Structure of Methane-Air Coflow Diffusion Flame

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INTRODUCTION

Laminar fuel-air coflow diffusion flame is one of the most important flames in fundamental flame studies, and was the subject of many studies in early days of research [1]. The structure is multi-dimensional in nature and it is very difficult to elucidate the physics and chemistry of what is going on in the flame. It is usually considered that the chemical reaction is not the rate-determining process, and chemists have little been interested in the flame structure since it was believed that they did not allow the study of chemical reactions. The only exception is a series of the works conducted by Smyth et al. [2]. Most research, therefore, has been concerned with the more formal study of the flame, such as shape and height. This makes a sharp contrast to the counterflow diffusion flame, the structure of which is one-dimensional and physics and chemistry have fully been revealed experimentally and numerically [3]. The remarkable success of Burke-Schumann flame surface model, based on a one-step global reaction, in predicting the shape of coflow diffusion flame has made the people to believe that this simple chemical structure actually prevails in the flame. Only recently some attempt was made to develop a generalized Burke-Schuman formulation to include the influence of finite rate chemistry [4]. In the methane-air flame, some observation revealed that it is not the original fuel that is burning in the downstream portion of the flame [2, 5]. The original fuel is all consumed in the upstream portion of the flame, and the downstream portion is supported by the burnout of H2 and CO, which are the intermediate products of the upstream portion. However, the detailed study on this kind of structure has become possible only recently as the numerical calculation of 2-D flame structure with detailed chemistry and rigorous transport properties can be implemented. Smooke and Giovangigli for the first time made this kind of study on an axisymmetric methane-air coflow diffusion flame [6]. They made clear that the original methane fuel is almost completely consumed in the upstream portion of the flame, and that the fuel burning in the downstream portion is H2 and CO. Thus the chemical structure of coflow diffusion flame is not so simple as can be described in terms of one step global reaction. On the other hand, independently of this study, we made a series of studies to compare NO emission characteristics of an axisymmetric coflow diffusion flame with those of the one-dimensional counterflow diffusion flame [7-9]. The studies have revealed that the local structure of the 2-D coflow diffusion flame, as well as NO emission characteristics, in the upstream portion of the flame, correlates very well with those of 1-D counterflow diffusion flame. In the comparison, we introduced a representative diffusion time as the linkage parameter [7,8]. In the downstream portion, on the other hand, the local NO emission characteristics, as well as the flame structure, do not correlate with those of the 1-D flame [8]. It is not the original fuel that is burning in the downstream portion, and the combustion kinetics is different from that in the upstream portion. As a matter of fact we cannot correlate the two flame structures with the distinct combustion kinetics. The implication of the result is serious in view of the popularity of laminar flamelet concept in turbulent diffusion flame modeling [10]. The concept is based on the premise that the local laminar flame structure can be specified in terms of two parameters (mixture fraction and scalar dissipation rate), being independent of the flame location. The above studies have revealed that the local flame structure also depends on the axial location.

In the present study, an axisymmetric methane-air coflow diffusion flame was studied numerically. The detailed local flame structures were studied, to identify effects of multi-dimensionality. The chemistry, which causes the distinct local flame structures, will be discussed.

RESULTS AND DISCUSSIONS

The theoretical model and the numerical method are identical with those of the previous studies [7-9]. The fuel methane is injected from an injector exit at room temperature and velocity with a Poiseuille flow profile, into the coflowing air of room temperature and a uniform velocity. The injector radius is 0.2 cm, the pressure is atmospheric, and the injection velocities of fuel and air are set equal to 50 cm/s. The injector wall temperature is the experimentally measured value of 700K. It is assumed that flow and flame are fully axisymmetric, and that bulk viscosity, work done by pressure, viscous dissipation, radiation and Dufour effect are negligible. Under these assumptions, the 2-D Navier-Stokes equations were solved. The thermochemical parameters and transport properties were calculated using CHEMKIN [11-13], and the kinetic mechanism adopted was the so-called GRI mechanism [14], including NO kinetics compiled by Miller and Bowman [15]. The resulting mechanism is composed of 49 species and 279 sets of forward and backward elementary reactions. Thermal diffusion is considered only for H and H_2. The computational method, as well as the computational mesh, was the same with that of the previous studies [7-9].

The obtained results have confirmed clearly that the original methane fuel is completely consumed in the upstream portion, and the fuel burning in the downstream portion is H2 and CO. The latter are the intermediate products of the upstream portion, and are transported downstream by a 2-D transportation mechanism. As mentioned before, the implication is potentially serious in the laminar flamelet modeling. The combustion kinetics, and hence the local structure, is different in the upstream and the downstream portion, and we have to decide which one we shall choose for the flamelet modeling. Basically we have to take the upstream portion, which correlates with the 1-D flame. However, we have to elucidate the criterion to legitimate this choice. In this respect, the approach to describe the flame structure in terms of the simplified kinetics [4] should be useful. However, more detailed study of chemical kinetics would be inevitable.

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