INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 43 (2018) 3822–3836

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Premixed hydrogen-air flames interacting with a hydrogen porous wall

Prashant S. Salimath [a], *Ivar S. Ertesvåg* [a,*], *Andrea Gruber* [b]

[a] *Department of Energy and Process Engineering, NTNU Norwegian University of Science and Technology, Kolbjørn Hejes vei 1b, NO-7491 Trondheim, Norway*

[b] *SINTEF Energy Research, Trondheim, Norway*

ARTICLE INFO

Article history:
Received 7 September 2017
Received in revised form
22 December 2017
Accepted 27 December 2017
Available online 1 February 2018

Keywords:
Permeable wall
S3D
Head on quenching
Flame-wall interaction
Wall heat flux
Detailed chemical mechanism

ABSTRACT

A laminar one-dimensional hydrogen-air flame travelling and quenching towards a chemically inert permeable wall (PW) is studied. Hydrogen flows through the wall into the premixed H_2-air. The S3D numerical code with detailed chemistry is used. PW results are compared against results of an impermeable wall (IW), including effects of varying wall mass flux, stoichiometry, inert dilution and unburned-gas and wall temperatures. The maximum reaction heat release rate occurs at the wall in all cases. For rich and stoichiometric mixtures, PW with fuel influx gave a moderate reduction of the quenching (i.e. maximum) wall heat flux compared to IW, whereas for a lean mixture, the increase is considerable. Effects of the fuel influx on the importance of individual elementary reactions and radicals and intermediate species are investigated. The lean PW cases have similarities to much richer IW cases. Both a lower wall temperature and dilution reduce the burned-mixture temperature and, consequently, the wall heat flux.

Introduction

Thermal degradation of hardware parts that are subjected to large wall heat fluxes during flame-wall interactions (FWI) is a critical issue in many energy conversion devices, such as internal combustion engines, gas turbine combustors and furnaces. The premixed FWI can be described as coupled thermo-chemical processes involving high temperature, propagating premixed flames impinging on colder walls, where flame quenching occurs at a normal distance from the wall known as quenching distance [1–9]. Dreizler and Böhm [10] reviewed numerical and experimental FWI studies. They discussed the role of laser diagnostics development and validation of collected data through numerical simulations.

Flame quenching occurs with a large heat release near the wall, and the resulting wall heat flux reaches its maximum value. Accurate determination of the quenching distance and the corresponding wall heat flux is significant, as strong thermal gradients occur near the wall, affecting hardware durability, pollutants formation and engine performance. The different stages of FWI mechanisms are understood through high-fidelity numerics in simple laminar premixed flame configurations in one-dimensional (1-D) head-on quenching and 2-D side-wall quenching configurations.

* *Corresponding author.*
E-mail addresses: Prashant.Salimath@ntnu.no (P.S. Salimath), Ivar.S.Ertesvag@ntnu.no (I.S. Ertesvåg), Andrea.Gruber@sintef.no (A. Gruber).

https://doi.org/10.1016/j.ijhydene.2017.12.166

Studies of transient quenching processes of flames have employed single-step and multi-steps chemical mechanisms. For low wall temperatures (around 300 K), the wall heat fluxes predicted by single-step chemical mechanisms have been seen to compare reasonably well to experimental observations. However, for higher wall temperatures these simple mechanisms have appeared to fail [4,11,12]. At high wall temperatures (above 400 K), it has been shown [6] that chemical processes play a significant role near the wall, involving exothermic radical recombination reactions. The detailed multi-step mechanisms employed in numerical codes have predicted well for wall heat fluxes and provided better understanding of radical recombination reactions involving radicals near the wall. Gruber et al. [3] showed that the role of exothermic radical recombination reactions was significant and contributed to 70% of the overall heat release at the wall for a laminar premixed hydrogen-air flame. Dabireau et al. [5] demonstrated that in a premixed $H_2 - O_2$ flame, the recombination reactions and reactions of intermediate species (HO_2, H_2O_2) together contributed 30% of the predicted wall heat flux.

Experimental study of FWI processes with quenching distances less than 1 mm near a wall is difficult due to strong thermal gradients [12,13]. Therefore, we tend to rely on numerical simulations. FWI processes of impermeable wall configurations are described by a normalized wall heat flux and the quenching Peclet number, defined as the position of maximum fuel consumption rate and normalized by the flame thickness. For hydrocarbon fuels, it has been observed that the wall heat flux is inversely proportional to the flame quenching distance with an assumption that no thermal boundary layer exists between the wall and the near-wall unburnt mixture [9,12,14,15]. Studies of hydrogen flames showed that their FWI behaviour differs from that of hydrocarbon flames for wall temperature maintained at 750 K, when quenching of the flame occurred much closer to the wall [5,7,16]. Owston et al. [7] extended the physical problem of [5] to a range between 298 and 1200 K and concluded that radical recombination reactions play a significant role in the evaluation of wall heat flux at higher wall temperatures.

The paper by Gruber et al. [17] (with two of the present authors) appears to be the first on numerical investigations on a fuel flux through a permeable wall into a flame. This potentially new design approach for combustion devices as a porous fuel diffuser possibly coated with H_2 selective permeable wall can replace conventional fuel nozzles and provide in-situ Co_2 – separation from the hydrogen fuel that is injected on the permeate side for mixing with the oxidant and combustion further downstream [18]. The hydrogen gas wall-permeation rate can influence the wall heat flux and avoid a flame coming very close to the wall. Hence, thermal degradation of hardware parts can potentially be reduced in comparison to an impermeable wall. Gruber et al. [17] discussed the transient nature of laminar FWI processes in 1-D and 2-D configurations and indicated a strong feedback mechanism between the permeating hydrogen flux and the flame on the permeate side.

A planar flame front propagates through a premixed fuel/air mixture towards a solid wall facing the flame. When reaching the wall, the flame quenches. The process can be analyzed as a 1-dimensional case, and is illustrated schematically in Fig. 1 for an impermeable wall (IW) and a fuel-permeable wall (PW) configuration. Both walls have chemical inert properties, that is, no adsorption or catalytic effects. In the PW case, the flame is partly premixed, as pure fuel (here H_2) flows into the domain and mixes with premixed fuel-air mixture on the permeate side.

Some aspects of the problem were considered by Gruber et al. [17] as part of a larger study. Numerical simulations with a detailed chemical mechanism and diffusion mechanisms were conducted for laminar hydrogen-air flames at atmospheric pressure on a planar and permeable (hydrogen selective) wall at constant wall temperature of 750 K and different H_2/air mixtures. It was found that for IW, the wall heat flux $(-\Phi_w)$ was slightly reduced and the quenching delayed in time as the undisturbed-mixture equivalence ratio (ϕ_u) was increased from 0.5 (fuel lean) to 1.5 (fuel rich). The net reaction heat release had its maximum point at the wall and it was larger for a stoichiometric mixture than for rich or lean mixtures. The temperature of the reacted mixture close to the wall around quenching approached, but was less than, the burned temperature of the freely propagating flame. The local equivalence ratio decreased towards the burned-mixture value as the flame front reached the wall and quenched. The PW cases of 17 were all conducted with a single permeate feed pressure (10 bar).

In the present paper, the physical problem is extended to operate the porous fuel diffuser configuration with different feed pressures at the porous wall. The resulting variation in hydrogen flow through the membrane influences the local chemistry near the wall and the heat transfer. We will also investigate FWI characteristics of the PW configuration,

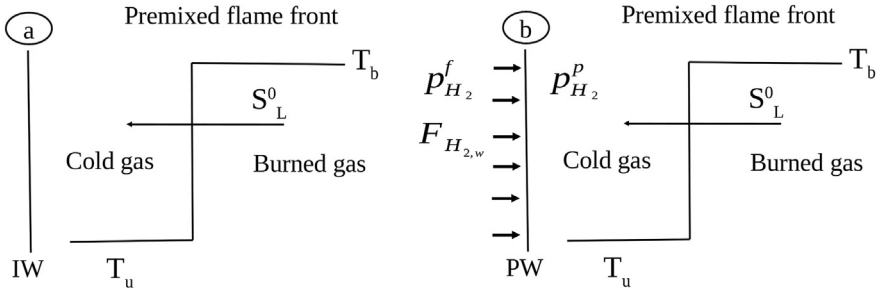

Fig. 1 – Head-on quenching configurations of (a) Impermeable wall (IW) and (b) Permeable wall (PW) with hydrogen flux in accordance with Eq. 5.