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# Experimental investigation of flame surface density and mean reaction rate during flame–wall interaction

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**Abstract**

Flame–wall interactions (FWI) of a turbulent side-wall quenching (SWQ) V-flame is characterized by planar laser diagnostics. Velocities and flame front positions are measured simultaneously by two-component particle image velocimetry (PIV) and planar laser induced fluorescence (PLIF) of the OH radical. Flame surface density and *reactive* flame surface density are derived from experimental data and evaluated in a physical and flame progress variable domain. The impact of the wall on flame structures is clearly observed. Additionally mean reaction rates are derived using both flame surface densities and a wall-influenced local consumption speed. Approaching walls reaction rates strongly decrease. Reaction rates are important for quantifying incomplete combustion near walls and impose a challenge for improved modeling approaches in numerical flame simulations. These experimental results are compared to previous direct numerical simulation (DNS) studies and flame surface density models from literature. Despite different Reynolds-numbers overall a good agreement between experimental data and modeling results is achieved. This is an indication that simplified chemical kinetic modeling in DNS is sufficient for representing kinematics of turbulent flames near walls.


*Keywords:* Flame surface density; Mean reaction rate; Flame–wall interaction; Side-wall quenching; Turbulent premixed flames

## 1. Introduction

Flame–wall interaction (FWI) is of key importance for the understanding and optimization of enclosed combustion processes (e.g. [1]). Near walls significant heat losses cause flame quenching and incomplete combustion. In case of turbulent flow conditions the presence of a wall changes the

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structure of turbulence such that turbulence–chemistry interaction is influenced by walls [2]. In consequence FWI does have a substantial impact on primary pollutant production and reduced thermodynamic efficiencies in applications such as gas turbine combustors or internal combustion engines [3].

The highly transient and small-scale nature of FWI is challenging for any numerical and experimental investigation of the underlying physical–chemical processes. A current problem of the numerical treatment of premixed turbulent FWI is the correct determination of the mean reaction rate $\overline{\dot{\omega}_R}$ close to walls. For turbulent flames undisturbed by walls various models exist that are more or less experimentally validated [2]. By the presence of walls some of the assumptions underlying these models are no longer valid. Substantial heat losses to walls and significantly changed turbulence structures in boundary layers superimposed by chemical kinetics have an important impact on flame characteristics prior to and during quenching. The flame surface density (FSD) model, however, can be adapted to effects imposed by walls. In this approach the turbulent flame is modeled as an ensemble of laminar flamelets (Peters [4]). These flamelets are conceived as thin layers separating unburned from burned gases. The FSD $\Sigma$ quantifies flame surface area per volume.

Following studies by Bray [5], Trouvé and Poinsot [6], and Bruneaux et al. [7] the mean reaction rate can be derived from the FSD. It depends on the instantaneous local FSD $\Sigma'$ and the local consumption speed of the flamelets $s_l$ by the following definition:

$$\overline{\dot{\omega}_R} = \rho_1^0 Y_1^0 \langle s_l \rangle_S \Sigma = \rho_1^0 Y_1^0 \langle s_l \Sigma' \rangle \quad (1)$$

where $\rho_1^0$ is the density of the unburned mixture and $Y_1^0$ is the initial fuel mass fraction. The term $\langle s_l \rangle_S$ is the surface-averaged consumption speed. According to Pope [8] $\langle s_l \rangle_S$ is equal to the ensemble average $\langle s_l \Sigma' \rangle / \Sigma$, where $\Sigma$ is the mean FSD.

In Eq. (1) the effect of chemistry on $\overline{\dot{\omega}_R}$, represented by $s_l$, is separated from the turbulence/combustion interaction which is represented by $\Sigma$. Both quantities $s_l$ and $\Sigma$ are affected by the presence of walls. Williams [9] and Wichman and Bruneaux [10] showed that the local consumption speed decreases close to the wall due to enthalpy loss and fuel depletion.

Using direct numerical simulations (DNS) Bruneaux et al. [7] investigated the evolution of $\Sigma$ for flames approaching walls. These authors derived models for all terms of the FSD transport equation in a head-on quenching configuration (flame propagation normal to the wall). It was shown that $\Sigma$ increases whereas the *reactive* FSD $\Sigma_R$ decreases when the flame approaches the wall. In this context $\Sigma$ does not include wall quenching because quenched flames were not considered in the statistics. In contrast for the calculation of $\Sigma_R$ quenching events were included. Alshaalan and Rutland [11] compared different models for the calculation of $\Sigma$ using DNS-results of a V-flame within a side-wall quenching geometry (inclined flame propagation toward wall). Compared to an adiabatic flame $\Sigma$ was reduced in the near-wall region and the wall normal profile of $\Sigma$ developed to an asymmetric shape. It was shown that models valid for flames far-off walls do not match results of near-wall DNS and cannot correctly predict the variation of $\Sigma$ with respect to the wall distance. Tayebi et al. [12] measured $\Sigma_R$ for a similar configuration by laser tomography. For flames near walls $\Sigma_R$ is reduced with increasing flame–wall interaction. However the shape of the FSD distribution over a flame progress variable was reported to be not affected by the wall.

In this study we focus on measuring flame surface densities and mean reaction rates ($\Sigma$, $\Sigma_R$, and $\overline{\dot{\omega}_R}$) of premixed V-shaped flames interacting with walls in a side-wall quenching geometry. Instantaneous flame front positions are deduced from planar laser induced fluorescence of the OH radical. Simultaneously the velocity field is determined by two-component particle image velocimetry. Data quality is sufficient for deriving $\Sigma$, $\Sigma_R$, and $\overline{\dot{\omega}_R}$ for side-wall quenching flames and to compare these quantities to DNS results and models reported in literature.

## 2. Experimental setup

### 2.1. Side-wall quenching burner

The burner (Fig. 1) consists of a converging Morel nozzle with quadratic cross-section to provide a top-hat velocity exit profile (edge length 40 mm). Well mixed fuel (methane) and dry air are fed to the burner plenum at room temperature. Honeycombs and fine meshes homogenize the flow before it enters the converging part of the nozzle. Sharp edges at the nozzle exit minimize recirculation zones. Turbulence intensities can be enhanced by an optional turbulence grid (blockage 45%, Fig. 1). A dried air co-flow surrounds the central flow. All flow rates are controlled by calibrated mass flow meters (Bronkhorst). A circular ceramic rod (Ø 1 mm) is placed above the nozzle stabilizing a V-shaped flame. One branch of this V-flame approaches a water-cooled steel wall (~300 K). Since the mean axial flow is parallel to the wall side-wall quenching (SWQ) occurs. In contrast to a previously used head-on quenching burner [13] this SWQ-burner leads to quasi-stationary flame–wall interaction. This speeds-up measurements significantly.