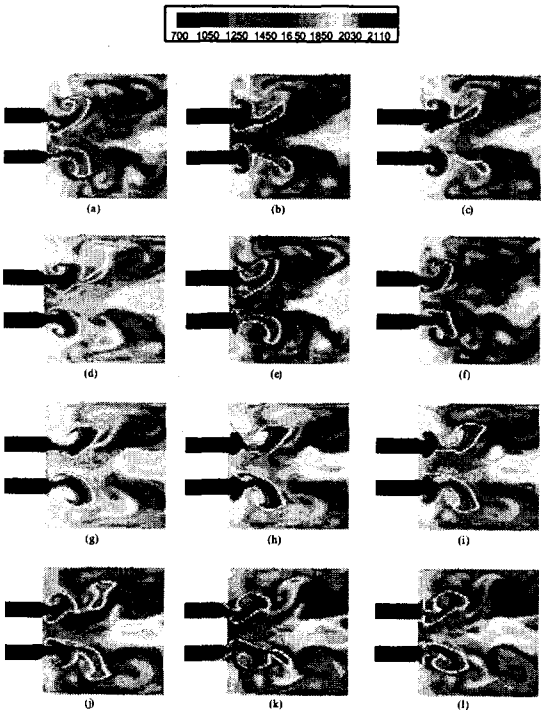

Fig. 2. Temperature contours near the primary combustion zone in the x-y plane (The time interval between pictures is about 0.3e-4 second.).

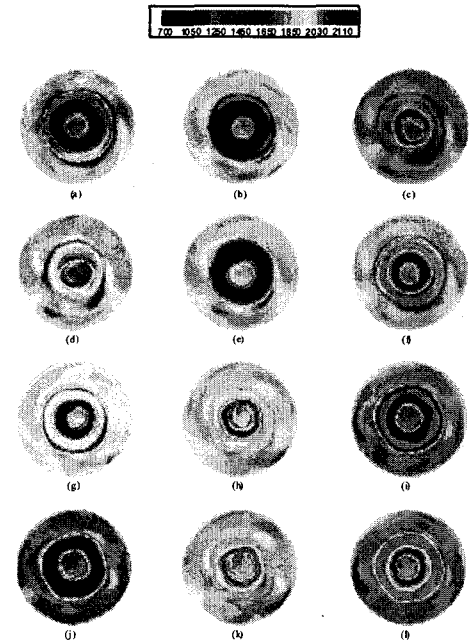

Fig. 3. Temperature contours in the primary combustion zone (x=0.023m) on the y-z plane (The time interval between pictures is about 0.3e-4 second.).

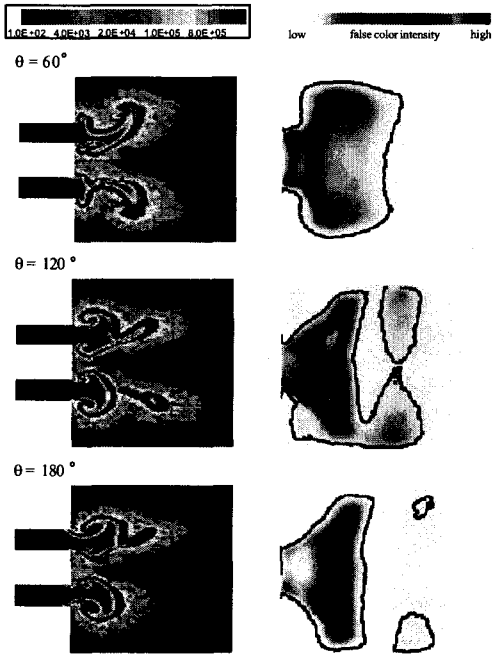

Fig. 4. Comparison of flame shapes between computational results (a) and experimental results(b): (a) heat release rate contours and (b) CH* emission image (Seo, 1999)

Table 1 Eigenvalues based on heat release.

Number(i)	λ_i	$\sum_{k=1}^{i}\lambda_k / \sum_{k=1}^{m}\lambda_k \times 100(\%)$
1 :	0.1936	19.3645
2 :	0.1213	31.4937
3 :	0.1120	42.6957
4 :	0.0820	50.8987
5 :	0.0782	58.7163
6 :	0.0659	65.3059
7 :	0.0573	71.0384
8 :	0.0529	76.3295
9 :	0.0417	80.5015
10 :	0.0308	83.5862
11 :	0.0277	86.3610
12 :	0.0232	88.6849
13 :	0.0204	90.7255
14 :	0.0199	92.7174
15 :	0.0189	94.6090
16 :	0.0158	96.1851
17 :	0.0142	97.6058
18 :	0.0133	98.9396
19 :	0.0106	100.0000
20 :	0.0000	100.0000

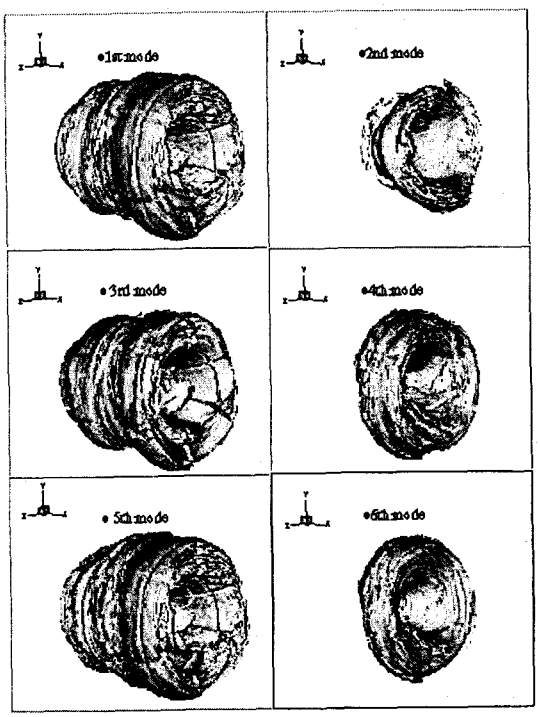

Fig. 5. Flame structures of 1st , 2nd , 3rd , 4th , 5th , and 6th mode in three dimensions