

Modeling of spiral counterflow heat recirculating combustors for MEMS application

Emre Özgül¹, Bayindir H. Saracoglu¹, Hasan Bedir*¹

¹Bogazici University Mechanical Engineering Department

Abstract

A two-dimensional numerical model is generated to investigate the micro-scale combustion and the extinction limits in such combustors. The Swiss roll type of spiral counter current heat recirculation combustor is modeled by unwrapping for the sake of simplicity. The diffusion of heat among the walls is simulated by using heat fluxes and transporting them throughout the geometry. The effects of Reynolds number, equivalence ratio on the temperature distribution and chemical reaction rate are investigated. Also, the extinction limits of propane-air, methane-air, ethane-air and butane-air mixtures are calculated.

Introduction

More than 30 years ago, the heat recirculating burners were studied in order to burn very lean mixture which couldn't be burned by conventional means and reduce the amount of pollutant emission of the combustion reactions [1].

A thermodynamic model was constructed for a spiral counter current excess enthalpy burner by Lloyd et. al.[2], and the thermodynamic efficiency of the combustor was calculated. The experimental data were also collected in the study. It was concluded that for all practical purposes there are no limits of flammability for combustion, when heat circulation is not accompanied by simultaneous dilution of the reactants with products.

The effect of heat recirculation in a combustor to expand the flammability limits of a mixture was studied by using global energy balance in the model of Jones et al.[3]. The model included the effects of global heat generation, recirculation and loss to interpret the extinction limits, however it was primitive to obtain quantitative achievements.

An experimental study on small scale excess enthalpy burners was made by Sitzki et. al.[4] with small size combustors. It was found that combustion could be sustained in a low-temperature "flameless" mode in which no visible flame occurs. The addition of catalytic materials in the combustion region was found to either increase or decrease the range of butane-air or propane-air flammable mixtures, by substantial amounts in both cases, depending on the Reynolds number. It was proved that; with catalysts, the extinction limits narrow at higher Reynolds numbers but broaden substantially at lower Reynolds number, which are the conditions most relevant to microscale combustion. They also indicated that, combustion in microscale combustion devices at low Reynolds numbers is possible, but requires heat recirculation via the "Swiss roll" or similar heat exchanger geometries, as well as catalytic combustion.

Vican et. al. [5] introduced a micro reactor based on "Swiss roll" combustion chamber. The burning behavior of hydrogen - air mixtures of equivalence ratios of 0.2 to 1.0 is observed. A layer of catalyst (platinum) was deposited inside channels of "Swiss roll" in order to reduce the range of operating temperatures. A global energy balance model was developed to analyze overall reactor performance characteristics. The study has shown that because of the small length scales and flow rates involved in the micro reactor, a nearly uniform reactor body and gas flow temperature was obtained.

The limits to self-sustaining catalytic combustion in a micro-scale channel were studied computationally using a cylindrical tube reactor by K. Maruta [6]. They showed that, when the wall boundary condition was adiabatic, the equivalence ratio at the extinction limit monotonically decreased with increasing Re. In contrast, for non adiabatic conditions the extinction curve exhibited U-shaped dual limit behavior, that is, the extinction limits increased/decreased with decreasing Re in smaller/larger Re regions, respectively. They also found that by diluting the mixture with N₂ rather than air, the fuel concentration and peak temperatures at the limit decreased substantially for mixtures with fuel to oxygen ratios even slightly rich of stoichiometric due to a transition from O(s) coverage to CO(s) coverage.

A first-principles model of counter-current heat-recirculating combustors was developed by Ronney [7]. The study includes the effects of heat transfer from the product gas stream to the reactant stream, heat loss to ambient and heat conduction in the stream wise direction through the dividing wall between the reactant and product streams. It was shown in the article that the stream-wise conduction through the dividing wall is a significant factor on extinction limit of the flame, especially at small dimensionless mass fluxes or Reynolds numbers that would be characteristics of micro scale devices. It was also noted that, the wall conduction is not only a heat loss mechanism;it also re-distributes thermal

*Corresponding author: bedirhas@boun.edu.tr

energy within the counter- current heat- recirculating combustor.

Cui and Matalon [8] have investigated numerically the flame propagation in channels and cracks. The results showed that unlike thin flames, known to be affected by the effective Lewis number of the mixture, in narrow channels Lewis number effects are negligible. Also it was shown that; as a result of heat losses to the walls the burning rate is generally reduced; in narrow channels the flame may be totally extinguished when the losses become excessive, but in wide channels there is only local extinction near the walls with the flame surviving at the center.

In another study [9], the characteristics of micro scale combustion were investigated experimentally by using a micro channel heated by an external source by Maruta and Parc. Methane-air mixture was used for investigations. The effects of the equivalence ratio and the averaged flow velocity on the characteristics of combustion in the micro channel were examined. Oscillatory combustion was observed at moderate equivalence ratios and lower velocity conditions within the flammability region. A simple analytical model predicting flame oscillations on the basis of the linear analysis of steady solutions was proposed. Results showed that; stable combustion can successfully be attained even for mixtures with equivalence ratios outside the conventional flammability limits. It was also shown that; in addition to the steady flame, combustion was also observed for low velocities of the flow. It was also noted that; the stationary stable combustion modes predicted by the theory are observed experimentally.

Chen and Buckmaster [10] propose a 2D model for "Swiss Roll" micro-scale combustor. In their model the combustor geometry was unwrapped in a straight tube in the middle of which combustion occurs. The original combustor has a rectangular geometry as in Ahn's experimental setup [11]. The heat diffusion from the walls, chemical reaction and heat transfer were considered in the model. As a result of the paper, while Reynolds number or equivalence ratio increases, the reaction rate increases and the flame front moves away from the center towards the inlet.

Suzuki and Horii [12] have investigated micro-scale catalytic combustion of butane in their study. A ceramic combustor with an embedded ignition heater was also designed and its prototype was fabricated using a high- precision tape-casting technology. The Pt/alumina catalyst layer was successfully integrated onto a ceramic micro channel. In this study, Suzuki and Horii have shown that the system works well for catalytic combustion of butane.

Kim and Kato [13] investigated the combustion characteristics of a small Swiss-roll combustor that was used as a heater. Three types of Swiss-roll combustors of different designs and two cases of heat transfer conditions were studied. Kim and Kato

showed that when the combustor becomes smaller, even though convective heat transfer becomes larger compared with the radiant heat loss for the same temperature; it requires a higher temperature for flame stabilization. They also stated that, a flame can be stabilized in a much smaller Swiss-Roll combustor only if the wall temperature of the combustor is sufficiently high. The temperature of the combustor can be controlled by controlling the equivalence ratio or the mean velocity. They also proved that the mean temperatures and the flammable limits of the combustors are governed by both the radiant heat loss from the combustors and the total chemical energy introduced into the combustors.

The experiments conducted by Ahn et. al. [11] showed the characteristics of heat - recirculating "Swiss Roll" square meso-scale, where the length scale of the medium is comparable with quenching distance, burners with the dimensions of 7 cm by 7 cm by 5 cm. the channel height of the combustor is 3.5 mm. The study investigated the extinction limits of the burner for gas - phase and catalytic combustion modes, burner temperatures. It showed that the presence of the platinum catalyst broadens the extinction limits in both lean and rich boundaries.

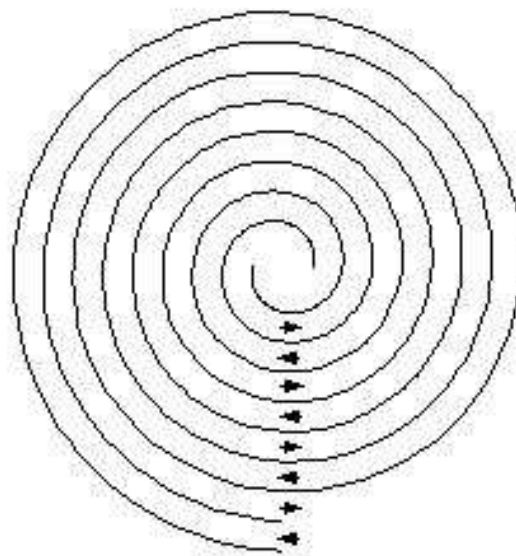


Figure 1: The geometry of the burner.

Governing Equations

The governing equations for steady, two dimensional flow of ideal gas with constant properties are given as follows.

$$(\rho u)_x + (\rho v)_y = 0 \quad (1)$$

$$(\rho u u)_x + (\rho v u)_y = (\mu u_x)_x + (\mu u_y)_y - p_x$$

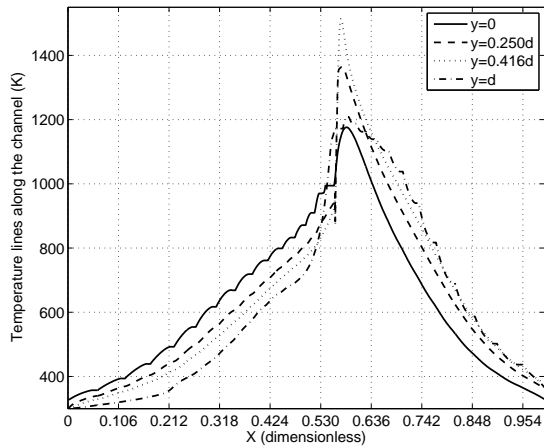


Figure 2: Temperature distribution at several channel heights $\phi = 0.41$, fuel is propane.

$$+(\mu/3)u_{xx} - (2\mu/3)v_{yx} + \mu v_{xy} \quad (2)$$

$$(\rho uv)_x + (\rho vv)_y = (\mu v_x)_x + (\mu v_y)_y - p_y + \mu u_{yx} + (\mu/3)v_{yy} - (2\mu/3)u_{xy} \quad (3)$$

$$\rho c_p (uT_x + vT_y) = k(T_{xx} + T_{yy}) - \sum h_i \dot{w}_i \quad (4)$$

$$(\rho u Y_i)_x + (\rho v Y_i)_y = (\rho D Y_{ix})_x + (\rho D Y_{iy})_y + \dot{w}_i \quad (5)$$

In the equations radiative heat transfer is neglected and chemistry is modeled with a one step global chemical reaction. The reaction rate \dot{w}_i is given by the phenomenological reaction rate expression;

$$\dot{w}_i = (v_i'' - v_i') B T^\alpha e^{(-E/RT)} \prod_{j=1}^N \left(\frac{X_j p}{RT} \right)^{v_j'} \quad (6)$$

Global reaction constants for fuels that are used in this study are illustrated in table 1.

| Fuel | B | E | v'_{fuel} | $v'_{oxidizer}$ |
|---------|---------------------|------|-------------|-----------------|
| Butane | $7.4 \cdot 10^{11}$ | 30.0 | 0.15 | 1.6 |
| Propane | $8.6 \cdot 10^{11}$ | 30.0 | 0.1 | 1.65 |
| Ethane | $1.1 \cdot 10^{12}$ | 30.0 | 0.1 | 1.65 |
| Methane | $1.3 \cdot 10^9$ | 48.4 | -0.3 | 1.3 |

Table 1: Global Reaction constants for fuels (unit of E is kcal/mole)

The governing equations are solved numerically. The spiral geometry (see figure 1) is unwrapped into a straight channel. Energy balance equations are written for the inner and outer walls which take into

account the heat flux to or from adjacent channels of the burner. The equations are discretized for the resulting rectangular domain. A similar unwrapping procedure was used by Chen and Buckmaster [10] for a rectangular Swissroll type burner.

Results and Discussion

In the heat recirculating spiral burner; the fresh fuel-oxidizer mixture flows through the rolls in the channels towards the center. The temperature of incoming mixture is progressively raised by the heat flux coming from the hot walls. Hence, by the time the fresh mixture arrives at the center of the burner, it has a considerably higher temperature relatively to the inlet value. Figure 2 shows the temperature distribution through the streamwise direction, at several channel heights. The wall temperature profiles ($y=0$ and $y=d$) have regions where the temperature is constant due to the unwrapping process as explained by Chen and Buckmaster [10].

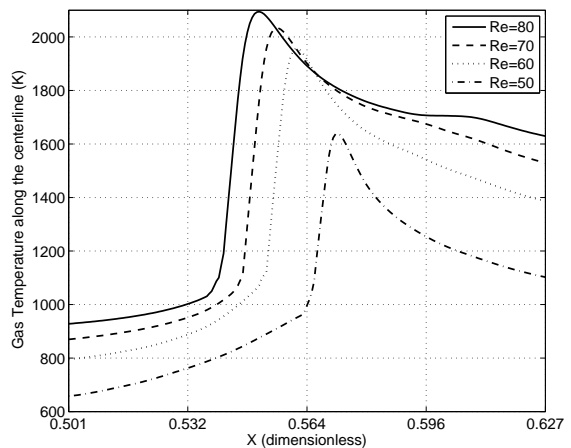


Figure 3: Effect of Reynolds number on gas temperature along the centerline.

After combustion at the center, the hot burnt product flows out of the burner through the exit channels. Furthermore, it transfers heat to the bounding walls along the way. Hence, the temperature of the walls separating incoming and outgoing streams are increased and so the temperature of the incoming stream.

The effect of increased mixture flowrates on the temperature is investigated and shown in figure 3 for Reynolds numbers of 60-80 based on channel height an inlet velocity. The fuel is propane and the equivalence ratio is selected as $\phi = 0.58$. This value is chosen because, it is the extinction limit of propane for $Re=50$ in the burner. As it is seen easily from the figure 3; an increase in Reynolds number results in an increase in gas temperatures.

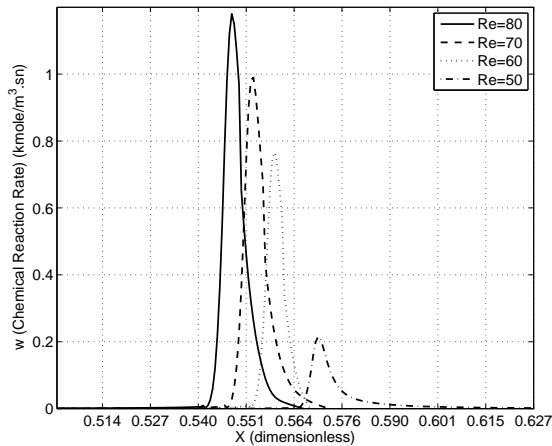


Figure 4: Effect of Reynolds number on reaction rate along the centerline.

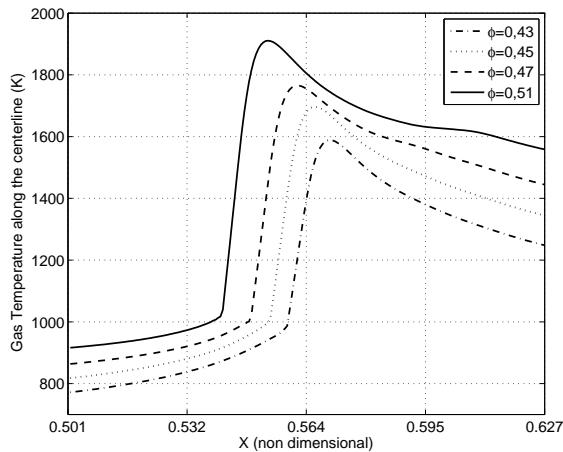


Figure 5: Effect of equivalence ratio on gas temperature along the centerline for propane-air mixture.

The chemical reaction rates at the central part of the burner are shown in figure 4 corresponding to the cases presented in figure 3. The reaction rate as expected increases with the increased mixture flow, moreover the reaction zone moves towards the inlet when the Reynolds number is increased. This is due to the increased heat recirculation at higher Reynolds numbers. Temperature gradient between the walls and the gas is much more than the gradient of gas temperature in streamwise direction; hence the recirculating heat flux from the wall is important. Besides; higher mass flow rate also means more fuel and oxidizer advancing to the center which increases the heat release rate.

The effect of equivalence ratio on the temperature distribution and chemical reaction rate is also investigated. For observing the effect; different equivalence ratios;

($\phi = 0.43$, $\phi = 0.45$, $\phi = 0.47$ and $\phi = 0.51$) are used. The Reynolds number is taken as $Re=100$. The gas temperature profiles are shown in figure 5, and chemical reaction rate profiles are shown in figure 6. As expected; the increase in equivalence ratio results in an increase of the gas temperature peak value. As the equivalence ratio increases, heat recirculation is also enhanced because of increased total energy release. Hence; the gas temperature and the wall temperature become higher which helps preheating.

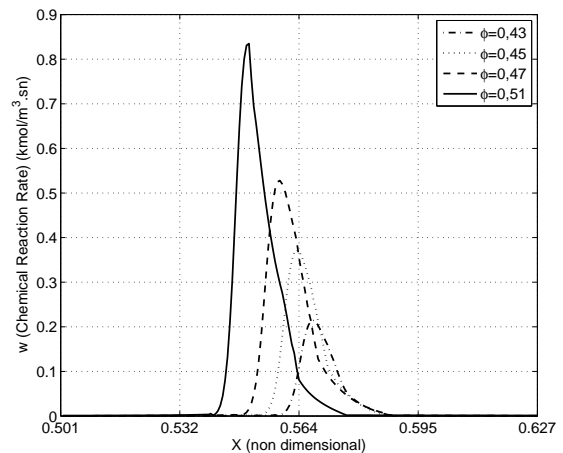


Figure 6: Effect of equivalence ratio on reaction rate along the centerline for propane-air mixture.

A shift of reaction zone towards the inlet is observed similar to the increase of Reynolds number case. As the heat release and consequently the heat recirculation is increased with the equivalence ratio (notice that the equivalence ratio is kept below the stoichiometric ratio) the reaction zone shifts from the center to the upstream.

In figure 7, gas phase temperature along the centerline is shown for different fuel-air mixtures at the same equivalence ratio ($\phi = 0.49$) and Reynolds number ($Re=100$). As it is seen in the figure 7, higher temperature values are obtained for the mixtures of which the fuel has higher heating value. The chemical reaction rates for the same fuel-air mixtures are shown in figure 8. The reaction rate peak value is different for each mixture and it is maximum for the fuel with the highest peak gas temperature and smallest for the fuel with smallest peak gas temperature. The combustion zone is also located at different places, similar to the previous cases it again changes with the heat recirculation. When the heat recirculation is higher (for butane-air mixture) the reaction zone is at a more upstream location, when the heat recirculation is relatively smaller (for methane-air mixture) the reaction zone is at a location more downstream.

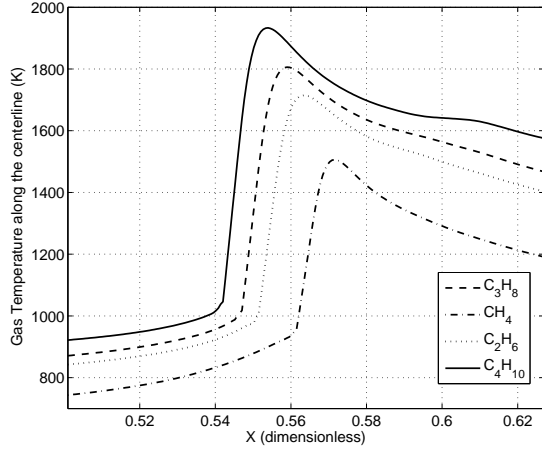


Figure 7: The gas temperature along the centerline at same equivalence ratio ($\phi = 0.49$) and $Re = 100$.

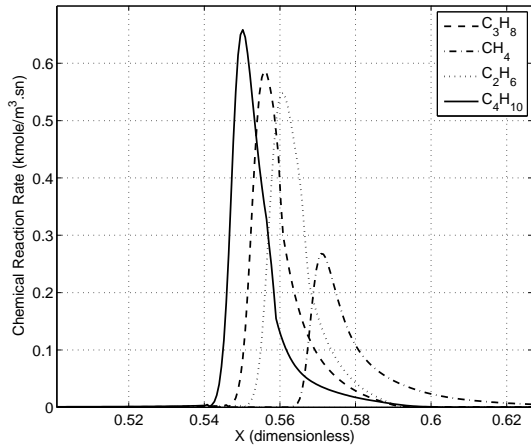


Figure 8: Chemical reaction rate for fuels burned at same equivalence ratio ($\phi = 0.49$) and $Re = 100$.

The extinction limit equivalence ratios as a function of Reynolds number for different fuel-air mixtures in the heat recirculation spiral burner are shown in figure 9. For all the fuels the equivalence ratio at the extinction limit decreases when the Reynolds number increases. Due to higher heat recirculation at higher Reynolds numbers the fuel-air mixtures are able to sustain combustion at leaner mixtures. When the extinction limit for different fuel-air mixtures at the same Reynolds number are compared, it is seen that fuels with higher heating values have lower equivalence ratio at extinction limit. The increased heat release for these fuels as explained before leads to an increased heat recirculation and hence the flammable region for these fuels are wider.

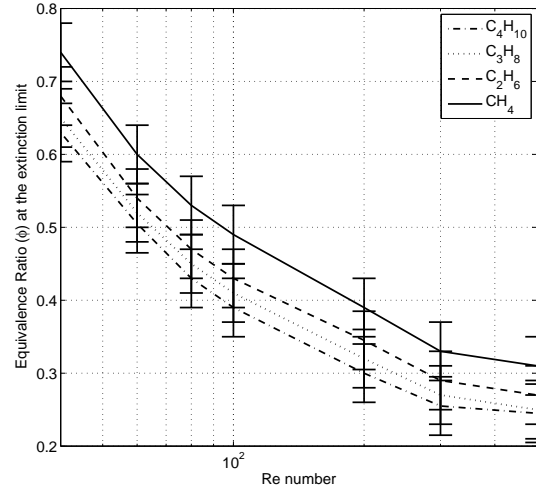


Figure 9: The comparison for the extinction limits of methane-air, propane-air, butane-air and ethane-air mixtures.

Conclusions

In this study a simplified model is generated to simulate the heat transfer and combustion in a heat recirculating spiral burner by unwrapping the geometry into a straight channel. The model incorporates two-dimensional momentum, continuity, energy, and species equations.

Effects of Reynolds number, equivalence ratio, fuel type on the temperature distribution and chemical reaction rate are investigated. For the range of Reynolds numbers and equivalence ratios examined in the present work; it is found that, higher values of Reynolds number or equivalence ratios result an increase in the reaction rate and peak temperature values. Also, the reaction zone moves from center to upstream direction. The main reason for that event is, the increase of heat recirculation when the Reynolds number or equivalence ratio increase.

Four different fuels are used in the present study. Fuel lean propane-air, methane-air, ethane-air and butane-air mixtures are selected. In the simulations, it is observed that, butane-air mixtures has the highest peak temperature value, and the methane-air mixtures has the smallest peak temperature under same conditions. Fuels with higher heating value have reaction zones at more upstream locations.

The extinction limits for different fuel-air mixtures in the burner are calculated. It is found that the equivalence ratio at the extinction limit decreases with the Reynolds number for all fuels studied. The heat recirculation in the burner extends the combustible region, enables use of leaner mixtures especially at higher Reynolds numbers. Furthermore, it is shown that, the equivalence ratio at the extinction limit of butane-air mixture is the smallest at a fixed Reynolds number, and the equivalence ratio at the extinction limit of methane-air mixture is the highest

among the fuels studied.

Acknowledgements

The authors like to acknowledge the support of Bogazici University Scientific Research Fund.

References

- [1] S. A. Lloyd, F. J. Weinberg, Limits to energy release and utilisation from chemical fuels, *Nature*, volume 275 (1975) 367-370
- [2] S. A. Lloyd, F. J. Weinberg, Limits to energy release and utilisation from chemical fuels, *Nature*, volume 257 (1975) 367-370
- [3] A. R. Jones, S. A. Lloyd, F. J. Weinberg, Combustion in heat exchangers, *Proc. R. Soc. Lond.* , volume 360(1978) 97-115
- [4] L Sitzki, K Borer, E Schuster, P Ronney, S Wussow, The Third Asia- Pacific Conference on Combustion (2001) Seul Korea
- [5] J Vican, B F Gajdeczko, F L Dryer, D L Milius, I A Aksay, *Proceedings of the Combustion Institute* 29 (2002) 909-916
- [6] K Maruta, K Takeda, J Ahn, K Borer, L Sitzki, P D Ronney, O Deutschmann, *Proceeding of the Combustion* 29 (2002) 957-963
- [7] D Ronney, *Combustion and Flame* 135 (2003) 421-439
- [8] C Cui, M Matalon, J Daou, J Dold, *Combustion Theory and Modeling* 8 (2004) 41-64
- [9] K Maruta, J K Parc, K C Oh, T Fujimori, S S Minaev, R V Fursenko, *Combustion, Explosion and Shock Waves* 40 (2004) 516-523
- [10] M Chen, J Buckmaster, *Combustion Theory Modeling* 8 (2004) 701-720
- [11] J Ahn, C Eastwood, L Sitzki, P D Ronney, *Proceedings of the combustion Institute* 30 (2005) 2463-2472
- [12] Y Suzuki, Y Horii, N Kasagi, S Matsuda, 17th IEEE Int. Conf. MEMS (2004) 312-315
- [13] N Kim, S Kato, T Kataoka, T Yokomori, S Maruyama, T Fujimori, K Maruta, *Combustion and Flame* 141 (2005) 229-240