Some Features of Propane-Air Flames Under Quenching Conditions

Artur Gutkowski, Luigi Tecce and Jozef Jarosinski

Department of Heat Technology and Refrigeration,
Technical University of Lodz, Stefanowskiego 1/15, 90-924 Lodz, Poland

1 Introduction

Flame-wall interaction is important for understanding combustion process near the wall. It is known that every flame can be quenched in a narrow channel if the distance between the walls is small enough. Heat loss from a flame to the wall is responsible for flame quenching. The minimum plate separation for which flame propagation can not be attained is named quenching distance D_Q. First detailed measurements of quenching distance D_Q were performed by Potter [1]. Its value depends on kind of fuel, mixture concentration and directions of flame propagation [2]. Quenching distance for methane and for propane flames was determined in [2] and [3]. For flames propagating in lean methane-air and rich propane-air mixtures quenching distance depends on direction of flame propagation (upward or downward). Flame stretch and preferential diffusion are the physical factors responsible for the differences ($Le < 1$).

The aim of this work was to determine the flame width, dead space and radius of the flame in narrow channels under conditions approaching those of quenching and to examine the influence of walls on laminar burning velocity for flames propagating in propane-air mixtures near the quenching limits. The considerations are limited to flame propagating downward in narrow channels.

2 Apparatus and experimental procedure

The experiments were conducted in eight vertical square channels of different sizes (2.5mm, 3mm, 4mm, 5mm, 6mm, 7mm, 8mm and 9mm). The length of these channels was 300mm. Two opposite side walls of 9mm channel were made of shadow quality glass windows. The ends of the channels were fitted with valves or covers. Careful calibration of the flow meters was made.

All channels volumes were filled with mixture by displacement; about 10 tube volumes were passed through the tube before ignition. Propane-air mixtures were used in the study. During all experiments one end of the tube was always open. Ignition of the mixture was located near the open end of the channel. A shadow system was used for flame photography, with a single mirror 0.3m in diameter and 2.5m radius of curvature. The flames were recorded by a conventional Panasonic S-VHS video camera and digital camera.

Beside experimental part, the numerical simulation of transient lean premixed propane-air mixture flame propagating in narrow channel was done using a commercial CFD code FLUENT to perform the computation. A symmetric two dimension domain was considered, because is clear from the experiment that only one dimension is important to determine the quenching distance and moreover the flame shape looks symmetric all the time. The model equations used, correspond to full Navier-Stokes for reactive flows, in the limit of low Mach number. Neglecting Soret and Dufour effects, the *mass, species, momentum, energy and ideal gas state* equations are solved. A single-step reaction model is examined, with Arrhenius dependence on the temperature.

Correspondence to : artur.gutkowski@p.lodz.pl

3 Results and discussion

From the pictures made by a digital camera one can see differences between the flames propagating in lean and reach mixtures.

Flames are characterized by some of their parameters. The following quantities were analyzed: flame speed u_q, flame width D_f, dead space D_d and flame radius R. Their definitions are indicated in Fig. 1.

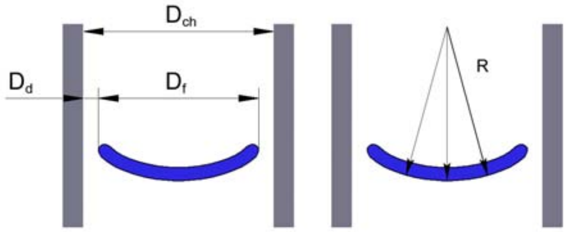


Fig. 1. Definitions of quenching channel D_{ch}, dead space D_d, flame width D_f and a flame radius R.

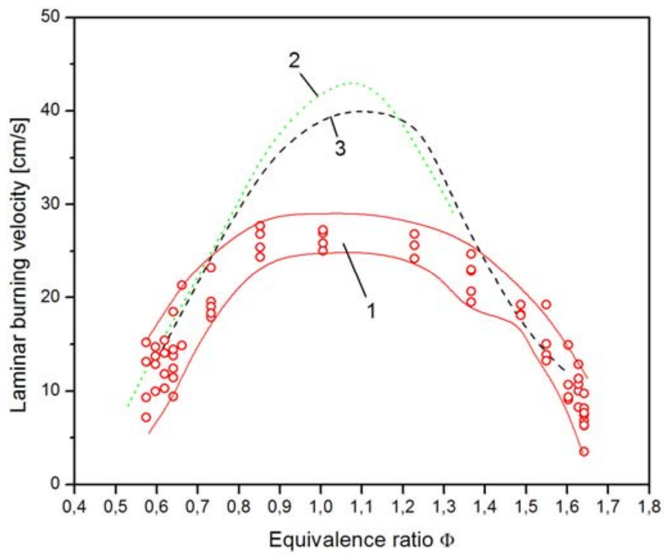
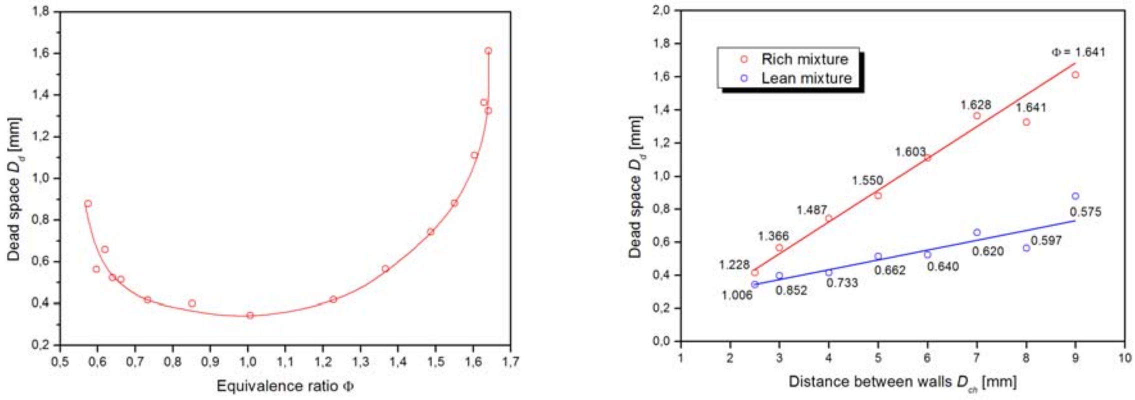


Fig. 2. Laminar burning velocity as a function of equivalence ratio for propane-air mixture. Comparison of laminar burning velocity under quenching conditions determined in the present work (1) with adiabatic laminar burning velocities (2), (3) and. Laminar burning velocities curves: 2 – Yamaoka and Tsui [4], 3 – Vagelopoulos and Egolfopoulos [5].

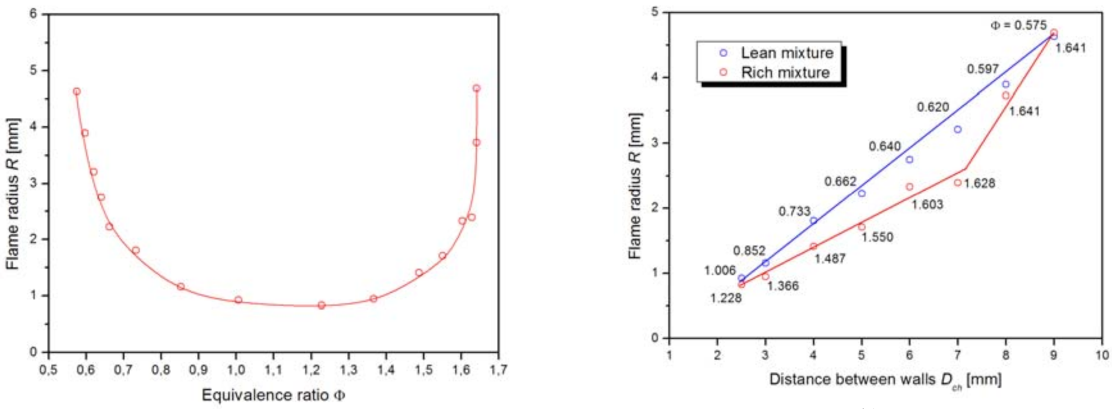
Laminar burning velocity was determined during downward propagation of the flame close to quenching conditions. Position of the flame as a function of time was taken from successive frames. Values of laminar burning velocity for propane-air mixture determined in this way are compared with those obtained under adiabatic conditions ([4, 5] in Fig. 2). Velocities taken for this comparison have the following properties: line 2 – with some stretch; lines 3 and – without stretch. There is some difference between adiabatic laminar burning velocity and laminar burning velocity obtained under quenching conditions due to heat transfer from the flame to the walls.

The channel walls locally quench the flame and create the region without chemical reactions – dead space. The dead space as a function of equivalence ratio and a distance between the walls is shown in Fig. 3a and 3b. Characteristic things are visible in these Figures. For flames propagating in rich mixtures a dead space is larger than for flames propagating in lean mixtures.



a) b)

Fig. 3. Dead space as a function of equivalence ratio Φ (a) and as a function of distance between walls D_{ch} (b).



a) b)

Fig. 4. Flame radius as a function of equivalence ratio Φ (a) and as a function of distance between walls D_{ch} (b).

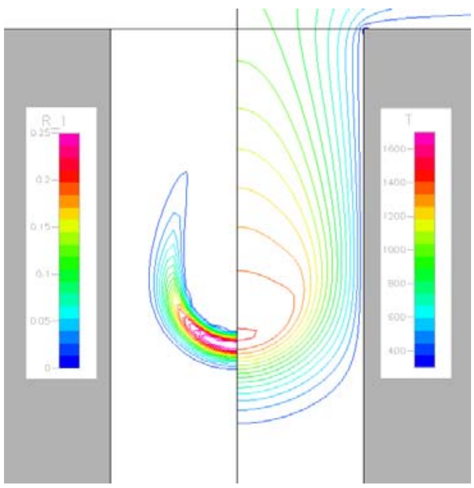


Fig. 5. Numerical simulation of flame propagating in a 4mm wide channel just before quenching. On the left and right sides are represented the contour lines of reaction rate and temperature, respectively. Equivalence ratio is Φ = 0.54.

The flame radius is shown in Fig.4a as a function of equivalence ratio and in Fig.4b as a function of distance between the walls. It can be seen that only rich flame propagating in channel 9mm is as flatten as this propagating in lean mixtures. Curvature increases for other rich flames propagating in narrower channels.

Fig. 5 shows numerical simulation of flame propagating in a 4mm wide channel before quenching. On the left and right sides are represented the contour lines of reaction rate and temperature, respectively.

4 Conclusions

As expected the laminar burning velocities in quenching u_q channels were found to be commonly lower than those under adiabatic conditions. Dead space between a flame and the channel walls appeared to be minimum for stoichometric mixture and to increase as approaching flammability limits. In general dead space has larger values for rich mixtures than the lean ones. Flame curvature has its maximum value for mixtures near stoichiometry (the smallest values of the flame radius) and decreased as approaching leaner and richer mixtures. Numerical simulations for equivalence ratio $\Phi = 0.54$ indicated that the maximum temperature under quenching conditions is $T_q = 1586K$ compared to adiabatic temperature $T_a = 1490K$.

Acknowledgements

This work was sponsored by the Marie Curie ToK project from the 6^{th} FP contract No MTKD-CT-2004-509847.

References

[1] Potter Jr. A. E.: *Flame Quenching*, Progress in Combustion and Fuel Technology, vol. 1, ed. J. Durcarme, M. Gerstain and A. H. Lefebvre, New York, Pergamon Press, 1960, pp. 145–182.

[2] Jarosinski J.: *Flame Quenching by a Cold Wall*, Combustion and Flame, 50, 1983, pp. 167–175.

[3] Jarosinski J., Podfilipski J.: *Properties of Propane Flames,* Eighteenth International Colloquium on the Dynamics of Explosions and Reactive Systems, Seattle, 2001, pp. 90–94.

[4] Yamaoka I. and Tsuji H.: *Determination of Burning Velocity Using Counterflow Flames,* Twentieth Symposium (International) on Combustion, The Combustion Institute, 1984, pp. 1883–1892.

[5] Vagelopoulos C. M., Egolfopoulos F. N.: *Direct Experimental Determination of Laminar Flame Speeds*, Twenty-Seventh Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, 1998, pp. 513–519.