Large Eddy Simulation of Turbulent Combustion Flow Based on 2-scaler flamelet approach

Nobuyuki Oshima & Takuji Tominaga

School of Engineering, Hokkaido University, Sapporo 060-8628, Japan

Keywords: Large eddy simulation, Flamelet approach, Turbulent combustion flow

Abstract: This paper investigates LES of turbulent combustion flow based on 2-scalar flamelet approach, where a G-equation and a conserved scalar equation simulate a propagation of premixed flame and a diffusion combustion process, respectively. The turbulent SGS modeling on these flamelet combustion approach is also researched. These LES models are applied to an industrial flows in a full scale gasturbine combustor with premixed and non-premixed flames. The numerical results predict the characteristics of experiment temperature profiles. Unsteady features of complex flames in combustor are also visualized.

Introduction

Turbulent flames are important because of their occurrence in spark ignition engines, and gas turbines in order to minimize NO_x formation. The challenges facing designers of combustion devices involve scale dependent unsteady dynamic behaviors that cannot be simulated well with standard ensemble or time averaged flow model, and more accurate prediction method is required. However, a practical approach based on a statistical turbulence models has difficulty to apply for the complex and unsteady interaction of turbulence and combustion flame. Conventional computer codes with Reynolds-averaged Navier-Stokes approaches, such as k-ε model or Reynolds stress model, have been widely used as the design tool of the combustor.. They can predict relatively steady flow field with sufficient accuracy and small computational cost. However, calculation of unsteady flow is impractical because of their time-averaged feature. In order to calculate unsteady flow accurately, the governing equations should be solved time-accurately. While a direct numerical simulation (DNS) is limited only in microscopic phenomena though it has revealed fundamental processes of the combustion flows. A large eddy simulation (LES) is another approach which can analyze a unsteady and complex interaction of turbulence and combustion directly in a practical object by use of a model only for the microscopic phenomena. This approach has been investigated by previous researchers in order to predict a premixed turbulent flame in the fundamental studies (Park 2000) and the practical application (Taniguchi 2003) to the combustor flow. They have indicated that the LES approach can be effectively applied to a thin laminar flamelet which is a common model of the premixed flames. Thus there is a clear need to develop LES for reacting flows.

An aim of this research is to develop a numerical prediction of the premixed turbulent combustion flows with a LES for the flow design of the gas turbine combustion equipment. As practical validations of numerical methods and models for turbulent premixed combustion, the LES is designed and applied practical flows in the combustors of gsturbine and power plant.

Modeling of turbulent combustion flow

In practical turbulent flow, the combustion process usually occurs in the very small length and time scale as the smallest turbulent smallest scales. In this case, the combustion state is categorized as fast-chemistry combustion and the turbulent flame can be modeled as the assembly of the laminar flamelet (Peters 1986). In the flamelet model, the position of the premixed flame surface and the flame propagation can be expressed as the iso-surface of a level set scalar G in G-equation (Williams 1985, Menon 1996), described as follows:

$$\frac{\partial G}{\partial t}+u_k\frac{\partial}{\partial x_k}G=S_L\left(\frac{\partial G}{\partial x_k}\frac{\partial G}{\partial x_k}\right)^{\frac{1}{2}} \qquad (1)$$

where S_L is the laminar burning velocity

The index of scalar G is assigned the value zero in unburnt region and unit in the burnt region with the thin flame identified by a fixed value of $0<G<1$.

In this work, in order to treat partially premixed combustion such as a lifted non-premixed jet flame, the laminar burning velocity is assumed to be prescribed function of the equivalence ratio or the mixture fraction ξ because the effect of the turbulent mixing of the fuel gas and the oxidizer change the laminar burning velocity S_L in space and time, written as:

$$S_L(x_i,t)=S_L(\xi(x_i,t)) \qquad (2)$$

where ξ is the mixture fraction, in order to know the mixing of the unburnt fuel gas and the oxidizer, the transport equation of the mixture fraction must be solved.

In the LES formulation, the set of flamelet equations in the current modeling can be derived by applying a spatial, density–weighed (Favre) filter to the mixture fraction transport equation and the flamelet G equation are solved.

$$\frac{\partial}{\partial t}\bar{\rho}\tilde{\xi}+\frac{\partial}{\partial x_k}\bar{\rho}\tilde{u}_k\tilde{\xi}=\frac{\partial}{\partial x_k}\left(\frac{\mu}{Sc}\frac{\partial\tilde{\xi}}{\partial x_k}-\eta_k^{\xi}\right) \quad (3)$$

$$\frac{\partial}{\partial t}\bar{\rho}\tilde{G}+\frac{\partial}{\partial x_k}\bar{\rho}\tilde{u}_k\tilde{G}=\frac{\partial}{\partial x_k}\left(\frac{\mu}{Sc}\frac{\partial\tilde{G}}{\partial x_k}-\eta_k^{G}\right)+\overline{\rho S_L\left(\frac{\partial G}{\partial x_k}\frac{\partial G}{\partial x_k}\right)^{\frac{1}{2}}} \quad (4)$$

where Sc is the Schmidt number. Subgrid flux terms η_k^{ξ} and η_k^{ϕ} are approximated using a gradient diffusion model as:

$$\eta_k^{\phi}=\bar{\rho}\left(\widetilde{\phi u_k}-\tilde{\phi}\tilde{u}_k\right)=\frac{\mu_{SGS}}{Sc_{SGS}}\frac{\partial\tilde{\phi}}{\partial x_k} \quad (5)$$

The last terms of right hand of equation (4) is modeled using subgrid burning velocity S_T and the gradient of filtered scalar G written as:

$$\overline{\rho S_L\left(\frac{\partial G}{\partial x_k}\frac{\partial G}{\partial x_k}\right)^{\frac{1}{2}}}=\bar{\rho}S_T\left(\frac{\partial\tilde{G}}{\partial x_k}\frac{\partial\tilde{G}}{\partial x_k}\right)^{\frac{1}{2}} \quad (6)$$

The interference between the turbulence and the flame surface is modeled in S_T, which should be modeled like the turbulent burning velocity in the ensemble averaging formulation. In LES, the SGS turbulent combustion speed S_T on the GS level is introduced by Yakhot's model (1988).

Numerical results

The model combustor (fig. 1) consists of cylindrical combustion chamber with the upstream swirl vanes for main premixed fuels and 6 pilot nozzles injecting fuel into the combustion chamber directly. Here premixed flames by main swirl flow and non-premixed flames by pilot nozzles are combined together. Fuel is assumed pure methane and its flame speed is preliminary calculated by CHEMKIN4.0 with GRI-MECH3.0 data.

Unstructured grid (about 3,500,000 nodes) is applied, where detailed figures in the equipment such as flame holder and cooling air slits are considered. Software "FrontFlow" (Oshima 2004) developed for such practical LES calculations is used for solving the combustion flow in this study.

Typical results of premixed flame surface (G=0.5 iso-surface) and instantaneous temperature distribution in the centerline section are shown in fig.2 and 3. Other detail profiles and comparison to experimental data are reported at the presentation.

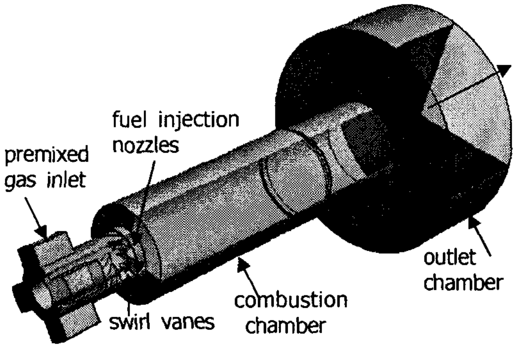

Fig.1 Schematic view of ccombustor

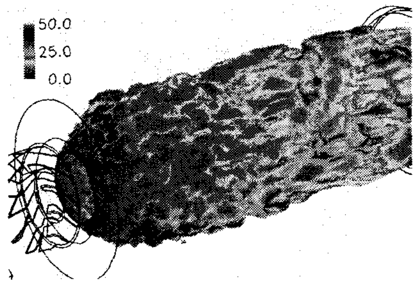

Fig.2 Visualization of the premixed flame surface (color shows the resolved flame thickness)

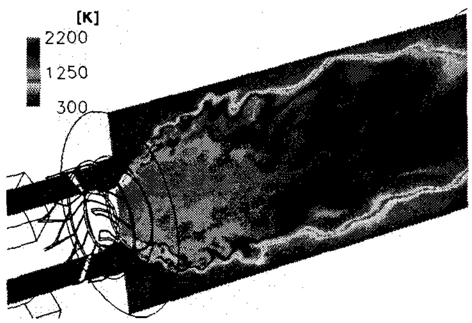

Fig.3 Instantaneous temperature distribution in the centerline section

Taniguchi,N., et.al.(2003) ASME FEDSM2003-45522
Peters, N. (1986), 21 th Symp. of Combustion pp.1231
Williams,F.A., (1985) Combustion Theory(2nd ed.), , Addison-Wesley
Menon, S. (1996) 6th Intern. Conf.on Numerical Combustion
Yakhot,V.(1988) Combustion Science and Technology Vol. 60
Tominaga, T. et.al (2003) Proc. Intern. Gasturbine Congress.
Oshima, N. (2005) Monthly Japan Soc. Applied Phys. Vol.74 No.8, 1087-1091 (in Japanese)