# FLAME QUENCHING BY THE WALL–FUNDAMENTAL CHARACTERISTICS

**Artur Gutkowski, Luigi Tecce, Józef Jarosiński**

*Technical University of Lodz*
*Stefanowskiego 1/15, 90-924 Lodz, Poland*
*tel.: +48 42 6362313, fax: +48 42 6367481*
*e-mail: artur.gutkowski@p.lodz.pl*

***Abstract***

*Knowledge of flame–wall interaction allowed us to understand the phenomena of near wall combustion and flame extinction. The study of near wall flame propagation is important because it is related to engineering applications, such as possible misfiring in internal combustion engines, optimization of combustion, and reduction of unburned hydrocarbons in the combustion products. In the present work different characteristics of the quenching distance were measured in square narrow quenching channels. The channel widths were changed from 2.5mm to 15mm, their length being 30cm. Propane/air mixture was employed in experiments. Direct visualization has been used to observe flame behaviour under quenching conditions. Numerical simulation revealed structure of limit flames during their propagation in quenching channels. It was found satisfactory agreement between numerical calculations and experiments. In conclusions it was confirmed that flame quenching depends on the relation between heat release rate to heat loss rate. Dead space appeared to be larger for rich mixtures in comparison with the lean ones. Flame curvature reached maximum value for stoichiometry and decreased for leaner or richer mixtures.*

***Keywords:*** *flame-wall interaction, quenching distance, flame parameters, flame speed, numerical simulation*

## 1. Introduction

Interest of combustion in small-scale devices has been growing for the sake of designing of small-scale power generation. It is also important in the development of small combustors and engines. Phenomena occurring near the walls of combustion chamber are main aspects of performance of the engine. Flame quenching by the heat loss to the wall interferes with more efficient work of devices. The minimum plate separation for which flame propagation can not be attained is named quenching distance $D_Q$. The first extensive survey and analysis of quenching distance problems was performed by Potter [1]. In accordance with this analysis quenching distance value depends on sort of fuel, mixture concentration and directions of flame propagation. Some time later quenching distance and some flame properties accompanying quenching conditions were studied for flame propagating in methane/air mixture [2].

Theoretical analysis of flat flame properties during its propagation near cold wall was performed by von Kármán and Millan [3]. Recently numerical investigation of unsteady premixed flames propagating in narrow channels with adiabatic and isothermal walls was presented in [4]. They confirmed existence of mushroom and tulip shaped flames depending on boundary conditions and way of ignition. Also Maruta and et al. [5] investigated experimentally, analytically and numerically characteristics of combustion in a channel with an inner diameter smaller than the conventional quenching distance, what was possible under conditions of heated channels wall. Zamashchikov [6] considered the dependence of the flame-front curvature on the composition of the mixture in the tubes of various diameters. Most experiments were performed with stationary flames.

The aim of this work was to determine the dead space $D_{ds}$ and radius of curvature $R$ of the flame propagating in narrow channels under conditions approaching those of quenching. The influence of the wall on flame speed was also examined. The considerations are limited to flame propagating downward in propane/air mixture in narrow square channels.

## 2. Experimental setup

The experiments were conducted in nine vertical square channels of different sizes (2.5mm, 3mm, 4mm, 5mm, 6mm, 7mm, 8mm, 9mm and 15mm). The length of these channels was 300mm (Fig. 1). 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. After each experiment with combustion channel was filled with air for five minutes to cool the walls. Propane-air mixture were used in the study. During all experiments the top end of the tube was always open. Ignition of the mixture was located near the open end of the channel. The flames were recorded by a conventional Panasonic S-VHS video camera and by a digital camera.

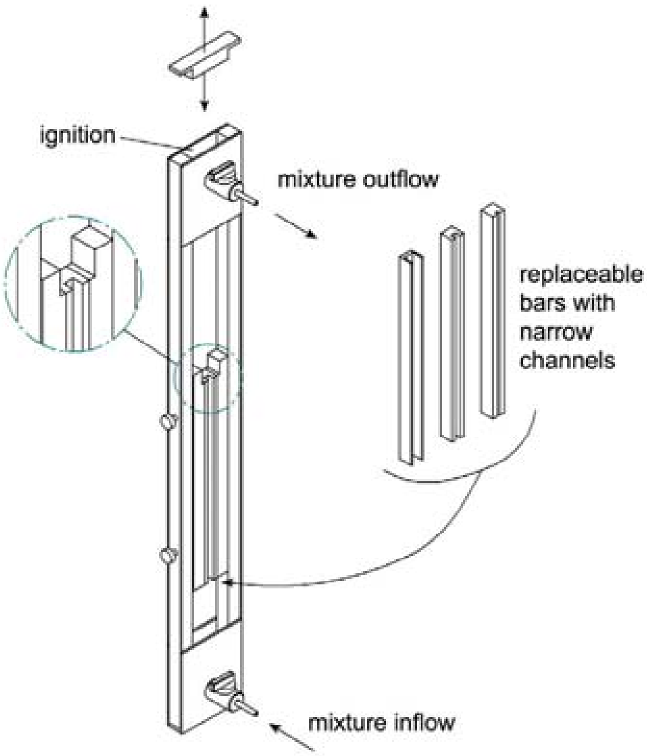



*Fig. 1. Experimental setup*

## 3. Experimental results and discussion

Flames are characterized by some of their geometrical parameters, such as flame width $D_{fw}$, dead space $D_{ds}$ and flame curvature radius $R$. Their definitions are indicated in Fig. 2.

Determined in experiments quenching distance as a function of mixture concentration is shown in Fig. 3a. It is worth noting that for the rich mixture, flames propagate in the same limit mixture concentration in channels: 8mm, 9mm and 15mm.

Laminar flame speed $S_{L,q}$ 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. Experimentally determined values of laminar flame speed are slightly larger than laminar burning velocity because all flames have curvature. Values of laminar flame speed determined in this way are compared in Fig. 3b with those obtained under adiabatic conditions $S_L^{\circ}$ [7] and under quenching conditions $S_{L,lim}$ [8]. According to Zeldovich et al. [8] burning velocity under quenching conditions should decrease to a limit value of $S_{L,lim} = 0.61 S_L^{\circ}$.

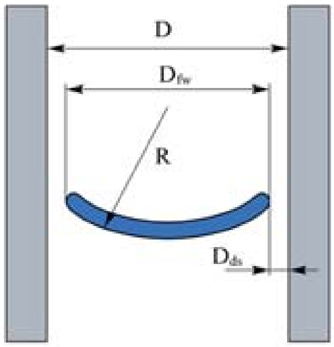
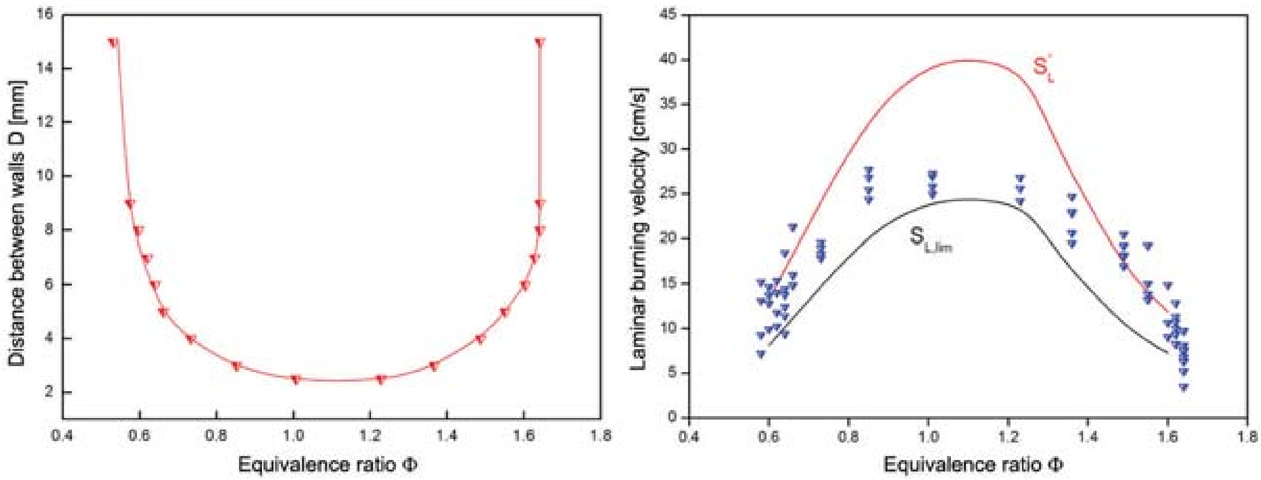


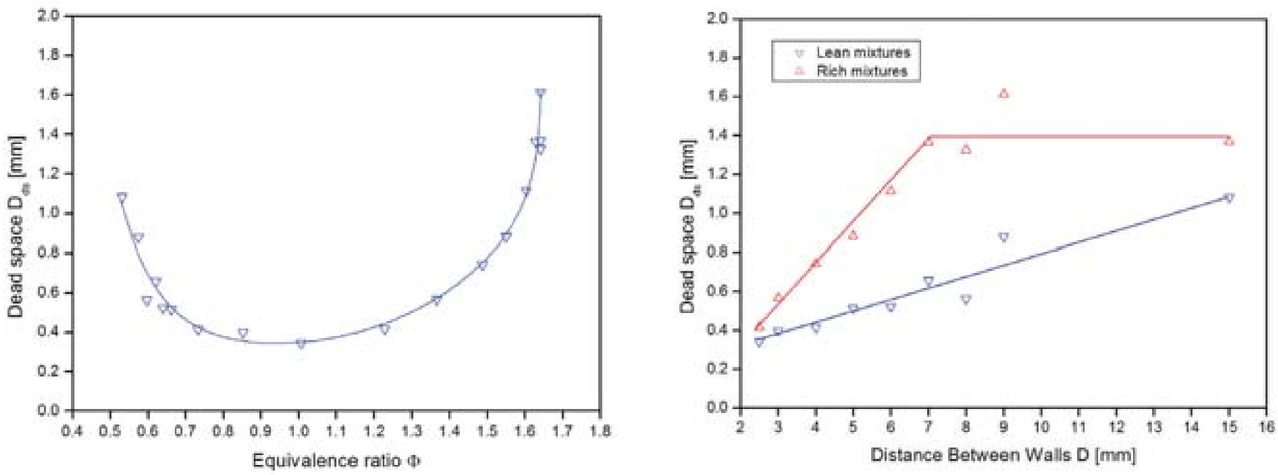

*Fig. 2. Definitions of flame parameters in quenching channel*

It is seen from Fig. 3b that experimental points of laminar flame speed obtained under quenching conditions are located sufficiently close to Zeldovich curve.




(a) (b)

*Fig. 3. Experimentally determined quenching distance (a) and limit burning velocity (b) as a function of equivalence ratio for propane/air mixture*




(a) (b)

*Fig. 4. Dead space as a function of equivalence ratio Φ (a) and as a function of distance between walls (b)*

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. 4a and 4b. For flames propagating in rich mixtures a dead space is larger than for flames propagating in lean mixtures.

The radius of flame curvature is shown in Fig. 5a as a function of equivalence ratio and in Fig. 5b as a function of distance between the walls. It can be seen that up to channel width of 9mm the flame curvature in lean and rich mixtures is nearly the same. Outside this channel size curvature increases for rich flames in comparison with lean ones.

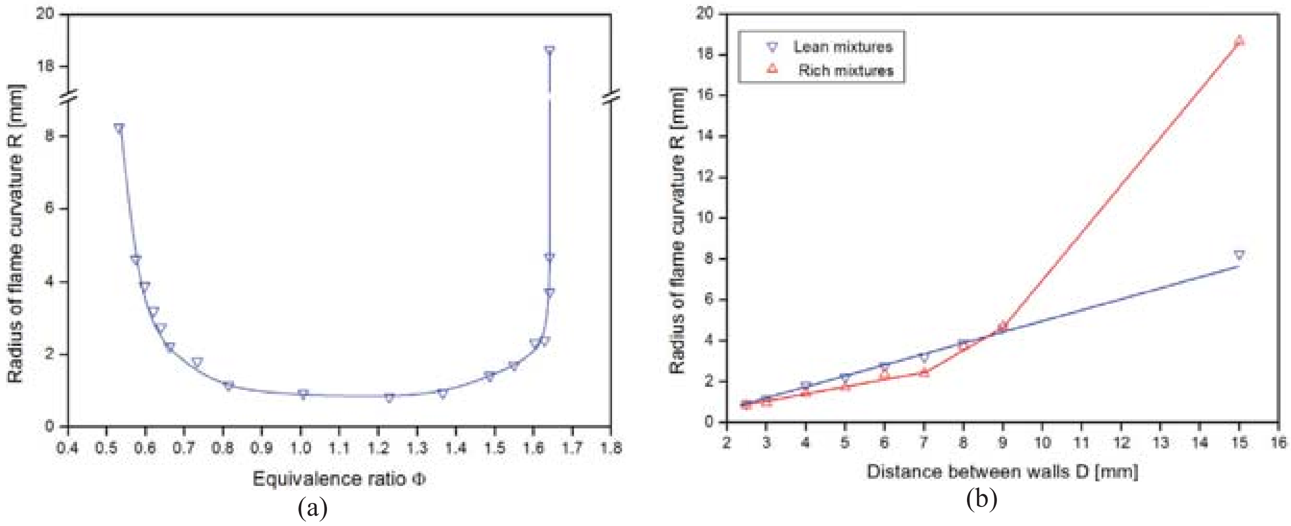



*Fig. 5. Rradius of flame curvature as a function of equivalence ratio Φ (a) and as a function of distance Between walls (b)*

## 4. Model of numerical simulation

The numerical simulation of transient lean premixed propane-air mixture flame propagating in narrow channel was done using FLUENT, a commercial CFD code [9], to perform the computation. A symmetric two dimensions domain was considered. A set of equations corresponding to full Navier-Stokes model for reactive flows at low Mach number was used for simulation. Neglecting Soret and Dufour effects, the equations solved are the following:
Mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = 0, \tag{1}$$

species:

$$\frac{\partial}{\partial t}\rho_k = -\nabla \cdot \left(\rho_k \mathbf{v} + \mathbf{j}_k\right) + r_k \qquad k = 1, ..., N, \tag{2}$$

momentum:

$$\frac{\partial}{\partial t}\rho \mathbf{v} = -\nabla \cdot \rho \mathbf{v}\mathbf{v} - \nabla p + \nabla \cdot 2\mu\left(\nabla \mathbf{v}\right)_0^S + \rho \mathbf{g}, \tag{3}$$

energy:

$$\frac{\partial}{\partial t}\left[\rho\left(u + \frac{1}{2}v^2\right)\right] = -\nabla \cdot \left[\rho\left(u + \frac{1}{2}v^2\right)\mathbf{v} + \mathbf{q} + p\mathbf{v} - 2\mu\left(\nabla \mathbf{v}\right)_0^S \cdot \mathbf{v}\right] + \rho \mathbf{v} \cdot \mathbf{g}, \tag{4}$$

ideal gas state equation:

$$p = \rho\left[\left(\sum_{k=1}^{N}\frac{y_k}{W_k}\right)R_0\right]T = \rho RT\ . \qquad (5)$$

A single-step reaction model is examined, with Arrhenius dependence on the temperature. The expression for the reaction rate for species *k* with stoichiometric coefficient $\nu_k$ is:

$$r_k = -W_k \nu_k A T^f \exp\frac{E}{R_0 T}\rho^\gamma \prod_j y_j^{\beta_j}\ . \qquad (6)$$

Symbols in the above formulae denote respectively: $\rho$: density, $\mu$: viscosity, $\boldsymbol{v}$: velocity, $p$: pressure, $T$: gas temperature, $u$: internal energy, $\boldsymbol{q}$: conduction heat flux, $\boldsymbol{g}$: gravity, $R_0$: universal gas constant; $\rho_k$, $J_k$, $y_k$, $W_k$, and $r_k$: partial density, mass diffusion flux, mass fraction, molecular weight and reaction rate of species *k* respectively. Here $2\mu(\nabla v)_0^s$ is the null-trace symmetric stress tensor.

The chemical scheme for one-step irreversible reaction is the following: $C_3H_8 + 5(O_2{+}3.76N_2) \rightarrow 3CO_2 + 4H_2O + 18.8N_2$. The constant parameters used in the expression for reaction rate were taken from literature [10]. Radiation heat flux is neglected as usually done in the literature. It may become significant with rich mixtures and luminous sooty flames at high temperatures: in this latter case radiation heat flux to the duct walls might not be neglected even for weak flames at the rich extinction limit. The boundary condition gas-wall was not fixed as isothermal or adiabatic, but considered coupled with solid part. Physical property of aluminum are assumed for the solid as a real boundary condition on the cold wall. Note the strong dependence of flame shape and structure on them [11]. To evaluate mass diffusivities coefficient for each species locally in the flame, the classic kinetic theory law for low-density gases is employed. Classic kinetic theory is also employed for evaluating thermal conductivity and molecular viscosity in the mixture. The heat capacity for each species is computed as a piecewise polynomial of temperature. The model was numerically solved from the CFD on a block structured mesh, where the finest part moves by manually hanging grid adaption covering the flame zone (Fig. 6).

In accordance with the recommendation of Kim [12], the cells size in the flame zone does not exceed the dimension of $50\,\mu m \times 50\,\mu m$ for each channel, because from the literature is known the dependence of the pre-exponential factor of the global kinetic from the mesh size of the grid.

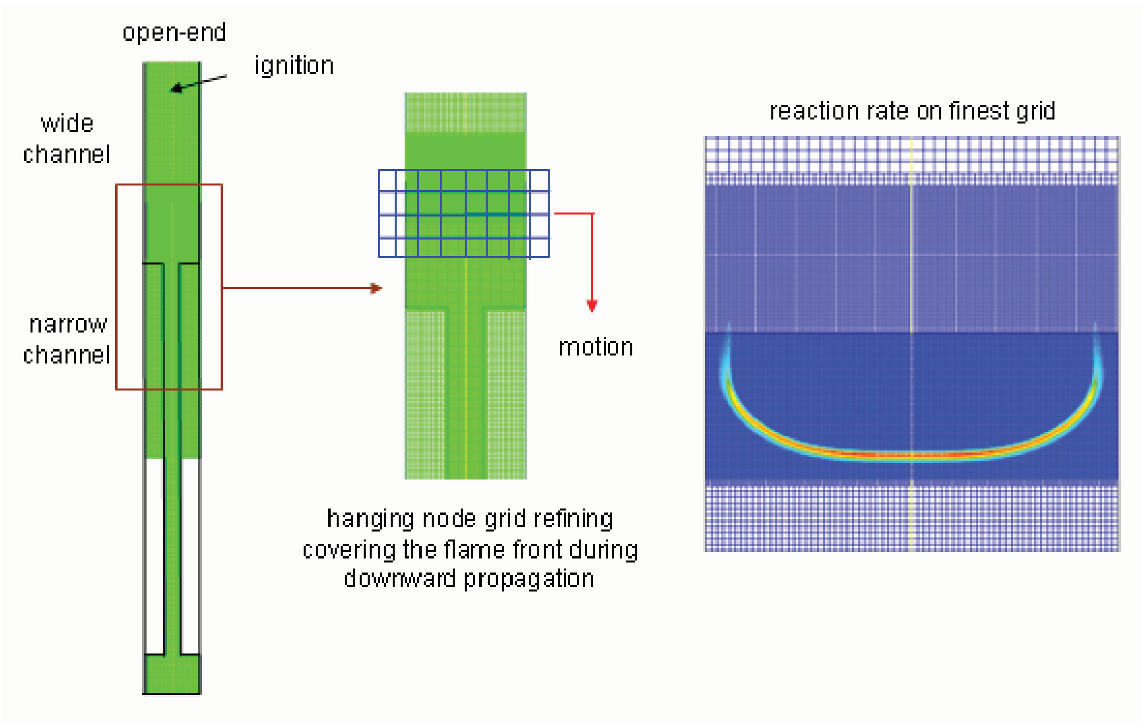



*Fig. 6. Schematic of narrow channel with grid dynamically refined during flame propagation*

Since the aim of this study is to analyze the various mechanisms to determine the quenching flame phenomena, the first step of simulation was to observe the quenching for each channel size. In first simulations extinction was obtained at fuel concentration significantly leaner than experimental ones. In consequent simulation, the pre-exponential factor was adjusted in order to establish better match with experimental extinction limit.

Special attention has been devoted to molecular heat and mass transfer; because it is known that the quenching distance depends on the Lewis number of the mixture. A post-processing of the detailed numerical results from simulation will be used to understand the real mechanisms of the flame extinction to the wall.

## 5. Results of numerical simulation

The aim of numerical simulation was to find a flame which is able to propagate total length of calculated domain with mixture concentration close to the experimental results. The same flame should be quenched if the mixture concentration will be leaner. It was achieved by changing pre-exponential factor in an equation of reaction. The case with propagating flame in a 4mm channel is shown in Fig. 7.

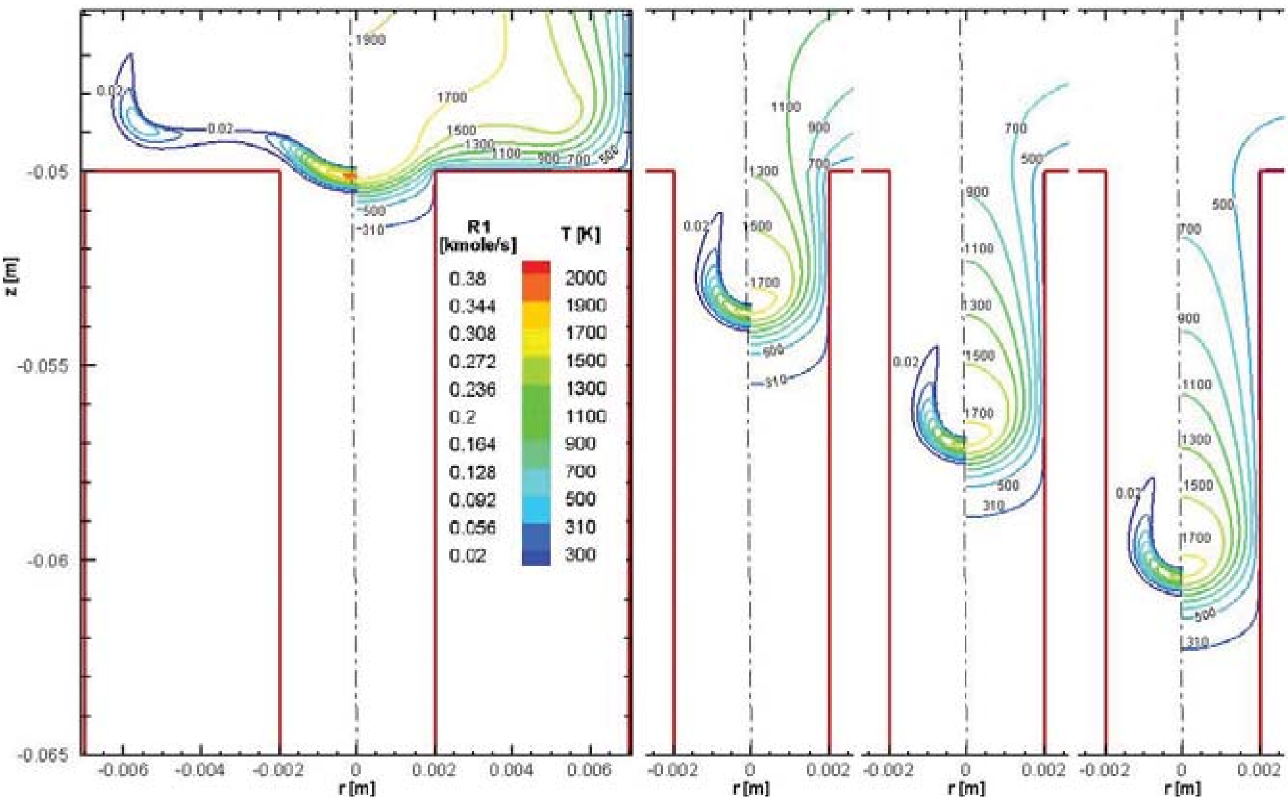



*Fig. 7. Flame propagation in a 4mm channel near quenching condition. On the left and right sides are represented the contour lines of reaction rate and temperature, respectively. Equivalence ratio is $\Phi = 0.73$*

Fig. 8 shows numerical simulation of flame quenching during downward propagation in a 4mm channel.

As it can be seen heat loss to the walls causes decreasing of flame temperature. Lower temperature leads to slowing down a reaction rate. The dead zone is increasing and flame is quenching in consequence. If we compare burning rates for these to cases obtained by integration it is clear that this parameter approach to the constant value for propagating flame. This same parameter is constantly decreasing for flame which is quenched (Fig. 9).

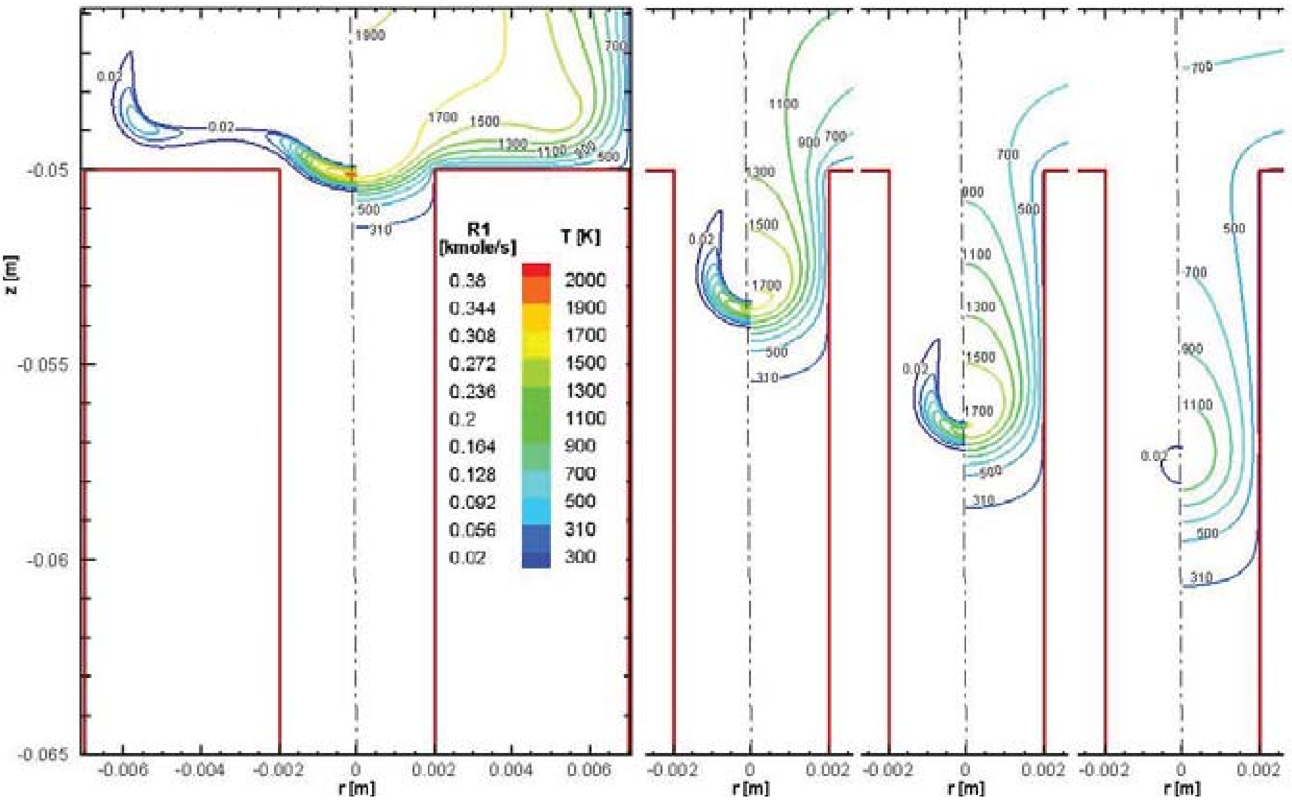



*Fig. 8. Process of flame quenching in a 4mm channel. On the left and right sides are represented the contour lines of reaction rate and temperature, respectively. Equivalence ratio is $\Phi = 0.7294$*

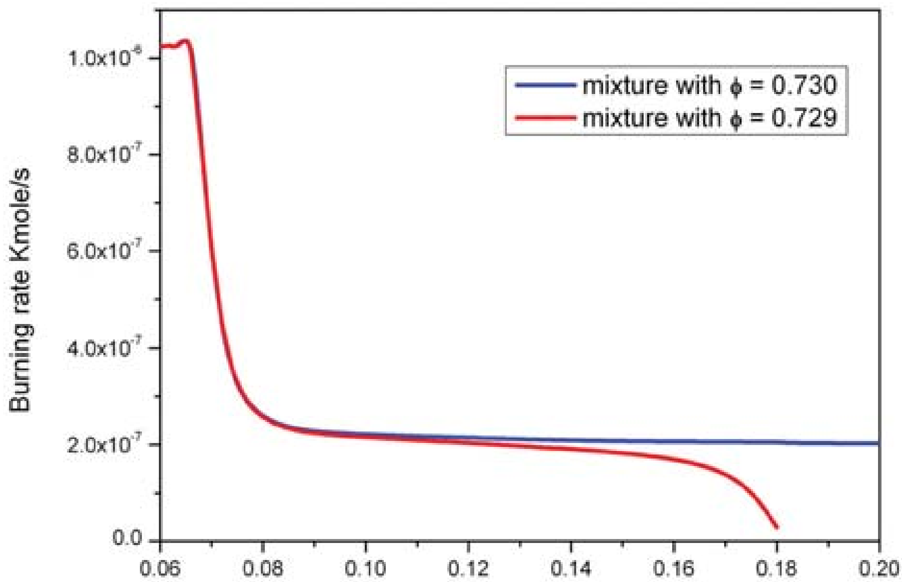



*Fig. 9. Burning rate for propagaiting flame (black line) and for quenching flame (red line)*

## 6. Conclusion

As expected the laminar flame speed $S_{L,lim}$ in quenching channels were found to be commonly lower than those under adiabatic conditions. Only flames propagating in rich mixtures in 4mm and 5mm are almost equal to the adiabatic values. This phenomenon can be explained by the preferential diffusion and flame stretch. 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 Φ = 0.73 indicated that the maximum temperature under quenching conditions is $T_q$ = 1740K compared to adiabatic temperature $T_a$ = 2000K.

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