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Experimental study on the effects of hydrogen addition on the emission and heat transfer characteristics of laminar methane diffusion flames with oxygen-enriched air

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A B S T R A C T

The effects of hydrogen addition on the emission and heat transfer characteristics of oxygen-enriched laminar methane diffusion flames were investigated in a laboratory-scale furnace with a co-axial burner. The volume fraction of hydrogen in the methane-hydrogen blend was varied from 0% to 50%, and the oxygen concentration was varied from 25% to 35%. Results showed that the addition of hydrogen led to an increase in the soot-free length and flame temperature while the degree of increase was less at higher oxygen concentrations. Adding hydrogen chemically enhanced the oxidation of CO to CO_2, and this chemical effect was stronger when the oxygen concentration increased. NO_x emissions increased significantly with the addition of hydrogen, while the rate of this increase decreased with greater oxygen concentrations. The total heat flux increased with the addition of hydrogen, while the rate of this increase was less at higher oxygen concentrations. Although the radiative heat flux increased with higher oxygen concentrations, it did not exceed 6% of the total heat flux at 35% O_2. Moreover, adding hydrogen decreased the radiative heat flux; this decrease was significant at higher oxygen concentrations.

Introduction

The consumption of energy resources is increasing rapidly due to increases in world population and demand for economic development. The most-used energy resource in the world is fossil fuels (such as natural gas, oil, and coal). However, fossil fuel reserves of Earth are limited and nearing depletion. Moreover, the use of fossil fuels produces a great number of pollutants, such as CO, CO_2, NO_x, and soot. Hence, searching for alternative energy sources and improving energy efficiency have been important concerns. Hydrogen–hydrocarbon hybrid fuel has been considered as an attractive way to reduce the dependency on fossil fuels and

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the emissions of pollutants while enhancing the performance of the combustion process [1–5]. Hydrogen is a green and renewable energy that produces water, instead of greenhouse gases, when combusted. Furthermore, hydrogen has a high burning velocity, high energy content, and low ignition energy [6]. Hydrogen can be produced from renewable energy resources, such as solar, biomass, and wind energy [7,8]. Previous research showed that the addition of hydrogen to hydrocarbon fuels improves combustion performance (e.g., combustion ignitability and stability) and reduces the pollutant emissions [1–5,9–15]. Choudhuri et al. experimentally investigated the effect of the addition of H_2 to natural gas in laminar diffusion flames [2]. The authors found that the addition of H_2 to natural gas led to a decrease in flame length, CO emission, and soot concentration. However, due to an increase in the flame temperature, NO_x emissions increased. Adding H_2 to CH_4 in turbulent diffusion flames also led to an increase in NO_x emissions and a decrease in CO emission, according to the study of İlbaş et al. [9]. Schefer et al. [10] found that the addition of H_2 to CH_4 increased the peak of OH concentration in the lean premixed swirl flames and lowered the lean stability limit. El-Ghafour et al. [11] studied the combustion characteristics of natural gas–hydrogen mixtures in turbulent diffusion flames, and showed that the flame stability improved and the CO_2 emission decreased significantly with the increase of the H_2 fraction in the fuel mixtures. Mishra et al. [12] reported that the addition of H_2 to liquid petroleum gas (LPG) laminar diffusion flame caused a decrease in residence time of the gases, and then resulted in a decrease in NO_x emissions. Liu et al. [13] numerically investigated the effects of hydrogen and helium addition to methane on soot formation, and revealed that the addition of hydrogen suppressed soot formation owing to decreased soot loading; however, hydrogen addition caused additional chemical effects that enhanced soot formation. Wu et al. [14] studied the effects of the addition of H_2 on the emission and heat transfer characteristics of laminar methane diffusion flames under a constant total input power. The authors found that the total heat flux along the furnace enclosure increased with the increase in the H_2 fraction, while the radiative heat flux decreased. The NO_x emissions increased significantly due to the increase in flame temperature with the addition of H_2. Dong et al. [15] studied the global characteristics of hydrocarbon–hydrogen (i.e., natural gas + H_2 and $C_2H_4 + H_2$) blended fuels; they reported that the radiant fraction and global residence time decreased with the addition of H_2, while the NO_x emissions increased and were dominated by the thermal NO_x route.

Oxygen-enrichment combustion has been widely used as a useful energy-saving technology for combustion systems. In many industrial combustors and furnaces, the use of oxygen-enriched technology increases flame temperature and flame stability, reduces exhaust volume and fuel consumption, and improves product quality [16]. Wu et al. [17] studied the effects of O_2 concentrations in the range of 21–30% on the heating rate, emissions, temperature distributions, and fuel consumption in the heating and furnace-temperature fixing tests for a gas-fired furnace. The results showed that increased O_2 concentration reduced the fuel consumption and increased the heating rate. The NO_x emissions increased with an increasing O_2 concentration due to the increased flame temperature. Oh et al. [18] experimentally studied the effects of the addition of H_2 on flame stabilization and flame luminescence in non-premixed oxy-methane flames. They observed that the flame stabilization area broadened with an increase in the H_2 fraction. The local intensity of the OH radical was enhanced with the addition of H_2, while the overall intensity of the OH radical decreased.

In the present study, the effects of the addition of H_2 on the emission and heat transfer characteristics of oxygen-enriched laminar methane diffusion flames inside a furnace were experimentally investigated. Low-level oxygen-enriched combustion was used, and the oxygen concentration was varied from 25% to 35%. Thus, only small modifications and retrofitting of the equipment were required. The volume fraction of hydrogen in the methane–hydrogen blend was varied from 0% to 50%. This study will be of benefit in helping the development of fundamental technology with respond to improve combustion in furnaces and reduce pollutant emissions. Moreover, to the authors' best knowledge, such a study of methane–hydrogen hybrid fuel combustion characteristics for low-level oxygen-enriched air flames has not been reported in the past. In an effort to contribute to addressing this deficit, the objective of the present work is to investigate the effects of the addition of H_2 to CH_4 on the flame length, flame temperature, exhaust emissions, radiative heat flux, and total heat flux in laminar diffusion flames under different oxygen concentrations. In addition, the behavior of methane–hydrogen hybrid fuel under oxygen-enriched air (25–35% O_2) were compared with that of methane–hydrogen hybrid fuel under 21% O_2 [14] to see how the combustion characteristics change for different oxygen concentrations. This study is expected to assist in developing a hydrogen-based economy and to provide more guidance for industrial applications.

Experimental method

Fig. 1 shows a schematic of the experimental setup used in this study. A detailed description of the experimental setup and procedure can be found in Wu et al. [14], so only a brief description is given here. A simple coaxial burner, consisting of a 7.6-mm-inner-diameter fuel nozzle and a 100-mm-inner-diameter co-flow air nozzle, was used to establish the laminar diffusion flames. Commercially available CH_4 (99.9% purity, Taiyo Nippon Sanao, Nagoya, Japan) and H_2 (99.999% purity, Taiyo Nippon Sanao, Nagoya, Japan) were used as the fuel and were supplied to the burner by a compressed gas tank. For the oxygen-enriched combustion cases, the oxygen and air were premixed before being introduced into the combustion chamber. Oxygen, with a purity of 99.5% (Taiyo Nippon Sanao, Nagoya, Japan), and dry air were supplied by a compressed gas tank and an air compressor, respectively. The fuel, oxygen, and air were fed into the combustion chamber at atmospheric pressure and at a temperature of 300 K. All gaseous flows were controlled by a commercial mass flow meter (CMS0050, Azbil Corporation, Japan) with an accuracy of ±1.0%. The oxygen concentration in the oxidizer (mixture of pure oxygen and air) was adjusted using mass flow meters. The flame image was observed and recorded by a digital camera (Sony DSC-HX400V, Japan) through a quartz window. The average value of the