Stretched flame behavior in a planar meso-scale channel with heat conducting walls

S Mokrin1,2, D Sharaborin3, E Odintsov4,1, G Uriupin1 and S Minaev1,2
1 Far Eastern Federal University, Sukhanova Str. 8, Vladivostok 690950, Russia
2 Institute for Applied Mathematics FEB RAS, Radio Str. 7, Vladivostok 690041, Russia
3 Kutateladze Institute of Thermophysics SB RAS, Academician Lavrentyev Ave. 1, Novosibirsk, 630090, Russia
4 Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, Institutskaya str., 4/1, Novosibirsk, 630090, Russia

msn_primat@mail.ru

Abstract. The influence of the wall on flow field, combustion regimes and flame extinction limit of premixed methane/air flames stabilized in the planar channel with heat conducting walls was experimentally investigated. Experimental data were compared with the results obtained in previous theoretical works. The influence of channel walls on gas flow was estimated by using PIV experiments with non-reacting gas flow and compared with the results of numerical simulation.

1. Introduction

Understanding of structure and extinction limit of premixed flames is important fundamental problem in combustion science and it is relevant in the field of development of clean combustion technologies. Counterflow flames are the basic objects for detailed investigations of combustion wave characteristics. This one-dimensional configuration is very convenient for both experimental and numerical investigations. The structure and flammability limits of counterflow flames at high and moderate flow rates under conditions of normal gravity were studied in early experimental and theoretical works [1–3]. The experimental investigations of low-stretched flames in normal gravity conditions are complicated because of the buoyancy effect related with natural convection. Microgravity experiments [4–6] yield valuable information about flame structure but they are expensive and need special facilities like drop tower, airplane, etc.

One of the ways to overcome the buoyancy effect is the stabilization of flame in a narrow channel. In papers [7–8] it was shown that such system allows the investigation of low-stretched flames in the normal gravity conditions. Proposed experimental approach is also very convenient to apply various experimental technics for flame diagnostics such as contact methods, optical methods, gas chromatography, spectroscopy, and etc. In our recent work [9] we obtained the flammability limit and combustion regimes of premixed CH4/Air flames stabilized in 5 mm channel. It was found that two stationary combustion modes exist: distant flame (DF) and near-stagnation plane flame (NSF) or
“flame tube”. Besides, the shape of extinction limits curve differs from C-shaped typical for conventional counterflow flames. In a narrow channel it has ε-shaped form. One-dimensional numerical simulation with the thermal-diffusion model using an overall one-step reaction conducted in paper [10] allowed us to reveal prime physical mechanisms of flame quenching on different branches of the extinction limit curve. These mechanisms, beginning with the upper limit and ending with the lower one on ε-shaped curve, are the following: stretch; radiative and convective heat losses; weakening of heat recirculation; heat dissipation to the burner. First two are direct analogs of the upper and lower limits on conventional C-shaped curve, while two latter are related with the effects of channel walls.

The main objective of this paper is to study the influence of the wall on flow field, combustion regimes, and extinction limit of premixed stretched flames stabilized in the planar channel with various gap size.

2. Experimental Setup
Experimental setup consists of counterflow slot-jet burner, mass flow controllers and AD/DA converter connected to PC. Counterflow burner consisted of two opposite directed slot-jet burners similar to that used in the work [11] mounted horizontally at the distance 2L=50 mm. Nozzle size was achieved by using the flanges with rectangular hole. We used the flanges with nozzles 40x5 mm and 40x3 mm to construct 5 mm and 3 mm channel respectively. Two rectangular grooves were made in the flanges under and above the nozzle to install the quartz plates. We used 50x50 mm and 1.3 mm thickness quartz plates as channel walls. To uniform flow, we filled each burner’s body by 1 mm ceramic balls and installed two layers of stainless steel mesh in front of the flange. To maintain the constant temperature of inlet gas we mounted the water-cooling system on the burner’s body. For flame visualization two digital HD photo cameras Nikon D7200 were used. The scheme of counterflow burner is shown in Fig. 1.

![Fig. 1. Scheme of counterflow slot-jet burner.](image-url)
Lean methane/air mixture was used in experiment. Mixture with equivalence ratio $\phi = 0.8$ for 5 mm channel and with $\phi = 0.9$ for 3 mm channel was ignited by external heater at chosen value of stretch rate. Furthermore, the stationary state was determined by indications of K-type thermocouples mounted on the outer surface of the quartz plate and at the nozzles between the layers of stainless steel mesh. After that, the equivalence ratio was reduced on the value $D\phi = 0.01$ to establish new stationary state. We considered that the stationary state was established when the temperature change was less than +/- 0.1 C/min. After measurement of flame characteristics, we reduced equivalence ratio to study next stationary state. When the flame extinguished, we fixed the extinction limit, and reduce the set value of stretch rate, and repeat the procedure from the beginning.

To examine the effect of gravity field on flame stabilization we rotated the counterflow burner from horizontal position to vertical one. It was found that influence of gravity field on flame location is insignificant even at low values of stretch rate. To study the influence of the wall on the flow field we applied particle image velocimetry (PIV) method. This method allows the investigation of the velocity field, vorticity, flow rate pulsations, shear stresses in the region of interest during one measurement. PIV method is also applied for reacting systems.

The scheme of PIV experimental setup is shown in Fig. 2. The PIV system consists of a high-resolution CCD camera (16 Mpx Bobcat ImperX), a double-pulsed Nd:YAG Laser (Beamtech Vlite 200, 200 mJ/pulse), a host computer, and synchronizer. Titanium dioxide particles (D = 1 µm) were used as tracers. The double-pulsed laser sheets were directed to the space between quartz plates parallel to them. The delay between laser flashes determining the displacement of the particles between two frames was in the range from 50 to 500 µs for different flow rates. As can be seen in Fig. 2 CCD camera was mounted perpendicularly to the quartz plates. Control of PIV system and data processing were implemented by “Actual Flow” program package developed in Kutateladze Institute of Thermophysics.

![Fig. 2. Scheme of PIV experimental setup.](image-url)
3. Results and Discussion

Flame extinction limits and combustion regimes were experimentally obtained for premixed methane/air flames stabilized in 3 mm and 5 mm planar channels in the range of stretch rates from 44 s\(^{-1}\) to 10 s\(^{-1}\). The stretch rate is determined as \(a = \frac{V_0}{L}\), where \(V_0\) is inlet gas velocity and the \(L\) is the half distance between burners.

In Fig. 3a the experimental dependence of flame position on stretch rate for 5 mm channel is shown. As can be seen from the figure the distant flame shifts to near-stagnation plane flame at stretch rate value more than 30 s\(^{-1}\). On the other hand, results of numerical simulation (see Fig. 3b) obtained in paper [10] demonstrate that both stationary regimes exit in region of non-dimensional stretch rate from \(10^{-2}\) to \(10^{-1}\). This disagreement between experiment and simulation can be explained by features of experimental method. During the experiments we fixed the stretch rate and reduced the equivalence ratio until the flame quenching. Fixing the equivalence ratio with increasing the stretch rate will reveal two stationary combustion regimes at same stretch rates predicted in paper [10].

![Fig. 3. Dependence of the flame front position on stretch rate. A – experiment, B – non-dimensional flame position vs non-dimensional stretch rate obtained numerically in [10].](image)

It is necessary to note that only normal flame regime was observed in experiments with 3 mm channel. We suggest that it is related with high convective heat losses from outside surface of channel walls.
Fig. 4. A) Experimental flame extinction limit curves obtained for 3 mm (green squares) and 5 mm (black rhombs) channels. B) Non-dimensional extinction limit curves calculated for different values of Peclet numbers.

In paper [10] it was shown that decreasing of the channel size leads to the intensification of interphase heat exchange and results to the expansion of flame extinction limit at low values of stretch rate. But as can be seen from Fig. 4a in experiments decreasing of channel gap resulted to the narrowing of flame extinction limit not only in the region of moderate stretch rates but in low one too. This disagreement with the theory is due to the fact that convective heat losses from channel walls were not included in the model described in paper [10]. When we modify the model, we obtained the calculated flame extinction limits for different Peclet numbers (see Fig 4b) which were in good agreement with experimental one.

To estimate the influence of the wall on flow field we conduct the series of PIV experiments with cold gas. Non-reacting flow field was calculated using the model including continuity and momentum equation with assumption of ideal gas. Numerical simulation was conducted using OpenFOAM CFD simulations software with icoFoam solver for incompressible laminar Navier-Stokes equations. All presented results were obtained with uniform 100x100 grid.

![Fig. 5. Comparison between PIV results and numerical simulation.](image)

Results of PIV experiments and numerical simulation for non-reacting flow in 3 mm channel are shown in Fig. 5. Streamlines corresponds the instant flow field is shown in Fig 5a. Figure 5b illustrates the comparison between velocity component \( V_y \) along the axis \( X=0 \) obtained experimentally and via 2D numerical simulation. In Fig. 5c the numerical simulation was conducted for 3D model and velocity component \( V_y \) calculated along the axis \( X=0 \) on the plane \( Z=0 \). Line DEF in Fig. 5 corresponds to velocity module on the plane \( Z=0 \) and line GHI in Fig. 5 corresponds to the velocity
component $V_y$ plotted on the plane $Z=0$ obtained in the experiment, 2D simulation, and 3D simulation respectively. Fig. 5 clearly shows that results of 3D numerical simulation are in better quantitative agreement with experimental data than two-dimensional one. It is explained by the fact that the 3D calculations considered the friction between the gas and the channel walls.

4. Conclusions
Reduced mathematical model proposed in paper [10] allowed us to explain the physical mechanisms determining extinction limits of counterflow premixed flames stabilized in a narrow channel with heat conducting walls. However, experiments showed that external heat losses should be considered during numerical simulation. Comparison of results of PIV experiments and numerical simulation shows that friction between gas flow and channel walls has a big influence and also must be taking into account.

5. Acknowledgment
The research was carried out within the state assignment of FASO of Russia No. 075-00400-19-01. Authors would like to thank Dr. Vladimir Dulin from Kutateladze Institute of Thermophysics SB RAS and Dr. Anatoly Chernov from Voevodsky Institute of Chemical Kinetics and Combustion SB RAS for their help in conducting of PIV experiments.

References
[1] Law C K, Ishizuka S and Mizomoto M 1981 Proc. Combust. Inst. 18 1791
[2] Sato J 1982 Proc. Combust. Inst. 19 1541
[3] Ishizuka S and Law C K 1982 Proc. Combust. Inst. 19 327
[4] Maruta K, Yoshida M, Ju Y and Niioka T 1996 Proc. Combust. Inst. 26 1283
[5] Fursenko R, Minaev S, Nakamura H, Tezuka T, Hasegawa S, Takase K, Li X, Katsuta M, Kikuchi M and Maruta K 2013 Proc. Combust. Inst. 34 981
[6] Okuno T, Akiba T, Nakamura H, Fursenko R, Minaev S, Tezuka T, Hasegawa S, Kikuchi K and Maruta K 2018 Combust. Flame 194 343
[7] Lee M J and Kim N I 2014 Combust. Flame 161 2361
[8] Lee M J, Cho M S and Kim N I 2015 Proc. Combust. Inst. 35 3439
[9] Mokrin S, Odintsov E, Uriupin G, Tezuka T, Minaev S and Maruta K 2017 Combust. Flame, 185 261
[10] Fursenko R, Mokrin S and Minaev S 2019 Proc. Combust. Inst. 37 1655
[11] Kaiser C, Liu J B and Ronney P D 2000 38th AIAA Aerosp. Sci. Meet. Exhib. 1