Radiation Reabsorption Effect on the Extinction Limit of the Counterflow Diffusion Flame

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Abstract

In recent years, to achieve two purposes of energy saving and NO_x reduction at the same time, a new concept of combustion, that is, High-Temperature Air Combustion Technology (HiCOT) has been developed. In HiCOT, air is preheated to a very high temperature more than 1100 K by exhaust gas recirculation, by which the energy of the exhaust gas is recovered. Since the exhaust gas is recirculated as a diluent of air, the oxygen concentration decreases, occasionally below 10 %. It has been proven by actual industrial furnaces that HiCOT not only improves the combustion efficiency but also decreases NO_x emission [1].

For application of HiCOT, it is important to investigate combustion characteristics of air and gaseous fuel diluted by exhaust gas. In this study, flame behaviors and extinction limits of the counterflow diffusion flame of methane and air diluted by carbon dioxide were studied experimentally and numerically, varying the stretch rate and the fuel concentration. Carbon dioxide was used as a diluent in air and fuel, instead of nitrogen to know the effect of radiation reabsorption. Stretch flames are unable to establish at very small stretch rates due to the natural convection caused by buoyancy under the normal gravity condition. Therefore, the experiments were performed under the microgravity condition at the Japan Microgravity Center (JAMIC) in Hokkaido, where we can obtain microgravity quality of about 10⁻⁵ G during 10 seconds. Extinction limits for the counterflow diffusion flame were measured at various stretch rates and dilution rates. The fuel was methane diluted by nitrogen and/or carbon dioxide, and the oxidizer was air diluted by carbon dioxide. To obtain extinction limits, the fuel concentration of fuel flow is gradually decreased until extinction occurs under the microgravity condition, maintaining a constant stretch rate, which is defined as the stagnation-point velocity gradient in this study. Figure 1 shows an experimental apparatus consisting of a counterflow burner, an igniter, a mixture supply system, a video system and a control system. The counterflow burner is made of brazen circular pipe with an inner diameter of 16 mm. The oxidizer and fuel flow supply system is composed of electric mass-flow controllers, a notebook computer, and analog-to-digital and digital-to-analog converters.

The fuel side is diluted by the mixture of nitrogen and carbon dioxide whose ratios are 10 : 0, 9 :1, 7 : 3 and 5 : 5, and also the air side is diluted by the same mixture ratio as the fuel side, keeping the oxygen percent of 21 % constant.



Figure 1. Schematic of the experimental apparatus.

oxygen percent of 21 % constant. The oxidizer temperature at the burner exit is 300 K in all-experimental conditions.

To investigate the effect of radiation reabsorption on extinction limits, the experimental conditions were numerically simulated. The mathematical model and numerical code employed here are from PREMIX[2], that is, a program simulating steady, laminar, one-dimensional premixed flames, modified by Ju[3] for the counterflow diffusion flames. Since the objective of this study is to investigate the effect of radiation reabsorption on extinction limits, the radiative source term was

included in the conservation equation of energy. Two different kinds of radiation models were adopted for calculating the gas radiation. One is the optically thin model, in which the reabsorption is neglected. The other is the statistical narrow-band model (SNB) with the reabsorption effect. Radiation from gaseous species of CO₂, H₂O and CO is taken into account. The computational method of radiative transfer equation for the SNB model is same as the study of Wang and Niioka[4]. The governing equations for mass, momentum, chemical species and energy are solved in a cylindrical coordinate. Transport properties were calculated from the CHEMKIN- II database[5], and the GRI-mechanism version 3.0 chemistry[6] were used, which consists of 36 species and 219 elementary reversible reactions. The distance between the two burner exits was 10 cm in the calculation.

Figure 2 shows the relationship between the stretch rate at extinction and the fuel

concentration [fuel / (fuel + CO_2 + N_2)]. Curves shifted on the right-hand side, that is, the flammable region reduces as carbon dioxide volume ratio increases. This is caused by the heat capacity of carbon dioxide larger than nitrogen. However, when the ratio of N_2 : CO_2 equal to 9 : 1, the extinction stretch rate limit is smaller than the



Figure 2. Experimental result of the variation of the stretch rate at extinction with fuel concentration.

ratio of 10 : 0 (diluted by only nitrogen) at low stretch rate region. Since the extinction occurs due to radiation heat loss in the low stretch rate region, the extinction concentration limits should increase with the increase of carbon dioxide concentration. Large reabsorption effect of carbon

dioxide should result in the increase of flame temperature and the extension of extinction concentration limit in low stretch rate region.

Figure 3 shows numerical results of the variation of stretch rate at extinction with fuel concentration [fuel / (fuel + CO_2 + N_2)], calculated by the SNB model as well as optically thin model. Comparing the calculated results of these two models, the extinction stretch rate limits calculated by optically thin model are overstimated in the low stretch rate region. In other words, the extinction at low stretch rate region is



Figure 3. Numerical result calculated by SNB and optically thin model of the variation of the stretch rate at extinction with fuel concentration.

caused by radiation heat loss, and therefore the effect of radiation reabsorption should not be neglected. The extinction concentration limits calculated by SNB and optically thin model monotonically increase with the increase of carbon dioxide concentration, in spite that the experimental curves intersected each other when the ratio of N_2 : CO₂ equal to 10 : 1 and 9 : 1. There may exist a problem in definition of the stretch rate at low stretch rates.

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