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Research Article

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Numerical investigation of geometrical modifications on premixed methane-air flame stability in a recirculation micro-combustor

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Abstract

This research numerically examines the influence of flow recirculation within a micro-combustor facilitated by an auxiliary chamber. Computational results indicate that incorporating this auxiliary chamber promotes flow recirculation, thereby enhancing flame stability. Employing a recirculating micro-combustor allows for higher inlet flow velocities without causing flame extinction. The configuration under analysis includes a main chamber and an auxiliary chamber. The main chamber features a stepped tubular design, while the auxiliary chamber, responsible for inducing recirculation, consists of a plain tube with a central conductive wire. The inclusion of both the wire and the step in the tubes contributes to greater flame stability in micro-combustors. However, the numerical findings reveal that flow recirculation within the micro-combustor provides a substantially greater stabilizing effect compared to the other two approaches.

Keywords: Methane; Air; Recirculation micro-burner; Geometry

1 Introduction

Today, due to advancements in semiconductor and micro machining technology, there is a possibility of producing equipment in small sizes, even down to a millimeter. This has led to the rapid development of micro electrical and mechanical systems (MEMS) and their applications. These systems include very small mobile systems, micro robots, small aerospace systems, and micro power generation systems. Despite their small size, these systems have the ability to produce a significant amount of energy. As a result, they are being developed for use in both economic and military sectors [1,2]. Due to the high surface-to-volume ratio in this type of combustion systems [3-6], thermal quenching of the flame and heat loss to the surrounding environment [6-8] are significant factors. These factors have a greater impact compared to medium and large combustion chambers. Thermal quenching can effectively disrupt the combustion process in this type of chamber, potentially leading to shutdown or blow out [5, 6 and 8]. As a result, recent studies in the field of micro photovoltaic systems have primarily focused on addressing these issues, particularly the heat transfer process.

Hua et al. [9], Kamali et al. [5], and Li et al. [10] each conducted separate numerical analyses of hydrogen-air premixed combustion in micro-combustors. Their work underscores key obstacles to stable combustion, including brief mixture residence times relative to reaction durations and extensive heat-transfer surfaces relative to combustion volumes. They determined that introducing a step in the micro-chamber extends the premixed flow's residence time, fostering stable burning. Furthermore, they noted that heat loss rates and wall shear stresses vary with the micro-combustor's diameter [10]. In a separate investigation, Baigmohammadi et al. explored the role of a highly conductive wire in enhancing flame stability within a micro-combustor, concluding that such a wire improves overall flame steadiness [11]. Zarvandi et al. also simulated the impacts of wire diameter and positioning in a micro-combustor, finding that

positional changes shift the flame and larger diameters bolster stability via improved heat transfer from the flame's downstream to upstream regions [12]. Additionally, Baigmohammadi et al. assessed the benefits of a catalytic element for flame stability by modeling methane-hydrogen-air premixed combustion with a central catalyst. Their outcomes showed that the catalyst significantly boosts flame stability, especially under elevated flow speeds [13]. Cai et al. numerically evaluated methane-air premixed flame dynamics and stability in a planar channel, considering channel dimensions. They observed that length adjustments affect mixture residence and external heat losses, while wall conductivity markedly influences flame form and position, particularly at varying inlet speeds [14]. Tang et al. performed numerical assessments of hydrogen-air premixed combustion in a micro-combustor linked to a micro-thermophotovoltaic (MTPV) setup for power production. Their results indicated that chambers with heat recirculation achieve roughly double the efficiency of straight-channel designs. Optimal inlet velocities were essential for maximizing MTPV output, yielding an overall efficiency of 0.7092 [15].

Wang et al. experimentally evaluated a micro-thermoelectric generator (micro-TEG) featuring a micro-chamber with consistent high surface temperatures and broad flame stability limits. They examined influences from fuel input, equivalence ratios, and hydrogen blending on power output, reporting minimum thermal efficiencies exceeding 79%, underscoring micro-combustion's high effectiveness [16]. Peng et al. numerically modeled a three-dimensional micro-tube with varied inlet nozzle configurations, analyzing effects on burning traits, flow patterns, species profiles, and heat performance. Their insights are highly applicable to micro-thermophotovoltaic (TPV) system designs [17]. In another effort, Peng et al. combined experimental and numerical methods to study hydrogen-air combustion in a stepped micro-combustor, comparing step lengths and wall thicknesses for impacts on flame stability and

thermal outcomes, aiding optimal micro-TPV selections [18]. Wan et al.'s review synthesized decade-long advancements in flame stabilization techniques for micro-combustors, covering wall cavities, heat recirculation, porous media, catalysts, and more. It concludes with recommendations for advancing stable micro-combustion [19]. Bazooyar et al. numerically modeled turbulent premixed hydrogen flames in a stepped and cavitied thermophotovoltaic chamber, simulating inlet temperatures, equivalence ratios, and velocities to assess stabilization [20]. Johara et al. offered a detailed overview of thermoelectric generator (TEG) principles, including Seebeck, Peltier, Thomson effects, and Joule heating, along with practical implementations [21].

Wang et al. detailed an analysis of high-Reynolds-number laminar methane-air flame dynamics, incorporating heat and flow recirculation synergies. They identified localized quenching from counterflows in recirculation zones and stretch effects, suggesting distinct flame formation mechanisms in micro-heaters versus traditional setups [22]. Aravind et al. were able to enhance the power generation of micro-burners for thermoelectric electricity production through innovative techniques, including current recirculation to increase heat absorption. The final findings demonstrate a notable enhancement in overall efficiency, ranging from 10 to 20 percent [23]. Gupta et al. investigated acetylene-air premixed flame dynamics in a multi-channel micro-combustor array, identifying flat, turbulent, and triple flame modes tied to flow behaviors. They noted that triple flame onset positions shift with rising Reynolds numbers and downstream recirculation lengths [24].

2 Numerical approach and boundary conditions

The configuration of the analyzed micro-combustor is illustrated in Figure 1. In this setup, premixed methane-air mixture enters from the left and proceeds rightward. The coordinate origin is positioned at the leftmost point along the centerline. As depicted in Figure 1, the burner

consists of two components. The primary component comprises the micro-step, while the secondary component consists of a simple tube and a high-conductivity wire connected to its center. also, this burner features three combustion zones:

a) The first zone: the flame is positioned inside the micro-step (X direction).
b) The second zone: the flame undergoes a 90-degree rotation and is positioned in the R direction.
c) The third zone: the flame is situated between the micro-step and the simple tube (-X direction).

The wire is positioned commencing at the backward-facing step, situated 1.50 mm downstream from the combustor's inlet. The flow regime within the computational domain remains laminar (Re < 1000). Given the axisymmetric configuration of the combustor and the laminar nature of the flow, only half of the structure was modeled. In this analysis, flames were presumed to exhibit axisymmetric behavior, with all factors potentially inducing asymmetry in such geometries being deliberately omitted. A Lewis number approaching unity ($\varphi = 0.9$) mitigated thermo-diffusive instabilities within the micro-combustor [25]. These instabilities, along with others noted, are generally regarded as the primary contributors to asymmetric flame patterns in compact-scale combustors [26–28].

Accordingly, the parameters employed in the investigation are summarized in Table 1. Notably, the external emissivity value of 0.2 represents an intermediate figure between that of weathered stainless steel (~ 0.85) and polished stainless steel (~ 0.075). Furthermore, the thermal conductivity of 20 $W \cdot m^{-1} \cdot K^{-1}$ for the combustor body aligns with properties of certain ceramics, including aluminum oxide or stainless steel. The inserted wire was modeled as a hypothetical high-conductivity element capable of enduring elevated temperatures. Of particular note, this simulated wire's attributes mirror those of materials like aluminum nitride (AlN), which

demonstrates resilience to high flame temperatures and possesses substantial thermal conductivity [29].All simulations conducted in this investigation, encompassing the resolution of the laminar Navier-Stokes equations (continuity, momentum in axial and radial coordinates, energy, and species transport) as well as the associated combustion kinetics, adhered to the methodology previously detailed by the authors in their prior works [11,12]. Accordingly, the governing equations were discretized via a finite-volume method, which was formulated based on Patankar's SIMPLER algorithm implemented on a collocated grid, as described by Rahman et al. [30]. To augment the accuracy of the calculations, the convergence criterion for all equations was specified as 10^{-6}. In the interest of conciseness, further particulars regarding the numerical techniques utilized are directed to the referenced publications.

3 Results and discussions

Primary outcomes, including grid independence, validation, recirculation effects on flame stability, and outer wall temperature profiles in the auxiliary chamber for methane-air flames, are addressed below.

3.1 Mesh study and Validation

Figure 2 demonstrates the verification of the computational code and its associated solvers employed in the simulations. Details regarding this code and the solvers have previously been outlined by the authors in references [11, 31]. The code adequately replicates earlier numerical [32] and experimental [33] findings, exhibiting a maximum discrepancy below 13%. In particular, it forecasts the observed temperatures with precision surpassing ±5%. Furthermore, a grid independence assessment was carried out to evaluate the influence of mesh resolution on the analyzed variables. As illustrated in Figure 2, augmenting the element count above 7520

produces negligible alterations in the temperature profile along the reference line at r = 0.3 mm within the combustor. Accordingly, this grid size was chosen for subsequent analyses.

3.2 Effect of the fluid flow circulation in micro burner

In this study, it has been observed that micro burner flow has a very high capability in flame stability, especially at high velocities, based on the simulated modeling. For example, when using the micro tube model, only the inlet mixture velocity can be increased up to 0.7 m/s. When using the micro step model, this velocity increases up to 2.8 m/s. By introducing a wire into the micro step, this velocity can be increased up to 4.8 m/s Figure (3). But when the circulation flow micro-burner is used, this velocity increases significantly and reaches to 25 m/s, which indicates the high capability of this type of micro-burner in flame stability. Figure (4).

The main reason why using flow circulation leads to flame stability is better and more heat transfer from the front flame to its back. In fact, by adding a tube to the micro step, we have created a new heat loop that has a high capability in preheating the inlet mixture (Figure 5).

3.3 Effect of the H2/H1 on flame characteristics in recirculation micro burner

Considering that dimensions and sizes are very important in micro burners, as a result, the first parameter that should be analyzed is the H2/H1 ratio in the recirculation micro burner. In this section, four ratios, namely H2/H1=0.5, H2/H1=1, H2/H1=1.5 and H2/H1=2, have been investigated. The results show that with the increase of the H2/H1 ratio, and due to the increase in the heat generation volume, the stability of the flame increases and it moves upstream (Figure 6). The increase in heat generation volume is due to the increase in the production of active radicals such as H, OH, CH3, O, etc., which increases with an increase in the H2/H1 ratio (Figure. 7 and 8). Generally, by increasing the H2/H1 ratio from 0.5 to 2, it is possible to prevent

flame blow out that occurs at a velocity of 22m/s and at H2/H1=0.5 and even increase the inlet mixture velocity to maintain flame stability.

3.4 Effect of the fluid flow velocity in the recirculation micro burner

Inlet velocity critically influences flame positioning within micro-combustors. As depicted in Figure 9, variations in inlet velocity alter both the flame's configuration and its spatial location. At elevated inlet velocities, the flame shifts downstream, attributable to heightened mass flow rates and consequent reductions in fluid residence time inside the combustor. Conversely, at reduced velocities, accelerated downstream progression of the reaction front occurs, stemming from diminished heat release rates. Given the escalation in mass flow, an optimal equilibrium emerges between augmented volumetric heat release and curtailed residence time, at which point flame stability is achieved.

This behavior arises because higher inlet velocities introduce greater quantities of reactant mixture into the micro-tube, thereby substantially elevating peak temperatures in the combustion chamber. While such velocity increases can enhance the combustor's efficiency, exceeding a predefined threshold may precipitate blowout. The aforementioned effects are illustrated in Figures 10-13, which reveal alterations in temperature distributions across the three zones and along the recirculating micro-tube's outer wall as inlet velocity rises.

Furthermore, as shown in Figures 14-16, elevating the premixed reactant's inlet velocity augments the mass fractions of key species, including H, OH, O, and CH_3. This enhancement results from the downstream displacement of the flame, which affords additional spatial extent for preheating the incoming mixture prior to its entry into the reaction zone. Such intensified preheating elevates flame temperatures and species concentrations. Additionally, under premixed conditions, increased velocity delivers more reactants to the reaction region, thereby amplifying

temperatures and heat release rates. Given the temperature dependence of radical species, this rise correspondingly increases their mass fractions within the recirculating micro-tube.

3.5 Effect of convective heat transfer coefficient in the recirculation micro burner

A principal utilization of micro-combustors pertains to their incorporation in micro-thermophotovoltaic (micro-TPV) systems. Consequently, an examination of the consequences of convective heat transfer from the walls on the combustion domain is deemed essential. In broad terms, augmenting the convective heat transfer coefficient induces a reduction in wall temperature attributable to amplified heat dissipation. As depicted in Figure 17, the temperature profile across the outer wall of the recirculating micro-combustor demonstrates a decline in wall temperature corresponding to elevations in the convective heat transfer coefficient and resultant heat transfer intensification.

Figure 18 delineates the mass-weighted average mass fractions of essential radicals, namely O, OH, CH_3, and H, under varying wall convective heat transfer coefficients within the recirculating micro-combustor. It is evident that escalations in this coefficient precipitate a diminution in radical concentrations owing to heightened heat extraction from the wall. Notwithstanding the absence of substantial radical depletion within the interval of h = 5 $W/m^2 \cdot K$ to h = 35 $W/m^2 \cdot K$, subsequent increments may culminate in flame quenching.

In essence, considering the escalation of the convective heat transfer coefficient alongside the elevated surface-to-volume ratio characteristic of micro-combustors, safeguards are imperative to preclude flame extinction or blowout stemming from the forfeiture of critical radicals such as O and OH. Accordingly, design and operational strategies for micro-combustors ought to be implemented to avert such instabilities.

3.6 Effect of external emissivity coefficient in the recirculation micro burner

Given that micro-thermophotovoltaic (micro-TPV) systems constitute a principal application of micro-tube combustors, an analysis of the consequences of radiative heat transfer from the micro-tube wall to the surroundings, along with its ramifications for the combustion domain, is deemed essential [34]. In broad terms, this form of heat transfer to the environment represents a dissipative loss that depletes active radicals, such as OH and O, in the vicinity of the micro-tube wall, thereby precipitating combustion instability and eventual flame quenching [35].

Figures 19a and 19b present the wall temperature distribution profiles under diverse emissivity coefficients along the recirculating micro-combustor. Analysis of Figure 19 reveals that elevations in the emissivity coefficient lead to diminished temperature levels on the outer wall of the recirculating micro-combustor. This effect arises from intensified radiative heat transfer rates, attributable to the pronounced relationship between temperature and radiative processes. As stipulated by the radiative heat transfer equation, such transfer escalates proportionally to the fourth power of temperature. In summary, the elevated surface-to-volume ratio inherent in micro-tubes renders the internal combustion process continually vulnerable to the quenching of active radicals [35], encompassing O, H, and OH. Consequently, parameters for the recirculating micro-combustor must be meticulously selected to ensure flame stability amid risks of blowout and extinction.

As illustrated, the escalation of heat transfer from the recirculating micro-combustor wall to the environment through radiative dissipation induces a downward trajectory in the mass fractions of OH and H radicals, as depicted in Figure 20.

4 Conclusions

This numerical assessment evaluates the potential of fluid flow recirculation within a micro-combustor, achieved through the implementation of an auxiliary combustion chamber, to

enhance premixed methane-air combustion processes. Utilizing a two-dimensional laminar premixed computational model, the influences of flow recirculation, auxiliary chamber height ratio (H_2/H_1), inlet mixture velocity, external convective heat transfer coefficient (h_{out}), and surface emissivity (ε) on temperature profiles and combustion evolution in a recirculating micro-combustor were quantified. The computational findings indicate that internal fluid flow recirculation exerts a profound and substantial impact on flame quality and stability. This approach serves as a critical mechanism for refining combustion dynamics in micro-combustors, by augmenting the formation of key species essential for sustaining effective flames at micro-scales. Additionally, flow recirculation bolsters flame quality and resistance to blowout under elevated velocities through enhanced production rates of OH, H, CH_3, and O radicals. Based on the results, the integration of flow recirculation within the combustor, coupled with the establishment of a secondary thermal circuit, renders the examined configuration more resilient to flame quenching induced by heat dissipation. Consequently, this advancement may broaden the applicability of such combustors in micro-thermophotovoltaic systems.

5 References

[1] I. A. Waitz, G. Gauba, and Y. S. Tzeng, "Combustors for micro-gas turbine engines," J. Fluids Eng., vol. 120, no. 1, pp. 109–117, Mar. 1998.

[2] L. C. Chia and B. Feng, "The development of a micropower (micro-thermophotovoltaic) device," J. Power Sources, vol. 165, no. 1, pp. 455–480, Feb. 2007.

[3] D. G. Norton and D. G. Vlachos, "A CFD study of propane/air microflame stability," Combust. Flame, vol. 138, no. 1–2, pp. 97–107, Jul. 2004.

[4] J. F. Pan, J. Huang, D. T. Li, W. M. Yang, W. X. Tang, and H. Xue, "Effects of major parameters on micro-combustion for thermophotovoltaic energy conversion," Appl. Therm. Eng., vol. 27, no. 5–6, pp. 1089–1095, Apr. 2007.

[5] R. Kamali, A. R. Binesh, and S. Hossainpour, “Numerical simulation of wall treatment effects on the micro-scale combustion,” in Proc. World Acad. Sci. Eng. Technol., Dec. 2007, vol. 26, pp. 444–451.

[6] T. T. Leach and C. P. Cadou, “The role of structural heat exchange and heat loss in the design of efficient silicon micro-combustors,” Proc. Combust. Inst., vol. 30, no. 2, pp. 2437–2444, Jan. 2005.

[7] K. T. Kim, D. H. Lee, and S. Kwon, “Effects of thermal and chemical surface–flame interaction on flame quenching,” Combust. Flame, vol. 146, no. 1–2, pp. 19–28, Jul. 2006.

[8] N. I. Kim and K. Maruta, “A numerical study on propagation of premixed flames in small tubes,” Combust. Flame, vol. 146, no. 1–2, pp. 283–301, Jul. 2006.

[9] J. Hua, M. Wu, and K. Kumar, “Numerical simulation of the combustion of hydrogen–air mixture in micro-scaled chambers. Part I: Fundamental study,” Chem. Eng. Sci., vol. 60, no. 13, pp. 3497–3506, Jul. 2005.

[10] Z. W. Li, S. K. Chou, C. Shu, H. Xue, and W. M. Yang, “Characteristics of premixed flame in microcombustors with different diameters,” Appl. Therm. Eng., vol. 25, no. 2–3, pp. 271–281, Feb. 2005.

[11] M. Baigmohammadi, S. Sarrafan Sadeghi, S. Tabejamaat, and J. Zarvandi, “Numerical study of the effects of wire insertion on CH4(methane)/AIR pre-mixed flame in a micro combustor,” Energy, vol. 54, pp. 271–284, Jun. 2013.

[12] J. Zarvandi, M. Baigmohammadi, and S. Tabejamaat, “A numerical study on the effects of the geometry and location of an inserted wire on methane–air flames in a micro–burner,” Energies, vol. 15, no. 1, p. 93, Jan. 2022.

[13] M. Baigmohammadi, S. Tabejamaat, and J. Zarvandi, “Numerical study of the behavior of methane-hydrogen/air pre-mixed flame in a micro reactor equipped with catalytic segmented bluff body,” Energy, vol. 85, pp. 117–144, May 2015.

[14] T. Cai, A. Tang, D. Zhao, C. Zhao, and Q. Huang, “Flame dynamics and stability of premixed methane/air in micro-planar quartz combustors,” Energy, vol. 193, p. 116767, Feb. 2020.

[15] A. Tang, T. Cai, Q. Huang, J. Deng, and J. Pan, “Numerical study on energy conversion performance of micro-thermophotovoltaic system adopting a heat recirculation micro-combustor,” Fuel Process. Technol., vol. 180, pp. 23–31, Nov. 2018.

[16] W. Wang, Z. Zhao, N. Kuang, H. Chen, and Z. Zuo, “Experimental study and optimization of a combustion-based micro thermoelectric generator,” Appl. Therm. Eng., vol. 181, p. 115431, Nov. 2020.

[17] Q. Peng, J. E, W. M. Yang, H. Xu, J. Chen, T. Meng, S. Qiu, and Z. Li, “Effects analysis on combustion and thermal performance enhancement of a nozzle-inlet micro tube fueled by the premixed hydrogen/air,” Energy, vol. 160, pp. 349–360, Oct. 2018.

[18] Q. Peng, J. E, W. Yang, H. Xu, J. Chen, F. Zhang, T. Meng, and S. Qiu, “Experimental and numerical investigation of a micro-thermophotovoltaic system with different backward-facing steps and wall thicknesses,” Energy, vol. 173, pp. 540–547, Apr. 2019.

[19] J. Wan and A. Fan, “Recent progress in flame stabilization technologies for combustion-based micro energy and power systems,” Fuel, vol. 286, p. 119391, Feb. 2021.

[20] B. Bazooyar and H. G. Darabkhani, “Analysis of flame stabilization to a thermo-photovoltaic micro-combustor step in turbulent premixed hydrogen flame,” Fuel, vol. 257, p. 115989, Dec. 2019.

[21] H. Jouhara, A. Żabnieńska-Góra, N. Khordehgah, Q. Ahmad, and L. Lipinski, “Thermal energy storage of molten salt–based nanofluid containing nano-encapsulated metal alloy phase change materials,” Energy, vol. 195, p. 116980, Mar. 2020.

[22] J. Wan and X. Cheng, “Numerical investigation of the local extinction and re-ignition mechanisms of premixed flame in a micro combustor with a flame holder and preheating channels,” Fuel, vol. 264, p. 116837, Mar. 2020.

[23] B. Aravind, B. Khandelwal, P. A. Ramakrishna, and S. Kumar, “Towards the development of a high power density, high efficiency, micro power generator,” Appl. Energy, vol. 261, p. 114386, Mar. 2020.

[24] A. Gupta, Q. U. Ali, K. Koutita, and O. Rybdylova, “Experimental investigation of the flow in a microchannelled combustor and its relation to flame behaviour,” Exp. Therm. Fluid Sci., vol. 116, p. 110105, Aug. 2020.

[25] A. Alipoor and K. Mazaheri, “Studying the repetitive extinction-ignition dynamics for lean premixed hydrogen-air combustion in a heated microchannel,” Energy, vol. 73, pp. 367–379, Aug. 2014.

[26] Y. Ju and B. Xu, “Effects of channel width and Lewis number on the multiple flame regimes and propagation limits in mesoscale,” Combust. Sci. Technol., vol. 178, no. 10–11, pp. 1723–1753, Oct. 2006.

[27] S. Senchenko, V. Bychkov, and M. Liberman, “Stability limits of curved stationary flames in cylindrical tubes,” Combust. Sci. Technol., vol. 166, no. 1, pp. 109–130, Jan. 2001.

[28] C. H. Tsai, “The asymmetric behavior of steady laminar flame propagation in ducts,” Combust. Sci. Technol., vol. 180, no. 3, pp. 533–545, Feb. 2008.

[29] T. B. Jackson, A. V. Virkar, K. L. More, R. B. Dinwiddie, and R. A. Cutler, “High-thermal-conductivity aluminum nitride ceramics: The effect of thermodynamic, kinetic, and microstructural factors,” J. Amer. Ceram. Soc., vol. 80, no. 6, pp. 1421–1435, Jun. 1997.

[30] M. M. Rahman, A. Miettinen, and T. Siikonen, “Modified SIMPLE formulation on a collocated grid with an assessment of the simplified QUICK scheme,” Numer. Heat Transfer, Part B: Fundam., vol. 30, no. 3, pp. 291–314, Oct. 1996.

[31] M. Baigmohammadi, S. Tabejamaat, and B. Kashir, “A numerical study on the effects of hydrogen addition levels, wall thermal conductivity and inlet velocity on methane/air pre-mixed flame in a micro reactor,” Energy Equip. Syst., vol. 2, no. 2, pp. 103–119, Dec. 2014.

[32] G. Chen, Y. Chao, and C. Chen, “Enhancement of hydrogen reaction in a micro-channel by catalyst segmentation,” Int. J. Hydrogen Energy, vol. 33, no. 10, pp. 2586–2595, May 2008.

[33] J. Li, S. K. Chou, Z. W. Li, and W. M. Yang, “Characterization of wall temperature and radiation power through cylindrical dump micro-combustors,” Combust. Flame, vol. 156, no. 8, pp. 1587–1593, Aug. 2009.

[34] J. Li, S. K. Chou, G. Huang, W. M. Yang, and Z. W. Li, “Study on premixed combustion in cylindrical micro combustors: Transient flame behavior and wall heat flux,” Exp. Therm. Fluid Sci., vol. 33, no. 4, pp. 764–773, Apr. 2009.

[35] S. Raimondeau, D. G. Norton, D. G. Vlachos, and R. I. Masel, “Modeling of high-temperature microburners,” Proc. Combust. Inst., vol. 29, no. 1, pp. 901–907, Jan. 2002.

345 **Table 1.** Some of the applied values in the study

Inlet velocity (V_{in})	1.5 m/s- 25m/s
Wire's thermal conductivity (K_{wire})	170 W/m.K
Wall's thermal conductivity (step & simple tube) (K_w)	20 W/m.K
External heat transfer coefficient (h_{out})	5 $W/m^2.K$-35 $W/m^2.K$
External emissivity coefficient (e)	0.2-0.8
Equivalence ratio (φ)	0.9

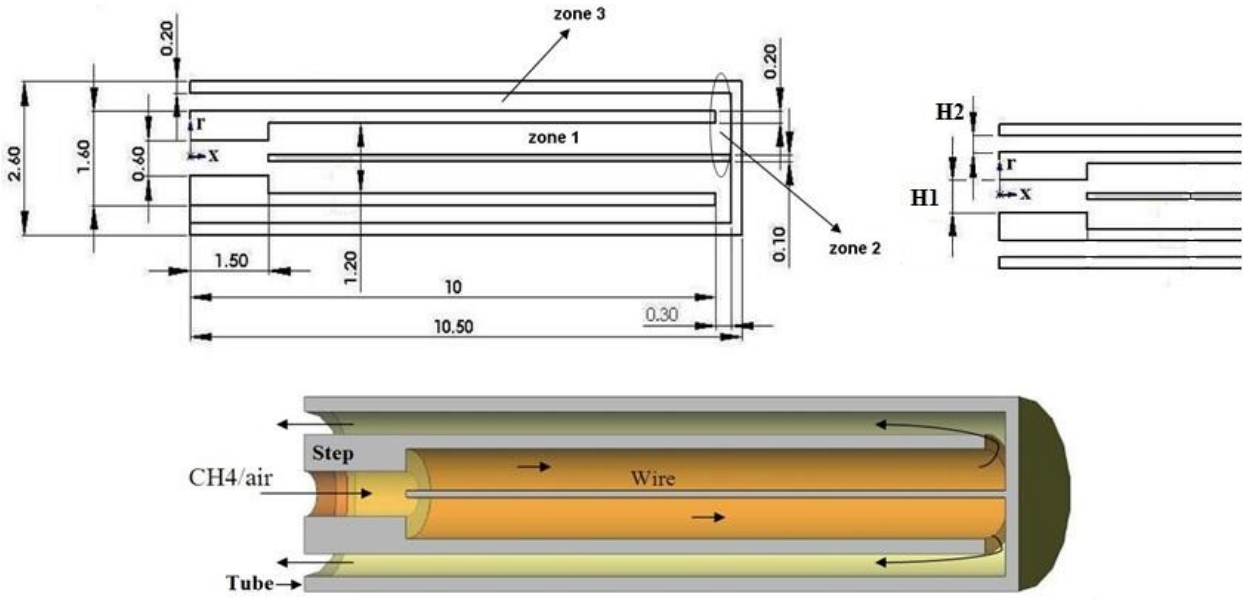


Fig 1. Configuration of the recirculating micro-combustor (dimensions in mm).

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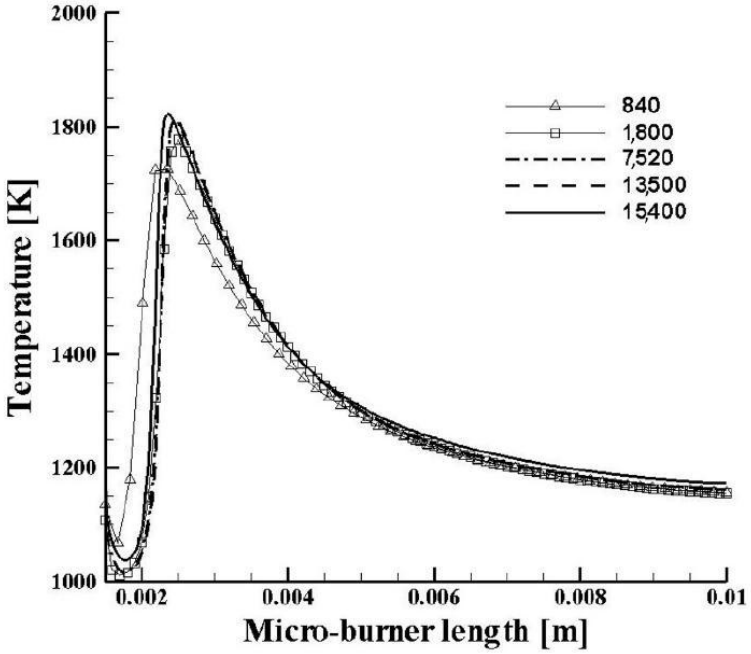


Fig 2. The studied computational mesh; temperature distribution on the auxiliary axis of r = 0.3mm (Primary combustion chamber)

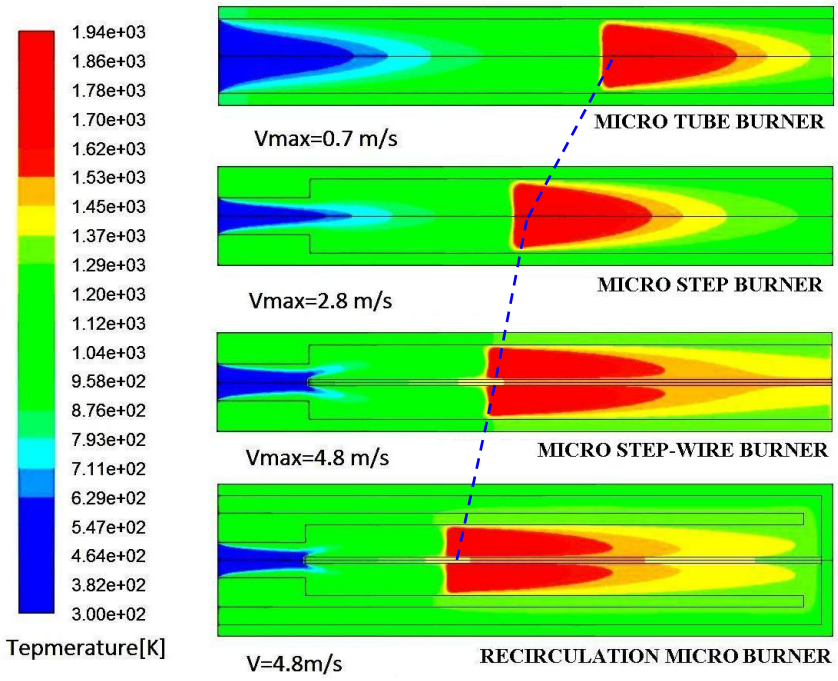


Fig 3. Flame shapes and positions: plain micro-tube vs. stepped, stepped-with-wire, and recirculating micro-combustor.

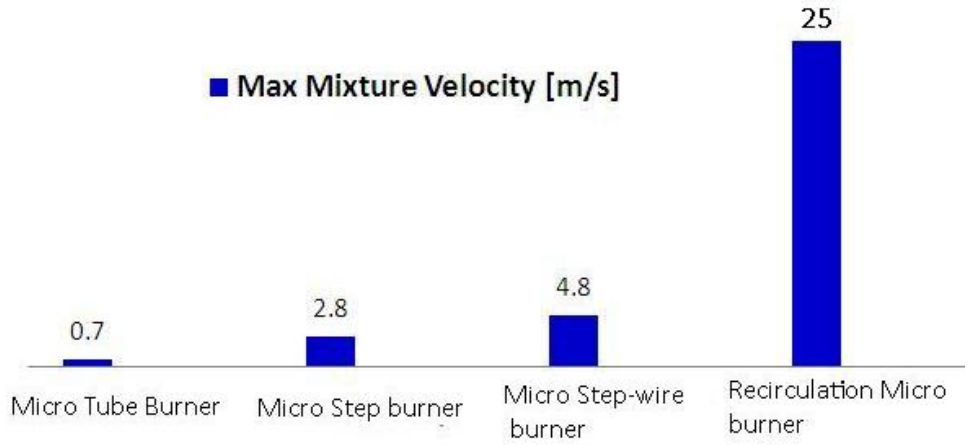
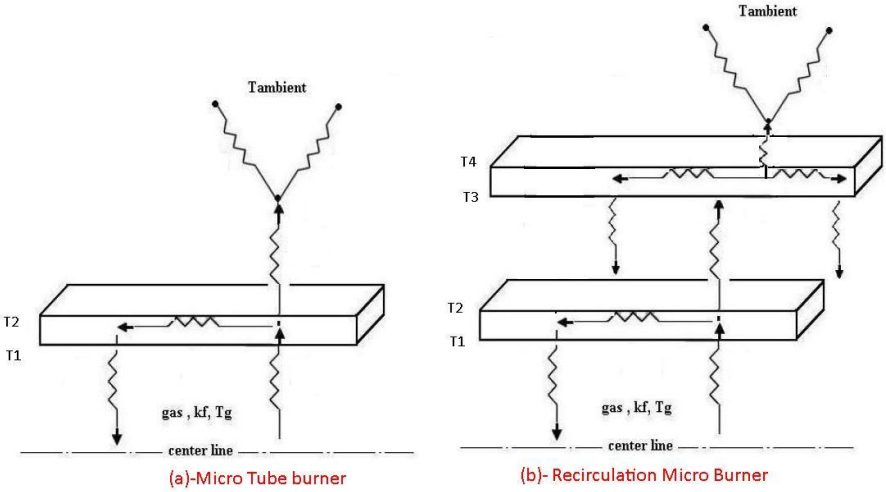


Fig 4. comparison of the maximum inlet velocity of mixture between the simple micro-tube and the micro step and micro step-wire and recirculation micro burner

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370 Fig 5. Schematic view of thermal model in (a)-micro tube burner (b)- recirculation micro burner

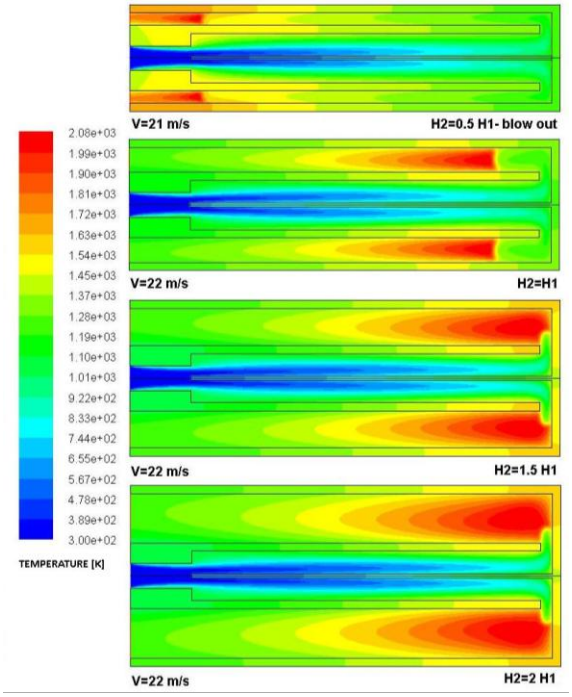


Fig 6. Flame shape and location in the recirculation micro burner for various H2/H1

375

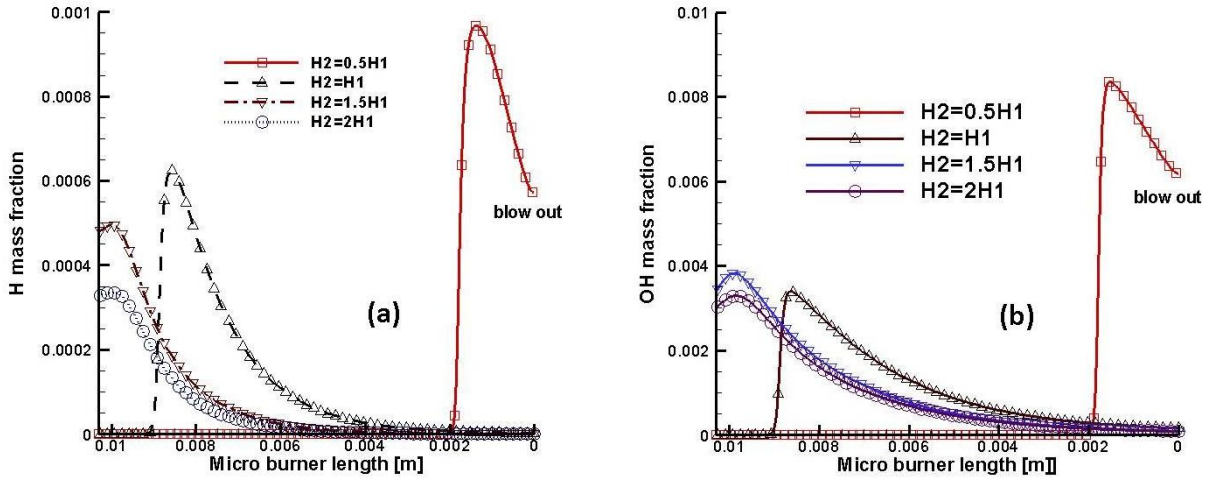


Fig 7. Distribution of H &OH mass fraction along the inner wall of zone 3 in the recirculation micro burner (Vin=22m/s)

380

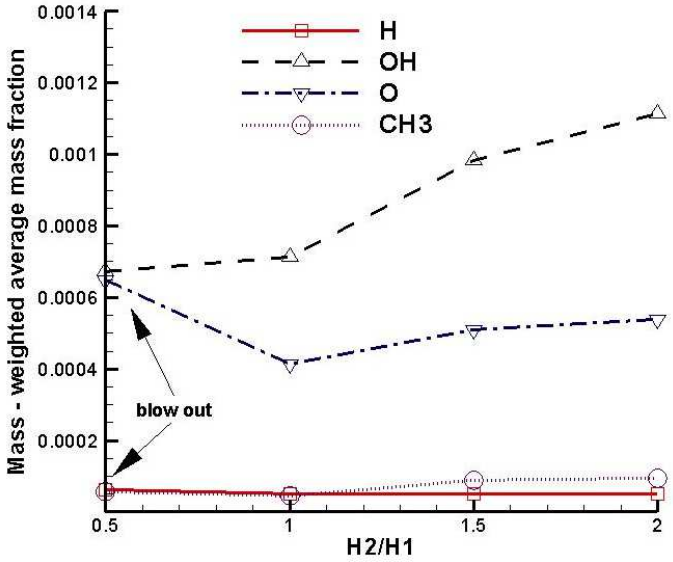
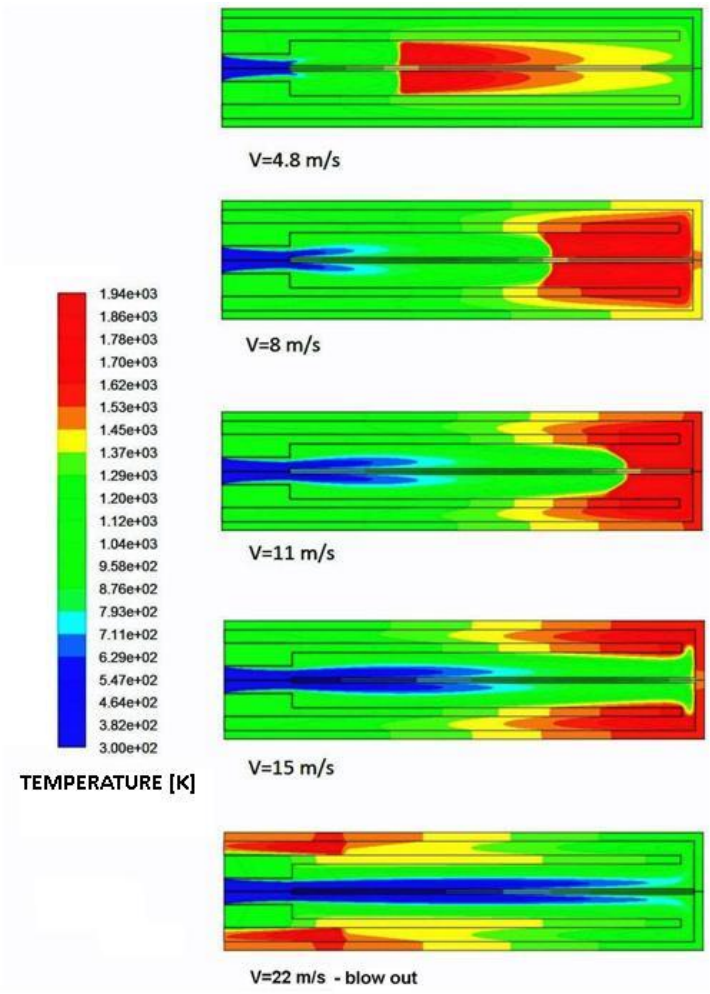


Fig 8. Variation of the mass-weighted average mass fraction of species versus variation H2/H1 of the recirculation micro burner (Vin=22m/s)



385

Fig 9. flame shape and location in the recirculation micro burner for various inlet velocities (H2=0.5H1)

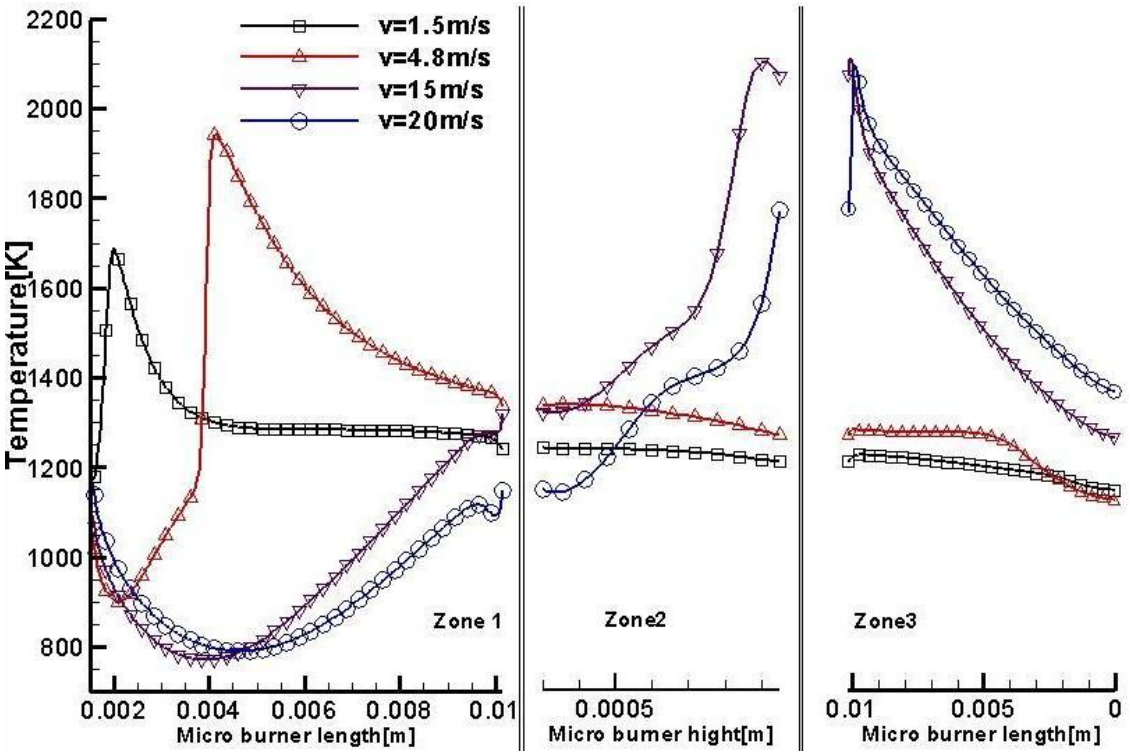
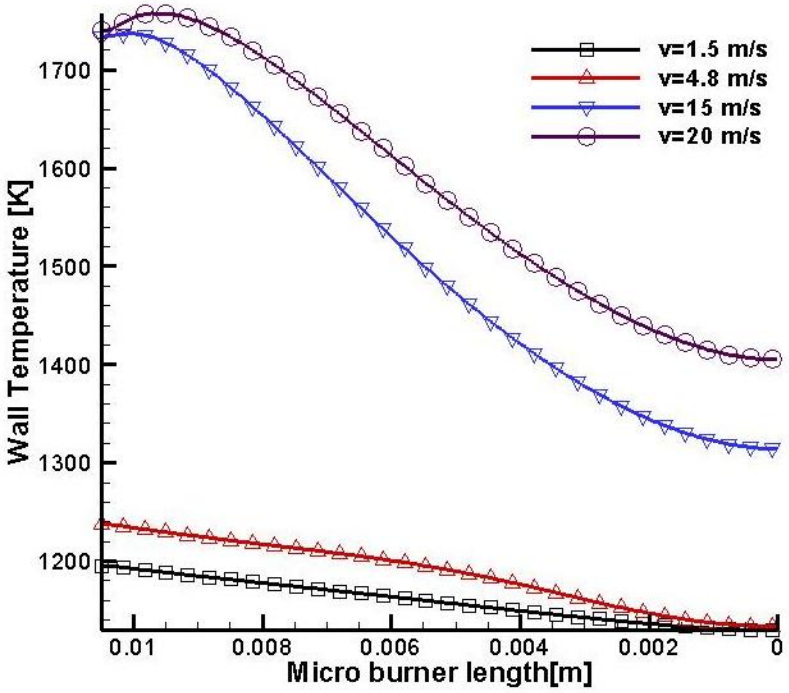
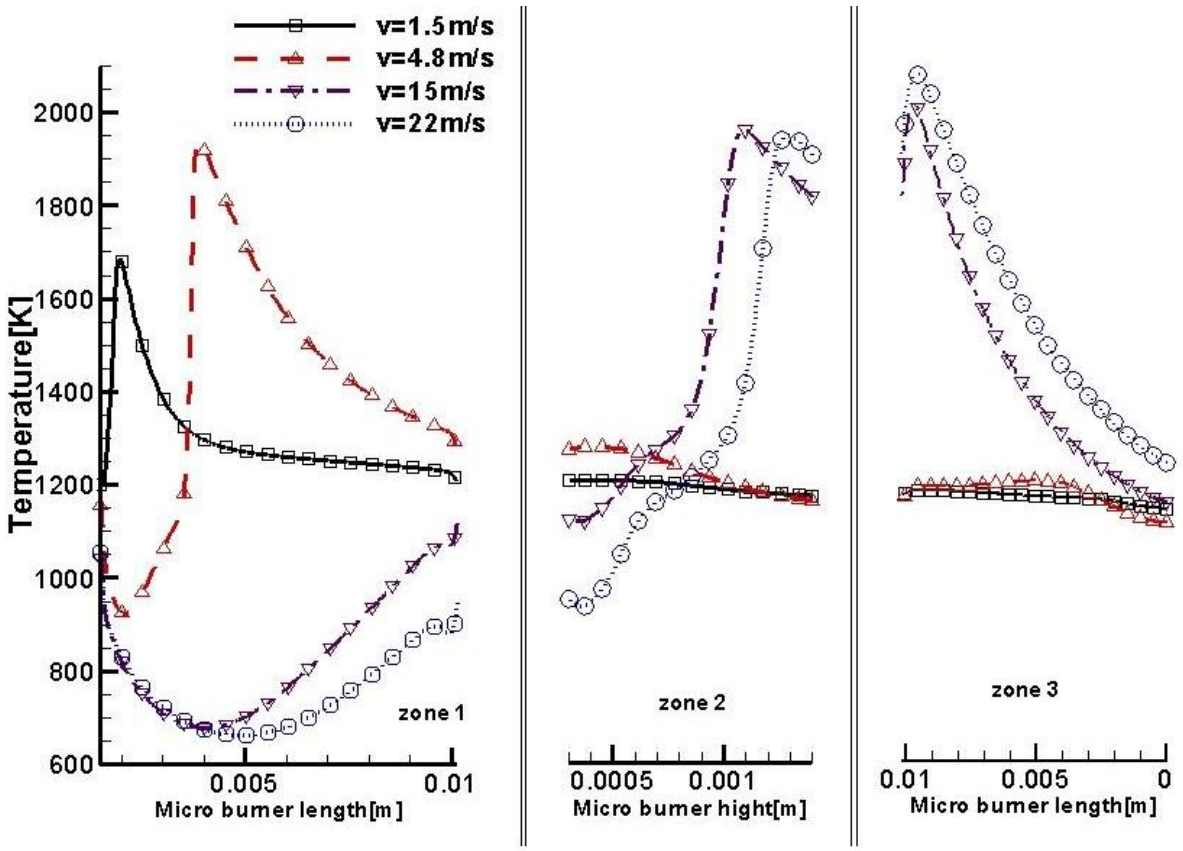


Fig 10. Distribution of temperature along the r=0.3mm (zone 1) and x=10.15mm (zone 2) and r=0.95mm (zone 3) in the recirculation micro burner (H2=0.5H1)

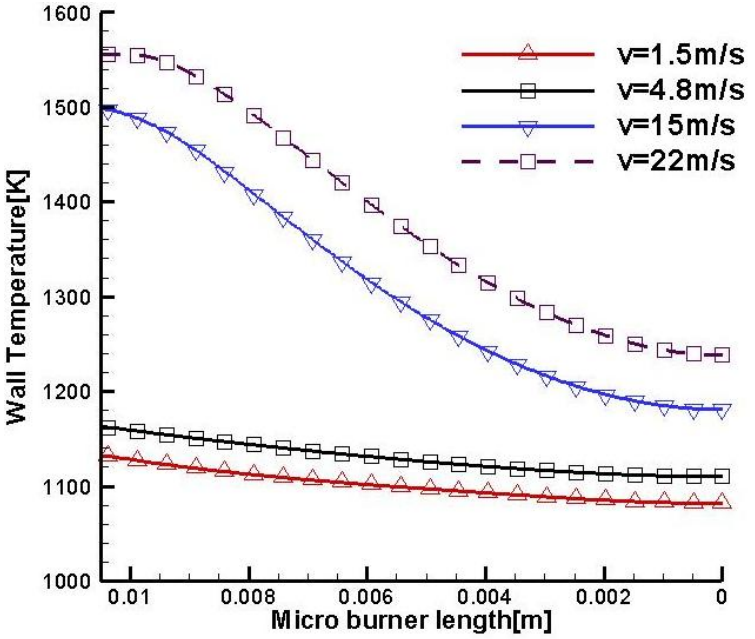


395 Fig 11. Distribution of temperature along outer wall in the recirculation micro burner (H2=0.5H1)



400

Fig 12. Figure 1. Distribution of temperature along the r=0.3mm (zone 1) and x=10.15mm (zone 2) and r=0.95mm (zone 3) in the recirculation micro burner (H2=2H1)



405

Fig 13. Distribution of temperature along outer wall in the recirculation micro burner (H2=2H1)

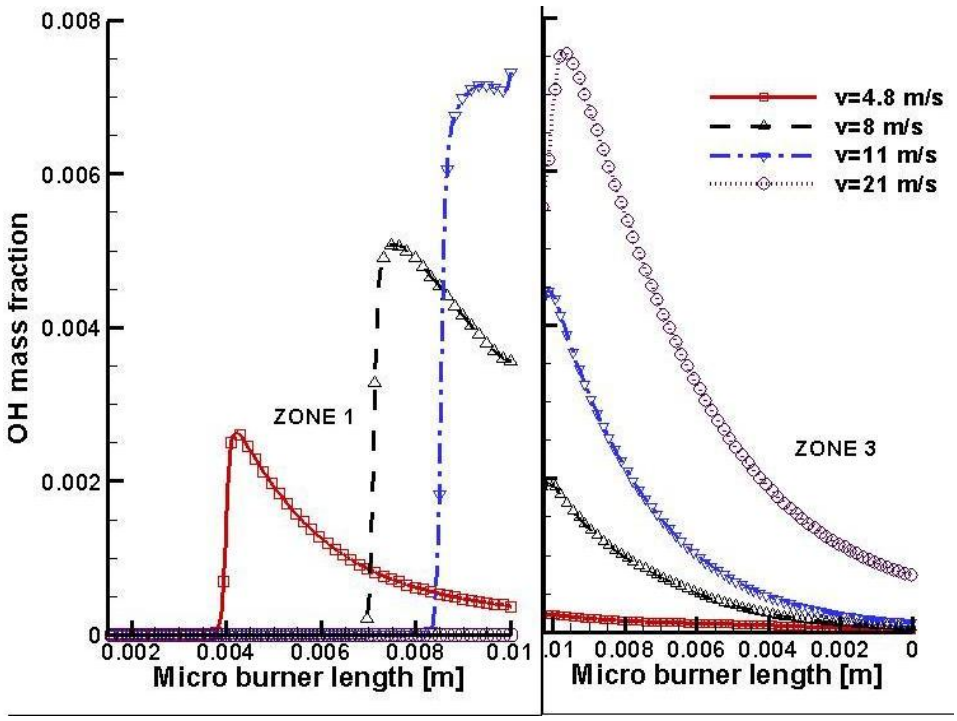


Fig 14. Distribution of OH mass fraction along the inner wall in the recirculation micro burner (H2=0.5H1)

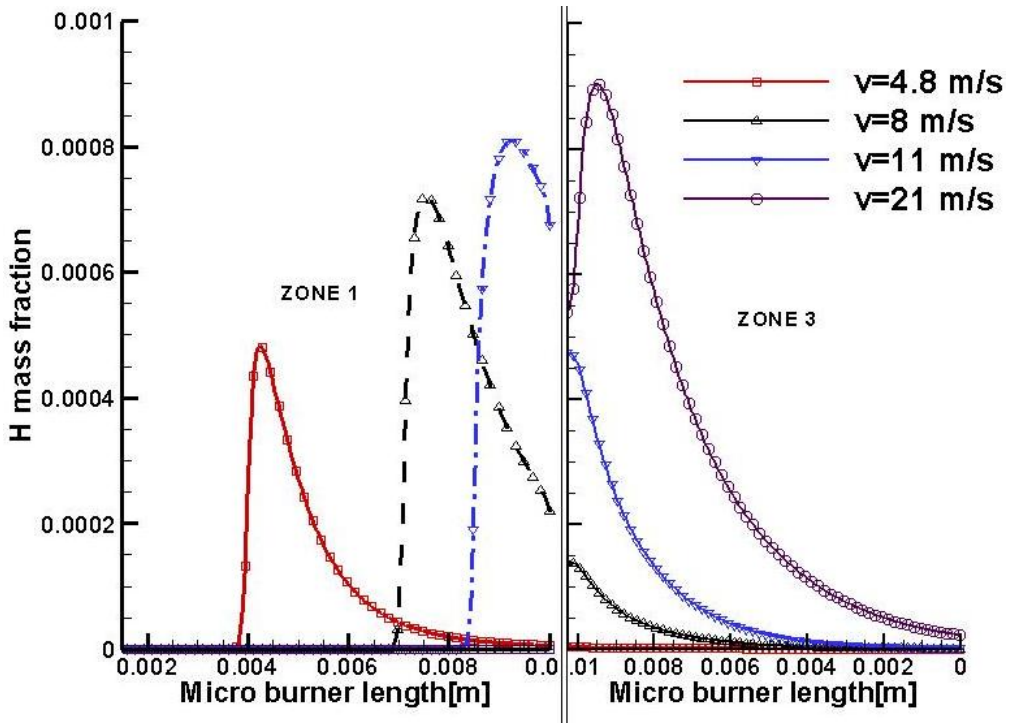


Fig 15. Distribution of H mass fraction along the inner wall in the recirculation micro burner (H2=0.5H1)

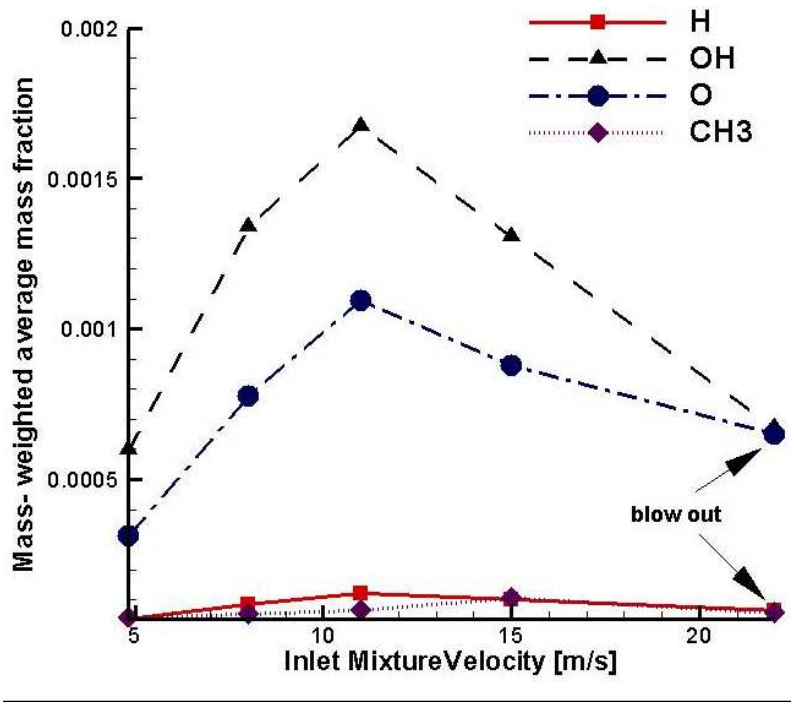
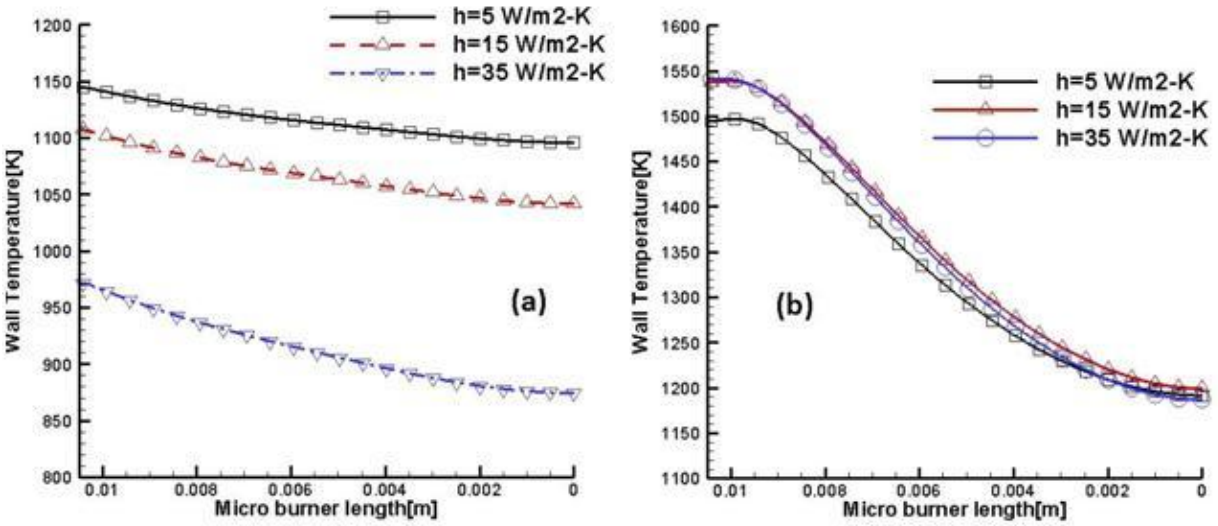


Fig 16. Variation of the mass-weighted average mass fraction of species versus variation velocities of the recirculation micro burner (H2=0.5H1)



425

Fig 17. Distribution of temperature along outer wall in the recirculation micro burner (a) v=4.8 m/s and (b) v=20 m/s.(H2=1.5H1)

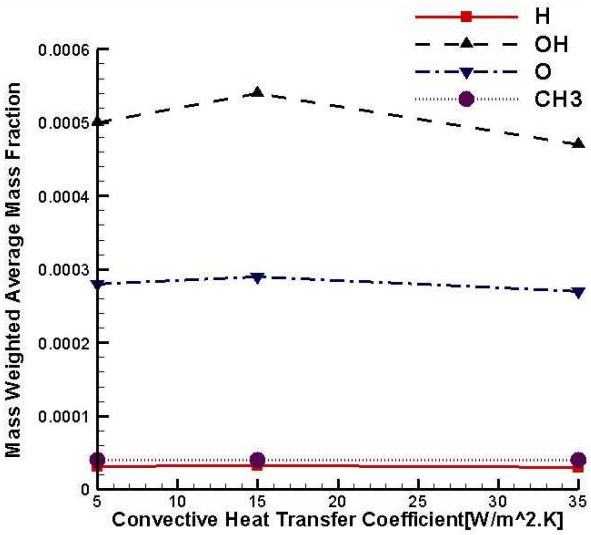


Fig 18. Variation of the mass-weighted average mass fraction of species versus variation convective heat transfer coefficient of the recirculation micro burner (v=4.8m/s & H2=1.5H1)

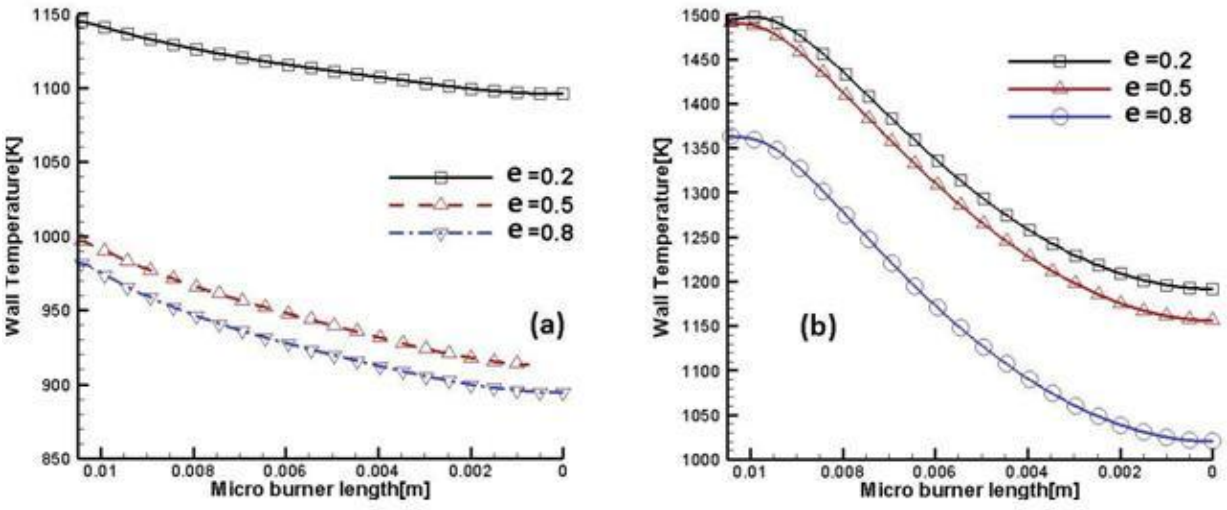


Fig 19. Distribution of temperature along outer wall in the recirculation micro burner (a) v=4.8 m/s and

(b) v=20 m/s.(H2=1.5H1)

440

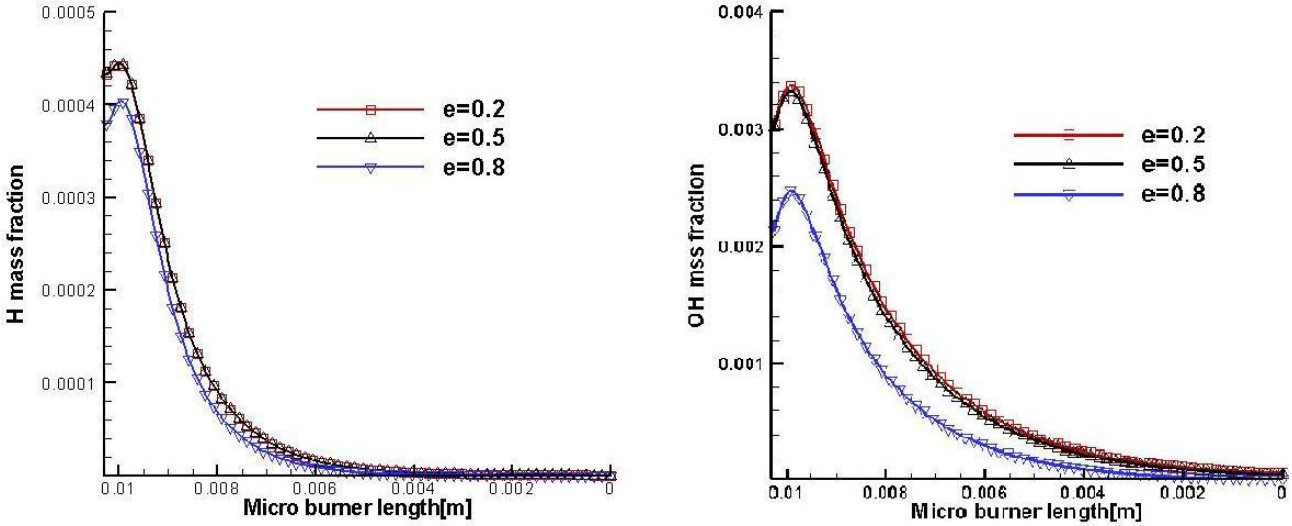


Fig 20. Distribution of H &OH mass fraction along the inner wall of zone 3 in the recirculation micro burner (v=20m/s & H2=1.5H1)