THE FLAME BROADENING IN A CYLINDRICAL MICRO-COMBUSTOR

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Abstract: In the present study a simple model of heat – recirculating cylindrical combustors is developed, by extending similar work carried out by T.T.Leach and C.P.Cadou [1].Attention is focused on the influence of the heat loss, the chamber radius and structure wall thickness. Special attention is devoted to the determination of flame speed in both adiabatic and non-adiabatic condition. Eventually the explicit expression is obtained for the flame speed in non-adiabatic condition as well as implicit equation for adiabatic condition. Moreover, it is shown that reducing the size of the combustor to sub-millimeter scale extremely increase the surface-to-volume ratio that leads to decrease flame speed and eventually results in flame quenching.

Keywords: Micro-Combustors, heat loss, chamber radius, wall thickness effect

INTRODUCTION

The technology of micro-scale combustion is a desirable, fast-growing and widespread research field, minimizing the size and weight of the portable power sources for micro electromechanical system (MEMS) devices, micro and Pico satellites have recently attracted extensive attention and desire among the researchers from around the world. Due to the fact that minimizing the size and weight of the satellite is a principal objective of the researches, special attention devoted to the miniaturizing of the satellites.

The performance of sub-millimeter thrusters for miniaturized satellites depends strongly on the efficiency and the power density of their sub-millimeter scale combustors. Reducing the size of the combustor to millimeter and sub-millimeter scale leads to large the surface-to-volume ratio that increases heat loss, which eventually results in the flame quenching. Heat recirculation through the structure of the combustor and heat loss to ambient are leading parameters in the combustion phenomena of a micro-combustor. This field has been widely investigated by some researchers. Ambatirudi and Rahman [2] analyzed the heat transfer in micro-channel heat sinks. In addition, Lee and Kwon [3] studied the heat transfer and quenching analysis of combustion in a micro combustion vessel. Daou and Matalon [4] investigated the effect of heat loss to the structure and passage width on premixed flames propagating in channels with constant-temperature walls. Ronney [5] studied non-adiabatic combustion in heat-recirculating combustors where heat from the post-flame region is transferred upstream to pre-heat zone. Hua et al. [6], In part I of their paper, performed the CFD numerical simulations to study the combustion of premixed hydrogen–air mixture in a series of chambers with same shape aspect ratio but various dimensions from millimeter to micron level. The effect of various heat transfer conditions at chamber wall, e.g. adiabatic wall, with heat loss and heat conduction within the wall, on the combustion was analyzed. In part II of this paper, the numerical modeling method developed to analyze the micro-combustion characteristics in a three-dimensional micro-combustor. In the recent analytical and numerical studies by Leach et al. they extended Mallard and Le Chatelier’s (1D) thermal flame [7] model to investigate the H2–air combustion in micro channels and noted that the heat exchange through the structure of the micro combustor leads to broadening of the reaction zone and they claimed that axial conduction of heat through walls plays a major role in determining the performance of micro-combustor.

This paper intends to extend leach et al.'s studies to determine the effects of heat loss on flame broadening through the micro scale combustor; besides that ,the effects of various parameters such as the chamber radius ,wall thickness are studied. as an improvement over leach et al.'s model, the explicit expression for the flame speed in non-adiabatic condition is concluded in the present study; moreover comparison is made between adiabatic and non-adiabatic flame broadening.

ANALYTICAL MODEL

Adiabatic condition

Based on the Mallard thermal model for flame propagation the freely propagating laminar flame speed and reaction zone thickness can be derived as follows:

$$S_L = \sqrt{\frac{k_r}{\rho_r c_p} \frac{T_f - T_i}{T_i - T_\circ} RR} \tag{1}$$

$$\delta_r = \sqrt{\frac{k_r}{\rho_r c_p} \frac{T_f - T_i}{T_i - T_\circ} \frac{1}{RR}} \tag{2}$$

in the present study, the heat transfer between the mixture and the structure of combustion chamber is considered as well as the diffusion through the mixture in the chamber. This process is composed of three stages:

1. Heat convection from gas mixture to its surrounding in the post flame zone.
2. Heat conduction through the chamber structure.
3. Heat convection from the structure to the gas mixture in the preheat zone.

Thermal resistor network for visualizing heat exchange between mixture and structure, and also heat loss to the environment is shown in Figure (1).

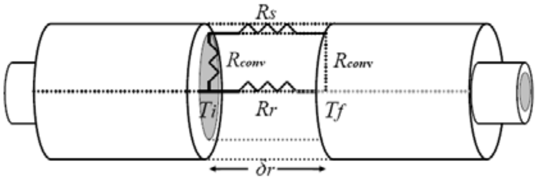

Fig. 1: Adiabatic thermal resistor network.

The thermal resistances can be expressed as follow:

$$R_s = \frac{\delta_r}{k_s \pi (r^2 - r_o^2)} \tag{3}$$

$$R_r = \frac{\delta_r}{k_r \pi r_o^2} \tag{4}$$

$$R_{conv} = \frac{1}{k_r Nu\, \pi r_o} \tag{5}$$

Where r_o, r, k_s and Nu are, the inner and outer chamber radius , structure thermal conductivity and Nusselt number, respectively. The effective thermal resistance of the thermal circuit defined as:

$$R_{eff}^{-1} = \left(2R_{Conv} + R_S\right)^{-1} + R_r^{-1} \tag{6}$$

Applying conservation of energy to the thermal circuit illustrated in Figure (1) leads to the following expression for the rate of conductive heat transfer:

$$\frac{T_f - T_i}{R_{eff}} = \rho_r \pi\, r_o^2 \delta_r \cdot RR \cdot C_P (T_i - T_o) \tag{7}$$

Therefore the flame speed and reaction zone thickness can be derived as follows:

$$S_L = \sqrt{\zeta \frac{k_r}{\rho_r c_p} \frac{T_f - T_i}{T_i - T_\circ} RR} \tag{8}$$

$$\delta_r = \sqrt{\zeta \frac{k_r}{\rho_r c_p} \frac{T_f - T_i}{T_i - T_\circ} \frac{1}{RR}} \tag{9}$$

Where ζ is the parameter that shows the change in the overall thermal resistance for flame propagation in micro combustor in comparison with (1) and (2) for freely flame broadening, and denoted by:

$$\zeta = 1 + \left(\frac{2r_o}{Nu\,\delta_r} + \frac{r_o^2}{\lambda \left(t^2 + 2r_o t\right)} \right)^{-1} \tag{10}$$

Non-adiabatic condition

In non-adiabatic condition, the heat loss to environment has a great effect on flame broadening in micro scale combustors due to their large surface to volume ratio which leads to more heat loss to surrounding. This effect can be shown in thermal circuit by adding thermal resistance of heat loss to adiabatic thermal network. Therefore the rate of conductive heat transfer from reaction zone to pre-heat zone can be defined as:

$$\overset{\circ}{q} = \overset{\circ}{q}_{gen} - \overset{\circ}{q}_{loss} \tag{11}$$

Where $\dot{q}_{gen}$ and $\dot{q}_{loss}$ are the heat generated by chemical reaction and heat loss to environment respectively. They are represented as follows:

$$\overset{\circ}{q}_{gen} = \overset{\circ}{q}_{gen,ad} \exp\left(\frac{E_a}{T_{f,ad}} - \frac{E_a}{T_f}\right) \tag{12}$$

$$\overset{\circ}{q}_{loss} = \frac{T_{s1} - T_e}{R_{loss}} \tag{13}$$

Where E_a, and R_{loss} are the activation energy of one-step stoichiometric methane-air combustion and heat loss thermal resistance, respectively. Heat loss thermal resistance is defined as:

$$R_{Loss} = \frac{\ln(\frac{r}{r_o})}{2k_s\pi\,\delta_r} + \frac{1}{h_e 2\pi r\,\delta_r} \tag{14}$$

T_{s1} is the inner wall temperature and is derived by using the energy conservation for non-adiabatic thermal circuit which is shown in figure (2).

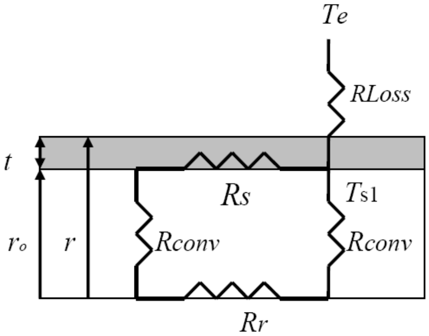

Fig. 2: schematic diagram of a non-adiabatic thermal resistor network

$$T_{s1} = \frac{T_f(R_{conv}+R_s) - T_i R_{conv} R_{loss} - T_e R_{conv}(R_{conv}+R_s)}{R_s R_{loss} - R_{conv}(R_{conv}+R_s)} \tag{15}$$

By considering flame temperature as fallow the generated heat of the combustion and the reaction rate are denoted as following expressions:

$$T = K\,T_{f,ad} \qquad 0<K<1 \tag{16}$$

$$\overset{\circ}{q}_{gen} = \frac{T_{f,ad} - T_i}{R_{eff}}\ \exp\left(\frac{E_a}{T_{f,ad}}\left(1-\frac{1}{k}\right)\right) \tag{17}$$

$$RR = RR_{add}\ \exp\left(\frac{E_a}{RT_{f,ad}}\left(1-\frac{1}{k}\right)\right) \tag{18}$$

Applying conservation of energy for the non-adiabatic thermal network and substituting (12)-(18) into energy equation yield the following third order polynomial equation :

$$c\delta_r^3 + d\delta_r^2 - (\beta ac + b)\delta_r - \beta ad = 0 \tag{20}$$

Since βad is proportional to the square power of reactant mixture thermal conductivity and its quantity is smaller than the structure thermal conductivity, this parameter is negligible in comparison with other parameters in equation (20).therefore, this equation is derived as a following second order polynomial equation:

$$c\delta_r^2 + d\delta_r - (\beta ac + b) = 0 \tag{21}$$

Where parameters a ,b ,c ,and d are defined as follows:

$$a = k_r r_o^2 \tag{22}$$

$$b = k_r^2 \lambda\ Nu\ r_o(t^2 + 2r_o t) \tag{23}$$

$$c = k_r Nu\ r_o \tag{24}$$

$$d = 2k_r \lambda (t^2 + 2r_o t) \tag{25}$$

Therefore δ_r and consequently, the flame speed can be derived from the equation (21) as follows*:*

$$\delta_r = \sqrt{\frac{\lambda^2}{Nu^2}\left(\frac{t^2+2r_o t}{r_o}\right)^2 + (k_r\beta\, r_o^2 + \lambda(t^2+2r_o t))} - \frac{\lambda}{Nu}\left(\frac{t^2+2r_o t}{r_o}\right) \tag{26}$$

$$S_L = RR\left[\sqrt{\frac{\lambda^2}{Nu^2}\left(\frac{t^2+2r_o t}{r_o}\right)^2 + (k_r\beta\, r_o^2 + \lambda(t^2+2r_o t))} - \frac{\lambda}{Nu}\left(\frac{t^2+2r_o t}{r_o}\right)\right] \tag{27}$$

DISCUSSION

Figure 3 shows the variation of parameter ζ as a function of the chamber radius for different Nusselt numbers under adiabatic structure condition.From this figure, the parameter ζ and as a consequence the non-dimensional flame broadening increase due to decreasing the chamber radius. Moreover, the rise in the Nusselt number which is the strength of thermal coupling between the fluid and the structure results in the augmentation in the parameter ζ and consequently the dimensionless flame speed. In addition, at either *Nu* = 0 or large chamber radius, the flame propagation behavior is akin to the freely flame propagation. This implies that ζ = 1 which indicates the adjustment of the flame propagation model in the combustors with the Mallard model.

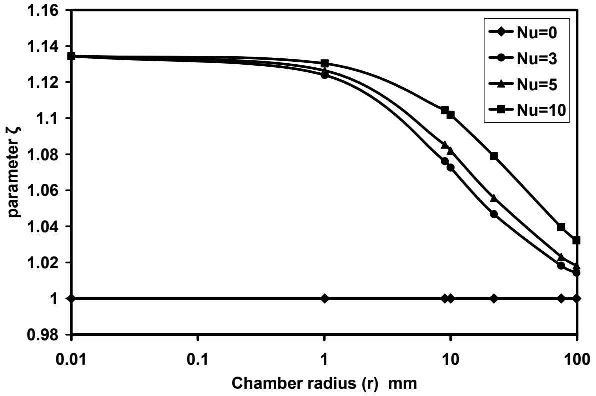

Fig. 3:Variation of parameter ζ as a function of the chamber radius for a range of Nusselt numbers

Figure 4 illustrates the variation of non-adiabatic flame speed for different ranges of parameter *k,* and the stochiometric combustion of methane and air with the certain initial conditions $,K_r = 0.035\ K_s = 31.2$ $T_0 = 300K, T_{f,ad} = 2223K, he = 1\ w/m^2K$ in the silicon combustor, Parameter *k* is a criterion denoting the non-adiabatic condition which means that when this parameter soars, the chamber condition is too close to the adiabatic condition and hence the higher flame speed is achieved. As seen, there is a considerable difference between the non-adiabatic propagation compared to the adiabatic propagation. This implies that although in the adiabatic condition, the parameter ζ and finally the non-dimensional flame broadening soar due to decreasing the chamber radius, in the non-adiabatic condition, a decrease in the chamber radius leads to the increase in the surface to volume ratio and as a result, increase in the heat loss from the structure which accordingly results in decreasing the flame speed. A major barrier for developing a practical micro-combustor is the increase in its surface to volume ratio.

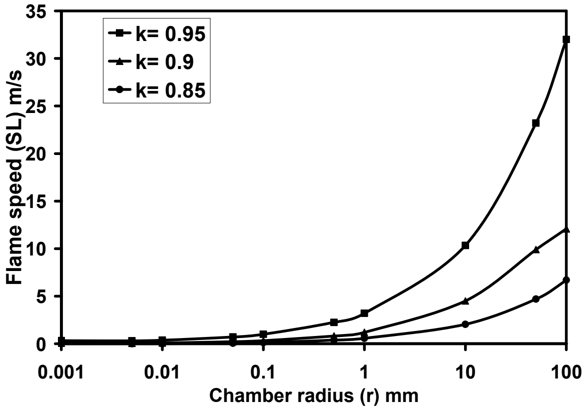

Fig. 4:Variation of the non-adiabatic flame speed as a function of the chamber radius for a range of parameters k

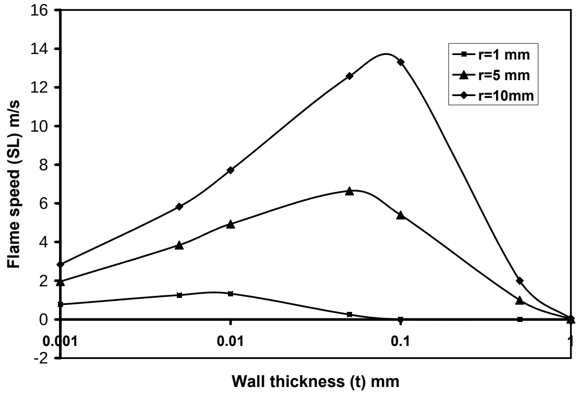

Fig. 5: Variation of the non-adiabatic flame speed as a function of the wall thickness for a range of chamber radiuses

Figure 5 clarifies the changes in the non-adiabatic flame speed versus the combustor wall thickness. As observed in this figure, the non-adiabatic flame speed goes up and down due to increasing the wall thickness. The critical value of non-adiabatic flame speed is dependent to the chamber radius and parameter *k*.

CONCLUSION

In summary, a simple analytical model was developed to analyze the heat recirculation phenomena in the cylindrical micro combustors, by applying the thermal network, visualizing heat transport to preheat zone and heat loss to ambient; we investigated the effect of chamber radius and combustor wall thickness. It is concluded that the high surface to volume ratio of a miniaturized combustor is a major barrier for developing a practical micro-combustor.

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