Investigation into Changing of Geometry and Boundary Conditions of Stepped Premixed Micro-Combustor

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Abstract
In the present study a micro-combustor having the geometry of a hollow cylinder is investigated, in which the combustor diameter in the entrance is less than its main part that is actually a stepped-form combustor and methane-air combustion is occurred within the chamber and the investigation is undertaken by solving 2D governing equations. In order to determine the effect of elongation of the entrance part and increase in the chamber diameter, a geometry with an inlet diameter of D_{in}=1 mm, inlet length of L_{in}=7 mm and a main diameter of D=2 mm as a reference case was compared with two geometries one with an inlet diameter of D_{in}=1 mm, an inlet length of L_{in}=10 mm and a main diameter of D=2 mm and the other having inlet diameter of D_{in}=1.5 mm, inlet length of L_{in}=7 mm and a main diameter of D=3 mm. All of them had the same total length and they were compared for inlet velocities of u=3 m/s, 2 m/s, and 1.5 m/s. The centerline temperature, the wall temperature, and the radiation efficiency are of the results more investigated in this study. In a constant geometry, increasing of the inlet velocity causes the flame temperature to increase, though slightly. Moreover, it leads to move the flame downstream. This increase has a more influence on the wall temperature and makes it rise to a higher level along the combustor in the inlet velocity of u=3 m/s. It was concluded that in a constant velocity, increasing of inlet length only makes delay in the flame formation and does not affects the flame temperature, significantly. Finally, it was shown that in the geometry with less inlet diameter and length, the radiation efficiency is placed at a higher level in comparison to the geometry with larger inlet diameter and length at all velocities. In addition, it was observed that increase in the inlet velocity leads to reduce the efficiency in all the three geometries and this reduction is more intense and with steeper slope for the geometry having larger diameter. In addition to the lack of research conducted on methane combustion in the geometries studied, the difference between the present study and others in this area is that the simultaneous effects of geometry and velocity on combustion parameters are studied in more details and also, it is used from a different combustion mechanism as compared to other studies

Keywords:
Micro-combustor, Radiation Efficiency, Flame Temperature

WITH THE ADVANCE OF HUMAN'S KNOWLEDGE AND THE GROWING NEED FOR ENERGY, THE DEMAND FOR USING MINIATURIZED COMBUSTION DEVICES (DUE TO HAVING HIGH ENERGY DENSITY) IS INCREASING. ACCORDINGLY, INVESTIGATING COMBU

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AS IT WAS MENTIONED, MANY RESEARCH WORKS HAVE BEEN DONE IN THE FIELD OF MICRO-COMBUSTORS INCLUDING EXPERIMENTAL AND NUMERICAL STUDIES. THE COMMON POINT OF MOST OF THESE STUDIES IS TO INVESTIGATE HOW QUENCHING (EXTINCTION) OCCURS IN THE FLAME OF THE COMBUSTOR.

FOR INSTANCE, J. LI ET AL. [15] PERFORMED A NUMERICAL STUDY ON INTRODUCTION

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1. The Problem Investigated

The issue is related to a hollow cylinder having two stages with different diameters (so-called step) (Figure 1), in which the inlet diameter decreases and then it is sized up (Backward Facing Step) and methane-air combustion occurs in it. we simulate this problem as a two-dimensional (2D) model, and the results will be presented in next section.

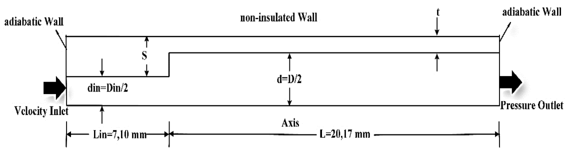


Fig 1. A section view of the micro-combustor with two different diameters along the chamber

In order to show how to the location and temperature of the flame is changed due to the change of geometry, we model the combustor with three different geometries including a combustor with inlet diameter of D_{in}=1 mm, main diameter of D=2 mm, inlet length of L_{in}=7 mm, and main length of L=20 mm, a combustor with inlet diameter of d_{in}=1 mm, main diameter of D=2 mm, inlet length of L_{in}=10 mm, and main length of L=17 mm, and finally a combustor with an inlet diameter of d_{in}=1.5 mm, main diameter of D=3 mm, inlet length of L_{in}=7 mm, and main length of L=20 mm and the obtained results will be compared. Moreover, we consider three different fuel-air mixture inlet velocities of u=1.5 m/s, 2 m/s, and 3 m/s for all the three geometries to investigate the flame behavior, when the equivalence ratio is equal to $\varphi = 0$ in all cases.

In this problem, we use from a 73-stage skeletal methane-air mechanism to model the chemical reaction, which comprises 17 different chemical species. In order to import this mechanism and the physical and chemical properties of the participating species, it is used from a mechanism file, a thermodynamic file, and a file of transport properties. These files are a part of GRI ver1.2 project, which is developed by Sankaran et al [28]. and its species and reactions are presented at the appendix section.

This mechanism gives true and reliable answers for equivalence ratios from $\varphi = 0.6$ to $\varphi = 1.0$, i.e. poor methane-air mixtures in the pressure range of 1 to 30 atmospheres. According to the governing equations mentioned above, 2D simulation is performed and the governing equations were discretized by finite volume method and solved with FLUENT 3.6 software.

In this problem, thermal conduction constant (K) is considered equal to 16 w/mk (for stainless steel). There is a uniform temperature of 300 ºk in the combustor entrance for air and fuel and pressure-outlet boundary condition is considered at the outlet.

1.1. Governing Equation and Numerical Method

Given an assumption, we consider the rotational velocity equal to zero and as a result, a symmetrical flow relative to the main and central axis will be obtained that turns the problem into a 2D type. In order to save calculation time, only half of the combustor is considered and the main axis is considered as the symmetric axis. Other assumptions of the problem are as follows:

1- It is ignored from the effects of Dufour or the thermal flux resulting from the change in concentration
2- The radiations from gases are neglected
3- Nothing is performed by changing the pressure or forces caused by the viscosity
4- Steady state

Considering these assumptions, the governing equations including continuity, momentum, chemical species and energy in gas phase for combustor having a hollow cylinder geometry are as follows:

Continuity:

$$\frac{\partial(\rho u)}{\partial x}+\frac{1}{r}\frac{\partial(\rho v r)}{\partial r}=0$$

x momentum:

$$\frac{\partial(\rho u u)}{\partial x}+\frac{1}{r}\frac{\partial(\rho u v r)}{\partial r}=-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\frac{4}{3}\mu\frac{\partial u}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\mu\frac{\partial u}{\partial r}\right)-\frac{\partial}{\partial x}\left(\frac{2\mu}{3r}\frac{\partial(vr)}{\partial r}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\mu\frac{\partial v}{\partial x}\right)$$

r momentum:

$$\frac{\partial(\rho u v)}{\partial x}+\frac{1}{r}\frac{\partial(\rho v v r)}{\partial r}=\frac{-\partial p}{\partial r}+\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial r}\right)-\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{2r\mu}{3}\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial x}\left(\mu\frac{\partial v}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{4r\mu}{3}\frac{\partial v}{\partial r}\right)-\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{2}{3}\mu v\right)$$

Energy:

$$\frac{\partial}{\partial x}(\rho u h)+\frac{1}{r}\frac{\partial}{\partial r}(\rho v h r)=\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(k\frac{\partial T}{\partial r}r\right)-\frac{1}{r}\frac{\partial}{\partial r}\left(r\rho\sum_{i=1}^{N}Y_i h_i V_i\right)-\frac{\partial}{\partial x}\left(\rho\sum_{i=1}^{N}Y_i h_i U_i\right)+q$$

Species conservation:

$$\frac{\partial(\rho u Y_i)}{\partial x}+\frac{1}{r}\frac{\partial(\rho v r Y_i)}{\partial r}=\frac{\partial}{\partial x}\left[D_i\frac{\partial(\rho Y_i)}{\partial x}\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[D_i r\frac{\partial(\rho Y_i)}{\partial r}\right]+\omega_i$$

Energy balance in the solid phase:

$$\frac{\partial}{\partial x}\left(k_s\frac{\partial T_s}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(k_s\frac{\partial T_s}{\partial r}r\right)=0$$

Taking into account the above conditions, FLUENT 6.3 software solves the problem governing equations such as continuity, momentum, chemical components (species), and energy in gas phase.

It is used from second-order upwind discretization scheme for discretizing the governing equations and it is used from SIMPLE algorithm (code) for the pressure–velocity relation, as well. The equations are solved implicitly by the help of Pressure-Based solver and Under Relaxation Factor (URF) method. The solver initially solves the momentum equations, then the continuity equation and thereafter, corrects the pressure and mass flow rates followed by solving the equations of energy and chemical species, respectively.

In FLUENT software, iterations are represented by a graph until the equations are converged. The range of dimensionless residuals in this problem is determined equal to 1×10^{-6} for the continuity, velocity, energy and concentration of chemical species.

The gas density will be calculated using the ideal gas law and also, viscosity, specific heat, and thermal conductivity are obtained by weighted average of the chemical species.

Numerical convergence is very difficult and time consuming due to the complexity of chemical equations and the problem, and experience has revealed that energy equation is the last parameter to get converged.

Heat losses from a non-insulated wall to the ambient is obtained from the following equation:

$$q_W = h_{conv}(T_{wo} = T_o) + \varepsilon\sigma(T_{wo}^4 - T_o^4)$$

where, convective heat-transfer coefficient (h_{conv}) and thermal radiation coefficient of the wall (ε) are equal to 5 w/mk and 0.2, respectively.

For computational iterations, the temperature of 2500 °K is considered as an initial guess at the entire computational domain. Being high this temperature is an important thing because combustion will not start at low temperatures.

We simulate a reference case for comparisons, in which the geometry is a combustor with inlet diameter of D_{in}=1 mm, main diameter of D=2 mm, inlet length of L_{in}=7 mm, and main length of L=20 mm and the boundary conditions are as follows:

At the inlet (x = 0): The temperature of air-fuel mixture is T_u=300 °K, inlet air velocities are u_o=1.5 m/s, 2 m/s, and 3 m/s, the mass fraction of methane is equal to Y_{CH4}=0.0498 and the mass fraction of oxygen is obtained by using methane mass fraction and an equivalence ratio of φ = 0.9.

At the combustor centerline (r = 0): There are no mass and energy flow across the symmetry line: $\frac{\partial u}{\partial r} = 0$, $\frac{\partial T}{\partial r} = 0$, $\frac{\partial Y_i}{\partial r} = 0$, $v = 0$

At the fluid-solid interface (r = r_O): non-slip wall boundary conditions (u= 0, and v=0), zero mass flow ($\frac{\partial Y_i}{\partial r} = 0$), and heat flux at the interface is obtained through Fourier's law.

Non-insulated wall (r = r_O): The heat transfer is defined by the following equation: $q_W = h_{conv}(T_{wo} - T_o) + \varepsilon\sigma(T_{wo}^4 - T_o^4)$

2. Results and Discussion

2.1. Independency of Solution from the Mesh

For the problem studied here, the solution was performed with different mesh configurations. Herein, the investigation for a geometry with inlet diameter of D_{in}=1 mm, inlet length of L_{in}= 7mm, and inlet velocity of V=2 m/s is done and the results are presented in figure 2.

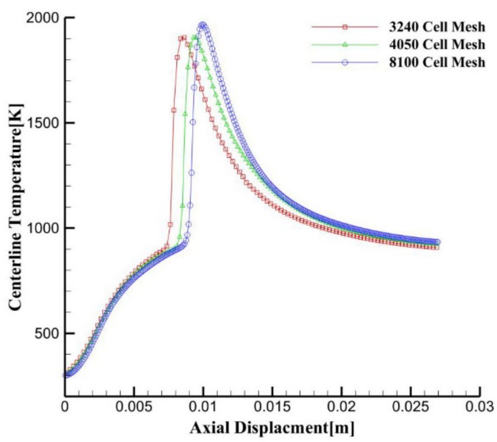


Fig 2. Comparison of results obtained from different Meshs related to the second problem

It can be observed that in a network with 4050 cells of gas and solid phases, it has almost identical results to the network with more cells and that is why we chose this network in the following. As can be seen, greater number of cells for a network does not affect the results, considerably. In the gas phase, the combustor has been discretized by meshes of size 0.2 and 0.05 in the axial and radial directions, respectively. Finer meshes were examined but no significant influence was observed.

2.2. Validation

Two validation cases were performed for the studied problem. The first reference case is a problem that is geometrically consistent with the problem we are investigating and oxygen-air combustion occurs in it, and the second one is a problem with a smaller geometry but methane-air combustion takes place in it. In the first problem, Li et al. [15] simulated methane-air mixture combustion in a geometry similar to the problem studied in this research, both numerically and experimentally. As can be seen in figure 3, results obtained from the present study are in good agreement with the experimental results and slightly different from the numerical simulation results. The maximum difference between the results is about 4 %, which arises from the mechanism used in the two studies.

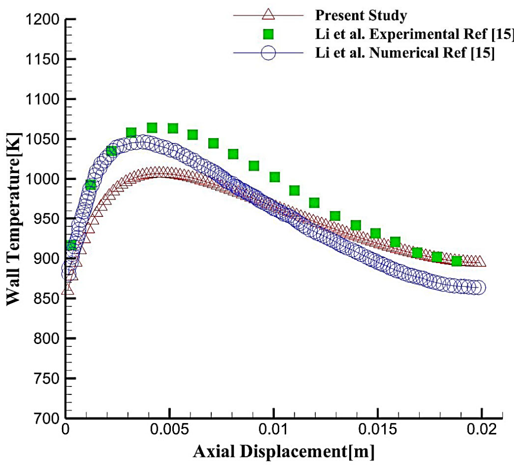


Fig 3. Comparison of the results of present study with those obtained by Li et al. [15]

The second case is a numerical problem related to a geometry smaller than current one but with methane-air mixture as the fuel, which is solved by Bigmohammadi et al. [1] and the results are presented in figure 4 compared with those of this study. As can be seen, there is also a good consistency between the two problems and the difference between the results is about 5 %. The reason for this difference is also the mechanism used to solve the problems.

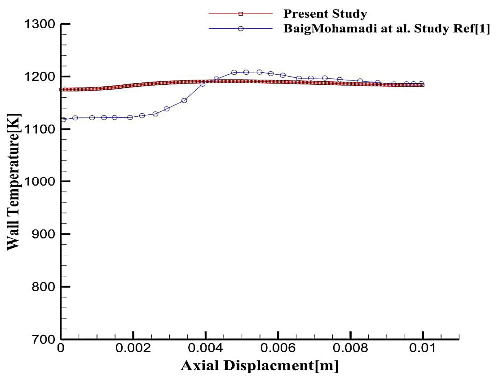


Fig 4. Comparison of the results of present study with the results obtained from the numerical problem solved by Bigmohammadi et al [1]

2.3. Effects of Inlet Velocity

Combustor with inlet diameter of D_{in}=1 mm, man diameter of D=2 m, and inlet length of L_{in}=7 mm

In this section, we investigate the results obtained from the simulation of a micro-combustor with the geometry of a hollow cylinder having inlet diameter of D_{in}=1 mm, man diameter of D=2 m, and inlet length of L_{in}=7 mm. The inlet air temperature is 300 ºK. The objective is to investigate the flame position and temperature for combustion in different inlet air velocities (u=1.5 m/s, 2 m/s, and 3 m/s) by the definition that the maximum temperature inside the combustor is called flame temperature. Figure 5 illustrates the diagrams of temperature on the centerline and the wall of a micro-combustor in different velocities of u=1.5 m/s, 2 m/s, and 3 m/s, in which the combustor diameter and length are equal to D_{in}=1 mm and L_{in}=7 mm, respectively.

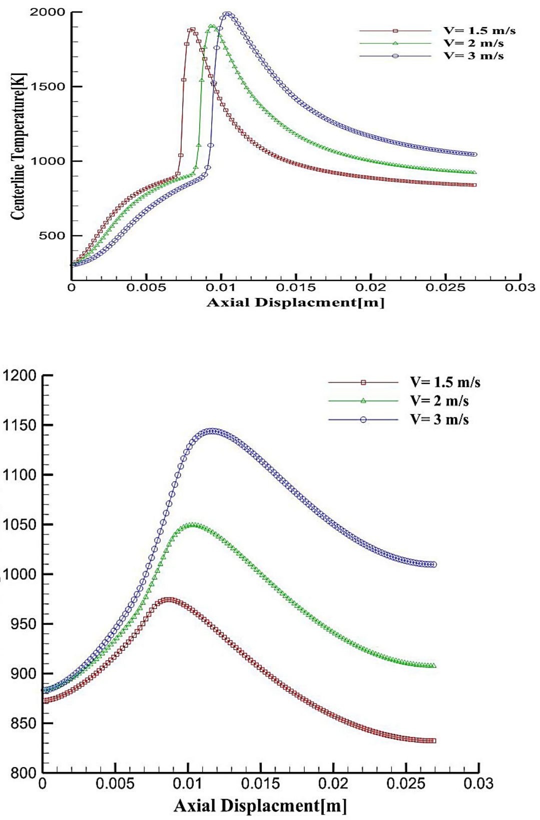


Fig 5. Diagrams of temperature on: (a) the centerline and (b) the wall of a micro-combustor for different inlet air velocities of u=1.5 m/s, 2 m/s, and 3 m/s with diameter and length values equal to D_{in}=1 mm and L_{in}=7 mm, respectively.

According to figure 5, it is obvious from diagram (a) that the maximum temperature is placed at the entrance of the combustor in lower velocities, which itself is an evidence of flame formation at the entrance of the chamber and consequently, the centerline temperature decreases quickly, indicating the compression of the flame. Meanwhile, the more the inlet velocity becomes, the less this reduction gets.

As is expected, as the air inlet velocity increases, the flame is blown further downstream and its temperature increases, as well. It can be seen from the diagram that before the formation of the flame, temperature at the centerline increases with steeper slope in lower velocities and then, it is approximately identical in all velocities.

The next point that is evident in the diagram is that mean temperature at the centerline gets increased for higher velocities so that, this value for the velocity of u=3 m/s is greater than for u=1.5 m/s and 2 m/s. In fact, in the higher velocities, more heat is released due to greater mixing of fuel and air and more complete combustion of these two and the flame encompasses a greater volume of the combustor. It must be noted that if the combustor length is less than a certain value, the mixing is not performed better and there may not be the time for combustion and the flame would go into extinction.

Increasing of the maximum temperature with increase in the velocity is due to the increased inlet flux of the fuel-air mixture and the delay in the flame formation is also for this reason. In a given limited length, since the opportunity for heat transfer with the ambient is fewer at higher velocities, the combustor outlet temperature gets a higher value for higher velocities. Increasing of velocity can finally lead to flame jump and extinction.

It can be seen from the diagram of figure 5(b) that the maximum temperature of the wall is placed approximately at a distance from the entrance that the flame is anchored inside the combustor. This place is after the inlet step that was also evident in the diagram of the centerline temperature, in which the flame is anchored after the first low-diameter part (i.e. the inlet step). After this place, the wall temperature decrease with a relatively gentle slope.

It is also obvious that by increasing of velocity, the wall temperature gets increased along the entire combustor length, which is evidently due to the increase in the flame temperature and the increase in the heat transfer coefficient between the fluid inside the combustor and the wall.

It is obviously seen that although the inlet velocities of u=1.5 m/s and u=2 m/s are closer relative to u=3 m/s, the wall temperature at the entrance are near to each other in the inlet velocities of u=2 m/s and u= 3m/s. The reason is that increase in the velocity causes increasing of heat transfer coefficient between the wall and the gas and it has a greater role on the wall temperature than the effect of the inlet flux. Moreover, due to the limited length of the combustor and delay in the flame formation in u= 3 m/s, the wall temperature in this velocity is deferent from the rest of them.

By increasing of velocity, the difference between maximum and minimum wall temperature increases, significantly. It is due to two reasons; first, as it was said, increase in the velocity makes the heat transfer coefficient increase and accordingly increases the amount of the heat transferred to the wall. Second, greater velocity results in greater flux and consequently, more inlet flux causes the flame and wall temperatures to be increased.

Figure 6 illustrates the contours of axial velocity, methane mass fraction, and temperature inside the whole combustor for inlet velocity of u= 3m/s. In these contours, the results of the analysis of a micro-combustor having diameter and length of respectively 1 mm and 7 mm, and inlet air temperature of 300 K are presented.

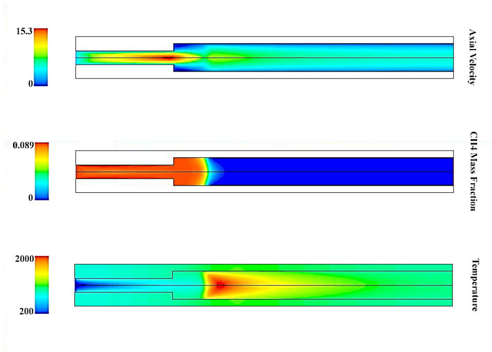


Fig 6. Contours of axial velocity, methane mass fraction, and temperature inside the combustor for inlet velocity of u= 3m/s (the combustor diameter and length are equal to 1 mm and 7 mm, respectively)

It can be seen from the axial velocity contour that the maximum velocity just occurs when the combustor diameter increases, i.e. at the place of the step. In addition, in this point, the velocity near the wall is close to zero from the larger diameter to a greater distance. The methane mass fraction is almost constant from the entrance of the combustor to after the step and the place where the flame forms and at the place the flame formation place, it drops to zero from its initial value along a very short distance. In fact, chemical reaction happens at this place and combustion occurs. According to the temperature contour, it can be found that where the flame is anchored and it continues along a limit part of the combustor.

3. Effects of the Combustor Geometry

3.1 Results of Investigation in u=1.5 m/s

This section is mainly aiming for comparing the results of a micro-combustor with stepped hollow cylinder geometry having different inlet diameter and length. For this purpose, we investigate the results of three hollow cylinders with the same inlet and main diameters of respectively equal to D_{in}=1 mm and D=2 mm, and inlet lengths of L_{in}=7 mm and 10 mm and also a geometry with inlet diameter of D_{in}=1.5 mm, main diameter of D=3 mm, and an inlet length of L_{in}=7 mm at inlet air velocities equal to u=1.5 m/s. The total length of all the three geometries is equal to L_t=27 mm.

Figure 7 shows the diagrams of temperature on the centerline and the wall along the combustor length. In this section, the inlet air temperature is also equal to 300 ºK and u=1.5 m/s.

(a) (b)

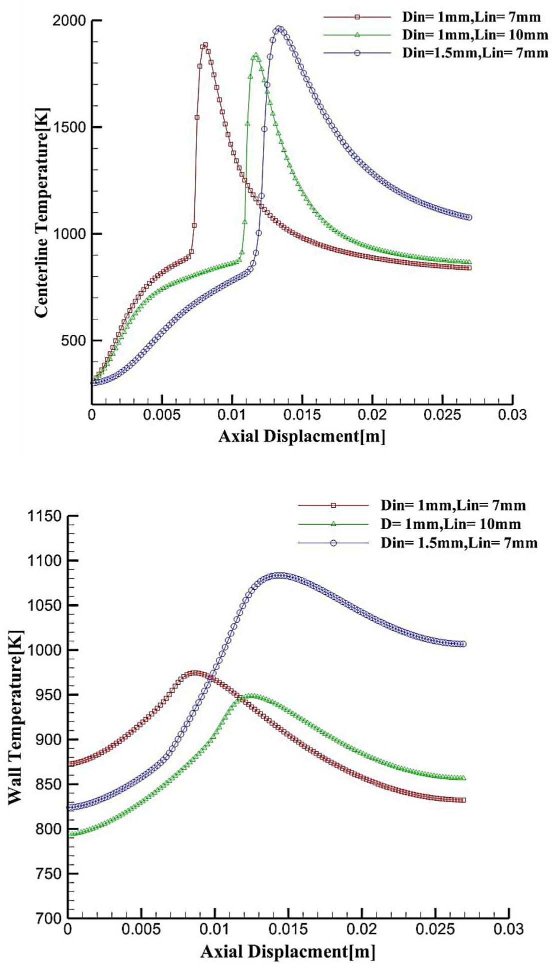


Fig 7. Diagrams of temperature on: (a) the centerline and (b) the wall of the studied combustor for u=1.5 m/s and inlet air temperature of 300 ºK in different geometries

It is clear from figure 7(a) that in a constant inlet diameter, the flame is blown downstream in the geometry with larger inlet length and generally, the flame is anchored after the step. It is also observed that the temperature gets a higher peak value in the geometry with less inlet length; of course, the difference is not significant. At the end of the chamber, the centerline temperature is higher for the geometry with larger inlet length compared to the geometry with less inlet length, although the maximum temperature is lower for the first case. The reason is that since the flame is anchored further from the entrance, the time of heat transfer with the ambient is shorter in the geometry with the larger inlet length.

The next point is that by increase in the inlet and main diameters in the geometry with D_{in}=1.5 mm, D=3 mm and L_{in}=7 mm, the flame is blown downstream, keeping constant the inlet and main lengths. This movement is greater than the corresponding value for the geometry having an inlet length of more than L_{in}=10 mm. In addition, the maximum temperature in this geometry is placed t a higher level than a geometry with smaller diameter. It is can also be seen from the diagrams that in the geometry with larger diameter, the slope of the centerline temperature is firstly less than the other two geometries, meaning that in the geometry with larger diameter, the inlet mixture is preheated at a lower rate. This is due to increasing of time interval between the center and the wall on one hand, and on the other hand, increasing of the inlet flux and the amount of fuel that need more heat.

At the end of the combustor, the centerline temperature is placed at a higher level with a significant difference, which is due to both the short time after flame formation and the greater time scale of heat transfer with the ambient in the geometry with larger diameter.

It can be seen from figure 7(b) that the wall temperature for the geometry with larger inlet length is firstly lower than the geometry with less inlet length, since the preheating is longer in the geometry with a larger inlet length. It can also be observed that we have the maximum temperature on the wall at the place where the flame is anchored. Thereafter, the wall temperature in the geometry with larger inlet length gets a higher level compared to the geometry with less inlet length, which is due to having less time for heat transferring to the ambient.

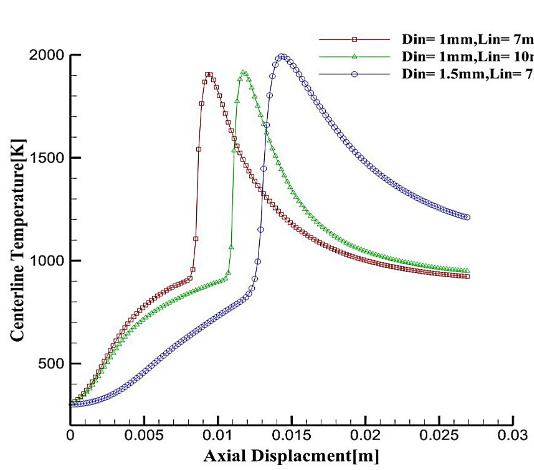
It is also observed that despite the initial lower wall temperature level in the larger-diameter geometry compared to the geometry with smaller diameter, the wall maximum temperature considerably gets a higher level in the larger-diameter geometry that is due to the higher flame temperature caused by greater corresponding inlet flux.

In the larger-diameter geometry, the wall temperature at the end of the combustor is significantly higher than other geometries and in general, the difference between maximum and minimum temperatures of the wall has a greater value in the geometry with larger diameter, while the wall temperature is relatively uniform in the smaller diameter. This difference is equal to 360 ºK for the geometry with inlet diameter of D_{in}=1.5 mm and is approximately equal to 100 ºK for the geometry with inlet diameter and length of D_{in}=1 mm and L_{in}=7 mm, respectively.

3.2 Results of Investigation in u=2 m/s

Investigated in this section is the results of a hollow cylinder having inlet diameter of D_{in}=1 mm, main diameter of D=2 mm, and inlet lengths of L_{in}=7 mm, and 10 mm as well as a geometry with inlet diameter of D_{in}=1.5 mm, main diameter of D=3 mm, and inlet length of L_{in}=7 mm in the inlet air velocity of u=2 m/s. The total length of all the three geometries is equal to L_t=27 mm. Figure 8 illustrates the diagrams of temperature on the centerline and the wall along the studied combustor length for the mentioned geometries. Again in this section, the inlet air temperature is equal to 300 ºK and u=2 m/s.

(a) (b)



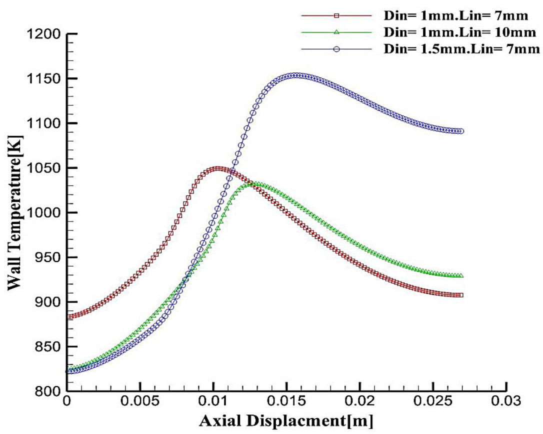


Fig 8. Diagrams of temperature on: (a) the centerline and (b) the wall of the studied combustor for u=2 m/s and inlet air temperature of 300 ºK in different geometries

It can be found in figure 8(a) that for the geometry with inlet diameter of D_{in}=1 mm, the flame is anchored further from the entrance in the geometry having larger inlet length (L_{in}=10 mm). In fact, also in this velocity, the flame is formed after the step in all geometries. However, for geometries of same diameter and different inlet lengths, the peak temperature of the centerline does not differ and is identical. Moreover, at the end of the combustor, the centerline temperature is slightly higher for larger inlet length. Actually, increasing of the combustor inlet length in this velocity only causes delay in the flame formation.

In the case of the geometry with inlet diameter of D_{in}=1.5 mm, main diameter of D=3 mm, and inlet length of L_{in}=7 mm, it should be said that despite the identical inlet length to the geometry with D_{in}=1 mm, the flame is blown downstream again. In fact, increase in the inlet diameter results in delayed flame formation so that, the combustor may experience flame jump and extinction by continuing this process. The maximum temperature on the centerline for the larger-diameter geometry is slightly higher than the smaller, here as well.

As was said so far, due to the delay in flame formation and less opportunity for heat transfer with walls in geometry with larger diameter as well as the higher temperature in this geometry, the centerline temperature at the end of the combustor is noticeably higher. The difference between temperatures of the end of the combustor for the geometry with inlet diameter of D_{in}=1.5 mm and the geometry with inlet diameter of D_{in}=1 mm is about 300 °K.

As can be seen in figure 8(b) the wall temperature at the entrance of the combustor in the geometry with larger inlet length has a lower value compared to the geometry with the same diameter but less inlet length. The maximum temperature of the wall is approximately at a place where the flame is formed inside the combustor, thereafter, it decreases slowly to some extent. As the temperature reaches its peak value, the wall temperature gets a higher level in the geometry with larger inlet length and finally, it has a little difference in these two geometries.

In the case of the geometry with inlet diameter of D_{in}=1.5 mm, it should also be said that from the entrance to the flame formation place, the wall temperature is lower than the other two geometries that have smaller diameter. However, it increases by a steeper slope as the flame is anchored so that, the maximum wall temperature in this geometry differs from that of the two others about 100 °K. Finally, due to less opportunity for heat transfer between the wall and the ambient, the wall temperature gets a higher level in this geometry.

The difference between maximum and minimum wall temperatures for the geometry with inlet diameter of D_{in}=1.5 mm and the two other geometries with inlet diameter of D_{in}=1 mm is approximately between 150 – 200 °K and specifically, in the smaller-diameter geometry, the wall temperature is more uniform.

3.3 The results of investigation in u=3 m/s

In this section, we investigate the results of a hollow cylinder with inlet diameter of D_{in}=1 mm, main diameter of D=2 mm, and inlet lengths of L_{in}=7 mm, and 10 mm as well as a geometry with inlet diameter of D_{in}=1.5 mm, main diameter of D=3 mm, and inlet length of L_{in}=7 mm, but in an inlet air velocity of u=3 m/s. The total length of all the three geometries is equal to L_t=27 mm. Figure 9 depicts the diagrams of temperature on the centerline and the wall along the studied combustor length for the mentioned geometries. In this section, the inlet air temperature is equal to 300 ºK and u=3 m/s.

(a) (b)

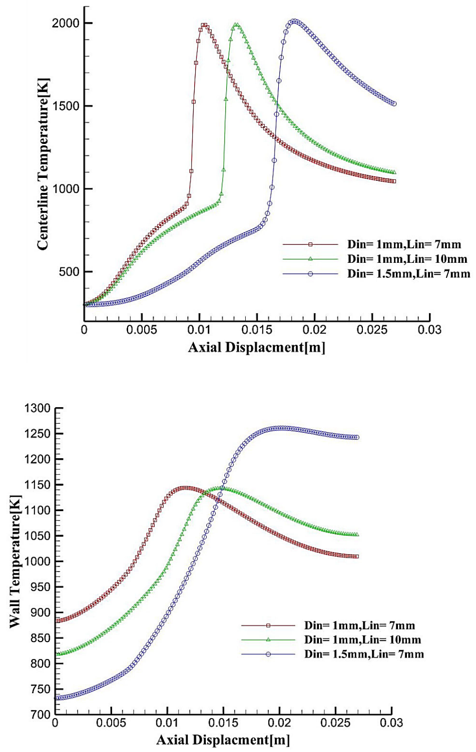


Fig 9. Diagrams of temperature on: (a) the centerline and (b) the wall of the studied combustor for u=3 m/s and inlet air temperature of 300 ºK in different geometries

It is clear in figure 9(a) that the flame is anchored after the step that for the geometry with inlet diameter of D_{in}=1 mm and inlet length of L_{in}=10 mm, the flame is anchored further from the combustor entrance as compared to the geometry with the same diameter but inlet length of L_{in}=7 mm. Also in this velocity, the peak temperature of the centerline is the same for both geometries. In fact, in higher velocities, increasing of the combustor inlet length without changing of other geometrical characteristics only causes delay in the flame formation. Of course, it may lead to flame extinction from somewhere onwards. Nevertheless, this increase in the length causes the temperature getting higher level at the end of the chamber.

Another point that can be drawn from the diagram is that in u=3 m/s, the maximum centerline temperature for the geometry with inlet diameter of D_{in}=1.5 mm, main diameter of D=3 mm, and inlet length of L_{in}=7 mm is equal to that of the geometry with inlet diameter of D_{in}=1 mm and different inlet length. In other words, there is no difference between the geometries in this velocity in terms of maximum centerline temperature, which could also be the same flame temperature.

It can be seen that in this velocity, increasing of diameter in the geometry with inlet diameter of D_{in}=1.5 mm has caused delay in the flame formation in such a way that, the flame has been drawn to the end of the combustor. Increasing of diameter or velocities greater than this value (i.e. u=3 m/s) may cause a flame jump and eventually extinction, in turn.

There is also a significant difference for the centerline temperature at the end of the combustor between the geometry with inlet diameter of D_{in}=1.5 mm and the two other ones with D_{in}=1 mm, which is a result of the less time for heat transfer with the ambient in the geometry with larger diameter. This difference is about 500 ºK.

It is obvious from figure 9(b) in this velocity (i.e. u=3 m/s), that the wall temperature along the combustor length is placed at a higher level for the geometry with inlet diameter of D_{in}=1 mm in both inlet lengths. The maximum wall temperature for the two geometries is almost the same place of the flame formation and after that place, the wall temperature for the geometry with inlet length of L_{in}=10 mm gets a higher level compared to the geometry with L_{in}=7 mm. In this velocity, the difference between wall temperatures at the end of the combustor for the two mentioned geometries is slightly higher.

In the case of the geometry with inlet diameter of D_{in}=1.5 mm and inlet length of L_{in}=7 mm, despite that the wall temperature at the entrance is lower than the other studied velocities, by increasing of temperature at the area of the flame formation inside the combustor, its maximum temperature is placed higher than other geometries and velocities. At the end of the combustor, the difference of wall temperature for geometries with inlet diameters of 1.5 mm and 1 mm is about 200 ºK in both inlet lengths.

The difference between the maximum and minimum wall temperature for the geometry with inlet diameter of D_{in}=1.5 mm is about 520 ºK, which is greater than the corresponding values in the previous velocities. This means that at higher velocities, the effect of increase in the diameter is higher. This value for geometries with an inlet diameter of D_{in}=1 mm and inlet lengths of L_{in}=7 mm and L_{in}=10 mm is equal to 260 and 290 ºk, respectively.

Figure 10 presents temperature contour in terms of ºK in the entire micro-combustor for hollow cylinders with inlet diameter of D_{in}=1 mm, main diameter of D=2 mm, and inlet lengths of L_{in}=7 mm, 10 mm and a geometry with inlet diameter of D_{in}=1.5 mm, main diameter of D=3 mm, and an inlet length of L_{in}=7 mm. The total length of all the three geometries is equal to L_t=27 mm.

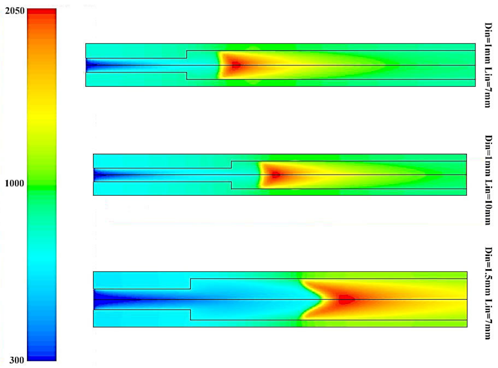


Fig 10. Temperature contour in terms of ºK in the entire micro-combustor for u=3 m/s in different geometries.

As can be seen from the contour shapes, in this velocity, the flame is anchored at the combustor center in all geometries and the maximum centerline temperature is actually the same flame temperature. It is also obvious that for an identical inlet diameter, larger inlet lengths results in delay in the flame formation.

It is found that increasing of diameter causes the flame to be moved to the end of the combustor and consequently results in more uniform wall temperature. It seems that further increase of the diameter makes the flame jump and extinct.

4. Conclusion

For any device such as micro-TPV generators that use radiation for energy generation, the issue of primary importance is radiation flux. I the present study, the wall is considered as a radiator, for which a radiation efficiency is defined. This efficiency is the ratio of the total radiation emitted from the entire wall in watts (W) on the total energy input to the system, which is specified from the high thermal value of methane and is obtained from the following equation:

$$\eta = \frac{\pi(D + 2t)\epsilon\sigma \sum_{i=1}^{N} T_{wo}^4 L_i}{\dot{m}_{CH4} H_C}$$

where, D is the combustor total diameter, t is the wall thickness, ϵ is radiation emission coefficient from the wall, σ is the Stefan-Boltzmann constant, and L_i is a part of the wall, in which the temperature can be considered uniform and equal to T_{wo} . In this equation, $\dot{m}_{CH4}$ represents methane inlet flux and H_C is the high thermal value of methane.

Figure 11 shows the diagram of radiation efficiency for inlet velocities of u=1.5 m/s, 2 m/s, and 3 m/s in hollow cylinders with inlet diameter of D_{in}=1 mm, main diameter of D=2 mm, and inlet lengths of L_{in}=7 mm, 10 mm and a geometry with inlet diameter of D_{in}=1.5 mm, main diameter of D=3 mm, and an inlet length of L_{in}=7 mm. The total length of all the three geometries is also equal to L_t=27 mm.

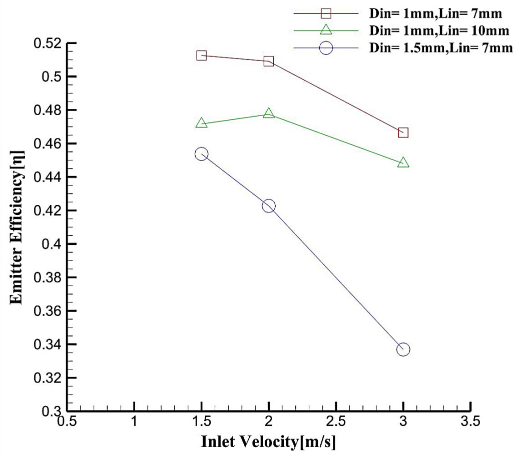


Fig 11. Diagram of radiation efficiency for inlet velocities of u=1.5 m/s, 2 m/s, and 3 m/s in the geometries studied

It can be seen from figure 11 that in all geometries, the radiation efficiency is decreased as the velocity increases, for which increasing of velocity is not a desirable process.

On the other hand, in the geometry having inlet diameter of D_{in}=1 mm and inlet length of L_{in}=7 mm, the highest radiation efficiency is obtained for all velocities. In other words, either increasing of the inlet length or increase in the diameter is considered as undesirable factors for radiation efficiency, although it leads to increase the flame temperature in some cases. Therefore, higher temperature is not necessarily associated with more efficiency in electrical energy generation through thermal radiation. In the case of using larger diameter, despite increasing of the area, in which thermal radiation is emitted and accordingly, increasing of the wall temperature, it also increases the input energy through burning of methane. Thus, all of this energy is not turned into radiation energy due to a variety of reasons including among them, the short length of the combustor, incomplete burning, etc., which leads to reduce the radiation efficiency.

In the case of the problem studied in this research, the highest level of radiation efficiency for all geometries is around the velocity of u=1.5 m/s, meaning that increasing of velocity does not lead to increase the efficiency. It can be observed that increased diameter significantly increases the variations of radiation efficiency relative to inlet velocities in such a way that, in the geometry with inlet diameter of D_{in}=1.5 mm and inlet length of L_{in}=7 mm, the radiation efficiency decreases sharply by increase in the velocity so that, at a velocity of u = 3m/s in this geometry, the radiation efficiency is significantly lower than the other points.

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