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Effects of hydrogen concentration on premixed laminar flames of hydrogen–methane–air

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ABSTRACT

The unstretched laminar burning velocities and Markstein numbers of spherically propagating hydrogen–methane–air flames were studied at a mixture pressure of 0.10 MPa and a mixture temperature of 350 K. The fraction of hydrogen in the binary fuel was varied from 0 to 1.0 at equivalence ratios of 0.8, 1.0 and 1.2. The unstretched laminar burning velocity increased non-linearly with hydrogen fraction for all the equivalence ratios. The Markstein number varied non-monotonically at equivalence ratios of 0.8 and 1.0 and increased monotonically at equivalence ratio of 1.2 with increasing hydrogen fraction. Analytical evaluation of the Markstein number suggested that the trends could be due to the effective Lewis number, which varied non-monotonically with hydrogen fraction at equivalence ratios of 0.8 and 1.0 and increased monotonically at 1.2. The propensity of flame instability varied non-monotonically with hydrogen fraction at equivalence ratios of 0.8 and 1.0.

1. Introduction

The depletion of fossil fuel reserves and the growing demands for energy necessitate diversification of energy sources and are among the major reasons for the kindled interest in alternative fuels. Natural gas, which predominantly consists of methane, and hydrogen are considered alternative fuels for internal combustion engines. However, full exploitation of these fuels as effective alternatives could be limited by some of their properties.

Natural gas has no sulfur content and its combustion emits less CO_2 than gasoline owing to the high H/C ratio of methane [1]. Owing to the high knock resistance of natural gas, it can be used in engines with high compressions ratios. Lean operation may result in increase in the thermal efficiency of natural gas spark ignition engines because of the increase in specific heat ratio of methane–air mixtures as the mixture becomes leaner, reduction in pumping loss and reduction in heat loss due to the reduced flame temperature [2]. However, methane has a small burning velocity, which could limit lean operation in the engines due to increased cycle-to-cycle variation and emission of unburned hydrocarbons [3,4]. Engine operation at stoichiometric equivalence ratio with the application of three-way catalysts and/or exhaust gas recirculation may result in lower exhaust emissions and improvement in thermal

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efficiency [5]. However, the small burning velocity of methane also limits the quantity of EGR that can be used without impairing engine operation stability.

Hydrogen, on the other hand, has a large burning velocity that is about six times larger than that of methane at stoichiometric conditions and a lower flammability limit that is lower than those of conventional fossil fuels. Hence, hydrogen addition is one of the practical means of increasing the burning velocity of the fuel in natural gas SI engines. Large burning velocity leads to robust cycles with lower tendencies of cycle-to-cycle variations, and permits engine operation at very lean conditions or with large amount of exhaust gas recirculation, without impairing engine operation stability. With more dilution, greater NOx emission control is achieved and thermal efficiency can be improved at part load due to reduced pumping work [5]. Addition of less than 50% volume fraction of hydrogen to methane has been reported to reduce CO and CO_2 emissions, and improve the break thermal efficiency at lean conditions [6,7]. Karim et al. [6] suggested that the excellent knock resistant qualities of methane would not be undermined significantly by the presence of relatively small amounts of hydrogen in the methane.

The effects of the hydrogen content on the fundamental combustion characteristics of the resulting multi-component fuel are not yet well understood. Clarification of these fundamental characteristics of the multi-component fuel is important for optimization of engines designs. Laminar burning velocity is one of the most important properties of a fuel governing its combustion behavior. It contains the physico-chemical information of the mixture, therefore many premixed flame phenomena, such as extinction, flash back, blowoff, and turbulent flame propagation, can be characterized with the laminar burning velocity being a reference parameter [8]. Measured values of laminar burning velocity are important for the development and validation of combustion models.

The Markstein number or the Markstein length, which is another important combustion property of a fuel, quantitatively expresses the sensitivity of the laminar burning velocity to flame stretch rate. It is directly related to the onset of flame instability due to thermo-diffusive effects and is a function of the Zel'dovich number and the Lewis number [9–11]. The Zel'dovich number represents the sensitivity of the chemical reaction to variations in the maximum flame temperature [12] while the Lewis number qualitatively characterizes the influence of thermo-diffusive effects on the flame. The Lewis number correlates linearly with the Markstein number and is easier to evaluate hence may be used to qualitatively express the effects of flame stretch rate on the burning velocity. However, the Markstein number is a quantitative and a more general expression of the relevant phenomena since it incorporates, in addition to the Zel'dovich and Lewis numbers, the influence of gas expansion on flame stretch effects. Once the Markstein number of a given unstretched flame is known, the stretched burning velocity can be evaluated for a given non-dimensional flame stretch rate. This could be very useful in modeling of combustion in engines. In turbulent combustion, the turbulent burning velocity may vary because of variation of the local burning velocity of the flamelets due to stretch and this variation has been reported to correlate with the Markstein number [13–15]. Again, the Markstein number, unlike the Lewis number, varies with the initial mixture pressure; thus, it may be used to model the effects of flame stretch–pressure interaction on the turbulent burning velocity. Hence, the Markstein number is a preferred parameter to the Lewis number in turbulent combustion [16].

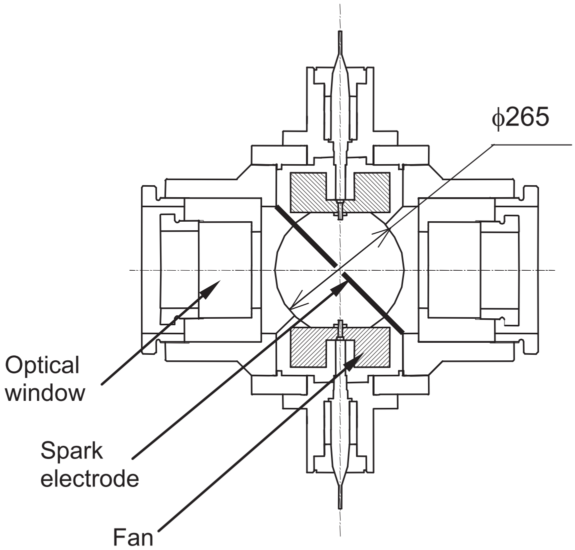

Fig. 1 – Schematic of the constant volume combustion chamber.

Fundamental experimental studies on the characteristics of hydrogen–methane flames have shown that laminar burning velocity increases with increase in hydrogen mole fraction in the fuel [17–19]. Using counter-flow flame configuration, Yu et al. [17] showed that the laminar burning velocities of methane–hydrogen mixtures increased linearly with addition of stoichiometrically small amount of hydrogen. Mandilas et al. [18] reported that 0.3 mol fraction of hydrogen in methane–hydrogen fuel doubled the laminar burning velocity at the lean flammability limit of methane. The Markstein length has been reported to decrease with increase in hydrogen concentration in the binary fuel [19]. However, to the best of our knowledge, experimental studies on the binary fuel that examined variations of the flame properties over the full range of hydrogen mole fraction in the fuel from 0 (methane only) to 1.0 (hydrogen only) are sparse.

The results of the numerical studies by Sankaran and Im [20] on spherically propagating flames of hydrogen–methane binary fuel showed a non-monotonic variation of burned gas Markstein length as the hydrogen fraction in the binary fuel was varied from 0 to 1.0 at equivalence ratio of 0.6. They suggested that the non-monotonic variation was due to competing effects of non-linear decrease of Zel'dovich number and Lewis number with increasing hydrogen concentration in the fuel. A similar non-monotonic variation of the burned gas Markstein length of the binary fuel at equivalence ratios of 0.8, 1.0 and 1.2 was reported in the numerical studies by Chen [21]. However, much attention has not been given to this non-monotonic trend in Markstein number of hydrogen–methane–air flames and experimental evidence of the phenomenon is sparse.