STUDIES ON THE LAMINAR FLAME SPEED OF BINARY FUEL BLENDS

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Summary Binary fuel blends are widely utilized in internal combustion engines as well as in the development of surrogate fuel models. Due to the strong nonlinearity of the chemical reaction process, the laminar flame speed of binary fuel blends cannot be obtained from the linear combination of the laminar flame speed of the individual fuel constituent. In this study, theoretical analysis is conducted for a planar premixed flame of binary fuel blends and a model for the laminar flame speed of binary fuel blends is developed. This model can predict the laminar flame speed of binary fuel blends when three laminar flame speeds are available: two for each individual fuel component and the third one for the fuel blends at one blending ratio. The performance of this model is assessed for different types of binary fuel blends. Good agreements with calculations or measurements are achieved by the model prediction.

INTRODUCTION

The laminar flame speed (also called the laminar burning velocity) is defined as the speed relative to the unburned gas, with which a planar, one-dimensional flame front travels along the normal to its surface. It is one of the most important parameters of a combustible mixture. In the literature, there are different theoretical models on the laminar flame speed, including the thermal theory, diffusion theory, and asymptotic theory. However, most of the previous studies were focused on the laminar flame speed of a single fuel component. Recently, fuel blends have been widely utilized in internal combustion engines [1] as well as in the development of surrogate fuel models [2]. Therefore, more studies were focused on the laminar flame speed of binary fuel blends, among which hydrocarbon fuel with hydrogen addition was the most extensively studied [3]. However, most of these studies only reported the laminar flame speed of fuel blends from experimental measurements or numerical simulations, and the model to predict the laminar flame speed of fuel blends was not proposed.

Due to the strong nonlinearity of the chemical reaction process, the laminar flame speed of binary fuel blends cannot be obtained from the linear combination of the laminar flame speed of the individual fuel constituent. The objective of this study is to develop a model which can accurately predict the laminar flame speed of binary fuel blends. First, the planar premixed flame of binary fuel blends is analyzed and a model for the laminar flame speed is proposed. Then, the performance of this model is assessed for different types of binary fuel blends at different equivalence ratios, pressures, and temperatures. Finally, the conclusions are drawn and the limitation of the present model is discussed.

MODEL DERIVATION

An adiabatic, planar, one-dimensional, premixed flame of binary fuel blends is considered in the theoretical analysis. Following the same way in which the planar flame of a single fuel is analyzed, one-step, irreversible, global reaction is assumed for each fuel component of the binary fuel blends. According to the energy conservation across the flame (i.e. the heat needed for increasing the temperature from the initial value to the adiabatic flame temperature is equal to the chemical heat liberated in the reaction zone), we can derive the following expression for the burning flux of binary fuel blends

$$m^2 = (q_1 Y_{1,u} m_1^2 + q_2 Y_{2,u} m_2^2)/(q_1 Y_{1,u} + q_2 Y_{2,u}) \tag{1}$$

where $m_i=\rho_{u,i}S_{L,i}$ with $S_{L,i}$ being the laminar flame speed of the i^{th} fuel component. q_i, and $Y_{i,u}$ are respectively, the chemical heat-release per unit mass of the i^{th} fuel component and the mass fraction of the i^{th} fuel component in the unburned mixture. The laminar flame speed of binary fuel blends can be obtained as $S_L=m/\rho_u$. Therefore, according to Eq. (1), the laminar flame speed of binary fuel blends depends on the square of the laminar flame speed weighted by the chemical heat release of each individual fuel constituent.

MODEL APPLICATION

The model given by Eq. (1) was used to predict the laminar flame speed of binary fuel blends. Unfortunately, good agreement was not achieved. The main reason is that the adiabatic flame temperature of binary fuel blends is not the same as that of each individual fuel component. Moreover, the chemical interactions between these two fuels are not considered since the one-step global reaction is assumed for each fuel component. We modify the model in Eq. (1) into the following form

$$m^2 = (Y_{1,u} m_1^2 + c Y_{2,u} m_2^2)/(Y_{1,u} + c Y_{2,u}) \tag{2}$$

in which the coefficient c is a free parameter. Since q_1 and q_2 are constants, the ratio q_2/q_1 in Eq. (1) is in fact included in the coefficient c. The densities of fuel blends and each individual fuel component are readily available. In order to

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predict the laminar flame speed of binary fuel blends, S_L, according to Eq. (2), we need know the coefficient c as well as the laminar flame speeds of each individual fuel component, $S_{L,1}$ and $S_{L,2}$ ($m_i=\rho_{u,i}S_{L,i}$ for i=1, 2). The coefficient c can be evaluated using the available date on the laminar flame speed of the binary fuel blends.

The model given by Eq. (2) is applied to the binary fuel blends of methane/hydrogen. The laminar flame speed of CH_4/H_2 mixtures at different equivalence ratios, pressures, and temperatures are calculated using the CHEMKIN-PREMIX code [4]. The detailed chemical mechanism, GRI Mech 3.0 [5], and the multi-component diffusion model including the Soret effect are used in the simulation. Moreover, the number of grid points is kept to be above 700 so that the flame structure is well resolved and the calculated laminar flame speed is grid-independent.

Figure 1 demonstrates the performance of the model given by Eq. (2) for stoichiometric CH_4/H_2 mixtures at normal pressure and temperature. The coefficient c is determined by ensuring that the laminar flame speed from model prediction and that calculated from PREMIX are the same at one selected blending ratio. For example, the solid line in Fig. 1 indicates that the coefficient should be c=1.50 so that at a=0.6, the same laminar flame speed is predicted by the model and by PREMIX. As shown in Fig. 1, good agreement is achieved by the model prediction though the flame speed changes nonlinearly with the hydrogen volume fraction. Moreover, it is demonstrated that the model prediction is not very sensitive to the coefficient c while the coefficient itself changes with the selected blending ratio, a. As a result, the selected blending ratio (which is used to determine the coefficient, c, of the model) does not strongly affect the model prediction. This is important for practical application of the present model since there is no stringent requirement on the value of the blending ratio selected as the base data for determining the coefficient, c. When flame speeds at different blending ratios are available, the coefficient c can be determined by minimizing the difference between the laminar flame speeds from model prediction and those calculated from PREMIX or measured in experiments.

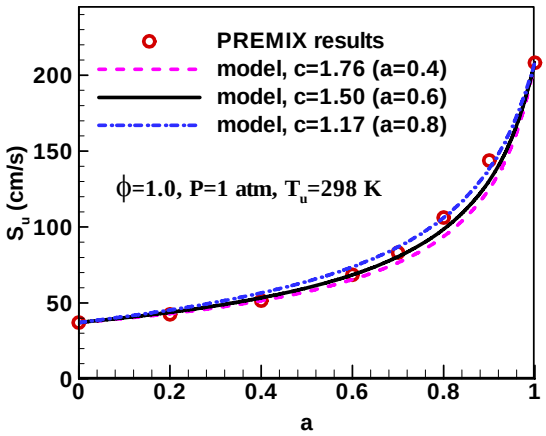

Fig. 1 Change of the laminar flame speeds of stoichiometric CH_4/H_2 mixtures with the hydrogen volume fraction in the fuel blends

Besides the results for stoichiometric mixtures under normal pressure and temperature, the results at different equivalence ratios, pressures, and initial temperatures all demonstrate that the laminar flame speeds predicted by the model given by Eq. (1) agree well with those calculated from PREMIX. Besides the simulation results from PREMIX, the laminar flame speeds of CH_4/H_2 mixtures measured by Huang et al. [6] are also used to demonstrate the performance of the model proposed in this study. Moreover, we also consider other types of binary fuel blends such as methane/dimethyl ether, propane/hydrogen, and n-dodecane/toluene and it is found that the present model, Eq. (2), can predict the laminar flame speeds of binary fuel blends.

CONCLUDING REMARKS

The laminar flame speed of binary fuel blends is investigated here through the one-dimensional, adiabatic, planar, premixed flame. Based on the energy conservation, the correlation (Eq. 1) for the laminar flame speed of binary fuel blends is derived and its modified form (Eq. 2) is proposed by introducing a free parameter c. The model shows that the laminar flame speed of binary fuel blends depends on the square of the laminar flame speed of each individual fuel component. The performance of this model is assessed for different types of binary fuel blends and good agreements with calculations or measurements are found to be achieved by the model prediction.

The shortcoming of the present model is that it is not parameter free: it contains the coefficient c. In order to predict the laminar flame speed of binary fuel blends according to the present model, we need know the coefficient c as well as the laminar flame speed of each individual fuel component. Therefore, the laminar flame speed at one selected blending ratio is needed to determine the coefficient c. Nevertheless, it is demonstrated that the selected blending ratio does not strongly affect the model prediction and thus for practical application of the present model there is no stringent requirement on the value of the blending ratio selected as the base data for determining the coefficient.

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