Flame / wall interaction and maximum wall heat fluxes in diffusion burners

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Abstract

Determining maximum wall heat fluxes in diffusion burners (rocket engines, Diesel engines or gas turbines) is a critical question for many combustion chambers. These fluxes are often due to flame / wall interaction (FWI) phenomena. This interaction may be due either to premixed or to diffusion flamelets impinging on walls. Possible FWI configurations in diffusion burners are analyzed and a proper laminar configuration for FWI studies (a diffusion flame impinging on a wall in a stagnation point flow) is identified. This case is studied for a variety of strain rates in terms of minimum distances between flame and wall and maximum wall heat fluxes. Results show that diffusion flames interacting with walls can generate heat fluxes which are larger than a premixed stoichiometric flame and that these mechanisms must be accounted for to predict wall heat fluxes in real burners.

Introduction

Determining wall heat fluxes is a key problem in the design process of combustion chambers in IC engines, gas turbines or rocket engines. This task is important for two reasons: first, *mean* fluxes at the wall must be evaluated to design cooling devices; second, *maximum* heat fluxes must also be estimated because they condition the lifetime of the burner. The mean wall fluxes are due to the convection of burnt gases along the chamber wall and can usually be estimated using correlations or CFD codes. The maximum fluxes are more difficult to determine: an important source of large wall fluxes is flame / wall interaction (FWI) during which flame elements are convected towards the wall and quench in its vicinity. This interaction has been studied in premixed flames theoretically [1], experimentally ([2,3]) and numerically both for laminar ([4,5]) and turbulent flows ([6,7]). These studies show that two generic FWI cases must be considered for laminar premixed flames (Fig. 1):

- Head on quenching (HOQ): if the premixed flame propagates towards the wall, HOQ is observed; the flame stops at a certain distance y_Q of the wall (of the order of the flame thickness) and the maximum wall flux Φ_Q^p (reached when the flame quenches) is of the order of one third of the total flame power $\rho_1 s_L^0 c_p(T_2 - T_1)$ where ρ_1 is the fresh gas density, s_L^0 is the flame speed and $c_p(T_2 - T_1)$ is the enthalpy jump through the flame [5].
- Side–wall quenching (SWQ): if the premixed flame propagates along the wall, the distance y_Q between wall and flame is larger than for HOQ and the flux slightly lower.

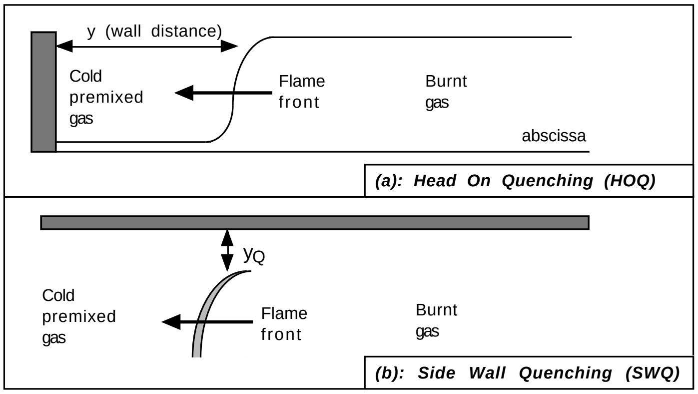

Figure 1: The basic configurations for flame/wall interaction in premixed flames.

DNS of FWI mechanims suggest that the simple estimates found for maximum wall fluxes in laminar flames also hold for turbulent cases ([4,6]): typically, the maximum heat flux observed in a turbulent premixed combustion chamber is the flux Φ_Q^p measured in laminar flames. At one bar, for wall temperatures of the order of 300 K, these fluxes are of the order of $0.5\ MW/m^2$ for a methane / air flame and can reach $5\ MW/m^2$ for a hydrogen / oxygen flame.

Although FWI is rather well understood in premixed flames and simple estimates can be found for maximum heat fluxes in premixed burners, much less work has been devoted to diffusion flames. This issue is essential for example in Diesel engines or in liquid fuel rocket engines in which reactants are introduced separately. Knowing which phenomenon determines the maximum flux on the walls of the engine is critical for design. Two separate questions must be addressed:

- What is the most representative configuration to consider for FWI in a diffusion burner ? A premixed flame or a diffusion flame ? Indeed, the premixed situation may still be the proper flame to consider, even in diffusion burners: Fig. 2 shows that, in such a burner, flame elements may consist of diffusion flamelets interacting with walls (Case 1). However, when chemistry is not infinitely fast, some premixing is expected[i] and recent LES of turbulent diffusion burners [8] show that a significant part of combustion takes place in premixed flamelets (Case 2) which can interact later with walls.

- If both cases are relevant, more information is needed on FWI for diffusion flames because this topic has received much less attention than FWI for premixed flames. A simple question is *whether* the maximum FWI heat flux for a diffusion flame can be larger than its value for a stoichiometric premixed flame.

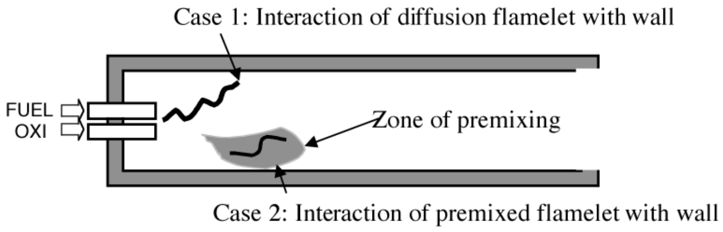

Figure 2: Possible flame / wall interactions in a diffusion burner.

Being able to predict maximum wall fluxes in diffusion burners therefore requires (1) the study of the combustion regimes (diffusion or premixed) within the chamber and (2) the study of FWI for diffusion flames. Point 1 is a difficult task which depends strongly on the burner geometry and operating conditions. Point 2, however, is more generic and is the objective of this work. This is done here first for laminar flames but the extension to turbulent cases can probably be performed as for premixed flames ([6,7]).

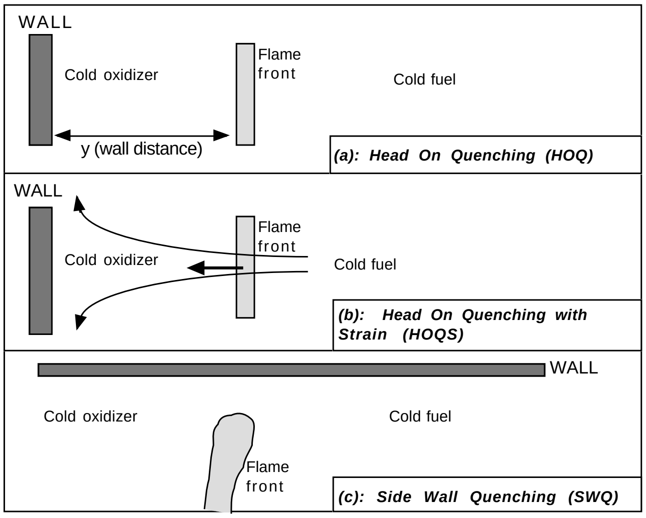

Figure 3: The basic configurations for flame/wall interaction in diffusion flames.

For diffusion flames, the first task it to identify generic FWI configurations (as done in Fig. 1 for premixed cases). This is a complex problem because diffusion flames near walls can have various topologies. Fig. 3 shows typical examples of such flames. The first one (Fig. 3a) is similar to the HOQ case observed for premixed flames: the diffusion

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[i] The presence of premixed flamelets is actually a design objective in Lean premixed prevaporized injection systems for gas turbines.

flame (maximum temperature T_2) is located at a distance y from the wall (fixed temperature T_W); the oxidizer (or the fuel) (at initial temperature T_W) is trapped between the flame and the wall. An important difference between HOQ for premixed and diffusion flames is that the diffusion flame has no propagation velocity. Therefore, it will remain at a fixed distance y from the wall while the oxidizer diffuses towards the flame. In this case, the maximum heat flux can simply be estimated by $\Phi = \lambda(T_2 - T_W)/y$ where λ is the thermal conductivity of the gas at the wall temperature. Moreover, since the initial flame wall distance y is a priori unknown, this case does not seem to be a good generic case for FWI. A better configuration is the strained diffusion flame pushed onto the wall (Fig. 3b). In this flow, called HOQS, a strained diffusion flame propagates and interacts with a wall. The only parameter controlling this interaction (in addition to chemical parameters and wall temperature) is the flow strain a. Finally, side wall quenching (SWQ) may also be observed for diffusion flames (Fig. 3c). The present study focuses on the second case (HOQS) because preliminary studies have shown that this case should lead to the largest wall fluxes. The presentation is organized as follows: first, a simple numerical model is built to study FWI in both premixed and diffusion flames. Then, the maximum wall heat flux Φ_Q^p measured during FWI of a stoichiometric premixed flame is computed as a reference for diffusion flames. Finally, diffusion FWI cases are computed for various strain rates and the maximum fluxes and minimum flame / wall distances are compared to the premixed case.

Numerical tool for FWI

A DNS code using a sixth-order compact scheme for spatial differencing and a third-order Runge Kutta scheme for time-advancement was set up to compute FWI both for premixed and diffusion flames. This code ([4,9]) solves the compressible Navier Stokes equations assuming a single-step reaction $Fuel + sOx \rightarrow Products$ (in mass) which is sufficient for the present work (extensions to complex chemical schemes and surface catalysis effects are possible ([10,11]) but were not activated for this study). Boundary conditions are setup using the NSCBC technique ([12]). The fuel reaction rate is expressed as:

$$\dot{\omega} = -A\rho^{n_f+n_o} Y_f^{n_f} Y_o^{n_o} exp(-\frac{T_a}{T}) \tag{1}$$

where the reaction exponents n_f and n_o are 2 and 1. The activation temperature is 16400 K. The stoichiometric ratio s is 8. Preferential diffusion is accounted for through a 0.3 Lewis number for fuel.

For the premixed case (next section), the computation is one-dimensional: the initial condition is a laminar stoichiometric flame propagating towards a wall. The wall and the fresh gases are at the same temperature $T_W = 750K$ (corresponding to typical wall temperatures in rocket engines).

For the diffusion case, the computation is two-dimensional: the initial condition is a strained diffusion flame profile obtained from asymptotic techniques [13] and located at a distance y_0 from the wall (temperature T_W). Oxidizer (temperature T_W) is trapped between the wall and the flame. The diffusion flame is then pushed by the flow towards the wall and quenches.

FWI reference case: the stoichiometric premixed flame

First, the case of a stoichiometric premixed flame interacting with a fixed temperature wall is computed. The maximum heat flux Φ_Q^p measured during this interaction will be used as the reference value to scale all other cases. Fig. 4 shows flame / wall distance, flame consumption speed and wall heat fluxes versus time. All values are normalized: the flame / wall distance y is scaled by the flame thickness $d = D_{th}/s_L^0$ (where D_{th} is the thermal diffusivity in the fresh gas), the flame consumption speed s_c is normalized by the unstrained planar flame speed s_L^0 and the wall heat flux by the flame power $\rho_1 s_L^0 c_p(T_2 - T_1)$. Before the interaction, the wall distance decreases linearly indicating that the flame moves at constant speed s_L^0. It then slows down and stops when $y/d = y_Q/d \simeq 5.5$. At this moment, the normalized heat flux $\Phi_Q^p/\rho_1 s_L^0 c_p(T_2 - T_1)$ is of the order of 0.13. The slight difference from previous work [5] comes from the different values of the Lewis number.

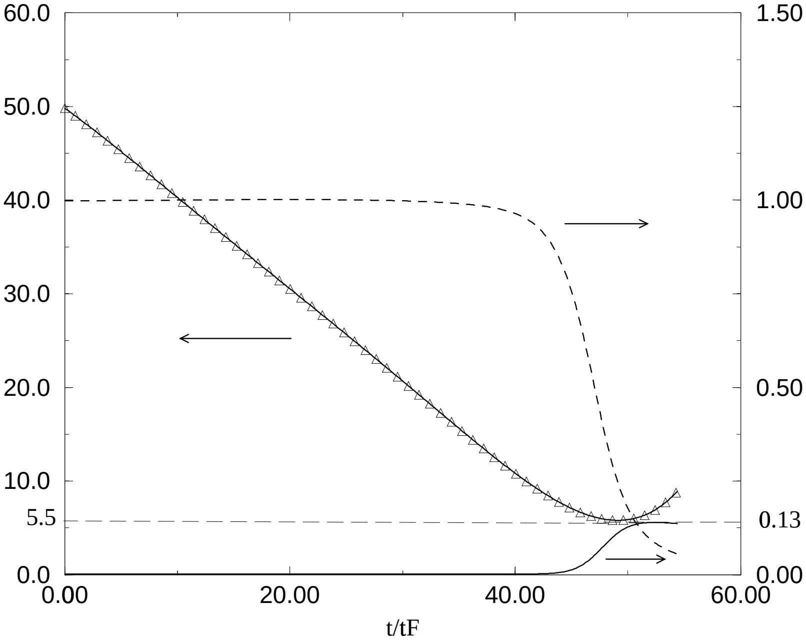

Figure 4: Normalized flame / wall distance y/d (△), consumption speed s_c/s_L^0 (- - - -) and wall heat flux $\phi/(\rho_1 s_L^0 c_p(T_2 - T_1))$ (———) during FWI for a stoichiometric premixed flame.

FWI for diffusion flames

Figs. 5 and 6 show snapshots of the streamlines and temperature fields at two instants for a diffusion flame interacting with a cold wall. *It is convenient to characterize the flow through its strain a, compared to the inverse of the flame time of the stoichiometric premixed flame* $t_F = d/s_L^0$*. For the present case,* $at_F = 0.08$. The color scale for the reduced temperature T/T_W goes from 1 (grey) to 4.5 (red). At time $at_0 = 7$, the flame has not sensed the wall yet and its structure corresponds to a strained diffusion flame (Fig. 5). At time $at_1 = 17.5$, the flame is interacting strongly with the wall and close to quenching (Fig. 6). A first important observation is that the structure of the flame remains almost perfectly one-dimensional and quenching occurs simultaneously for all points along the wall.

The evolutions of the flame / wall distance and of the maximum flux versus time are displayed in Fig. 7. Contrary to the premixed case (Fig. 4), the flame / wall distance does not decrease linearly: in this stagnation point flow, the velocity normal to the wall on the axis decreases as the flame gets closer to the wall. The flame then gets quenched at a distance y such that $y/d \simeq 2.6$ which is less than the distance observed for the premixed flame. The maximum wall heat flux reaches a value $\Phi_Q/\rho_1 s_L^0 c_p(T_2 - T_1) \simeq 0.29$ which is slightly more than the value computed for the premixed case.

Profiles of normalized temperature, reaction rate, fuel and oxygen mass fractions along the symmetry axis of the computation are displayed at $at_0 = 7$ on Fig. 8 (before the flame senses the wall, see Fig. 7) and $at_1 = 17.5$ on Fig. 9 (after the moment when the heat flux is maximum). Temperature is normalized by the wall temperature T_W, the reaction rate is scaled by the maximum reaction rate in the laminar premixed flame $\dot{\omega}_{prem}^{max}$. When the flame is far from

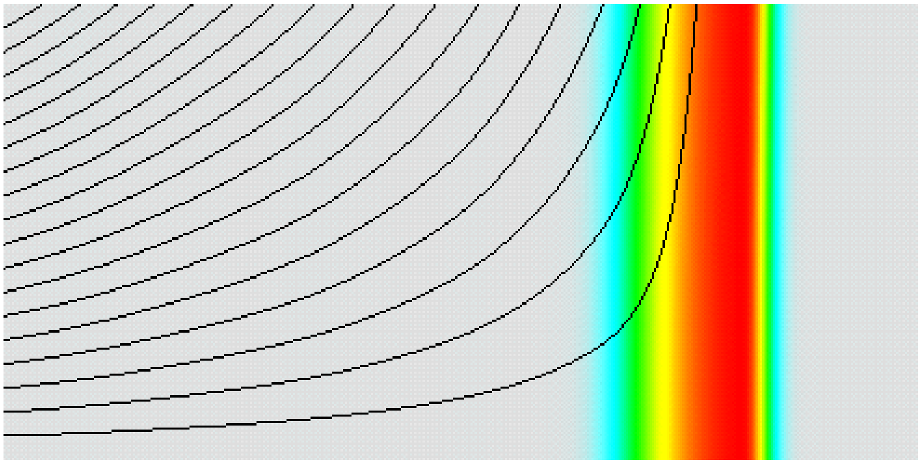

Figure 5: Streamlines and temperature contours at time $at_0 = 7$.

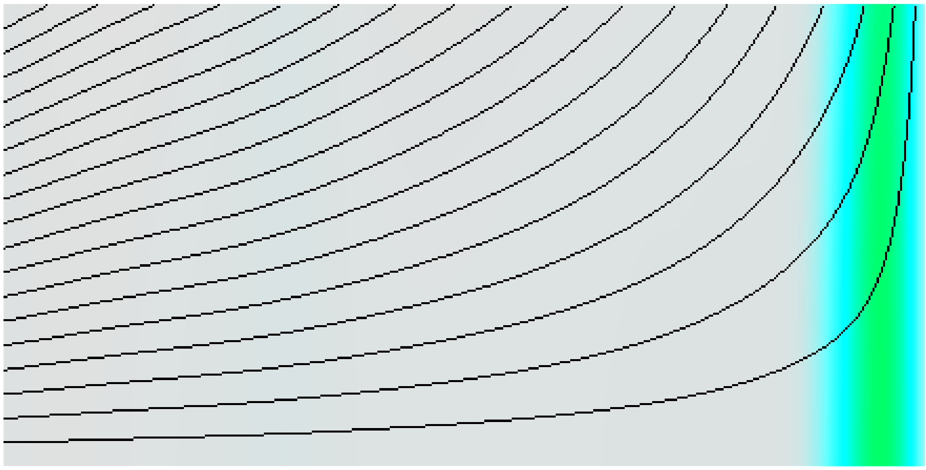

Figure 6: Streamlines and temperature contours at time $at_1 = 17.5$.

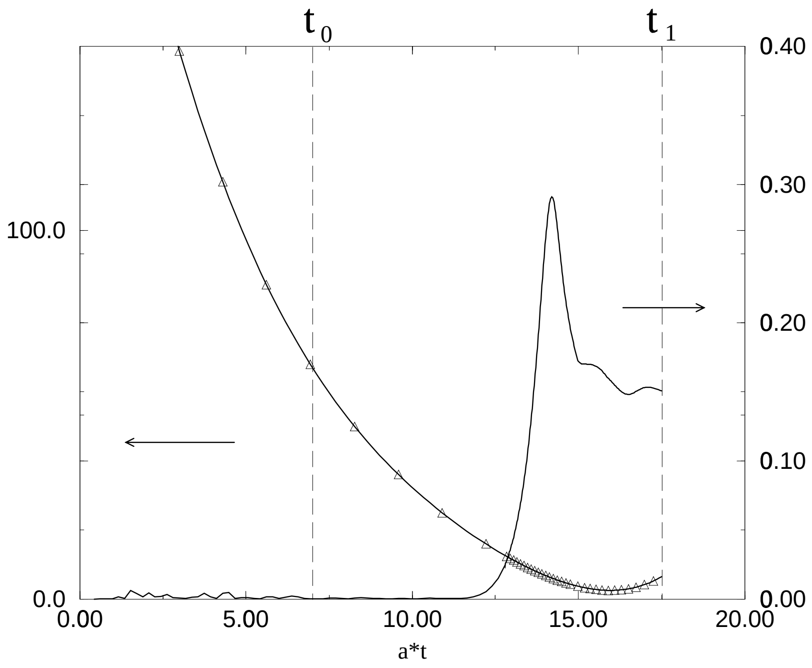

Figure 7: Normalized flame / wall distance y/d (△) and wall heat flux $\phi/(\rho_1 s_L^0 c_p(T_2-T_1))$ (———) for FWI of a diffusion flame in a stagnation point flow with $at_F = 0.08$.

the wall (Fig. 8), its structure matches very well the structure of a strained diffusion flame as predicted by asymptotic analysis [13]. Later, for $at_1 = 17.5$, the flame is interacting strongly with the wall and is quenching. The maximum reaction rate has decreased and the temperature profile at the wall is steep. The oxygen mass fraction profile shows that almost all the oxygen has burned out, contributing to the rapid quenching of the flame.

Effects of strain on FWI of diffusion flames

Fig. 5 to 9 characterize the interaction of a diffusion flame with a wall in a strained flow with a strain a such that $at_F = 0.08$. To investigate the effects of strain, the computations were repeated for various values of the flow strain ranging from $at_F = 0.03$ to $at_F = 1.2$. Results are summarized in Fig. 10: when the flow strain is increased (or in other words, when the flame is pushed more strongly onto the wall), the minimum flame / wall distance *decreases* and the maximum wall heat flux ϕ_Q increases. For the conditions used in this paper, ϕ_Q continues to increase even at large strain values and bending effect is observed only at high strain rates. *The maximum flux* Φ_Q *is reached for* $at_F \simeq 1$ *and is such that* $\Phi_Q/\rho_1 s_L^0 c_p(T_2-T_1) \simeq 0.95$ *which is much larger than the value obtained for the premixed flame (*0.13*). Similarly, the normalized minimum flame / wall distance goes to values as small as* 1 *as compared to* 5.5 *for perfectly premixed flames.* Obviously, in this configuration, the strained diffusion flames pushed towards the wall come closer to the wall and create larger heat fluxes than stoichiometric premixed flames.

Conclusions

The context of this work was the determination of maximum wall fluxes in diffusion burners. These fluxes are usually generated by the interaction of flame elements with the walls. The objectives of the paper were to investigate how

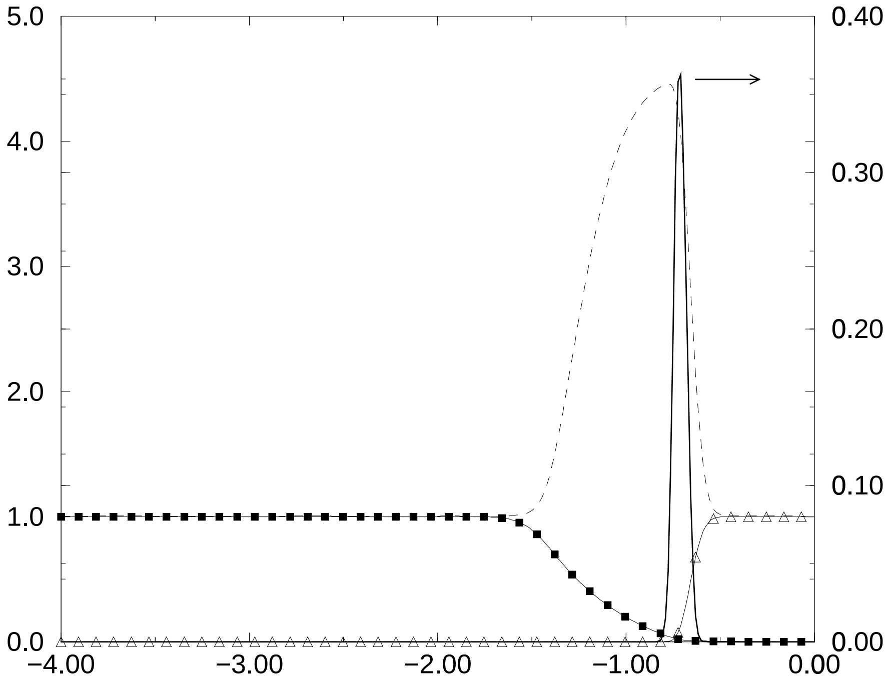

Figure 8: Cuts along the symmetry axis at $at_0 = 7$: temperature T/T_W (- - - -), reaction rate $\dot{\omega}/\dot{\omega}_{prem}^{max}$ (———), fuel Y_f (■) and oxygen Y_o (△) mass fractions for FWI of a diffusion flame in a stagnation point flow with $at_F = 0.08$.

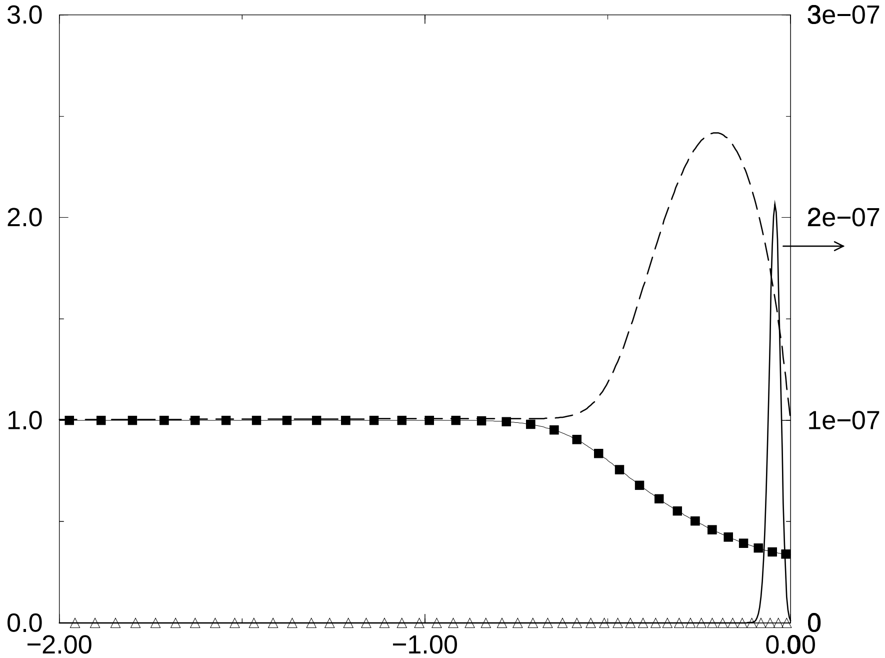

Figure 9: Cuts along the symmetry axis at $at_1 = 17.5$: temperature T/T_W (- - - -), reaction rate $\dot{\omega}/\dot{\omega}_{prem}^{max}$ (———), fuel Y_f (■) and oxygen Y_o (△) mass fractions for FWI of a diffusion flame in a stagnation point flow with $at_F = 0.08$.

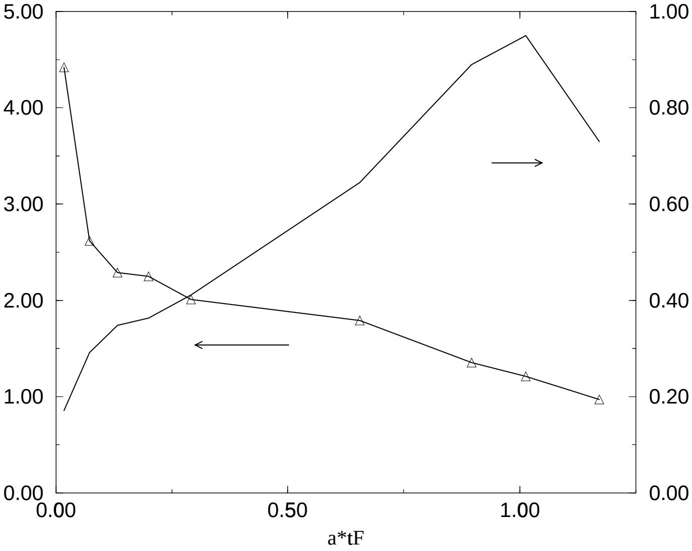

Figure 10: Dependence on strain a of minimum normalized flame / wall distance y/d (△) and maximum normalized wall heat flux $\phi/(\rho_1 s_L^0 c_p (T_2 - T_1))$ (———) for FWI for diffusion flames in a stagnation point flow. *The strain a is normalized by the flame time* t_F *of the stoichiometric premixed flame. The maximum normalized wall heat flux for a premixed flame is* 0.13 *and the minimum normalized flame / wall distance is* 5.5.

laminar diffusion flames (representative of diffusion flamelets found in turbulent burners) interact with and quench near cold walls. Simulations of strained diffusion flames interacting with walls have been performed for various values of strain and compared to the reference case of a stoichiometric premixed flame. Results show that strained diffusion flames can quench slightly closer to the wall than the stoichiometric premixed flame and generate heat fluxes which are larger than propagating premixed flames. This simple result demonstrates that the maximum heat fluxes observed in a diffusion burner can be due not only to locally premixed flamelets (in cases where chemistry is not fast enough to avoid local premixing) but also to diffusion flame elements pushed by the turbulent flow towards the wall. These fluxes are very large (typically of the order of 10 MW/m^2 for a hydrogen oxygen flame at atmospheric pressure) suggesting that they can be the source of problems at the wall and require more attention in the future.

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Acknowledgments

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