Large Eddy Simulation of Premixed Turbulent Combustion
Using the Flamelet Model Based on the G-equation

Hideyuki Oka

Maritime Safety Department, National Maritime Research Institute, Mitaka, Tokyo

A new model for large eddy simulation (LES) of premixed combustion has been proposed and tested in the present paper. The model is based on the G-equation, in which a level set method and the dynamic subgrid model of turbulent flame speed are incorporated. The mathematical feature of the filtered G-equation in the present formulation is consistent with that of the original one due to the introduction of the level set method. Therefore, discontinuity in hydrodynamic quantities across corrugated flames can be properly captured. In addition, the turbulent flame speed can be computed dynamically as a part of the calculation by modifying its procedure in conjunction with the level set method. For comparison, numerical simulations by two different G-equation models have been also conducted. It is found that the level set approach to the G-equation is effective to prevent the thin flame from broadening. It is also confirmed that the subgrid turbulent intensity is one of the most important factors in modeling the turbulent flame speed.

1 INTRODUCTION

Numerical simulations using Computational Fluid Dynamics (CFD) techniques have come into wide use in design and development of combustion systems. The most popular computational approach is to use Reynolds-averaged Navier-Stokes (RANS) solvers. The conventional RANS solvers based on various turbulence models often fail to capture unsteady flow phenomena accurately. Direct numerical simulation (DNS) of turbulent reacting flows places extreme demands on computational resources, so that DNS can be conducted only for greatly simplified reaction systems and very low Reynolds numbers. As an alternative, large eddy simulation (LES) of turbulent combustion is considered to be a promising approach to computational prediction of unsteady reacting flows. LES is widely used for non-reacting flows, but is still at an early stage for turbulent combustion flows.

In recent years, flamelet models for premixed combustion have received much attention as one of promising models for practically relevant combustion. In the flamelet concept, the characteristic chemical time is much shorter than the characteristic flow time, so that premixed combustion can be represented as the propagation of laminar flamelets corrugated by turbulent eddies. In other words, premixed flame, which is assumed to be an infinitely thin sheet separating fresh and burnt gases, is convected by the velocity field \( \mathbf{u} \), while it propagates normal to itself with the local laminar flame speed \( S_L \). This is mathematically expressed as the G-equation\([1]\):

\[
\frac{\partial G}{\partial t} + u_i \frac{\partial G}{\partial x_i} = S_L |\nabla G|,
\]  

\[ (1) \]
where $G(\mathbf{x}, t)$ is a field variable to track the position of the flame surface.

In a LES context, the $G$-equation is generally used to describe the filtered $G$-field, where the propagation of the filtered flame speed must be modeled. However, no universal model has been available so far because the turbulent flame speed is not a well-defined quantity. To overcome this difficulty, Im et al.\cite{im} proposed a dynamic subgrid model for the filtered flame speed under the assumption of no heat release, that is, under the isothermal condition. Park et al.\cite{park} applied this dynamic model to a practical two-dimensional combustor.

In the above two studies, the scalar $G$ was considered as a reaction progress variable such as $G = 0$ in the unburnt gases mixture and $G = 1$ in the combustion product, and the subgrid scale (SGS) transport term in the filtered $G$-equation was modeled using a classical gradient-diffusion assumption. On the other hand, a new combustion model based on the $G$-equation concept has been recently formulated by Pitsch and Duchamp de Lageneste\cite{pitsch}. They introduced a popular level set approach, which has been successful in the computation of free boundary problems. In the level set approach, $G$ is defined as a signed normal distance to the flame surface ($G = G_0$), which can be expressed mathematically by $|\nabla G(\mathbf{x}, t)| = 1$ on condition that $G < G_0$ in the unburnt gases mixture and $G > G_0$ in the combustion product. Unlike a conventional approach by Im et al.\cite{im} and Park et al.\cite{park}, the SGS transport term was modeled using the curvature of the flame surface. As for the filtered flame speed, they proposed their original model and used it in their simulations. Hence, LES using both the level set approach and the dynamic subgrid model of the filtered flame speed has not been reported yet.

The objective of this study is to propose a new combustion model based on the $G$-equation by combining the level set method and the dynamic subgrid model of the filtered flame speed. The simulations using the models of Park et al.\cite{park} and Pitsch and Duchamp de Lageneste\cite{pitsch} are also conducted, and are compared to the result by the present model. To carry out this numerical investigation, we consider a simple model combustor with a cylindrical premixer and a rectangular combustion chamber, where a simple premixed hydrogen-air jet flame is stabilized in a backward-facing step without swirling.

## 2 GOVERNING EQUATIONS

### 2.1 Flow equations

The governing equations in the present LES methodology are the filtered equations for mass, momentum and energy conservation as well as the equation of state in Cartesian coordinates. In the present study the flow is much slower than the speed of sound, so that the low Mach number approximation of the Navier-Stokes equations is used in the current formulation. In the variables appearing below, the bar and tilde denote spatial and Favre filtering, respectively. The LES equations are written in dimensionless form as

the continuity equation:

$$
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho \bar{u}_i)}{\partial x_i} = 0,
$$

(2)

the Navier-Stokes equations:

$$
\frac{\partial \rho \bar{u}_i}{\partial t} + \frac{\partial (\rho \bar{u}_i \bar{u}_j)}{\partial x_j} = -\frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \left( \frac{\bar{u}_i}{Re} + \mu \right) \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \right],
$$

(3)

the energy equation:

$$
\frac{\partial \rho \bar{h}}{\partial t} + \frac{\partial (\rho \bar{h} \bar{u}_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \frac{\bar{h}}{RePr} \frac{\partial \bar{T}}{\partial x_i} \right) + \frac{\partial}{\partial x_i} \left( \frac{\mu_v}{Pr} \frac{\partial \bar{h}}{\partial x_i} \right),
$$

(4)
the equation of state:

\[ p^0 = \overline{\rho T}, \]  

(5)

where \( \rho \) is the density, \( \mathbf{u} \) is the fluid velocity, \( h \) is the enthalpy, and \( T \) is the temperature. Coefficients, \( \mu \) and \( \lambda \), denote the viscosity and the thermal conductivity, respectively. The pressure \( p \) is independent of the constant acoustic pressure \( p^0 \) and represents the normal force field due to the incompressible fluid dynamic disturbances. The dimensionless parameters, \( Re \) and \( Pr \), are the Reynolds and Prandtl numbers, respectively. In this study they are defined as

\[ Re = \frac{\rho u U L}{\mu}, \quad Pr = \frac{\mu}{\rho \lambda}. \]  

(6)

where \( L \) is the diameter of the inlet nozzle, \( U \) is the mean flow velocity inside the nozzle, and the subscript \( u \) represents the unburnt state. Temperature dependency of the viscosity and the thermal conductivity are taken into consideration in dimensionless form as \( \overline{\mu} = \overline{\lambda} = T^{\delta_1 \delta_2}. \) Closure of the filtered governing equations can be achieved using the popular Smagorinsky model, so that the subgrid eddy viscosity \( \mu_\varepsilon \) is obtained as

\[ \mu_\varepsilon = (C_\varepsilon \Delta)^2 \sqrt{\frac{2}{3} \delta_{ij} \tilde{S}_{ij}}, \quad \tilde{S}_{ij} = \frac{1}{2} \left( \frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right), \quad \Delta = (\delta_1 \delta_2 \Delta)^{\frac{1}{2}}. \]  

(7)

Here, \( \tilde{S}_{ij} \) is the rate of strain tensor, \( \Delta \) is the filter length scale, and \( \delta_i \) is the local mesh spacing. In this study, the Smagorinsky coefficient \( C_\varepsilon \) and the turbulent Prandtl number \( Pr_t \) are set to 0.18 and 0.9, respectively, which were recommended for premixed combustion flows.  

### 2.2 The \( G \)-equation

To complete the mathematical formulation for reacting LES, the chemical reaction should be properly included. The filtered \( G \)-equation which is often employed in many cases of LES is expressed as follows:

\[ \frac{\partial \tilde{G}}{\partial t} + \frac{\partial \tilde{u}_i \tilde{G}}{\partial x_i} = S_T |\nabla \tilde{G}| - \frac{\partial}{\partial x_i} \left[ \tilde{p} \left( \tilde{u}_i \tilde{G} - \tilde{u}_i \tilde{G} \right) \right], \]  

(8)

where \( S_T \) is the turbulent flame speed, that is, the filtered flame speed. In the present \( G \)-equation model, \( \tilde{G}(\mathbf{x}, t) \) is defined as a signed normal distance from the filtered flame surface under condition that \( \tilde{G} < 0 \) in the unburnt gases mixture and \( \tilde{G} > 0 \) in the combustion product, so that the SGS transport term is modeled using the flame surface curvature as follows:

\[ -\nabla \cdot \left[ \tilde{p} (\tilde{u} \tilde{G} - \tilde{u} \tilde{G}) \right] \approx -\frac{\mu_t}{S_{CT}} |\nabla \tilde{G}|, \]  

(9)

where \( S_{CT} \) is the turbulent Schmidt number set equal to \( Pr_t \). Using the filtered scalar \( \tilde{G} \), the surface curvature \( \tilde{\kappa} \) is expressed as

\[ \tilde{\kappa} = \nabla \cdot \tilde{n} = -\frac{\nabla^2 \tilde{G} - \tilde{n} \cdot \nabla (\tilde{n} \cdot \nabla \tilde{G})}{|\nabla \tilde{G}|}, \quad \tilde{n} = -\frac{\nabla \tilde{G}}{|\nabla \tilde{G}|}. \]  

(10)

Next, the turbulent flame speed \( S_T \) must be provided to derive a closed set of equations. The dynamic subgrid model by Im et al. is applied to the propagation term of Eq. (8). However, their dynamic model was formulated by prescribing the value of \( \tilde{G} \) in the range \( 0 \leq \tilde{G} \leq 1 \) in a way similar to the so-called progress variable. Since \( \tilde{G} \) has the property of distance function in
the present level set formulation, it is impossible to directly apply the above dynamic model to the propagation term. Therefore, the following Heaviside function is introduced as a new variable corresponding to the progress variable:

$$H(\tilde{G}) = \begin{cases} 
1 & \text{if } \tilde{G} > 0, \\
0 & \text{if } \tilde{G} < 0, \\
0.5 & \text{otherwise.} 
\end{cases} \quad (11)$$

As a result, the filtered flame speed can be written in the present formulation as follows:

$$\frac{\overline{\mathcal{S}}}{S_L} = 1 + C \left( \frac{\overline{q}}{S_L} \right)^n, \quad C = \frac{(S_L)^n}{\left[ \overline{|\nabla H|} - \overline{|\nabla \tilde{H}|} \right]^{n}} \left[ Q^n \overline{|\nabla H|} - q^n \overline{|\nabla H|} \right], \quad (12)$$

where $n$ is a model parameter, $q$ is the root-mean-square (rms) of the subgrid turbulent intensity, and $Q$ is the rms of the test-grid scale turbulent intensity. Here, $\left( \overline{\cdots} \right)$ denotes test filtering. The width of the test filter, $\Delta_t$, is given as $\Delta_t = 2 \Delta$. Following Im et al.\cite{Im}, $n$ is set to unity and each turbulent intensity is modeled as

$$\overline{q}^2 = \overline{\tilde{u}_i \tilde{u}_i} - \overline{\tilde{u}_i \tilde{u}_i}, \quad Q^2 = \overline{\tilde{u}_i \tilde{u}_i} - \overline{\tilde{u}_i \tilde{u}_i}. \quad (13)$$

The $G$-equation model has to be solved together with the flow equations since $\tilde{G}$ is coupled with the thermodynamic variables through the filtered enthalpy $\tilde{h}$ in the energy equation. The chemical energy of the fuel mixture is included as $\tilde{h} = \bar{\tilde{T}} + \Delta h_f [1 - H(\tilde{G})]$. Here, $\Delta h_f$ is the heat of formation of the premixed fuel. The enthalpy $\tilde{h}$ and the heat of formation $\Delta h_f$ are non-dimensionalized using $c_p T_b$, where $c_p$ is the specific heat of the mixture at constant pressure. The heat of formation determines the amount of heat which is released during combustion, and it can be estimated as $\Delta h_f = T_b/T_u - 1$, where $T_b$ is the burnt gases temperature.

3 NUMERICAL METHOD

3.1 Computational domain and grid

We consider a simple model combustor where a premixed hydrogen-air jet is injected from a circular inlet into a rectangular combustion chamber. The schematic configuration is shown in Fig. 1. This geometry provides a recirculation zone which is similar to those found in modern gas turbine combustors. In the present simulation, the computational domain is taken only in
the rectangular chamber. For discretization, we use simple Cartesian coordinates on a staggered non-uniform mesh. Figures 2(a) and 2(b) show the present grid system in the x-y and y-z sections, respectively. As shown in (a), the grid points are clustered in the upstream region in the streamwise direction. The circle at the center of (b) indicates the location of the inlet nozzle, which is approximated stepwise in the practical computation. Hence, the grid points are clustered in the vicinity of the inlet as well as solid walls of the combustion chamber.

3.2 Discretization

The governing equations are discretized in space using a second-order central difference method. In particular, for convective terms, we employ the fully consistent and conservative finite-difference method proposed by Kajishima\cite{Kajishima} to improve the accuracy of numerical simulations in a rectangular grid system of non-uniform spacing. For temporal integration, we use the fractional step method with the second-order Adams-Bashforth scheme.

In spite of the use of the above highly accurate schemes, $\bar{G}$ will no longer be a distance function (i.e., $|\nabla G| \neq 1$) at later times even if we choose $\bar{G}(x,0)$ to be as such.\cite{Kajishima} In order to accurately compute the propagation term and the SGS transport term in the filtered $G$-equation, it is necessary to maintain $\bar{G}$ as the signed normal distance to the flame surface. For this purpose, the reinitialization procedure developed by Sussman \textit{et al.}\cite{Sussman} is carried out in conjunction with modification proposed by Peng \textit{et al.}\cite{Peng} In addition, the auxiliary reinitialization technique developed by Chang \textit{et al.}\cite{Chang} is also used in order to avoid unexpected movement of the flame surface position due to numerical errors during the reinitialization process. A detailed description of the reinitialization procedure is given, for example, in the references [11] and [12].

3.3 Boundary conditions

The wall function by Spalding's law is used along solid walls. No-slip boundary condition is, however, imposed on the vertical wall at the inlet. For thermal conditions, adiabatic walls are assumed in this study. The convective boundary condition\cite{Spalding} is used at the outlet boundary. Since the present simulation is carried out only in the downstream region of the backward-facing step, an appropriate inflow condition is needed at the inlet boundary. The axial velocity at the inlet is simply given by the seventh power law, on which "white noise" of 10%, 5% and 5% is superimposed in the x, y and z directions, respectively.

4 RESULTS AND DISCUSSION

Computational conditions in this study are given in the Table 1. The numerical results by the present combustion model are shown in Fig. 3. The LES result of fully developed non-reacting flow is given as the initial flow condition. Figure 3(a) shows a typical example of the instantaneous flame configuration and the velocity vectors in the vertical section through the center of the inlet nozzle. The instantaneous temperature profile in the same section is shown in Fig. 3(b). The flame position is also depicted by a solid black line. The formation of small cusps on the instantaneous flame surface is not observed due to the effect of the curvature term. In the case of treating $G$ as a progress variable, Im \textit{et al.}\cite{Im} pointed out that numerical difficulties arise due to the formation of cusps in practical computation unless a diffusive term is included in the $G$-equation. In contrast, the present computation can be carried out stably because the level set approach is applied to the present formulation. In addition to stability, it is seen from Fig. 3(b) that the sharp temperature gradient across the flame is numerically obtained due to the introduction of the level set method.
Table 1: Conditions of simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference velocity ($U$)</td>
<td>11.0 [m/s]</td>
</tr>
<tr>
<td>Reference length ($L$)</td>
<td>5.0 [cm]</td>
</tr>
<tr>
<td>Reference acoustic pressure ($\rho^2$)</td>
<td>0.1 [MPa]</td>
</tr>
<tr>
<td>Laminar burning velocity ($S_L$)</td>
<td>0.33 [m/s]</td>
</tr>
<tr>
<td>Fresh gases temperature ($T_{fg}$)</td>
<td>300 [K]</td>
</tr>
<tr>
<td>Burnt gases temperature ($T_{bg}$)</td>
<td>1430 [K]</td>
</tr>
<tr>
<td>$H_2$/air equivalence ratio ($\phi$)</td>
<td>0.4</td>
</tr>
<tr>
<td>Computational domain ($X \times Y \times Z$)</td>
<td>10.0×2.0×2.0</td>
</tr>
<tr>
<td>Number of grid points</td>
<td>96×48×48</td>
</tr>
<tr>
<td>Reynolds number ($Re = \rho u L / \mu$)</td>
<td>34300</td>
</tr>
<tr>
<td>Prandtl number ($Pr = \mu_c / \rho c_p$)</td>
<td>0.7</td>
</tr>
<tr>
<td>SGS Prandtl number ($Pr_{SGS}$)</td>
<td>0.9</td>
</tr>
<tr>
<td>SGS Schmidt number ($Sc_{SGS}$)</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Figure 3: Instantaneous and time-averaged flow fields by the present combustion model: (a) instantaneous flame configuration and velocity vectors; (b) instantaneous temperature distribution; (c) time-averaged temperature distribution. Solid black lines in (b) and (c) indicate the flame position.

The $G$-equation in the present model contains no diffusive term and has the same mathematical nature as the original equation (1), so that the premixed flame can be maintained as a thin sheet separating the unburnt and the burnt gases. Figure 3(c) shows the time-averaged temperature profile in the same section as in Fig. 3(b). The time-averaged flame position is also depicted by a solid black line. The dimensionless distance between the flame tip and the inlet nozzle is about 1.5. A similar flame configuration was shown in the experiment of Kishi et al. [14] where their experimental conditions are the same as those of the present simulation except that their combustion chamber is cylindrical. Therefore, it seems that the numerical result obtained by the present model is in qualitative agreement with the above experimental result.

Next, the numerical results by the conventional $G$-equation model are shown in Fig. 4. In this case, the $G$-equation is written as follows:

$$
\frac{\partial \bar{G}}{\partial t} + \frac{\partial \bar{m}_w \bar{G}}{\partial x_i} = \bar{S}_T (\nabla \bar{G}) \cdot \nabla \bar{G} + \frac{\partial}{\partial x_i} \left( \frac{\mu_c}{Sc_i} \frac{\partial \bar{G}}{\partial x_i} \right),
$$

(14)

where $\bar{G}$ is defined as $\bar{G} = 0$ in the fuel mixture and $\bar{G} = 1$ in the combustion product. The filtered turbulent flame speed $\bar{S}_T$ is dynamically calculated in the same way as the present model. In Eq. (12), however, $G$ instead of $H(\bar{G})$ is used to compute the coefficient $C$, since $G$ is treated as the progress variable in this case. Figures 4(a), 4(b) and 4(c) show the same physical quantities as in Figs. 3(a), 3(b) and 3(c), respectively. Compared to Fig. 3, the different flame configuration is obtained and small cusps are formed on the instantaneous flame surface in Fig. 4. However, as mentioned in the preceding paragraph, the cusps are not amplified and no numerical difficulty arises due to the introduction of a diffusive term in the $G$-equation. The flame configuration is represented by the isosurface of mean temperature (865 K), because the $\bar{G}$ value corresponding to the flame surface cannot be determined from the range $0 < \bar{G} < 1$. In contrast to the temperature profile in Fig. 3(b), the sharp gradient cannot be obtained in the vicinity of the flame surface in Fig. 4(b). The profile of $\bar{T}$ is approximately as wide as that of $\bar{G}$ since $\bar{G}$ is directly proportional.
Large Eddy Simulation of Premixed Turbulent Combustion

Figure 4: Numerical results obtained by the conventional $G$-equation model of Eq.(14). Physical quantities shown in (a), (b) and (c) are the same as in Fig. 3.

Figure 5: Numerical results obtained by the $G$-equation model of Pitsch and Duchamp de Lageneste\textsuperscript{[4]}. Physical quantities shown in (a), (b) and (c) are the same as in Figs. 3 and 4.

to $\tilde{T}$ through the relation $\tilde{G} = 1 + (\tilde{T} - \tilde{T}_i)/\Delta h_f$. Hence, we can see from Fig. 4(b) that the region $0 < \tilde{G} < 1$ broadens contrary to the flamelet concept that premixed flame is assumed to be an infinitely thin sheet. This is because the mathematical character of Eq.(14) is inconsistent with that of Eq.(1). Thus, it is difficult to confine the turbulent flame speed only at the flame surface in the conventional $G$-equation model. As a result, the time-averaged flame configuration in Fig. 4(c) is different from that in Fig. 3(c), though the distance between the flame tip and the inlet nozzle is only about 3% shorter than that of the previous case.

To examine the effect of the filtered turbulent flame speed $\bar{S}_T$, the numerical results using the $G$-equation model proposed by Pitsch and Duchamp de Lageneste\textsuperscript{[4]} are shown in Fig. 5. In their model, the $G$-equation is the same as the present one. Hence, $\bar{G}$ is defined as a signed normal distance from the flame surface. Unlike in Figs. 3 and 4, however, $\bar{S}_T$ is not determined dynamically. They proposed the following new model:

$$\bar{S}_T \frac{S_L}{S_L} = 1 + \frac{q - b_2}{S_L} \sqrt{\frac{D_{\alpha} / S_\alpha}{1 + (b_2/b_1)^2 \cdot D_{\alpha} / S_\alpha}}$$

(15)

where $D_{\alpha}$ is the turbulent Damköhler number, and $b_1$ and $b_2$ are taken from Peters\textsuperscript{[14]} to be $b_1 = 2.0$ and $b_2 = 1.0$. Figures 5(a), 5(b) and 5(c) show the same physical quantities as in Figs. 3(a), 3(b) and 3(c), respectively. As seen in Fig. 3(b), the sharp gradient of temperature across the flame is maintained in Fig. 5(b) due to the introduction of the level set method. However, significant difference of the flame configuration is observed in comparison with the results in Fig. 3. The distance between the flame tip and the inlet nozzle in Fig. 5(c) is about 20% shorter than that in Fig. 3(c). This means that the $\bar{S}_T$ model of Pitsch and Duchamp de Lageneste\textsuperscript{[4]} overestimates its value, compared to the dynamic subgrid model. In this study the subgrid turbulent intensity $q$ is estimated by Eq.(13), which is based on the scale similarity model\textsuperscript{[14]}, while Pitsch and Duchamp de Lageneste\textsuperscript{[4]} deduced $q$ from $C_i \Delta (2S_{ij} S_{ij})^{1/2}$ in the same way as used in the dynamic Smagorinsky model. Hence, the difference of the flame configurations may be influenced by the models of $q$ in addition to $\bar{S}_T$. In this point, further work is needed to determine the most appropriate model of the subgrid turbulent intensity.
Finally, time-averaged quantities on the center line in the $x$ direction are shown in Fig. 6. Hereafter, cases 1, 2 and 3 means the simulations presented in Figs. 3, 4 and 5, respectively. Figures 6(a), 6(b) and 6(c) show dimensionless time-averaged velocity $V_a$ and temperature $T_a$ of cases 1, 2 and 3, respectively. The circle on the temperature profile represents the flame position in each case. As mentioned previously, it is seen from (a) and (c) that the sharp temperature gradient across the premixed flame is maintained due to the introduction of the level set approach to $G$-equation. From (b) it is also confirmed that the conventional $G$-equation model produces an unrealistic temperature profile contrary to the flamelet concept. As for velocity, a rapid increase occurs just after passing through the flame in (a) and (c), which is caused by thermal expansion due to heat release. However, in (c) there is also an increase before the flame position. This results from the difference of the filtered flame speed models. Unlike in (a) and (c), $V_a$ in (b) reaches its maximum in the upstream side of the flame position. This means that thermal expansion occurs in the side of the unburnt mixture due to unphysical flame thickness caused by the diffusive term of the conventional $G$-equation model. The maximum values of $V_a$ in both (b) and (c) are about 1% smaller than that in (a), and therefore there is no remarkable difference between each case. Figure 6(d) shows time-averaged SGS turbulent intensity $q_a$ of each case. In cases 1 and 3 the turbulent intensity reaches its maximum value at the flame position, respectively, while in case 2 the maximum $q_a$ is observed at a different point away from the flame position. In addition,
the maximum $q_a$ of case 2 is about 30% smaller than those of the other cases. Therefore, it is very important to prevent flame thickness from broadening in a numerical simulation of premixed combustion.

5 CONCLUDING REMARKS

A new premixed combustion model based on the $G$-equation has been proposed by the combination of the level set method and the dynamic subgrid model of the filtered turbulent flame speed. Using this model, large eddy simulation has been carried out for a premixed hydrogen-air jet flame in the simple combustor which consists of a circular inlet and a rectangular combustion chamber. The numerical results have been compared with those of the other two $G$-equation models. In the case of using the conventional $G$-equation model in which $G$ is treated as a reaction progress variable, the theoretically sharp gradient of the $G$-field across the flame is gradually smoothed out and the premixed flame unphysically broadens contrary to the flamelet concept. On the other hand, the $G$-equation models based on the level set approach can capture the sharp gradient of the temperature and prevent the flame from broadening.

As for the filtered turbulent flame speed, the dynamic subgrid model and the recently developed algebraic model have been compared in the same level set framework of the $G$-equation. In the present simulation, remarkable difference has been observed between the two models. It seems that the subgrid turbulent intensity model is an important factor in the evaluation of the turbulent flame speed. In order to improve the $G$-equation models for LES, it is necessary to further examine how to model the subgrid turbulent intensity in addition to the turbulent flame speed.

In this study the numerical results of the proposed $G$-equation model have not been quantitatively compared with experimental data due to the different configuration of combustion chambers. Hence, further study for validation is now under way in order to make a comparison with published experimental data on two-dimensional bluff body stabilized flame\cite{17}. On the other hand, the application of an immersed boundary method\cite{18} is now under study to deal with the cylindrical chamber of Kishi et al\cite{14} without changing coordinate systems. The immersed boundary method that can handle arbitrarily complex geometry in Cartesian grids is an attractive technique for large eddy simulation of turbulent combustion flow when the proposed $G$-equation model is applied to practical combustors in the future.

ACKNOWLEDGEMENT

This research was carried out as a research activity at the Center for Smart Control of Turbulence funded by the Ministry of Education, Culture, Sports, Science and Technology, Japan.

References


