International Journal of Science, Technology and Society
2015; 3(1): 24-27
Published online Jnauary 20, 2015 (http://www.sciencepublishinggroup.com/j/ijsts)
doi: 10.11648/j.ijsts.20150301.13
ISSN: 2330-7412 (Print); ISSN: 2330-7420 (Online)

Combustion in micro channel investigating the effect of wall thermal conductivity of micro-channels on flame stability

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To cite this article:
Zafar Namazian, Heidar Hashemi, Jafar Namazian. Combustion in Micro Channel Investigating the Effect of Wall Thermal Conductivity of Micro-Channels on Flame Stability. *International Journal of Science, Technology and Society.* Vol. 3, No. 1, 2015, pp. 24-27.
doi: 10.11648/j.ijsts.20150301.13

Abstract: In this work, the computational fluid dynamics is used to model a micro torch. This is to investigate the effect of wall conductivity for different operating conditions on combustion characteristics as well as flame stability. The effect of convective heat transfer coefficient on the flame stability, out of the burner, is also studied. The results show that the wall conductivity and the convective heat transfer coefficient are very important to determine heat transfer to upstream. Finally, it is observed that if intermediate conductivity value of a wall is used, it can produce more stable combustion flame. In contrary, in very low and high conductivity, the flame becomes unstable. If the convective heat transfer coefficient of the outer fluid increases, flame becomes unstable again.

Keywords: Flame Stability, Micro Channel, Thermal Conductivity, Combustion

1. Introduction

High potential of hydrocarbon fuels can create a great opportunity for development of combustion in power micro systems in order to respond increasing demands such as portable power vehicles, small-unmanned aerial vehicles, micro satellite propulsion power, chemical reactors and micro sensors. Due to the high energy density of hydrocarbons, micro-scale combustions are eventually replaced expensive batteries and incompatible with the environment used in laptops, cell phones and other communication devices [1]. Because of very high heat transfer coefficients of micro systems, additionally, there is the possibility of lowering the combustion temperature, which can considerably minimize NOx formation [2, 3].

Recent advances in Nano and micro technologies have dramatically accelerated to minimize the size and number of operating mechanical devices, portable communications and medical imaging [4]. Many attempts are being done to make a compact, increased longevity and instant recharge power supply from a few milliwatts to hundred watts. Today, the portable devices heavily rely on batteries so that the battery market becomes very big which is about 37 billion dollars a year [5]. With the rapid growth of portable devices such as mobile phones, notebook computers and other electronic devices, the market demands for power generating micro sizes is going to grow. Unfortunately, now the energy density of batteries is very low. Even the most advanced lithium ion batteries can only have energy densities about 0.2 kWhr/kg [6, 7]. Low energy density can support notebooks or video cameras only for few hours. In addition, this kind of batteries needs to be rechargeable for several times, but only batteries with a limited number of charge cycles are available. On the other hand, disposal of used batteries cause various environmental concerns. Moreover, being heavy and bulky, low durability, low efficiency and lack of power resources for instant recharge also greatly make mechanical and chemical applications of micro systems necessary [5, 8].

Experiments conducted by Davy [9], followed by many researchers [10, 11], indicate that propagation of flames in the spaces below millimeter is impossible. Depending on the geometry, composition and flow rate, when flame of a methane/air normally places in critical dimensions like 1-2 millimeter, the flame may be fallen off. Flames on a small scale by two main mechanisms, radical extinguish and thermal extinguish, can be quenched [12]. If thermal quenching occurs when sufficient heat is removed through wall of the combustion, it can no longer be sustained. Radical quenching occurred by radicals adsorbed on the walls and the formation of stable species. The small size of the system significantly is prone to do them both quenching mechanisms. Due to the high surface to volume ratio, increasing the heat transfer from the flame to the wall and increasing the mass transfer of radical to the wall will happen. In addition to the extinction of the flame, flames erupting out of the burner when the fuel speed occurs over the flame speed [13]. In this mechanism, the reaction tends to be passed down and eventually comes out of the micro torch. The results of recent experiments, a stable flame micro torch through appropriate modification of the surface of the ceramic material to limit heat loss and radical, the combustion of a mixture of methane/air between parallel plates with a gap of less than 300 micro meters were feasible [14, 15]. In relation to micro-scale combustion abundance of experimental and numerical works are done, but effect of the wall conductivity on the flame stability is not addressed in detail. In this work, the computational fluid dynamics is used to model a micro torch to investigate the effect of wall conductivity for different operating conditions on combustion characteristics and flame stability, also the effect of convective heat transfer coefficient of the fluid out of the burner on the flame stability is studied. The results show that the wall conductivity and the convective heat transfer coefficient of the fluid out of the burner to determine heat transfer to upstream that is necessary to sustain combustion, are very important. Finally, it is observed that if the intermediate value of conductivity of the wall is used (in this work about 10 watts per meter Kelvin) it produces more stable combustion flame, but in very low and very high conductivity, flame becomes unstable. If the convective heat transfer coefficient of the outer fluid increases (at around 15 watts per square meter Kelvin) flame becomes unstable again.

2. Numerical Simulation

Methane-air mixture with the stoichiometric ratio into a micro torch is inserted. The micro torch consists of two parallel plates with infinite width and 1cm length. Wall thickness (L_W) is limited. Finite volume method for separation of the continuity equations, momentum, energy and chemical species conservation equations in the fluid as well as the two-dimensional energy equation of the walls (Eq. (1)) is used.

$$\frac{\partial}{\partial t}(\rho h) = k_w\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \quad (1)$$

Using Fluent software, the simulation is performed assuming steady-state flow. The initial simulations are with the consideration that radiation gas wall makes the temperature decrease, and as a result, the combustion distance of the input mixture would also slightly increase. However, these changes are not significant and in order to investigate separately the effect of wall conduction on the stability of the flame radiation, the flame radiation is not considered. Fluid density is calculated using the ideal gas law. Fluid viscosity, specific heat and thermal conductivity of the weighted average mass fraction of species can be calculated according to equation (2).

$$\mu = \sum_i Y_i \mu_i, \qquad C_{\mathrm{p,f}} = \sum_i Y_i C_{\mathrm{p},i}, \qquad k_{\mathrm{f}} = \sum_i Y_i k_i \quad (2)$$

Since the recent experimental works have investigated radical quenching mechanisms [14], and also numerical simulations have been carried out [16], in this work the mechanism of thermal quenching and flame stability would be checked.

2.1. Boundary Conditions

1. Fluid enters at a uniform velocity in the inlet.
2. Central symmetry boundary condition is applied between the two plates.
3. Pressure is uniform in the output.
4. Non-slip and no-flux chemical species boundary conditions exist between the wall and the fluid. Heat flux on the boundary wall fluid is calculated using the Fourier and continuity of the temperature. The edges of the inlet and outlet pipes are assumed insulated. Newton's law of cooling to estimate the heat transfer from the outer wall of the tube is used.

3. Grid Generation and Solution Methods

In the simulations, the non-uniform density of nodes for network around the reaction zone (central line and input) is used. The density of nodes decreases from left to right as shown in Fig. 1. The reaction zone is expressed by a horizental yellow line color in the middle of Fig. 1.

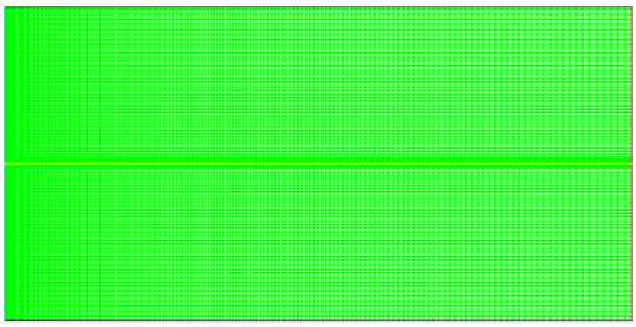

Fig. 1. *Network used in this work.*

Computing using networks with different node density is performed to determine the optimal grid that has the desired accuracy and computation time to a minimum. Fig. 2 shows the temperature profiles in the central line used for some networks.

Large networks consisting 500 nodes do not predict the maximum temperature well. Calculations obtained by using finer grids give an exact answer. Use of mesh density greater than 6000 nodes does not show any advantage in accuracy compared to the number of nodes. All calculations presented in this work are obtained using a mesh consisting of 6000 nodes. It should be noted that in order to achieve the above figure, the inlet velocity of the fluid, the wall thickness and distance between the plates are respectively 0.8 meters per second, 150 micrometer and 500 micrometer. Wall conductivity and convective heat transfer coefficient have been considered respectively 10 W/m.K and 8 W/m^2.K.

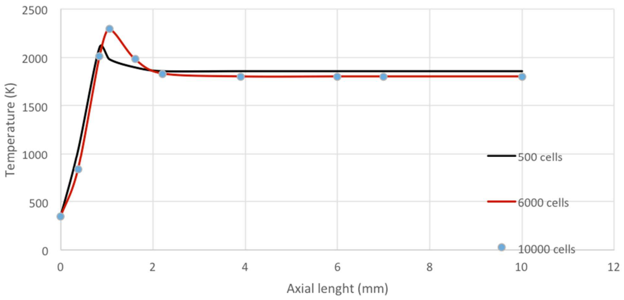

***Fig. 2.** Centerline temperature distribution for different networks.*

4. Results

Simulations indicate that the thermal conductivity of the wall plays a vital role in the stability of the flame. Wall plays a dual role in the overall heat transfer. On the one hand, it provides a path to heat transfer from the combustion zone downstream to upstream so as to supply heat for ignition and flame stability. On the other hand, the wall allows heat transfer to the outside, which makes a quenching occur and cause a delay in ignition flame. High temperature of the wall and the formation of hot spots can cause serious problems, such as the melting of the material. Thermal conductivity of the wall has a great impact on the wall temperature profiles. Fig. 3 illustrates axial profiles of the wall temperature for different thermal conductivity of the wall.

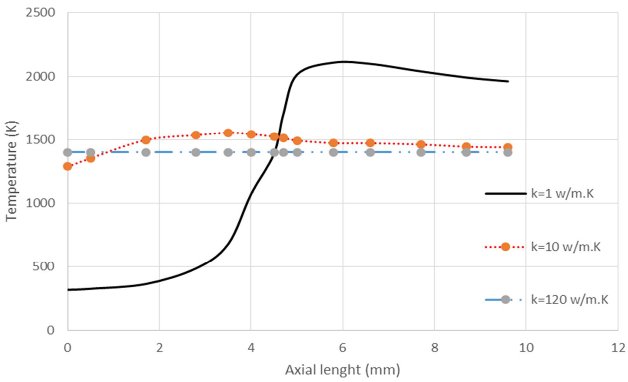

***Fig. 3.** Temperature distribution of the wall center line for the different thermal conductivity coefficient.*

At a very low wall thermal conductivity, it is observed that the temperature gradient is much steeper in the wall, the wall temperature is lower at upstream and higher temperatures at downstream of the wall. On the other hand, at the medium-sized thermal conductivity of the walls, more uniform axial temperature profile is observed, and materials with high thermal conductivity such as metals have practically fixed temperature distribution. Although the temperature gradient is insignificant across the wall for all cases, but the wall with high thermal conductivity greatly reduces the axial temperature gradient, and the energy is distributed at the wall so that it reduces the maximum temperature. For example, Fig. 3 already shows that when the wall thermal conductivity is very small, the wall temperature is close to adiabatic flame temperature about 2200 K. When the thermal conductivity of the wall considered is medium and high, respectively, the maximum wall temperature is about 1600 and 1400 K. In addition to the wall conductivity as a parameter influencing the ignition, external heat transfer coefficient has significant effect on combustion stability. This effect can be seen in Fig. 4. According to Fig. 4, when the external heat transfer coefficient increases, heat dissipation would increase and also heating the mixture of fuel and air would become slow. As a result, the wall temperature near the entrance is reduced, and the location of the flame transfers to downstream. Finally, with increasing external convective heat transfer coefficient of about 15 watts per square meter Kelvin, quenching will be occurred or erupting of flame takes place outside the burner. In order to understand the initial resistance against heat transfer to the outside, the overall heat transfer coefficient, U, is calculated through the following relationship.

$$U = \left(\frac{L_w}{k_w} + \frac{1}{h}\right)^{-1} \tag{3}$$

For a relatively thin walls, the initial resistance to heat transfer occur in the outer fluid, even when the low conductivity of the wall is used. Above calculations show that for walls with high conductivity and large external heat transfer coefficient, the heat transfer through the wall quenching is created.

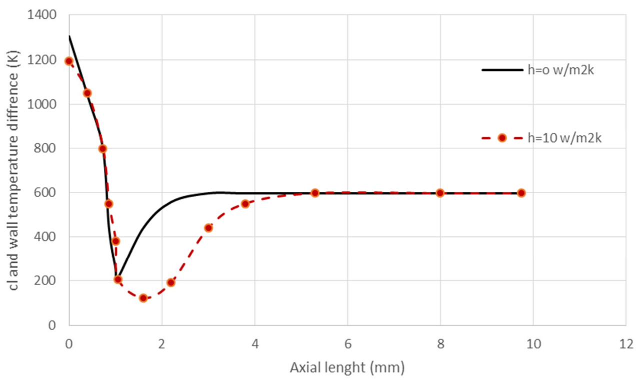

***Fig. 4.** Temperature difference between the centerline and the wall for different convective heat transfer coefficients.*

For these cases, as shown in Fig. 3, the axial wall temperature distribution is almost uniform, then, a larger surface area is compared to those with lower conductivity especially near the burner inlet subjected to higher temperature. This increases the effect of heat loss, resulting in a lower flame stability. With increasing heat loss, the average flame temperature is reduced, as shown in Fig. 3. It should be noted that to obtain the above figures, the inlet velocity of the fluid, the wall thickness and distance between the plates are respectively 0.8 meters per second, 150 micrometer and 500 micrometer. Wall conductivity and convective heat transfer coefficient have also been considered respectively 10 W/m.K and 8 $W/m^2.K$.

5. Conclusions

In this work, the computational fluid dynamics is used to model a micro torch to investigate the effect of wall conductivity and convective heat transfer coefficient for different operating conditions on combustion characteristics and flame stability. For walls with low thermal conductivity, the flame is located substantially downstream and transmission of flame from the burner may occurre depending on the length of the burner and the flow rate. Moreover, low heat flux through the wall to upstream causes the upstream wall temperature being low. As a result, the pre-heating and ignition temperature are reached slower which lead transfering the flame location to downstream. When heating upstream of the flame does not do well, it has more prone to instability. When the wall conductivity slightly increased and the average value is reached, a sharp drop at the location of flame to inlet of the burner occurrs. In this case, the flame stability is fully established. In those systems that have walls with high thermal conductivity and low thermal loss, thermal conductivity at the wall plays an insignificant role to locate the flame. In contrast, for higher heat dissipation, external walls with high thermal conductivity makes the flame located in downstream and cause its extinction. By increasing the heat transfer coefficient of the outer wall, quenching and instability of flame are also observed.

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