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Analysis of turbulent diffusion flames with a hybrid fuel of methane and hydrogen in high pressure and temperature conditions using LES approach

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ABSTRACT

In the present study, large eddy simulations (LES) of a turbulent diffusion flame with a hybrid fuel of methane and hydrogen are carried out to investigate the effects of operating conditions on the flame shape and the pollutant formation. A parametric study is performed by changing the values of hydrogen concentration and the background pressure and temperature. A flamelet-progress variable approach (FPVA) is used for a tabulated chemistry and a dynamic subgrid scale (SGS) model is used as the LES model. The result shows a good agreement with a previous experiment in the statistics of flow fields and composition. Also, the results affected by each operating parameter show consistent tendency with previous studies. Then, we investigate how the effect of added hydrogen changes for different background pressure and temperature conditions including those of a direct injection internal combustion engine. It is found that both the high compression ratio and hydrogen addition can lead to more compact and focused reaction zone by changes in the reaction and mixing rates. This also affects the pollutant formation, and the reduction of CO and NO is observed with hydrogen addition.

Introduction

In the field of combustion research, enormous efforts have been made so far in order to increase the efficiency and decrease the amounts of pollutants from internal combustion (IC) engines. An example of the relatively recent progress in spark-ignition engine is the direct injection that aims at a higher specific power output and reduced fuel consumption compared to conventional port fuel injection (PFI). Applying the direct injection technique to a methane-based fuel such as compressed natural gas (CNG) is considered very promising, since it improves the charging efficiency significantly and thus the power density of IC engine, over the PFI counterpart. In addition, the recent finding of shale gas as well as various sources of renewable gas will make it more practical in the near future.

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Along with the use of natural gas as a fuel, lean burn by fuel stratification has received much attention with its high efficiency and favorable pollutant emissions. Here, the fuel stratification can be induced by late fuel injection during the compression stroke. However, this lean burn strategy suffers combustion stability either in premixed or diffusion phase of combustion, where the latter is observed in only recent study of gasoline direct injection engine.

One of the well-known techniques to stabilize a methane flame is to use a hybrid fuel by adding some hydrogen. So far, many studies have been done on flames with a methane and hydrogen mixture. In the present study, we are interested in turbulent diffusion jet flames as it resembles the latter stage of combustion inside a direct injection IC engine. The background condition inside an IC engine is characterized by a high pressure and temperature at the end of the compression stroke. Under this condition, an analysis based on accurate simulation techniques is very useful to understand the effects of a hybrid fuel on the combustion characteristics.

In the literature, there are many previous studies on non-premixed turbulent combustion with a mixture of methane and hydrogen. Tabet et al. [1] performed a numerical study on an influence of hydrogen addition on hydrocarbon turbulent non-premixed flame. Hydrogen addition leads to an improvement in mixing that results in a faster consumption of methane. As hydrogen concentration increases, however, the amount of NO_x also increases because of a higher flame temperature. El-Ghafour et al. [2] performed an experimental study on a diffusion flame with a natural gas and hydrogen mixture. They reported that, when the hydrogen concentration increases, the flame stability increases as the limit condition of the flame lift off and blowout is relaxed. A high concentration of H_2 leads to the increased flame temperature and shifts the high temperature zone to upstream. As reported by Ziani et al. [3], another effect of hydrogen addition is to reduce production of CO and CO_2, because the concentration of carbon in the fuel mixture is reduced by additional hydrogen. Oh et al. [4] found the effect of hydrogen addition on the behavior of non-premixed oxy-methane jet flame. It was found that the flame length decreases when the hydrogen concentration increases. The effect of background pressure on non-premixed combustion was investigated by Tabet et al. [5]. They found that high background pressure leads to deterioration of mixing and decrease of OH radical. This results in a thicker flame reaction zone compared to low background pressure.

Although several studies have been performed so far on turbulent diffusion flames with a mixture of methane and hydrogen, they did not consider a condition similar to that of an IC engine. The background pressure and temperature of the combustion chamber at the time of late injection are significantly higher than those of ambient, which depend on the compression ratio of the engine. As the hydrogen addition increases, the stability of the flame increases but the pollutant formation such as NO_x also increases [1–9], which can also be affected by the background temperature. Therefore, a comprehensive study on these parameters is desirable to understand the effectiveness of hydrogen addition in a direct injection IC engine fueled with natural gas.

Another limitation of the previous studies based on numerical simulation is that most of them used a Reynolds-averaged Navier-Stokes (RANS) model. This model has an advantage in terms of the computational cost. However, small-scale fluctuation of the velocity and scalars in the flame cannot be predicted accurately. The fluctuation components in a turbulent diffusion flame are very important, because they have direct effects on the mixing, flame stability and sources of the combustion noise. As the compression ratio increases, the Reynolds number increases as well, which raises the importance of small-scale fluctuations. In this regard, the approach of large eddy simulation (LES) is very attractive, as it can describe the fluctuation of the flame more accurately.

The main objective of the present study is to perform a parametric study based on a LES approach to analyze the effects of hydrogen concentration, background pressure and temperature on the turbulent diffusion flame of methane/hydrogen hybrid fuel. Various flow variables are investigated to analyze flame temperature, flame shape, formation of radicals and pollutants.

In Section 2, the combustion problem considered in the present study is described and the numerical approach based on LES is explained briefly. In Section 3, the simulation results are validated using the previous experimental and numerical studies. In Section 4, the individual and combined sets of the parameters are investigated to present the effects of hydrogen addition on reaction phenomena in background conditions including those of a direct injection IC engine.

Simulation backgrounds

Problem description

Fig. 1 shows the configuration of a burner for a diffusion flame (DLR-A) used in the experimental studies by Bergmann et al. [10], Meier et al. [11] and Schneider et al. [12]. The burner has a fuel nozzle with the diameter $D = 8$ mm at the center. The fuel nozzle is surrounded by a squared nozzle with the radius $l = 140$ mm to supply a co-flow of air at the velocity of 0.3 m/s. The bulk velocity of the fuel stream is 42.2 m/s. Here, the jet velocity is similar to that of the injected fuel in a direct injection IC engine from a simple analysis using the Bernoulli equation.

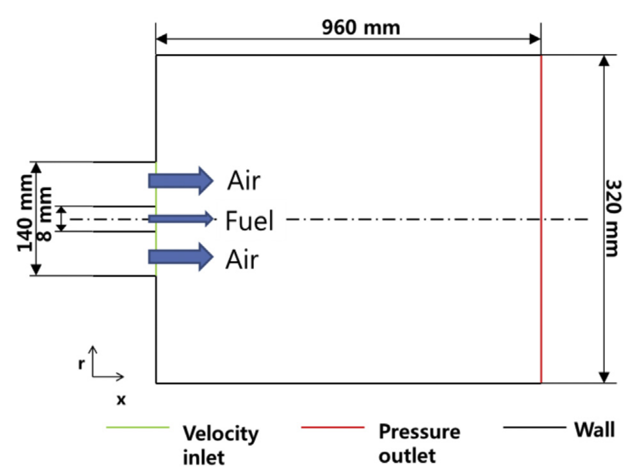

Fig. 1 – A schematic diagram of the computational domain.