



# Radical quenching of metal wall surface in a methane-air premixed flame



Yu Saiki<sup>a,\*</sup>, Yong Fan<sup>b</sup>, Yuji Suzuki<sup>b</sup>

<sup>a</sup> Department of Mechanical Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466-8555, Japan

<sup>b</sup> Department of Mechanical Engineering, The University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-8656, Japan

## ARTICLE INFO

### Article history:

Received 3 April 2015

Revised 29 July 2015

Accepted 29 July 2015

Available online 14 August 2015

### Keywords:

Flame-wall interaction

Chemical quenching effect

Surface reaction

Metal surface

Planar laser induced fluorescence

## ABSTRACT

In order to quantify chemical quenching effect of metal wall surfaces, a methane-air premixed flame formed in narrow quartz plate channels is investigated. Stainless steel321 (SUS321) and Inconel600 are chosen as the surface materials for their high oxidation/heat resistivity. Thin films of SUS321 and Inconel600 are deposited on the quartz plates using a vacuum arc plasma gun to realize equivalent thermal boundary condition with different surface reactions. In addition, two types of alumina thin films are prepared using atomic layer deposition (ALD) and sputtering techniques to explore the surface roughness effect. Microscopic OH-PLIF and numerical simulation with detailed chemistry are employed to examine the near-wall flame structures. When the wall temperature  $T_w \geq 1073$  K, OH concentrations near the SUS321/Inconel600 surfaces are significantly lower than that near the quartz surface. Based on the PLIF data, the initial sticking coefficient  $S_0$  associated with radical adsorption is estimated to be 0.1 and 0.01 for the SUS321/Inconel600 and quartz surfaces, respectively, indicating stronger radical quenching effect on these metal surfaces. On the other hand, OH profile near the sputtered-alumina surface, which has larger roughness, is in good accordance with that near the ALD-alumina surface. This implies that the radical adsorption is independent on surface roughness.

© 2015 The Combustion Institute. Published by Elsevier Inc. All rights reserved.

## 1. Introduction

Flame-wall interaction (FWI) is a two-way coupling process between flame and solid wall resulting in flame quenching, and of great importance in the design process of downsized combustors for internal combustion engines, gas turbines and rocket engines [1–5]. The solid wall imposes thermal, fluidic, and chemical boundary conditions affecting the flame dynamics and quenching.

FWI is classified into two typical cases, i.e., head-on quenching (HOQ), where flame propagation is perpendicular to the wall, and side-wall quenching (SWQ), where the propagation is parallel to the wall. The fundamental processes of FWI have been investigated in HOQ and SWQ configurations through theoretical/numerical analysis and quenching distance/wall heat flux measurements. Poinot et al. [1] performed two-dimensional direct numerical simulations with simple chemistry to examine HOQ for laminar and turbulent premixed flames. They showed for the turbulent case that a minimum Peclet number, which is defined as the ratio of a quenching distance to a characteristic flame thickness, and maximum heat flux through the wall are the same order as for the laminar case. Based on their DNS results, a law-of-the-wall model was proposed to

describe the interaction between a turbulent flame and a wall, and its performance was tested in a piston-engine computation. Andrae et al. [2] simulated SWQ of stoichiometric and lean propane-air premixed flames in a boundary layer flow. They showed for stoichiometric and near-stoichiometric flames that the intermediate hydrocarbons are the dominant emission due to the heat loss in contrast to the leaner flames, where the fuel itself becomes more dominant. Boust et al. [3] measured quenching distance and wall heat flux simultaneously for methane-air premixed flames under various pressures in HOQ and SWQ. They found that the quenching distance and the maximum wall heat flux become respectively smaller and higher with increasing the pressure both in HOQ and SWQ. They also obtained a simplified model of laminar flame-wall interaction taking heat losses without flame stretch into account, and validated it through comparison with the experimental data. Dreizler and Bohm [4] reviewed fundamental studies on FWI, and focused on optical diagnostics to probe thermal, fluidic and chemical properties of HOQ and SWQ. Recently, Bohlin et al. [5] developed hybrid femtosecond/picosecond rotational coherent anti-Stokes Raman spectroscopy (CARS), and made time-resolved HOQ measurement of a methane/air premixed flame. They found that, as the flame approaches to the metal wall, the temperature gradient increases, and decreases during quenching.

In micro-scale combustion [6–8], the wall effect becomes more significant, since the surface to volume ratio becomes large. Prediction and management of wall quenching become key issues to sustain flame. Intensive works on the thermal effect have been carried

\* Corresponding author. Fax: +81 52 735 5337.

E-mail addresses: [saiki.yu@nitech.ac.jp](mailto:saiki.yu@nitech.ac.jp) (Y. Saiki), [fan@mesl.t.u-tokyo.ac.jp](mailto:fan@mesl.t.u-tokyo.ac.jp) (Y. Fan), [ysuzuki@mesl.t.u-tokyo.ac.jp](mailto:ysuzuki@mesl.t.u-tokyo.ac.jp) (Y. Suzuki).

out to investigate the effect of heat loss to the wall on flammability and flame instability. Vlachos et al. [9–11] examined the thermal effect on ignition and extinction behaviors of hydrogen-air and methane-air flames in a stagnation point flow geometry using detailed gas-phase chemistry. Maruta et al. [12–13] observed flame oscillation phenomenon, which is called flames with repetitive extinction and ignition (FREI), in straight micro tubes with an axial temperature gradient. They confirmed through experiment and stability analysis that steady flame is formed at the high/low mixture flow velocities, while the FREI occurs at the intermediate velocities. Fan et al. [14–15] studied flame propagation and quenching in planar micro channels. They measured the spatio-temporal flame velocity and temperature with the aid of phase-locked OH-PLIF techniques.

The wall chemical effect, which is associated with radical adsorption and recombination on the wall surface, has also been studied [9–11, 16–30]. Vlachos et al. [10] numerically investigated the role of chemical effect in methane-air premixed flames near wall surfaces and showed that the ignition and extinction characteristics are significantly influenced by removal of  $\text{CH}_3/\text{H}$  and  $\text{H}/\text{O}/\text{OH}$  radicals, respectively. Popp et al. [16–17] simulated the chemical effect on HOQ of laminar methane-air and propane-air premixed flames in a range of wall temperatures between 300–600 K. They claimed that the chemical effect has a non-negligible influence on the near-wall flame structure at high wall temperature, and suggested that adsorption and surface recombination especially for H and OH radicals have to be considered in order to simulate HOQ accurately. Egolfopoulos et al. [18] examined the effect of H radical wall recombination on stagnation point methane-air premixed flames numerically and showed that the H recombination significantly affects the extinction strain at high wall temperature. Aghalayam et al. [19–20] and Raimondeau et al. [21] carried out numerical simulations of hydrogen-air and methane-air premixed flames with chemical quenching models including radical adsorption, radical recombination and desorption of stable molecules. They showed that both the thermal and the chemical effects play a key role in controlling the flame propagation in micro-burners [21]. Andrae et al. [22] simulated lean methane-air premixed flames in a boundary layer flow to examine the chemical and the thermal effects. They found that at lower wall temperature (600 K) the thermal effect plays a dominant role in the wall quenching, while at higher wall temperature (1200 K) the chemical effect becomes more significant. Bai et al. [23] conducted quasi-one-dimensional theoretical analysis on flame propagation in a tube with gas/surface chemistry, and discussed the thermal and the chemical effects on the quenching limits separately. The same group, Zhang and Chen [24] also theoretically analyzed a stagnation flame stabilized by a wall to examine the chemical effect on the flame bifurcation and extinction.

Miesse et al. [25] measured the quenching distance for a methane-oxygen premixed flame in planar channels with different wall materials. They found that the quenching distance is unchanged at low wall temperature ( $T_w = 500$  K) due to the thermal effect. On the other hand, at high wall temperature ( $T_w = 1273$  K), the quenching distance strongly depends on wall materials, and much smaller quenching distance can be realized on alumina/cordierite surfaces if compared with a quartz surface. Kim et al. [26] investigated the quenching distance of a methane-air premixed flame for different wall materials/treatment. They showed that even metallic surface like stainless steel can have smaller quenching distance by reducing the surface defects with annealing treatment. Taking into account the competition between the gas and the surface reactions, they classified the quenching mechanism into low (373–673 K), intermediate (673–873 K) and high (873–1073 K) wall temperature regimes. Yang et al. [27] also explored the quenching distance for different wall materials and analyzed their surface structures and compositions by X-ray diffraction/X-ray photoelectron spectroscopy. They claimed that the adsorbed hydroxyl

group on the surfaces might play an important role in the wall chemical effect.

On the other hand, information on the flame structure in the vicinity of the wall surface is limited. Prakash et al. [28] employed LIF to measure OH radical concentration in a low-pressure hydrogen-oxygen flame near alumina, quartz and platinum surfaces. Based on the measured OH concentration, they suggested that the alumina is the least reactive among these surface materials. Yang et al. [29] conducted OH-PLIF in a methane-air premixed slit burner between zirconia ceramics, silicon and stainless steel304 walls. They showed that the OH intensity close to the surface is increased in order of stainless steel, silicon and zirconia ceramics, which is in accordance with the quenching distance reported.

In our previous study [30], the wall chemical effects in narrow quartz channels with different surface materials were investigated through OH-PLIF and numerical simulation with detailed reaction mechanisms. Aluminum and platinum thin films were deposited on the quartz substrates to establish equivalent thermal boundary condition with different wall surface reactions. It was found that the wall chemical effect becomes of increasing importance at high wall temperature of 1073 K. The highest OH concentration is obtained on the alumina surface. By using a radical quenching model [21], the initial sticking coefficient associated with radical adsorption has been estimated to be 0 and 0.01 for the alumina and the quartz surfaces, respectively. However, the wall chemical effect on base metal surface remains unknown.

The objective of the present study is to elucidate the wall chemical effect of metal surface in a methane-air premixed flame. Thin films of stainless steel321 (SUS321) and Inconel600 are chosen as the surface materials for their high oxidation/heat resistivity. In addition, two types of alumina thin films prepared with different deposition techniques are examined to investigate the surface roughness effect. The near-wall flame structure and the initial sticking coefficient  $S_0$  associated with the radical adsorption are investigated through microscopic OH-PLIF as well as numerical simulation with detailed gas and surface reaction mechanisms.

## 2. Experimental and numerical procedures

### 2.1. Experimental setup

Figure 1 shows a schematic of the experimental setup for a planar quartz channel and the quartz plates with surface coating. Details of the experimental setup have been described in [30]. Two quartz plates are placed parallel to each other with a 3-mm-wide gap. A methane-air premixed flat flame is formed between two plates by using a porous burner. The bulk mean velocity and equivalence ratio  $\phi$  for the mixture are 0.22 m/s (at 293 K) and 0.95, respectively. Each quartz plate is heated with an infra-red (IR) lamp heater from its backside, where a black quartz plate is fusion-bonded for absorption of the IR light. Wall temperature  $T_w$  is measured with K-type thermocouple, which is plugged into 1-mm-diameter hole opened in the transparent quartz plate. The thermocouple is located 1.5 mm from the wall, where the thermocouple reading is in agreement with the wall surface temperature measured by a radiation thermometer within 15 K [14]. Hereafter,  $x$  and  $y$  denote the streamwise and the wall-normal directions, respectively.

In the present study, SUS321 (Fe-Ni(9–13%)-Cr(17–19%)-Ti(>5 × C%)) and Inconel600 (Ni-Fe(6–10%)-Cr(14–17%)) are chosen as the surface materials. Since SUS321 and Inconel600 have high oxidation/heat resistivity, they are often utilized for practical combustion equipment. Thin films of SUS321/Inconel600 (~100 nm in thickness) are deposited on the quartz substrates by using a vacuum arc plasma gun (ARL-300, ULVAC). Figure 2(a) shows principle of the vacuum arc plasma gun. An annular anode and a cylindrical cathode are coaxially arranged, and the substrate is placed

Download English Version:

<https://daneshyari.com/en/article/10264793>

Download Persian Version:

<https://daneshyari.com/article/10264793>

[Daneshyari.com](https://daneshyari.com)