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# Experimental investigation on the effects of hydrogen addition on thermal characteristics of methane/air premixed flames

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## HIGHLIGHTS

- Flame temperature profiles were measured using traveling thermocouple technique.
- The rate of heat release were estimated to characterize hydrogen influence.
- Hydrogen addition causes decreases in both thicknesses of flame and reaction zone.
- $OH + H_2 \Leftrightarrow H + H_2O$ is one of the most governing reaction to the early heat release.

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## ABSTRACT

This paper presented an experimental study on the measurements of premixed laminar methane/air flames with and without hydrogen addition. The premixed flames were stabilized on a McKenna flat fame burner at atmospheric pressure. The traveling thermocouple approach was used to measure the axial flame temperature profiles over ranges of equivalence ratios and hydrogen enriching ratios. The measured temperatures, corrected by considering radiation loss, were analyzed to estimate the rate of flame heat release, by solving the continuity equations of mass, energy, and species which were applied to a flat flame. Some of important flame properties, such as the peak temperature, the average temperature, the flame thickness, the thickness of reaction zone and combustion efficiency, were presented to characterize the effect of hydrogen enrichment on laminar flame propagation. It is shown that the presence of hydrogen in laminar flame can promote flame reaction to some extent. With an increase of hydrogen addition fraction in fuel, the peak rate of heat release and combustion efficiency show increases, while the average temperature gives decrease. The analysis of the heat release profiles suggested that hydrogen addition has significant effect on the early part of flame heat release profile. The flames enriched by hydrogen show linear approximations in the plots of the logarithmic heat release rate against the reciprocal of flame temperature. A modeling for one dimensional premixed laminar burner-stabilized flame had been implemented with GRI-Mech 3.0 detailed kinetic reaction mechanism, based on the measured temperature profiles of these premixed flames. And then an analysis on the heat release was performed for each reaction. It suggested that the reaction $OH + H_2 \Leftrightarrow H + H_2O$ gradually increases its contribution to the early heat release with the increase of hydrogen enrichment, which is due to the fact of hydrogen addition resulting in an increased concentration of radical H in flame. The promoted H formation accelerates the flame burning velocity, and then thins the thicknesses of flame and reaction zone to a great extent.


## 1. Introduction

Studies relevant to the measurements of laminar flame structure have been featured in a number of experimental investigations for at least five decades. Such measurements are of practical importance for understanding combustion reaction kinetics of fuel. The axial temperature distribution of laminar flame is one of the most important aspects of flame structure. These measured temperatures can be used to evaluate the rate of heat release, which is useful to find the dominating reaction routines and explore microscopic chemical processes of flame combustion [1,2]. The measurement of flame temperature has been a hot subject of a number of investigations since long ago. As early as 1960s, Dixon-Lewis and Williams [3] measured the temperature profiles of premixed hydrogen/oxygen flames, and investigated the rates of heat release to make a physical chemistry analysis on reaction procedure. Cook and Simmons [4] reported the flame structure of

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**Nomenclature**

| | |
|---|---|
| $(dT/dz)_{max}$ | peak gradient in temperature profile, K mm$^{-1}$ |
| HAB | flame height above burner, mm |
| $H_R$ | hydrogen fraction in fuel, namely hydrogen enriching ratio, % |
| $\dot{M}$ | mass burning flux, g cm$^{-2}$ s$^{-1}$ |
| $P_0$ | initial pressure, MPa |
| q | rate of heat release, J cm$^{-3}$ s$^{-1}$ |
| $q_{max}$ | peak rate of heat release, J cm$^{-3}$ s$^{-1}$ |
| $q_k$ | heat release rate of the *k*th reaction, J cm$^{-3}$ s$^{-1}$ |
| $Q_A$ | actual heat release of flame, J cm$^{-2}$ s$^{-1}$ |
| $Q_e$ | heat release during the early part of combustion, J cm$^{-2}$ s$^{-1}$ |
| $Q_{e,k}$ | heat release of of the *k*th reaction during the early part of combustion, J cm$^{-2}$ s$^{-1}$ |
| $Q_T$ | theoretical heat release of flame, J cm$^{-2}$ s$^{-1}$ |
| $T$ | flame temperature, K |
| $T_a$ | average temperature of flame, K |
| $T_{ig}$ | ignition temperature of mixture, K |
| $T_o$ | initial temperature of mixture, K |
| $T_{max}$ | peak temperature of flame, K |
| $W_{j,k}$ | molar weight of the *j*th species in the *k*th reaction, g mol$^{-1}$ |
| $z$ | distance coordinates through flame |

*Greek symbols*

| | |
|---|---|
| $\phi$ | equivalence ratio of flame |
| $\rho_0$ | initial density of mixture, g cm$^{-3}$ |
| $\lambda$ | thermal conduction of mixture at temperature *T*, J m$^{-1}$ -K$^{-1}$ s$^{-1}$ |
| $\overline{C}_p$ | average specific heat of mixture at temperature *T*, J kg$^{-1}$ K$^{-1}$ |
| $\delta_F$ | flame thickness, mm |
| $\delta_R$ | thickness of reaction zone, mm |
| $\dot{\omega}_{j,k}$ | creation rate of the*j*th species in the *k*th reaction, mol cm$^{-3}$ s$^{-1}$ |
| $\eta$ | combustion efficiency, % |
| $\eta_{e,k}$ | heat release contribution of the *k*th reaction in the early part of combustion, % |

*Superscripts and subscripts*

| | |
|---|---|
| 0 | at reference conditions |
| j | *j*th species |
| k | *k*th reaction |

lean propane/oxygen flames diluted by argon. The heat release rates were analyzed for premixed laminar flames with various equivalence ratios, and subsequently the crucial reactions which control the early propagation of those flames were proposed.

Methane is being considered as one of the most promising gaseous fuels in the world. Its reserve is abundant and it has a high calorific value. Besides, methane can be mixed with air uniformly and burned completely to achieve lower pollutant emissions. But methane remains relatively slow burning velocities which will reduce engine's power output and increase energy consumption. Hydrogen has higher burning velocities, which is an excellent fuel additive into other fuels to achieve fast combustion. Therefore, methane/air flame enriched by hydrogen has become an important research issue in the last decades. Huang and his co-workers [5,6] implemented a series of experimental and numerical investigations on the laminar burning characteristics of premixed methane/hydrogen/air flames. The results showed that the unstretched laminar burning velocities are increased, and the peak values of the unstretched laminar burning velocities shifts to the richer mixture side with the increase of hydrogen fraction. Experimental study conducted by Deng et al. [7] reported that hydrogen addition can improve engine performance and lower pollutant emissions, to some extent.

There have been many relevant researches [8–10]. Generally, most of these were from a macro view, to measure the engine performances, the flame speeds, the Markstein lengths, etc., but gave little regard to the flame features for exploring the reaction kinetics of blended fuel. Recently Ferrières et al. [11] conducted a measurement of the chemical structure of premixed natural gas/hydrogen flames with same C/O ratio, which presented information of the intermediate distributions at different flame heights, and the main reaction pathways were thus identified. Woong and Chang [12] made a numerical simulation on partially premixed methane/hydrogen flames established in a one-dimensional counterflow field, in which the flame structure and the variations in the peak flame temperature, the rate of heat release and flame speed against the mixture equivalence ratios were investigated.

As the complicacy in reaction kinetics analysis, there still remains perplexity regarding chemical and physical interactions of hydrogen/methane/air system. The present study was concerned with flame temperature measurement to provide a comprehensive investigation on the thermal characteristics of premixed methane/hydrogen/air laminar flames stabilized on a flat burner. The flame temperature profiles were measured by a traveling thermocouple. The measured flames covered ranges of equivalence ratios and hydrogen fractions with a same volumetric flow rate. The flame properties, such as the rate of heat release, the characteristic thickness of flame, were made in comparison with those of methane/air flames at the same equivalence ratios. A modeling work had also been performed for the premixed laminar burner-stabilized flame on the basis of the measured flame temperatures, and then the rate of heat release contribution was analyzed for each reaction, to examine the effects of hydrogen addition.

## 2. Experimental setup and analyses approach

The traveling thermocouple approach was used to measure the axial temperature distributions of premixed laminar flames. The experimental setup consisted of a McKenna flat flame burner, fuel supplies and means of measuring flame temperature. This system herein was closely similar as that used by Ferrières et al. [11] and Powell et al [13], and the detailed description about it can be seen in these literatures. The burner contained a cooling circuit keeping the temperature of the burner plate constant, fuel inlet and shroud gas inlet. The surface of burner was made up of sintered bronze with a diameter of 60 mm, and the body of burner was surrounded by a Pyrex glass to avoid aerodynamic effect on flame stabilization. Methane/air and methane/hydrogen/air flames were stabilized on the burner at atmospheric pressure. The tested fuels were methane and hydrogen, whose purities were above 99.9%. In experiments, gaseous fuels and compression air were introduced into a mixing bomb with suitable proportions. Their respective mass flows were measured and controlled by mass flow controllers (SIARGO, Model MF5706) with a reported accuracy of 2% full-scale. A mixing bomb was used to mix fuels with air. After mixed uniformly, the mixture passed into the flat burner to burn. The volumetric flow rate remained constant in the current experiment, to eliminate the effect of mixture flow velocity on flame