Effect of a smooth temperature gradient on the combustion of a preliminary mixed methane-air mixture

A A Ponomareva\textsuperscript{1,2}, S N Mokrin\textsuperscript{1,2}, G V Uriupin\textsuperscript{2} and S S Minaev\textsuperscript{1}

\textsuperscript{1} Institute of Applied Mathematics FEB RAS, Vladivostok, Russia
\textsuperscript{2} Far Eastern Federal university, Vladivostok, Russia

ap_k@inbox.ru

Abstract. In this work, the ranges of different combustion modes of a methane-air mixture were studied in dependence on the flow velocity under conditions of a smooth temperature gradient of the channel. To carry out the experiments, a laboratory setup was designed and constructed to obtain a smooth temperature gradient in a quartz tube, and experiments were performed to determine the temperature gradient. The boundaries of different combustion regimes were determined for the mixtures with different fuel-air ratio coefficients (0.8, 1, 1.2), moreover, transient modes between main regimes were found.

1. Introduction

Obtaining data on the oxidation kinetics of various fuels is important for the development of new combustion technologies. Characteristics of fuel combustion were previously studied in systems such as a perfect mixing reactor [1], a flow reactor [2, 3], shock tubes [4-6] and special “rapid compression machines” [7–10]. Currently, a microflow reactor is widely used to verify the kinetic models of combustion of various fuels [11–13]. The reactor is usually a quartz tube with an inner diameter less than critical one for a combustible mixture calculated from ambient temperature. A quartz tube is heated by an external heat source, which forms a stationary temperature gradient along the gas flow in the tube. The mixture of fuel and oxidizer is fed into the tube from the cold end. It is moving into the microchannel and rapidly heating up from the walls due to the small diameter of the tube. When a certain temperature is reached the mixture ignites and stabilizes at a certain place in the quartz tube depending on the flow rate (one of the modes). With the continuous heating of tube's walls it is possible to sustain combustion in a tube having an internal diameter smaller than the ordinary quenching diameter, even in a case of lean gas-air mixture [11-15]. The results of [13, 14] showed that, despite the small diameter of the reactor, reactions on the surface of the quartz tube can be neglected.

During the study of a flame behavior inside such reactors three combustion modes were revealed: a stable flame for high flow velocities, an unstable combustion regime with periodic ignition and extinction (FREI) in the intermediate flow rate range, and a weak flame at low flow velocities [11-15]. It was also found that the temperature gradient has a strong effect on flame behavior [13, 15-17].

Numerical simulation of the behavior of flames in a heated microchannel with the wall temperature smoothly increasing in the downstream direction demonstrated that at very small values of the temperature gradient and at a low gas-air ratio ($\phi \leq 0.8$) flame stabilization is possible in the entire velocity range [16]. Moreover, as the theoretical investigation shown the smooth temperature gradient...
could enlarge the distance between ignition points and extinction point in FREI regimes up to several centimeters.

In this work, we studied the behavior of a pre-mixed methane-air mixture in a narrow-heated channel in the speed range from 5 to 150 cm/s in a setup with a new type of reactor of the conical spiral form.

2. Experimental details

A new type of microreactor was done using a quartz tube ~ 100 cm long with an inner diameter of 2 mm and an outer diameter of 4 mm. The tube was twisted into a conical spiral. The diameter of the base of the spiral is 80 mm, the height is 60 mm. The geometric parameters of the spiral were selected so that the turns of the spiral did not overlap each other in the frontal and lateral projections. A flat cylindrical burner was installed at the base of the spiral, operating on a pre-mixed methane-air mixture. Thus, it was possible to construct a compact microreactor with a very smooth temperature gradient, in which the maximum temperature is reached at the top of the spiral.

The temperature distribution (Fig. 1) inside the reactor was studied using a NEC TH9100WB thermal imager, which was placed on the top of the same axis with a spiral tube and the center of an external cylindrical burner. The measurements of the thermal imager were corrected according to the data obtained using a K-type thermocouple. The tip of the thermocouple was in a direct contact with the heated wall and was hold in this position for several minutes in order to obtain an average temperature.

![Figure 1](image.jpg)

**Figure 1.** The temperature distribution in a spiral-type microflow reactor obtained using a thermal imager.

A study of the flame behavior in a heated microchannel with the wall temperature smoothly increasing in the downstream direction was performed in the velocity range from 5 to 150 cm/s. The flow inside the tube was laminar under atmospheric pressure. The position of the flame front was recorded using a Nikon D7200 digital camera. The camera captured the image from the mirror, which was installed at an angle above the reactor in order to display a top view. This recording method allows performing an easier estimation of the flame position using a polar coordinate grid. From the images the angle of the flame position was determined in polar coordinates centered at the beginning of the spiral (maximum temperature). Then, using the common-used formula for a conical spiral (1), the distance to the point with the maximum temperature (that was chosen as the zero point) was determined.
where \( r_1 \) and \( r_2 \) are the radii of the first and second turns, \( \eta \) is the radius of the spiral for the calculated point; \( h_i \) is the distance between the turns along the vertical axis.

3. **Results and Discussion**

In the experiment, the temperature of the tube varies from 500 to 1350K, and the length of the working area was no more than 85 cm. The temperature gradient was calculated by processing images obtained by the thermal imager. As can be seen from Figure 2, the temperature change has an almost linear dependence on the length of the tube of about 50 cm. As further experiments showed, this particular segment of the tube is the main reaction zone where all visible effects can be seen. In the further section of the tube, the temperature change is even smoother.

When studying a stoichiometric methane-air mixture, the boundaries of two main combustion modes were found: a stable flame was observed at flow velocities from 39 to 150 cm/s (the A zone on fig. 3), the FREI mode was from 9 to 37 cm/s (the B zone on fig. 3). The detection of weak flame at low flow velocities was not included in this study. To visualize a weak flame, it is planned to use special methods using optical filters. That is the main goal of future experiments. We also observed transient effects between the main modes. At a speed of 38 cm/s, the flame ignites at the upstream, slowly moves downstream (as in stable mode until the flame stabilizes), and then begins to oscillate (as in FREI mode). This effect was previously observed and described in papers [15, 18]. At the velocity of 8 cm/s, the flame oscillates several times (as in FREI mode), disappears, and for some time there is no visible flame (perhaps there is a weak flame that we can see without filters). The effects have been repeated continuously and shown a temporary dependence. It should be noted that due to the high luminosity of the first two turns of the spiral and the insufficient recording speed of the used camera, difficulties arose in determining the ignition points in the FREI modes. In Fig. 3. The first

![Figure 2. Experimental obtained data of temperature change of spiral microflow reactor (the dashed lines point out of the ends of marked turns).](image-url)
visible flame positions that have appeared on the recorded videos are indicated. Thus, the ignition zone is marked on the graph.

![Figure 3](image)

**Figure 3.** The position of the reaction zone depending on the velocity of the mixture (experimental results); ovals mark the extreme positions of the flame during transient effects.

As experiments for the mixture with $\varphi = 1.2$ showed, the lower boundaries of the main combustion regimes shifted in the direction of higher velocities: a stable flame was observed at flow velocities from 41 to 150 cm/s, the FREI mode was from 15 to 39 cm/s. The transient effects like as for the mixture with $\varphi = 1$ were also detected at 40 cm/s and 14 cm/s, respectively. In addition, the distance between the ignition and extinction points also changed significantly and became almost two times less (from 28 cm (see Fig. 3) to 13 cm).

Investigation of the flame behavior in case of methane-air lean mixture with $\varphi = 0.8$ demonstrated that the stable flame regime had the same boundaries as for the stoichiometric mixture. On the other hand, the FREI regime became to be wider, up to 6 cm/s. The distance between the ignition and extinction points varies from 32 cm (at higher velocities) to 20 cm (at the boundary between the FREI and a weak flame regimes). Concerning to the transient effects, we could observe only one of them: between stable flame regime and FREI regime at 38 cm/s. It was not possible to detect the transient effect at low velocities probably due to the large measurement interval (velocities were changing with the step of 1 cm/s).

4. **Concluding Remarks**

New construction of microreactor with smooth temperature gradient was developed. The spiral shape of microtube allowed us to achieve almost linear temperature gradient in temperature range from 500 to 1300 K. Thus, the resolution and sensitivity of experimental setup became higher. As a result, we found the features of flame behaviour for different methane-air mixture as well as the transition effects between stable flame and FREI regimes and between FREI regime and weak flame.

**References**

[1] Dagaut P *et al* 2009 *Proc. Combust. Inst.* **32** 229
[2] Mueller M A *et al* 1999 *Int. J. Chem. Kinet.* **31** 113
[3] Fischer S L *et al* 2000 *Int. J. Chem. Kinet.* **32** 713
[4] Gauthier B M et al 2004 Combust. Flame 139 300
[5] Chaos M and Dryer F L 2010 Int. J. Chem. Kinet. 42 143
[6] Burcat A et al 1971 Combust. Flame 16 29
[7] Livengood J C and Wu P C 1955 Symp. Combust. 5 347
[8] Griffiths D F et al 1993 Combust. Flame 95 291
[9] Minetti R et al 1994 Combust. Flame 96 201
[10] Kizaki Y et al 2015 Proc. Combust. Inst. 35 3389
[11] Yamamoto A et al 2011 Proc. Combust. Inst. 33 3259
[12] Hori M et al 2012 Combust. Flame 159 959
[13] Suzuki S et al 2013 Proc. Combust. Inst. 34 3411
[14] Oshibe H et al 2010 Combust. Flame 157 1572
[15] Di Stazio A et al 2016 Exp. Therm. Fluid Sci. 73 79
[16] Mazurok D B et al 2014 Combust. Explo. Shock+ 50 25
[17] Grajetzki P et al 2018 Comb. Sci. and Tech. 190 1950
[18] Tsuboi Y et al 2007 Proc. ASME Int. Mechanical Engineering Congress and Exposition (Seattle, Washington) IMECE2007-43339 p 155