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## Effect of different wall materials and thermal-barrier coatings on the flamewall interaction of laminar premixed methane and propane flames



#### Thomas Häber\*, Rainer Suntz

Institute of Chemical Technology and Polymer Chemistry (ITCP), Karlsruhe Institute of Technology (KIT), Engesserstr. 18/20, 76131 Karlsruhe, Germany

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ABSTRACT

We investigate the flame-wall interaction of laminar, premixed methane/air and propane/air flames in a stationary, sidewall-quenching configuration over a wide range of equivalence ratios. Both, the wall material (stainless-steel, cast iron, aluminum), the type of thermal-barrier coating (soot, zirconium dioxide, titanium dioxide) and its thickness (only for zirconium dioxide) were systematically varied. The flame-wall interaction is characterized by the measurement of quenching distances, which are based on the separate analysis of chemiluminescence images of electronically excited OH\* and CH\* radicals. A method has been developed to determine the position of the wall in the chemiluminescence images with sub-pixel accuracy. It turns out, that while the quenching distance strongly changes with stoichiometry and fuel, it only weakly depends on the wall material and type of coating, although the quenching distance tends to decreases with increasing thickness of the ceramic coating. Overall, the data confirms present scaling laws with a quenching Peclet number of  $Pe_Q \approx 7.5$ . Quenching distances determined independently for OH\* and CH\* differ more strongly than the distances of peak mole fractions in an undisturbed flame, without the influence of the wall.

#### 1. Introduction

Flames interact very intensively with (cold) walls of the reaction chamber up to the point of extinction. This is caused, on the one hand, by the heat conduction and radiation to the wall and the associated decrease in the temperature in the reaction zone and, on the other hand, by the destruction of reactive free-radical intermediates by recombination reactions on the surface of the wall. First systematic investigations have been carried out by Lewis and von Elbe et al. (Blanc et al., 1947, 1948; Elbe and Lewis, 1948; Harris et al., 1948) as well as by Friedman and Johnston (Friedman and Johnston, 1950) already in the middle of the last century. The authors determined quenching distances under various flame and wall conditions. Even so almost seven decades have been spent on the investigation of flame quenching near (cold) walls, one is far from having a quantitative understanding of the phenomena. For the most part, this may be attributed to the circumstance, that a multitude of influencing factors contribute to the extinction of the flame near the wall, e.g. fuel type, stoichiometry (in the case of a premixed flame), pressure, wall material, wall temperature and flow conditions, and so on.

A series of pollutants emitted by the exhaust gas from combustion engines, especially unburnt hydrocarbons, carbon monoxide (CO) and soot, are preferably formed in zones close to walls. For example, in combustion engines more than 50% of the unburned hydrocarbons may originate from near-wall regions (Alkidas, 1999), because the steep temperature drop leads to the quenching of reaction processes. Since the formation and oxidation of soot can be described with a radical mechanism (Appel et al., 2000; Frenklach and Wang, 1991), it is not surprising that the strongly temperature-dependent processes are decisively influenced by the presence of cold walls.

In combustion engines, the formation of deposits on the combustion chamber walls and the piston cannot be completely avoided, especially if the underlying combustion process is diffusion controlled, like e.g. in direct injection Diesel engines or direct injection spark ignition engines, especially under stratified operation conditions. Even so these engines operate under integral lean conditions, the ignition of the fuel/airmixture takes place in a zone with near stoichiometric composition formed somewhere between the fuel jet and the surrounding air. Towards the fuel rich side of the reaction zone, soot particles are formed. It strongly depends on the originally formed soot concentration, on the residence time of the particles in the oxidation zone of the flame as well as the flame temperature, whether soot particles are completely oxidized or whether a small fraction is emitted with the exhaust gas of the engine.

The situation with respect to flame quenching and pollutant formation in modern engines is additionally exacerbated by the

E-mail address: thomas.haeber@kit.edu (T. Häber).

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<sup>\*</sup> Corresponding author.

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downsizing trend, which leads to higher wall-surface to volume ratios of the combustion chamber. Downsized (highly boosted) engines are significantly more fuel-efficient compared to larger sized engines. This is achieved by a de-throttled operational mode for spark ignition engines as well as a decrease of friction losses by the reduced size and number of cylinders of the engine and their lower rotational speed levels during operation. Furthermore, depending on the operating condition, in modern direct-injection spark ignition engines, fuel impinges onto the piston wetting its surface. When the fuel-air mixture is ignited, the pyrolytic decomposition of the fuel and the formation of heavy sooting pool fires result in a considerable increase in the formation of deposits on the piston surface and/or the walls of the combustion chamber. The deposits may have a very crucial influence on the surface morphology of the wall and therefore change the momentum and heat transport between the fluid and the wall, which in turn might affect the turbulent flow (Jiménez, 2004; Walsh, 1982) and ultimately also the flame-wall interaction. However, there are only few detailed studies available concerning the effect of different wall materials or surface deposits/coatings on the quenching distance.

The quenching distance is an important parameter to describe flame wall interactions. It measures how far the flame approaches the wall and it is directly related to the heat exchange between flame and wall (Bellenoue et al., 2003; Boust et al., 2007; Kosaka et al., 2017; Sotton et al., 2005). It has been shown for methane-air flames (Bellenoue et al., 2003; Sotton et al., 2005) that for different wall materials (polished steel, steel covered with carbon black or ceramics), the quenching distances for both, head-on (HOQ) and sidewall-quenching (SWQ), differ considerably from each other, especially at increasing pressures. For example, at 1.5 bar the quenching distances for ceramics were about half as large as for polished steel, while those of soot-covered steel were roughly between the two for the flames examined (Bellenoue et al., 2003). The effect of surface temperature and material has also been studied in micro-burners and for flames between heated. parallel plates (Kim et al., 2006; Miesse et al., 2004; Saiki et al., 2015; Yang et al., 2013; Yang et al., 2011). These studies have shown that the flame-wall interaction at low surface temperatures ( < 500 K) is governed solely by the heat losses to the wall, while at high wall temperatures, wall surface reactions become the dominating factor. Some authors investigated the quenching distance and wall heat flux as a function of wall surface temperature in sidewall and head-on configurations (Hasse et al., 2000; Jainski et al., 2017; Kosaka et al., 2017; Popp and Baum, 1997). They found that at the point of flame-wall interaction, the heat flux to the wall increases with increasing wall surface temperature accompanied by a decreasing quenching distance, hence, confirming correlations derived earlier by, for example, Poinsot et al. (1993) or Boust et al. (2007).

Most of above studies focus on stoichiometric methane/air flames and investigate the flame wall interaction as a function of wall surface temperature or pressure. To date, there is no study systematically investigating the effect of wall materials, thermal barrier coatings and various fuels on the quenching distance for a wide range of mixture compositions and coating layer thicknesses. This paper aims to fill this gap by presenting detailed results on the flame-wall interaction of laminar, premixed methane/air and propane/air flames at blank, soot and ceramic coated stainless-steel walls as well as aluminum and castiron walls using a wire-stabilized premixed flame. In addition to using different materials and coatings, we also vary the mixture composition over a wide range of equivalence ratios for both fuels. For ceramic coatings, we also investigate the effect of systematically changing the coating thickness, which has not been done before. We will confirm that, for all conditions, the quenching distance scales with the flame thickness and that flame-wall interaction can be described to a first approximation by a unified Peclet number.



Fig. 1. Experimental setup of the sidewall-quenching burner (side-view, see text for details) (Jainski et al., 2017).

#### 2. Experiment

#### 2.1. Sidewall-quenching burner

Flame quenching near cold walls is studied using a generic sidewallquenching (SWQ) burner setup developed by Dreizler and co-workers (Bohlin et al., 2016; Jainski et al., 2017). Fig. 1 illustrates the burner configuration used in our investigations.

The premixed fuel/air mixture enters the burner from the bottom. After passing through a settling chamber, it is homogenized by a honeycomb structure and a set of fine wire meshes and exits the burner through a Morel-shaped quadratic nozzle (Morel, 1975) with an exit area of  $40 \times 40 \text{ mm}^2$ . A circular ceramic rod (, AL23, Friatec AG) placed 16 mm downstream of the nozzle exit anchors the V-shaped flame. One branch of the flame interacts with the wall, which is aligned parallel to the initial, vertical major flow direction. Wall and ceramic rod are spaced 10 mm apart. The rod itself is not centered over the nozzle, but is shifted by 5 mm to the left. The relative positions of nozzle, ceramic rod and wall were determined empirically, with regard to maximum flame stability. A co-flow of pure nitrogen encloses the central fuel/air flow. Table 1 lists the operating conditions of the sidewall-quenching burner. The coordinate system is defined such that z is along the vertical direction, being zero at the nozzle exit. The x-axis is perpendicular to the wall surface, with its origin at the wall and being positive towards the ceramic rod.

Methane (99.5%, Air Liquide) or propane (99.5%, Air Liquide) are

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