

Numerical Analysis of Hydrogen-Fueled Micro Cylindrical Combustor with Parallel Partitions for Thermophotovoltaic Applications

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Abstract - This paper examines the effects of integrating parallel partitions into a hydrogen-fueled micro cylindrical combustor on thermodynamic and performance parameters by numerical simulation means. The lengths of the parallel partitions are varied to assess how flame dynamics and heat transfer mechanisms are affected. To achieve this, several simulations are conducted using ANSYS Fluent. The results showed that partitioning the flame path improves the heat absorption rate by the outer walls, as the mean wall temperature and its uniformity across the external walls are enhanced. In addition, employing partitions lowers the average exhaust gas temperature by 131.5 K, indicating a greater retention of thermal energy. This, in turn, improves the exergy and radiation efficiencies for the cases with partitions. It is important to note that separating the flow channel increases the pressure drop as the inlet flow collides with the partitions. The long partition length is the optimal case, as it provides a larger area of contact between the flame and the solid walls and also holds the flame in an ideal position.

Keywords: Hydrogen combustion, Heat Transfer, Micro Combustor, Thermophotovoltaic, Renewable Energy

1. Introduction

Micro-electromechanical systems (MEMS) have recently attracted significant attention from researchers due to their high performance efficiency and long lifespan [1]. As a result, these technologies have been widely applied in various fields, including micro swing engine [2], micro thermoelectric device [3], and biomedicine [4]. Additionally, the micro-thermophotovoltaic (MTPV) system is considered one of the most important micro power generation devices due to its compact size, ease of maintenance, and robust structure [5]. The MTPV system consists of a micro combustor, a filter, and a photovoltaic cell, where the thermal energy produced by combustion in the micro combustor is radiated to the photovoltaic cell to generate electricity. Therefore, improving heat transfer mechanisms from the combustion process to the external walls is crucial for increasing output power density. Various techniques have been implemented to enhance energy conversion efficiency, such as external heating method [6], bluff-body combustion [7], and catalytic combustion [8].

Incorporating alternative green and renewable energy sources is a crucial step toward advancing the energy sector's sustainability and decarbonization. In recent years, hydrogen – which has been utilized in various combustion-based applications such as internal combustion engines [9], marine engines [10], Wankel rotary engines [11], and gas turbine [12] – shows promise due to its high energy content, high diffusion mobility, and fast burning velocity [13]. Furthermore, hydrogen, as a carbon-free fuel, reduces greenhouse gas emissions [14] and requires a simpler exhaust gas treatment system compared to conventional fuels [15]. However, maximizing the benefits of the high thermal energy released from hydrogen combustion in micro combustor applications requires special considerations, as micro combustors typically suffer from short residence times. One solution to address this issue is optimizing the combustion chamber design to improve the heat absorption rate of the external walls.

"In the literature, scholars have proposed several design geometries for micro combustors to enhance heat transfer processes. For example, Rong et al. [16] investigated the thermodynamic and emission characteristics of an ammonia-fueled micro combustor employing dual inlets and outlets with a reverse flow configuration. They reported that the proposed structure improves wall temperature uniformity across the outer walls and generates a vortex in the outlet regions, which helps reduce NO_x emissions. Zhao et al. [17] examined the thermal performance of an ammonia-methane-fueled micro combustor with a single-channel inlet, a double-channel outlet, and a heat recirculation structure. They found that the new design configuration enhances the mean wall temperature by 81.66 K and reduces the standard deviation of the wall temperature by 3.74 K. Cai et al. [18] studied the effects of employing staggered bluff bodies in a hydrogen-fueled micro combustor on thermal performance parameters. They highlighted that the longitudinal vortices generated by the staggered

bluff bodies improve the mixing process and heat transfer coefficient, resulting in a mean wall temperature 73 K higher than that of the conventional structure.

Despite the extensive investigations conducted to optimize the configurations of micro combustors, there is still considerable room for improvement in the thermodynamics and output energy of such applications. One of the key parameters for enhancing heat transfer capacity is increasing the solid wall surface area, which provides a greater opportunity for higher absorption rates of thermal energy [19]. Tang et al. [20] conducted an investigation into the effects of inserting parallel partitions in a micro planar combustor on thermal performance. The results revealed that separating the flame path with parallel partitions increases the mean wall temperature by more than 100 K compared to the traditional design. To the best of the author's knowledge, the use of parallel partitions in micro cylindrical combustors has not yet been studied. Therefore, this paper aims to numerically investigate the effects of parallel partitions integrated into a hydrogen-fueled micro cylindrical combustor on key thermal parameters and system efficiency.

2. Numerical Methodology

2.1. Geometric Model

Fig. 1 shows the schematic layout of a micro cylindrical combustor integrating parallel partitions, which was created using ANSYS Design Modeler. The dimensions of the geometry are listed in Table 1. The purpose of employing the partitions is to increase the surface area of the solid domain, thereby allowing for greater contact between the high-temperature flame and the solid, facilitating more heat transfer to the external walls.

2.2. Conservation equations

The computational fluid dynamic (CFD) software ANSYS Fluent R2 2023 was used to perform the numerical works by means of solving the governing equations of mass, momentum, energy, and species, which read as:

$$\nabla \cdot (\rho \vec{v}) = 0 \quad (1)$$

$$\rho \vec{v} \cdot \nabla \vec{v} = - \nabla P + \nabla \cdot (\vec{\tau} - \vec{\tau}')$$

where

$$\vec{\tau} = \mu \left[\nabla \vec{v} + (\nabla \vec{v})^T - \frac{2}{3} \nabla \cdot \vec{v} I \right] \quad (3)$$

$$\nabla \cdot (\vec{v}(\rho E + p)) = \nabla \cdot \left(k_{eff} \nabla T - \sum_j h_j \vec{J}_j + (\vec{\tau} \cdot \vec{v}) \right) + S_h \quad (4)$$

$$\nabla \cdot (\rho \vec{v} Y_i + \vec{J}_i) = R_i \quad (5)$$

where ρ is the density, $\vec{v}$ velocity vector, P static pressure, $\vec{\tau}$ viscous stress, $\vec{\tau}'$ Reynolds stress, μ molecular viscosity, I unit tensor, E total energy of the fluid, k_{eff} effective conductivity, T temperature, h_j enthalpy of species, $\vec{J}_j$ diffusion flux of species j , S_h enthalpy source term of fluid, Y_i local mass fraction of species i , $\vec{J}_i$ diffusion flux of species i , and R_i reaction net rate of production.

The current investigations disregard the effects of surface reaction, Dufour effect, and gravity due to their negligible impact [21]. Additionally, the flow is assumed to be incompressible because the Mach number is low. As the Reynolds number exceeds 500 [22], the turbulent flow properties and their effects on combustion are accounted for by employing the turbulent modeling approach, namely the Realizable $k-\epsilon$ model [23]. The Eddy Dissipation Concept (EDC) is applied as a combustion model to utilize the chemical mechanisms of 19 species and 63 chemical reactions, which include hydrogen mechanisms [24]. Other numerical settings along with the equations used to compute the the area-weighted-mean wall

temperature ($T_{w,m}$), wall temperature uniformity (R_T), pressure loss, exergy efficiency, and radiation efficiency can be found in [25].

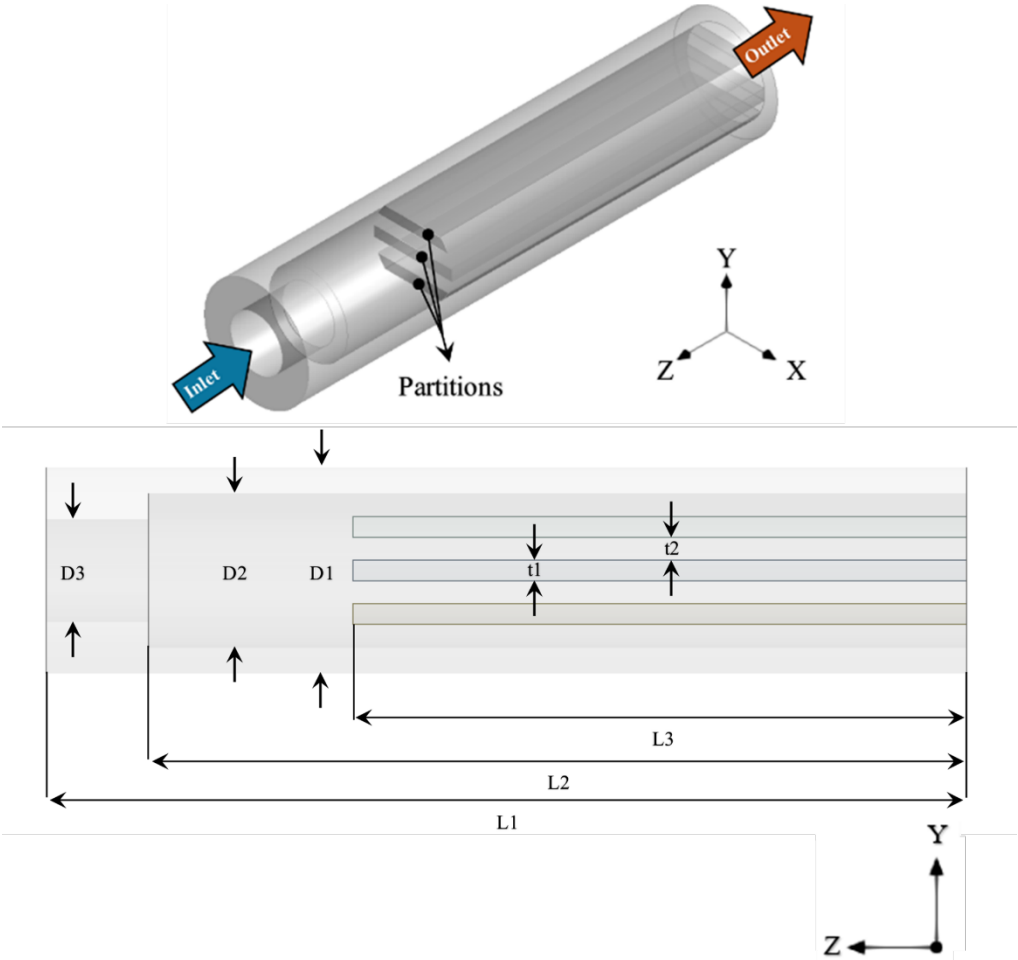


Fig. 1: Schematic representation of a micro cylindrical combustor housing parallel partitions.

Table 1: Dimensions of geometry.

Variable		Values (mm)			
		C1	C2	C3	C4
Length	L1	18	18	18	18
	L2	16	16	16	16
	L3	NA	6	9	12
Diameter	D1	4	4	4	4
	D2	3	3	3	3
	D3	2	2	2	2
Thickness	t1	NA	0.4	0.4	0.4
	t2	NA	0.6	0.6	0.6

2.3. Grid Independence and Model Validation

The mesh sensitivity analysis is a critical stage for each CFD work to balance the accuracy of numerical results and computing power. This sub-section compares three mesh densities of 100,098 (Mesh-I), 405,328 (Mesh-II), and 811,520 (Mesh-III) cell numbers at an inlet velocity and equivalence ratio of 8 m/s and 1, respectively.

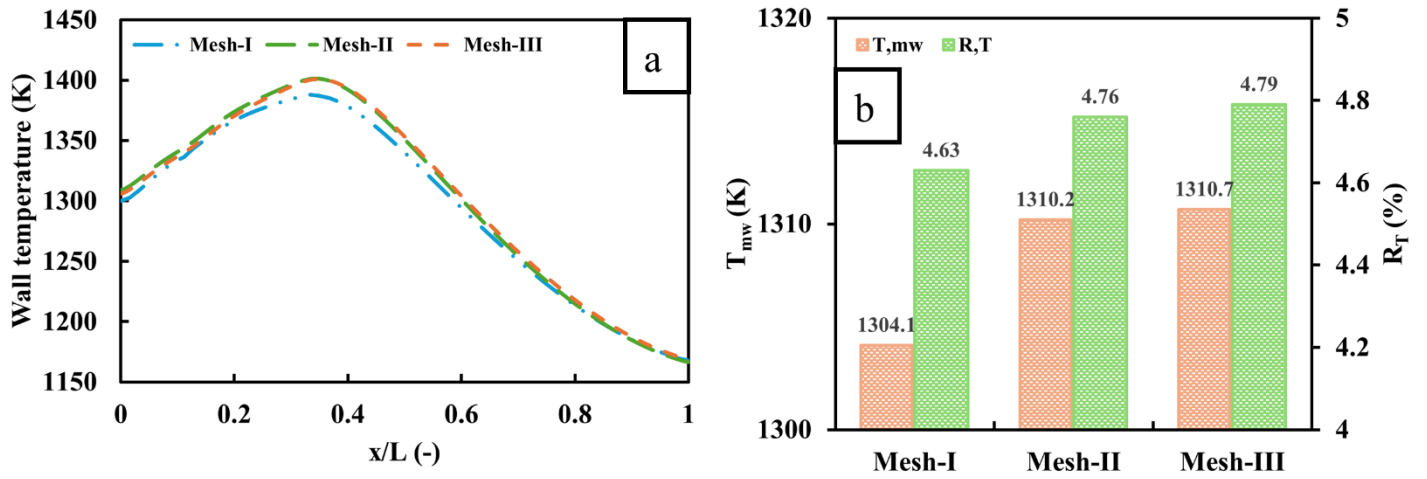


Fig. 2: Comparisons of (a) wall temperature with respect to the dimensionless length (x/L) and (b) $T_{w,m}$ and R_{tw} of different mesh resolutions. x stands for the distance from the inlet, and L represents the distance from the inlet and outlet.

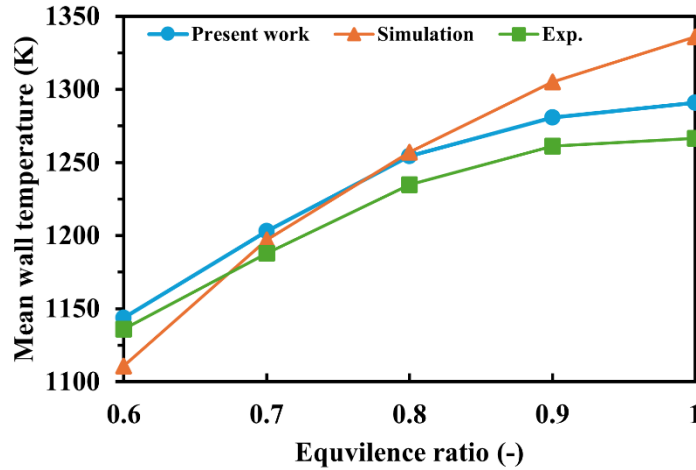


Fig. 3: A validation of the current numerical work against an experimental [26] and numerical [27] findings with respect to the mean wall temperature at different equivalence ratios.

Fig. 2 demonstrates variations in wall temperatures along the outer walls with respect to the dimensionless length (x/L), $T_{w,m}$ and R_{tw} . As can be seen in Fig. 2 (a), the low mesh resolution (Mesh-I) underpredicts the wall temperature in the inlet and middle geometry regions, whereas the medium (Mesh-II) and high (Mesh-III) mesh resolutions are nearly identical. These results are confirmed by the trends of $T_{w,m}$ and R_{tw} as depicted in Fig. 2 (b) as differences of $T_{w,m}$ and R_{tw} between Mesh-I (Mesh-II) and Mesh-III are 6.7 K (0.5 K) and 0.16 % (0.03 %), respectively. Therefore, Mesh-II offers a balance between accuracy and computational effort and is selected for all subsequent simulations.

The turbulence model, combustion model, and numerical settings need to be validated to ensure the reliability and accuracy of the results in the present CFD work. To do this, the mean wall temperature from the current numerical simulations is compared with both experimental [26] and numerical [27] data at a 12 m/s inlet velocity and various equivalence ratios as shown in Fig. 3. The mean wall temperature in this work is consistent with both experimental data and kinetic modeling, increasing with the equivalence ratio. The maximum error between this work and the experiment (simulation) is 1.93% (3.37%) in the outlet (outlet) region. These discrepancies can be attributed to measurement uncertainties in the experiment

and the use of different mesh densities in the simulations. Since the maximum percentage errors outlined above are acceptable, this implies that the numerically predicted results in the current work are reliable and feasible.

3. Results and discussion

This section compares the conventional design of micro cylindrical combustor (C1) with a micro cylindrical combustor inserting parallel partitions (C2, C3, and C4) with respect to the temperature distribution over the domain, T_{mw} , R_T , pressure loss, average exhaust gas temperature (T_{eg}), exergy efficiency, and radiation efficiency at an inlet velocity and equivalence ratio of 8 m/s and 1, respectively. To optimize the newly proposed design, short (C2), medium (C3), and long (C4) partition lengths are investigated.

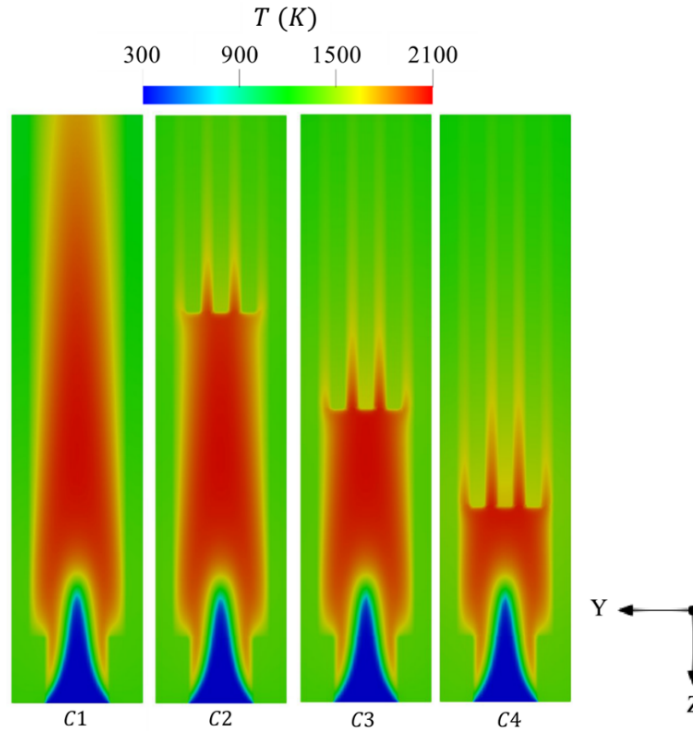


Fig. 4: Variations of temperature across a y-z plane of different design configurations.

Fig. 4 displays a comparison of temperature variations across different structures of a micro cylindrical combustor. As can be seen in Fig. 4, the area occupied by the high-temperature flame is larger in C1 due to the absence of partitions. However, employing parallel partitions suppresses hydrogen flame propagation, resulting in narrower variations of the flame with high thermal energy as the length of the partitions transitions from short (C2) to long (C4). This suggests that the partitions reduce the volumetric space of fluid inside the combustor and then retain the flow with high heat content, increasing dwell time and thereby improving the absorption rate of thermal energy by the external walls.

Fig. 5 demonstrates the effects of C1, C2, C3, and C4 configurations on T_{mw} , R_T , pressure loss, T_{eg} , exergy efficiency, and radiation efficiency. Inserting parallel partitions is an effective method for significantly increasing T_{mw} as the differences of T_{mw} between C1 and C2, C3, and C4 are 20.03 K, 33.53 K, and 40.7 K, respectively. These improvements lie in that the partitions acts as a flame holder, which elongates the residence time of hot gases, and also increases the surface area of contact between the flame and solid, which enhances the heat transfer mechanisms. The R_T trends as shown in Fig. 5 (a) illustrates that establishing the partitions leads to a more evenly distributed flame over the outer walls. However, the short length of partitions (C2) seems to optimize R_T , indicating a retention of flame at an optimal position. These outcomes are confirmed by T_{eg} findings as seen in Fig. 5 (b), where the conventional design (C1) increases wasted thermal energy

compared to the cases with partitions (C2, C3, and C4). This results in improvements in both exergy and radiation efficiencies as depicted in Fig. 5 (c), suggesting that the heat transfer processes are enhanced in C2, C3, and C4 cases. Nevertheless, configuring partitions increases the collision rate between the inlet mixture and the solid domain, leading to higher pressure losses in the C2, C3, and C4 test cases, thus requiring more pumping power. In contrast to the short (C2) and medium (C3) partition lengths, the long partition length (C4) exhibits the highest values for key thermal parameters and system's efficiencies, possibly due to hold the greatest thermal energy.

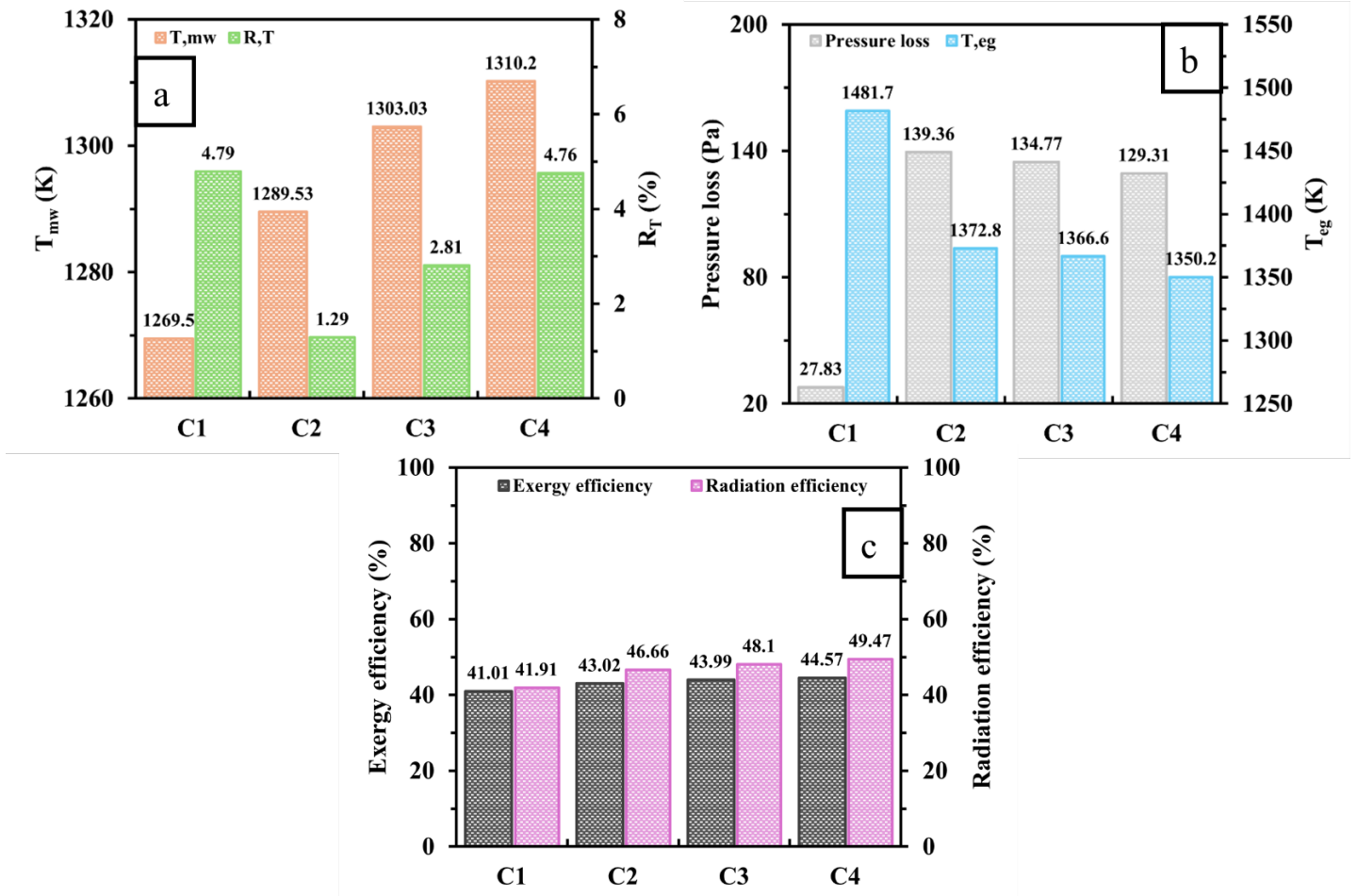


Fig. 5: Comparisons of (a) T_{mw} and R_T , (b) pressure loss and T_{eg} , and (c) exergy, and radiation efficiencies under different micro cylindrical structures.

4. Conclusion

This work numerically investigates the effects of housing parallel partitions in a hydrogen-fueled micro cylindrical combustor on thermal performance and output energy density. The length of the partitions is varied to optimize the newly proposed configuration. The results reveal that, compared to the conventional design, configuring the parallel partitions increases T_{mw} and results in a more even distribution of temperature over the outer walls. This can be attributed to the longer dwell time of the high-temperature flame, due to the partitions holding the flow with high heat content. Furthermore, partitioning the flame path increases the contact surface between the hot gases and the solid walls, leading to an improvement in the heat transfer capacity from the combustion process to the external walls. These effects result in a reduction of wasted thermal energy, as T_{eg} decreases by 131.5 K compared to the traditional design. Consequently, the exergy and radiation

efficiencies are enhanced by 2.66% and 7.56%, respectively. However, the new configuration increases pressure losses due to a higher collision rate between the inlet flow and the partitions. The long partition length optimizes thermodynamic and performance parameters, as it retains the highest thermal energy and contains the largest contact surface area with the solid walls.

References

- [1] W. P. Gooi, P. L. Leow, J. Puspanathan, M. H. F. Rahiman, X. F. Hor, and S. M. Din, "Miniature planar 3D ECT sensor based on distributed electrode arrangement," *Flow Measurement and Instrumentation*, vol. 94, p. 102461, Dec. 2023, doi: 10.1016/j.flowmeasinst.2023.102461.
- [2] W. Dahm, J. Mijit, R. Mayor, G. Qiao, A. Benajmin, Y. Gu, Y. Lei, M. Papke, and S. Wu, "Micro internal combustion swing engine (MICSE) for portable power generation systems," in *40th AIAA Aerospace Sciences Meeting & Exhibit*, 0 vols., in Aerospace Sciences Meetings. , American Institute of Aeronautics and Astronautics, 2002. doi: 10.2514/6.2002-722.
- [3] L. Q. Jiang, D. Q. Zhao, C. M. Guo, and X. H. Wang, "Experimental study of a plat-flame micro combustor burning DME for thermoelectric power generation," *Energy Conversion and Management*, vol. 52, no. 1, pp. 596–602, Jan. 2011, doi: 10.1016/j.enconman.2010.07.035.
- [4] C. Chircov and A. M. Grumezescu, "Microelectromechanical Systems (MEMS) for Biomedical Applications," *Micromachines (Basel)*, vol. 13, no. 2, p. 164, Jan. 2022, doi: 10.3390/mi13020164.
- [5] A. Banerjee and D. Paul, "Developments and applications of porous medium combustion: A recent review," *Energy*, vol. 221, p. 119868, Apr. 2021, doi: 10.1016/j.energy.2021.119868.
- [6] D. Zhao, C. Ji, X. Li, and S. Li, "Mitigation of premixed flame-sustained thermoacoustic oscillations using an electrical heater," *International Journal of Heat and Mass Transfer*, vol. 86, pp. 309–318, Jul. 2015, doi: 10.1016/j.ijheatmasstransfer.2015.03.012.
- [7] A. Fan, H. Zhang, and J. Wan, "Numerical investigation on flame blow-off limit of a novel microscale Swiss-roll combustor with a bluff-body," *Energy*, vol. 123, pp. 252–259, Mar. 2017, doi: 10.1016/j.energy.2017.02.003.
- [8] J. Ran, L. Li, X. Du, R. Wang, W. Pan, and W. Tang, "Numerical investigations on characteristics of methane catalytic combustion in micro-channels with a concave or convex wall cavity," *Energy Conversion and Management*, vol. 97, pp. 188–195, Jun. 2015, doi: 10.1016/j.enconman.2015.03.058.
- [9] Q. Zuo, D. Yang, Z. Shen, W. Chen, C. Lu, L. Chen, and S. Lei, "Effect of premixed ratio on combustion and emission characteristics in a spark ignition engine with hydrogen-ammonia direct injection," *Fuel*, vol. 393, p. 135051, Aug. 2025, doi: 10.1016/j.fuel.2025.135051.
- [10] B. Ma, B. Liu, Y. Wang, and L. Liu, "Analysis on the combustion performance of ammonia-hydrogen coaxial stratified injection in low speed marine engine," *Applied Thermal Engineering*, vol. 270, p. 126253, Jul. 2025, doi: 10.1016/j.applthermaleng.2025.126253.
- [11] H. Wang, X. Wang, Y. Ge, S. Wang, J. Yang, and C. Ji, "Analyzing the impact of hydrogen direct injection parameters on flow field and combustion characteristics in Wankel rotary engines," *Energy*, vol. 319, p. 135004, Mar. 2025, doi: 10.1016/j.energy.2025.135004.
- [12] G. E. Marin, G. R. Mingaleeva, M. S. Novoselova, and A. R. Akhmetshin, "Adding hydrogen fuel to the synthesis gas for the possibility of combustion in a gas turbine," *International Journal of Hydrogen Energy*, vol. 96, pp. 378–384, Dec. 2024, doi: 10.1016/j.ijhydene.2024.11.305.
- [13] G. Bagheri, S. E. Hosseini, and M. A. Wahid, "Effects of bluff body shape on the flame stability in premixed micro-combustion of hydrogen–air mixture," *Applied Thermal Engineering*, vol. 67, no. 1, pp. 266–272, Jun. 2014, doi: 10.1016/j.applthermaleng.2014.03.040.
- [14] T. Cai, D. Zhao, L. Ji, and A. K. Agarwal, "Removal and mechanism analysis of NO_x emissions in carbon-free ammonia combustion systems with a secondary fuel injection," *Fuel*, vol. 344, p. 128088, Jul. 2023, doi: 10.1016/j.fuel.2023.128088.

- [15] J. Li, J. E, J. Ding, L. Cai, and B. Luo, "Investigation on thermophotovoltaic performance enhancement of the hydrogen fueled micro combustors with the center-cleared twisted tapes for micro-thermophotovoltaic system," *Applied Thermal Engineering*, vol. 264, p. 125483, Apr. 2025, doi: 10.1016/j.applthermaleng.2025.125483.
- [16] H. Rong, H. Zhao, and T. Cai, "Thermodynamic and emission analysis of an ammonia fueled micro-combustor with double-channel reverse flow structure," *International Journal of Hydrogen Energy*, vol. 49, pp. 1303–1314, Jan. 2024, doi: 10.1016/j.ijhydene.2023.11.083.
- [17] H. Zhao, D. Zhao, and S. Becker, "Thermal performances investigation on an ammonia-fuelled heat-recirculating micro-combustor with reduced chemical mechanism," *Applied Thermal Engineering*, vol. 236, p. 121685, Jan. 2024, doi: 10.1016/j.applthermaleng.2023.121685.
- [18] T. Cai, Y. Sun, and D. Zhao, "Enhancing heat transfer performance analyses of a hydrogen-fueled meso-combustor with staggered bluff-bodies," *Fuel Processing Technology*, vol. 218, p. 106867, Jul. 2021, doi: 10.1016/j.fuproc.2021.106867.
- [19] W M Yang, S K Chou, C Shu, H Xue, and Z W Li, "Development of a prototype micro-thermophotovoltaic power generator," *Journal of Physics D: Applied Physics*, vol. 37, no. 7, p. 1017, Mar. 2004, doi: 10.1088/0022-3727/37/7/011.
- [20] A. Tang, J. Pan, W. Yang, Y. Xu, and Z. Hou, "Numerical study of premixed hydrogen/air combustion in a micro planar combustor with parallel separating plates," *International Journal of Hydrogen Energy*, vol. 40, no. 5, pp. 2396–2403, Feb. 2015, doi: 10.1016/j.ijhydene.2014.12.018.
- [21] S. Ni, D. Zhao, M. Sellier, J. Li, X. Chen, X. Li, F. Cao, and W. Li, "Thermal performances and emitter efficiency improvement studies on premixed micro-combustors with different geometric shapes for thermophotovoltaics applications," *Energy*, vol. 226, p. 120298, Jul. 2021, doi: 10.1016/j.energy.2021.120298.
- [22] C. H. Kuo and P. D. Ronney, "Numerical modeling of non-adiabatic heat-recirculating combustors," *Proceedings of the Combustion Institute*, vol. 31, no. 2, pp. 3277–3284, Jan. 2007, doi: 10.1016/j.proci.2006.08.082.
- [23] T.-H. Shih, W. W. Liou, A. Shabbir, Z. Yang, and J. Zhu, "A new k - ϵ eddy viscosity model for high reynolds number turbulent flows," *Computers & Fluids*, vol. 24, no. 3, pp. 227–238, Mar. 1995, doi: 10.1016/0045-7930(94)00032-T.
- [24] S. Ni, D. Zhao, W. Wu, and Y. Guan, "NO_x emission reduction reaction of ammonia-hydrogen with self-sustained pulsating oscillations," *Thermal Science and Engineering Progress*, vol. 19, p. 100615, Oct. 2020, doi: 10.1016/j.tsep.2020.100615.
- [25] F. Almutairi, "A Numerical Study on Key Thermal Parameters and NO_x Emissions of a Hydrogen-Fueled Double-Channel Outlet Micro Cylindrical Combustor Employing a Heat-Recirculating Configuration for Thermophotovoltaic Applications," *Processes*, vol. 12, no. 9, 2024, doi: 10.3390/pr12091848.
- [26] Y. Wenming, C. Siawkiang, S. Chang, X. Hong, and L. Zhiwang, "Effect of wall thickness of micro-combustor on the performance of micro-thermophotovoltaic power generators," *Sensors and Actuators A: Physical*, vol. 119, no. 2, pp. 441–445, Apr. 2005, doi: 10.1016/j.sna.2004.10.005.
- [27] W. Zuo, Y. Zhang, Q. Li, J. Li, and Z. He, "Numerical investigations on hydrogen-fueled micro-cylindrical combustors with cavity for micro-thermophotovoltaic applications," *Energy*, vol. 223, p. 120098, May 2021, doi: 10.1016/j.energy.2021.120098.