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Partially premixed flamelet modeling in a hydrogen-fueled supersonic combustor

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ABSTRACT

In scramjet combustors, the combustion process is usually partially premixed, that is, both the non-premixed and the premixed regimes should be taken into account. Based on the multi-regime flamelet (MRF) model proposed for low Mach number flows, a modified MRF model that applies to supersonic flow conditions has been developed. Taken a hydrogen-fueled model combustor as test case, the good agreement between the calculation and experiments was obtained. The distribution of weighting coefficient, which is defined based on the concept of combustion regime index, shows that the flow field in the supersonic combustor is partially-premixed. The premixed regime distributes in the backflow region, the shear layer and the boundary layer. Comparisons between the results of steady laminar flamelet (SLF) model and the modified MRF model show that the latter one gives a more precise prediction of temperature profiles, indicating the modified MRF model has better versatility and accuracy.

Introduction

In many practical combustion devices, including gas turbines and spray fueled aircraft combustors, the reaction process is neither fully non-premixed nor typically premixed, but partially premixed in reality. Even in the so-called representative non-premixed flames, for example, the plane parallel shear reactive flow and the counter-flow flame, the partially premixed characteristics still exist in the processes of flame ignition, propagation and stabilization. In supersonic combustors, the main stream is often dominated by diffusion flame, however, the local premixed combustion is also prevailing in the boundary layer, separation region and backflow zone [1]. Existing numerical simulations of scramjet combustors employing flamelet-type turbulent combustion models are often conducted under the premise that the flow is in non-premixed combustion regime [2–4] and neglecting the local premixed combustion. Therefore, certain error is believed to be introduced by this assumption. Thus, the partially premixed flamelet model should be developed to improve the prediction accuracy of the flow field.

Among the existing research on partially premixed flamelet modeling, the main approaches can be divided into two categories: one is to solve the G-equation and the mixture fraction equation (Z-equation) [5,6]; the other is to solve the progress variable equation (C-equation) and the Z-equation [7]. For the latter one, the flamelet/progress variable (FPV) model [8] and the multi-regime flamelet (MRF) model [9,10] are included. The MRF model avoids the difficulty in solving the G-equation, meanwhile, it also possesses the advantage of FPV model, that is, it is able to deal with the unsteady, lifted

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flame dynamics. In addition, whether a certain spacial location is under non-premixed or premixed regime in the flow filed can be judged by the combustion regime index proposed in MRF model. In this way, the assumption that whether the flamelet regime is non-premixed or premixed before calculation in the previous flamelet models is not needed in the MRF model. Thus, the MRF model is believed to have wider versatility and can be more precise.

Note that the classical flamelet models were developed under the premise that the Mach number is rather low and the density keeps constant [9–11], and the application of MRF model to supersonic flow is also rarely reported. Nevertheless, in the supersonic combustor, the pressure is no longer homogeneous, and the strong interaction between the shock wave and the flame cannot be ignored. Therefore, it is not appropriate to directly apply the traditional flamelet model, as well as the MRF model, to supersonic combustion. Several modifications have been proposed during last decade [2,12,13]. In high speed compressible flow, the increase of kinetic energy is rather considerable, even comparable to the chemical heat release. The shock capturing algorithm can no longer be valid if the intense coupling between velocity and temperature is not considered. In order to use the shock capturing algorithm in compressible flow field simulation, a concise modification has been proposed by Oevermann [2], in which the temperature is not obtained by direct interpolation from flamelet libraries as in the traditional subsonic flamelet models, but calculated by the coupling solving of the energy equation in the supersonic flow field. The modification method, however, is commonly used in the non-premixed supersonic flame [14].

In the current paper, a modified MRF model that applicable to supersonic conditions has been developed. Comparison of a hydrogen-fueled supersonic combustion between steady laminar flamelet (SLF) model and the modified MRF model are investigated. Then, the local non-premixed and premixed regimes are analyzed according to the weighting coefficient.

Partially premixed flamelet model

In multi-regime flamelet model, there are the three crucial questions need to be addressed, that is, the individual predictions of non-premixed and premixed regimes, the definition of the combustion regime index, and the reasonable combination between the results of each regime.

Non-premixed flamelet modeling

For the non-premixed regime, the flamelet/progress-variable (FPV) approach is employed. In the counterflow diffusion flame, by coordinate transformation from physical space to mixture fraction space, the non-premixed flamelet equations can be derived as [5]:

$$\rho\frac{\partial Y_i}{\partial \tau} = \frac{\chi}{2Le_i}\rho\frac{\partial^2 Y_i}{\partial Z^2} + \dot{\omega}_i$$
$$\rho\frac{\partial T}{\partial \tau} = \rho\frac{\chi}{2}\frac{\partial^2 T}{\partial Z^2} - \sum_{i=1}^{ns}\frac{h_i}{c_{p,i}}\dot{\omega}_i \quad (1)$$

where ρ is the density, T is the temperature, Z is the mixture fraction, $Y_i, Le_i, \dot{\omega}_i, h_i, c_{p,i}$ are mass fraction, Lewis number, mass production rate, specific enthalpy and specific heat of species i. χ is the scalar dissipation rate, which is defined as:

$$\chi = 2D(\nabla Z)^2 \quad (2)$$

where D is the diffusion coefficient.

Given a certain set of stoichiometric scalar dissipation rate values χ_{st}, the non-premixed flamelet equations can be solved and the diffusion flamelet lookup tables $\varphi_{non} = \varphi_{non}(Z, \chi_{st})$ are then obtained, where the scalar variable φ_{non} represents the species mass fraction Y_i.

Pierce [8] gave the variations of maximum temperature against the scalar dissipation rates of a typical complete set of diffusion flamelet solutions shown in Fig. 1. This diffusion flamelet curve, which is also referred to as the S-shaped curve, is consisted of three branches: the steady burning branch, the unsteady branch and the extinction line. By introducing an additional scalar, the progress variable C, flame states which are not capable of being represented previously in the steady flamelet model can be solved by the progress-variable approach [8].

The progress variable denotes the global extent of reaction of the local mixture. It is usually defined using the mass fraction of major product species. For hydrogen fuel, the progress variable is:

$$C = Y_{H_2O} \quad (3)$$

By the definition of progress variable mentioned above, the lookup tables $\varphi_{non} = \varphi_{non}(Z, \chi_{st})$ can be converted to the form of $\varphi_{non} = \varphi_{non}(Z, C)$. Then, the Favre mean values of scalars φ_{non} in the flow field are obtained by the probability distribution function (PDF) integral,

$$\varphi_{non}(x_i) = \int_0^1\int_0^\infty \varphi_{non}(Z,C)\tilde{P}(Z,C)dZdC \quad (4)$$

where $\tilde{P}(Z,C)$ denotes the joint-PDF of the mixture fraction Z and the progress variable C. In particular, the joint-PDF $\tilde{P}(Z,C)$ is modeled as $\tilde{P}(Z,C) = \tilde{P}(C|Z)\tilde{P}(Z)$. In this work, the Beta distribution is applied to $\tilde{P}(Z)$ and the Delta distribution is used for the description of $\tilde{P}(C|Z)$.

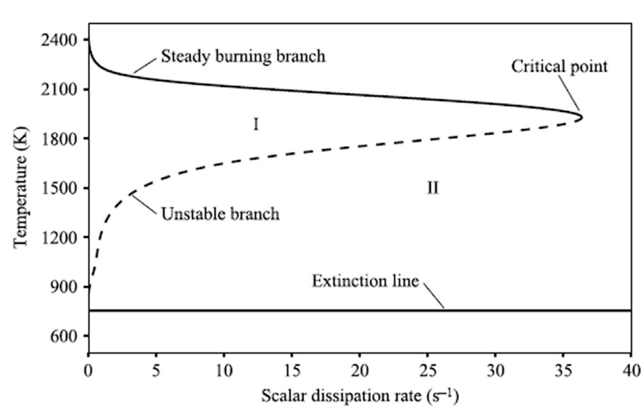

Fig. 1 – The S-shaped curve of diffusion flamelet solutions [8].