Evaluation of the Effects of Coated Walls on Flame Stability of C₁-C₃ Alkane/air Mixtures in a Slit Burner

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1 Introduction

The interaction between flame and wall has been one of the key issues for high-efficiency and low-emission combustion technologies. At large surface-to-volume ratio, such as in compact or micro-miniature devices, this interaction is more prone to result in instability or maintenance difficulties in gas-phase combustion due to enhanced heat loss and elevated radical annihilation on the wall surface [1]. Although the wall thermal effects have been studied in depth, the studies that consider surface chemical effects remains insufficient. Raimoudeau et al. [2] claimed that the effects of heat loss and surface reaction on the near-entrance flame propagation are important after simulating micro-scale methane/air flames with a radical quenching model. Miesse et al. [3] first noticed that the quenching distance significantly varies with the types of bulk walls at high wall temperature of 1000 °C. Yang et al. [4] found that the wall made of ZrO_2 exhibited the largest near-wall OH radical intensity and the shortest quenching distance. In essence, the chemical effect on the surface can be accurately clarified only after the inconsistency in thermal boundary conditions of different materials is eliminated. Coating on the same substrate is the easiest strategy to approach the similar thermal boundary condition. Saiki et al. [5] fabricated thin films of different materials on the same quartz plates to study the effects of wall surface reaction. Subsequently, Hiber et al. [6] studied the influences of the common thermal barrier coatings (TiO₂ and ZrO₂/Y₂O) on flame wall interactions using a sidewallquenching burner. Wan et al. [7] recently reported that the wall chemical effects of metal coatings (Fe, Ni, and Cr) may exert strong influence on the low-temperature oxidation of DME/air mixtures, which changes the species pools and OH and CH₂O distributions in the weak flame. The above studies have shown that the surface reaction has a significant effect on the flame characteristics, especially the flame quenching behaviors at small or micro-scale conditions. From the point of view of application, coating the wall surface with suitable materials is an effective means of improving the flame stability whilst enhancing equipment durability and saving manufacturing costs. This work is intended to experimentally evaluate the interaction between C₁-C₃ alkane flames and different coatings in a slit burner. The Al₂O₃ thermal barrier coating and the wear-resistant AlCrN coating are investigated.

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2 Experimental Setup

The slit burner combustion and the OH-PLIF measurement systems have been described in our previous study [8]. Herein, the detailed description of the optical path is omitted. A slit burner, assembled with two parallel movable heating plates and a nozzle with 10 square cells $(1 \times 1 \text{ mm}^2)$, was used to form premixed C₁-C₃ alkane/air flames. The mixtures calibrated using mass flow controllers were supplied at an equivalence ratio of 1.0 and a flow velocity of 1.0 m/s (Re = 70). Two parallel holder blocks with ten SiC electrical heating elements inside were used to fix the tested walls and maintain the wall temperatures at 200-600 °C. The gap distance between two walls can be adjusted manually with a precision of 0.01 mm. The polished STS 304, with a dimension of $50 \times 50 \text{ cm}^2$ and a thickness of 3 mm, was used as a blank reference. The two coating materials of Al₂O₃ and AlCrN were deposited on the STS 304 substrate by plasma spray-physical vaopr deposition (PS-PVD) and cathodica arc physical vapor deposition (arc-PVD), respectively. Table 1 lists the corresponding surface properties of different walls.

In order to compare the present experimental data accurately, we must take into account the heat transfer process between the flame and coated wall due to the different effective 'R-values' (thermal resistances). However, as it should be explained that, when the Al_2O_3 and AlCrN thin films, which are less than 0.15 mm, are deposited on STS304 substract, the effective 'R-value' is weak enough to be ignored for the two kinds of wall-coating systems. Furthermore, H aber et al. [6] also found that the quenching Peclet number turned out to be almost insensitive to the coating material as well as to the coating thickness (0.05-0.15 mm) at the cold wall. Therefore, the the simply establishing the same thermal boundary condition is sufficient to discuss the effects of coating walls on flame stability, especially for the high-temperature heat walls in the present study. In general, a deatiled CFD simulation will be carried out to provide more in-depth quantiative explanation of the proportion of heat effects for wall-coating systems in the future.

Table 1 The surface properties of different wall materials.

material	coating thickness	surface roughness	thermal conductivity (high tem.)	component
STS 304		3.0 nm	25 W m ⁻¹ K ⁻¹	Fe-Ni, Cr, Mn
Al_2O_3	120.0 μm	160 nm	$1.47 \text{ W m}^{-1} \text{ K}^{-1}$	Al_2O_3
AlCrN	6.2 μm	100 nm	4.83 W m ⁻¹ K ⁻¹	AlN, CrN

3 Results and discussion

3.1 Quenching process

The OH-PLIF images of flame with decreasing the gap distance were captured using ICCD camera. For demonstration, the successive OH images in propane/air flame for the STS 304 walls at 600 $\,^{\circ}$ C is shown in Figure 1, and the other cases have similar results. At the gap of 5.04 mm, the stable flame with an approximation-elliptic shape is initially anchored on the nozzle exit. Then, the combustion space is narrowed as the gap decreases, leading to a shorter and narrower flame, and the OH intensity is decreased due to a reduction in the residence time of the mixture. When flame propagates in a 1.84 mm gap close to the quenching threshold, the heat loss to the wall and the radical annihilation results in the flame instability. In addition, the flame is lifted due to the enhanced preference diffusion and flame stretch effects. Finally, once the gap is less than 1.84 mm, the excessive flame stretch causes the flame to quickly extinguish. The instability phenomena are found to be similar to some previous works [4,9].



Figure 1. Flame quenching process of propane/air mixture between two STS 304 walls at 600 °C.

The variation of the propane/air flame position versus the wall temperature and material is drawn in Figure 2. Starting from nozzle outlet, the location of the maximum OH intensity in the flame is defined as the flame position. As the gap is large enough, the flame is stable and the flame position does not basically change as the gap distance decreases. However, when the gap is reduced to a certain value, the flame rapidly propagates downstream and the flame position rises almost linearly until flame quenching. As the wall temperature increases, the transition gap becomes narrower and the decrease of the corresponding flame position after transition gap indicates the enhancement of the flame stability. Besides, the effect of wall materials on the flame position is also significant and will be discussed in what follows.



Figure 2. Variation of the flame position of propane/air mixture with gap distance and wall temperature.



Figure 3. Variation of flame position with the wall temperature and material.

For STS 304 and AlCrN-coated walls, as shown in Figure 3, the C_1 - C_3 alkane/air flames have substantially the same variation tendencies of the flame positions with the wall temperature and gap distance, and the maximum deviation between them is within 0.3 mm. This means that the AlCrN coating has no promotion effect on flame stability compared with STS 304. In contrast, the Al₂O₃-coated wall remains the much lower

3

Fan Li Evaluation of the Effects of Coated Walls on Flame Stability in a Slit Burner

flame position, especially at the low wall temperature and narrow gap. Under the identical condition, the methane/air mixture presents the highest flame position, whereas the ethane/air mixture shows the lowest one. Warnatz [10] reported that the laminar flame speeds of C_1 - C_3 alkanes decrease in the opposite order, which is related to their respective activities. At the same inlet velocity, the higher flame speed can sustain the flame core closer to the nozzle exit.

3.2 Quenching distance

Herein, the quenching distance refers to the minimum gap between two parallel plates at which the flame can propagate through. As shown in Fig. 4 (a), the quenching distances are wall temperature dependent and monotonously decrease with the growth of wall temperature due to less heat loss from the flame and the preheating of unburned mixture by hot walls. On the low-temperature walls, surface reactions leading to radical quenching can hardly be activated, and the heat loss effects play a dominant role in determining the quenching distance. Based on one-dimensional thermal quenching theory, the quenching distances of Al_2O_3 -and AlCrN-coated walls should be much shorter than that of STS 304 wall since the two coated walls reveal a greater thermal resistance. However, the results shows that with the increase of wall temperature, the Al_2O_3 -coated wall can more easily sustain stable flame, whereas the AlCrN-coated wall is more likely to extinguish the flame. This means that the chemical properties of different wall materials may be one of the main reasons for the different quenching distances of C_1 - C_3 alkane/air mixtures.



Figure 4. Variation of the quenching distance with the wall temperature and material for premixed C₁-C₃ alkane/air flames.

As shown in Figure 4 (b), the quenching distance of the different types of fuels are significantly different, decreasing in the order of methane, propane, and ethane, corresponding to the decease of flame position. The quenching distance is significantly correlated to the level of the chemical reaction activity for different alkanes, and the more reactive fuel can maintain a smaller quenching distance. The flame temperature field is also affected by the wall temperature due to different heat transfer processes and fluid flow boundaries. Therefore, a coupled mechanism of the flame dynamic characteristics and thermal boundary conditions is inferred as the important factor in determining various quenching distances of C_1 - C_3 alkane/air flames.

3.3 Near-wall OH distribution

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Fan Li Evaluation of the Effects of Coated Walls on Flame Stability in a Slit Burner

Figure 5 (a) shows the normalized OH radical distribution near the right STS 304 wall and two coating walls. At 200 °C, all the normalized OH distributions are almost the same, further indicating the wall thermal effect dominates at the low-temperature wall. For the higher wall temperature of 600 °C, various chemical effects on these walls begin to play an important role in the OH radical distribution. The AlCrN-coated wall exhibits the strongest chemical effect, resulting in the lowest OH concentration near the surface. On the inert Al₂O₃-coated wall, the OH distribution is much higher than that on the other two walls, indicating that the radical quenching is the most suppressed. Notably, at the wall temperature of 400 °C, the OH distribution near the STS 304 wall is slight decreased. As mentioned by Kim et al. [11], the heterogeneous reaction rate is enhanced exponentially in this temperature condition, whereas the reaction rate levels off once the wall temperature beyond a certain limit. As a result, a severe consumption of OH radical in gas-phase flame zone is observed on the STS 304 wall at 400 °C.



Figure 5. (a) Normalized OH radical distribution, and normalized OH fluorescence intensity near the wall surfaces heated to (b) 200 $^{\circ}$ C and (c) 600 $^{\circ}$ C.

For more detailed comparison, the normalized OH fluorescence intensities in the vicinity of the three walls are shown in Figures 5 (b) and (c). All the normalized OH intensities for different walls remarkably increase as the gap decreases. At 200 °C, the Al₂O₃-coated wall exhibits slightly higher intensity compared with the other two walls, while the difference of the latter two walls is negligible. The chemical effects of different materials due to surface reaction is very weak near the low-temperature walls since the surface reaction is activated by mass transfer step only at high temperatures. At 600 °C, the normalized OH intensity is strongly dependent on the wall materials, which is in accordance with the aforementioned quenching distance results. The maximum normalized OH intensity of Al₂O₃-coated wall is the highest within ~ 0.25 mm, followed by STS 304 wall and the AlCrN-coated wall, indicating the existence of serious radical quenching on the AlCrN-coated surface.

4 Conclusion

Flame-wall interactions are not only related to the surface properties, but also closely to the fuel properties. Al₂O₃ and AlCrN coatings may be potentially very effective in developing good oxidation- and wear-resistance surfaces in small or micro-scale chambers. Limited by the material type and coating technology, the thickness of the inert Al₂O₃ coating is large, but this coating has the optimal effect in suppressing the flame quenching in narrow channels. Compared with the STS 304 wall, the AlCrN coating does not effectively inhibit the chemical quenching effect on its surface. More importantly, a very thin layer of the AlCrN coating makes it possible to be used in certain ultra-precision micro components. On the other hand, the quenching characteristics of different alkane fuels are directly related to the flame dynamic characteristics. The more reactive ethane has the smallest quenching distance, while the less reactive methane has the largest one. The measurement of normalized intensities of OH radicals near the surface would be one of the methods for assessing the radical adsorption and recombination behaviors between the flames with different coating walls.

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