

CHAPTER 3

EXERGY ANALYSIS OF A COMBUSTOR

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ABSTRACT

This study presents an exergy analysis of a premixed hydrogen/air miniature combustor, focusing on the impact of different bluff body ratios on combustion characteristics and exergy performance. The primary objective was to investigate the combustion efficiency and stability at varying bluff body geometries and inlet velocities, with an emphasis on improving energy conversion. The results show that the bluff body ratio of 0.3 provided the best overall combustion performance, with stable flame development and efficient energy conversion at inlet velocities between 10 m/s and 12 m/s. Higher velocities, specifically at 14 m/s, led to decreased flame stability and reduced exergy efficiency due to poor mixing and potential cooling effects. The exergy efficiency peaked at velocities around 10 m/s, demonstrating the system's ability to effectively convert energy into useful work while minimizing energy loss. This analysis contributes to the development of more efficient combustion systems, offering insights into optimal design parameters for sustainable energy use. The findings support the achievement of the United Nations Sustainable Development Goal (SDG) 7, "Affordable and Clean Energy," by advancing the design of miniature combustors with improved energy efficiency.

Keywords: Heat transfer, CFD, combustion, bluff body

3.1 INTRODUCTION

The prospective uses of miniature combustors in micro gas turbines, portable power production, and other small energy systems have attracted a lot of interest. Achieving steady combustion, maximizing fuel and air mixing, and reducing emissions are the main obstacles in the development of micro combustors. Researchers have investigated number of designs and techniques, emphasizing the challenges of mixing, evaporation, and droplet atomization in a small volume and little residence period. Additionally, it covered promising approaches to overcoming these obstacles, such as self-aspirating designs and electrospray Sankar et al., (2023). The combustion behavior of central porous fuel inlet designs and double chamber designs in micro liquid film combustors was examined by Shih & Liu, (2014). New elements of portable power generation with high specific energy and power were revealed by the findings Li et al., (2008). The effects of combustor geometry and input velocity on flame stability were examined by Yilmaz et al., (2018). Moreover, examining different bluff body ratios, improving understanding how this design influenced not only flame behaviour but also the exergy performance of the system. Knowing that stable combustion leads to better temperature distribution and reduced energy loss and directly linked to higher exergy efficiency. Cho et al., (2022), added a catalytic surface to micro combustors and observed a dramatically increases methane combustion efficiency and lowers unburned hydrocarbons. These surfaces, often coated with materials like platinum or palladium, help trigger combustion reactions at lower temperatures by providing active sites for methane and oxygen to react more easily. This not only helps maintain a stable flame in small scale systems, where heat loss is a concern, but also significantly improves how completely the fuel is burned leading to fewer unburned hydrocarbons and better overall performance of the combustor. Nauman et al., (2024) found that recirculation zones in the combustor, for instance, help balance flame propagation and flow, enhancing stability at high Reynolds numbers, according to research on liquid n-heptane. Furthermore, Li et al., (2019) found that the methane-air combustion in Swiss-roll combustors having dual inlets and outlets shown a stable flame and an even temperature distribution lead to efficiently decreasing heat loss, the counter-flow double-channel design increased thermal efficiency even more. According to the study's findings, the counter-flow configuration and oval-shaped threads together provide a potential way to achieve high thermal efficiency and low NO_x emissions in hydrogen/ammonia fueled micro combustor, making it a good choice for sustainable energy applications by Zhao et al., (2023). The thermal performance of a heat recirculating micro-combustor with pin fins intended for use in micro-thermal voltaic systems was thoroughly investigated numerically in the work by You et al., (2022). With emphasis on enhancing heat transfer and recirculation, the

study sought to improve the performance and efficiency of micro-combustors used in small scale power production systems. For tiny systems that need effective heat used, such as micro thermal voltaic units, pin fins were added to the micro-combustor design to maximize thermal management. Increased heat exchange between the combustor walls and the combustion gases is made possible by the pin fin construction, which also improves flow distribution.

Exergy analysis is a thermodynamic method used to evaluate the efficiency of energy systems, focusing on both the quantity and quality of energy. Unlike traditional energy analysis, which only considers total energy, exergy looks at the potential to perform useful work. This helps identify areas where energy loss can be minimized, as it measures the work potential of energy by comparing a system's state to its surroundings. When a system is in equilibrium with its environment, its exergy is zero, indicating no further work can be done. In combustion systems, such as hydrogen fuelled micro combustors, exergy analysis helps optimize performance. For example, in micro-thermophotovoltaic (MTPV) applications, implementing a wavy structure in the combustor has been shown to improve both thermal and exergy efficiency. The wavy design enhances heat transfer between combustion products and the combustor wall, leading to higher and more uniform temperatures, which improves the system's overall energy conversion efficiency. Studies have demonstrated that adjusting factors such as the equivalence ratio and wavy structure can significantly impact exergy and radiation energy. Increasing the wavy number, for instance, boosts exergy and radiation efficiency, which translates into better power output for micro-power systems. Exergy analysis, therefore, is an essential tool for identifying opportunities to enhance system performance by reducing energy wastage and improving energy utilization by Cai et al., (2021).

3.2 METHODOLOGY

3.2.1 Geometry

In this study, a bluff body was used into the miniature combustor to help stabilize the flame during combustion. A bluff body is a solid object placed in the flow path of the fuel-air mixture to intentionally disturb the flow and create a recirculation zone behind it. This zone helps trap hot gases, which in turn supports continuous ignition and stabilizes the flame. Bluff bodies are commonly used in combustion systems to improve flame anchoring and reduce the risk of blowout or flame extinction. For this simulation, three different bluff body ratios were used 0.1, 0.2, and 0.3 based on the ratio of bluff body height to inlet height. These ratios help determine how much the flow is blocked by the bluff body and how it influences the combustion process. Miniature combustor was model using ANSYS Fluent 2024 R2. A 2-dimensional asymmetrical miniature combustor with bluff body is

used to shorten the simulation's time. About 20 mm in length ($H2$), 2 mm inlet width ($V1$), 2 mm bluff body length ($H4$) were the dimensions of the micro combustor and 0.2mm was the bluff body high. The bluff body was symmetrically included into the micro combustor's upper surfaces. The gap between the bluff body and the outlet, ($H3$), has a value of 15mm. The miniature combustor's dimensions and detailed sketch are displayed in Fig. 3.1 and Table 3.1, respectively.

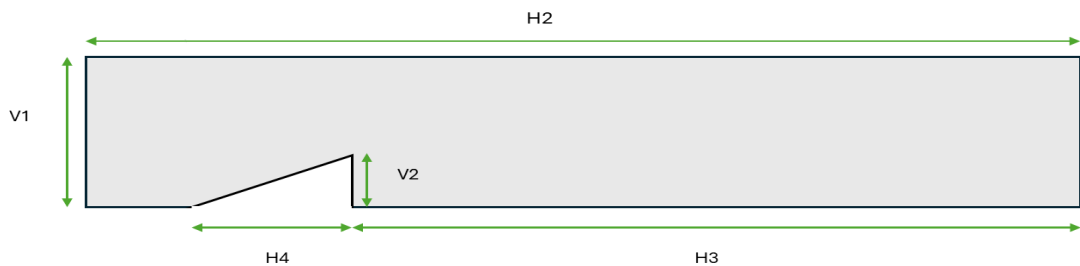


Fig. 3.1: The geometry sketch of the miniature combustor with bluff body

Table 3.1: The geometric parameters

Parameters	Value
V1	2.0 mm
V2	0.2 mm
H2	20.0 mm
H3	15.0 mm
H4	2.0 mm

3.2.2 Meshing

The process of dividing the computational domain into simple elements is called meshing. The mesh of the domain affects the precision, convergence, and simulation accuracy. Hence, it is crucial to have a decent strategy in meshing in order to obtain a low cost of time and more precise solution. Detailed resolution was ensured by selecting a linear element order with a size of 0.0001 m. Meshing size 0.0001 m is equal to one per tenth size of flame thickness. In summary, the meshing procedure of the bluff body combustor was refined to accurately model combustion dynamics, providing insights into the influence of bluff body geometries on stability and combustion efficiency.

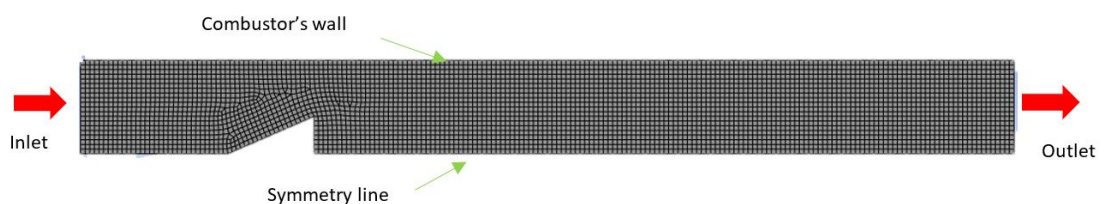


Fig. 3.2: Numerical domain with boundary condition

3.2.3 Numerical Model

The simulation of the miniature hydrogen-air combustor was carried out using a 2D model that includes a single inlet and a single outlet. The simulation parameters are shown in Table 3.2. The inlet conditions were set at a temperature of 300 K and inlet velocities of 8 m/s, 10 m/s, 12 m/s, and 14 m/s. The outlet was set to atmospheric pressure. The temperature of 300 K was chosen to represent standard ambient conditions, which are commonly used in combustion simulations to maintain consistency and allow for easier comparison with previous studies. The use of multiple inlet velocities was intended to analyze how changes in flow speed affect the combustion behavior and exergy performance of the system. By varying the inlet velocity, the study can observe the impact on flame stability, temperature distribution, and recirculation behind the bluff body. This helps to determine how well the combustor performs under different flow conditions. The bluff body blockage ratios used in this analysis were 0.1, 0.2, and 0.3, allowing comparison of flame response and efficiency across different levels of flow disturbance. These variations provide a more complete understanding of how geometry and inlet velocity together influence combustion and energy conversion in the miniature combustor.

Table 3.2: Simulation parameters of the miniature combustor

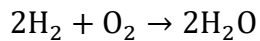
Boundary Conditions of the miniature combustor with bluff body analysis			
Boundary	Parameter	Magnitude	Unit
Inlet	Velocity	8, 10, 12, 14	m/s
	Temperature	300	K
	Gauge pressure	0	Pa
	Species mole fraction	H ₂ = 0.03 & O ₂ =0.97	
	Equivalence ratio,	1	
	Height	2	mm
Outlet	Gauge pressure	0	Pa
	Height	2	mm
wall	Material	Aluminium	
	External emissivity	1	

Below are the steps for the calculation regarding above about equivalence ratio (ϕ)=1.0.

1. Equivalence Ratio (ϕ) definition:

$$\phi = \frac{\text{Actual Fuel-to-Air Ratio (FAR)}}{\text{Stoichiometric Fuel-to-Air Ratio (FAR}_{st})} \quad (3.1)$$

2. One step stoichiometric combustion of Hydrogen:



- Molar mass of hydrogen (H_2) = 2 g/mol
- Molar mass of oxygen (O_2) = 32g/mol
- The stoichiometric fuel-to-air ratio (FAR_{st}) is:

$$\text{FAR}_{st} = \frac{\text{mass of hydrogen}}{\text{mass of oxygen}} = \frac{2\text{g}}{32\text{g}} = 0.0625$$

3. Actual Fuel-to-Air Ratio (FAR) for $\phi = 1.0$:

Since $\phi = 1.0$, the actual FAR is the same as the stoichiometric FAR:

$$\text{FAR} = \text{FAR}_{st} = 0.0625$$

3.3 RESULTS AND DISCUSSION

3.3.1 Model Validation

The simulation results in this study are validated by referring to the research titled experimental and numerical investigation on combustion characteristics of premixed hydrogen/air flame in a micro-combustor with a bluff body, which provide The temperature data from their study is used for comparison to check the accuracy and reliability of the past research by Wan et al., (2012). The micro-combustor is 16 mm long with a 1 mm wall thickness, and the chamber has a width of 10 mm and a height of 1 mm. It includes a bluff body with an equilateral triangular cross-section (0.5 mm side length) placed 1 mm from the inlet. Both the combustor and bluff body are made of quartz glass for high-temperature resistance. The design also incorporates thermal management, accounting for heat losses through natural convection and radiation, with a heat transfer coefficient of 20 W/m²/K and an ambient temperature of 298 K (25°C).

Table 3.3: Comparison between the present and Wan et al. 2012.

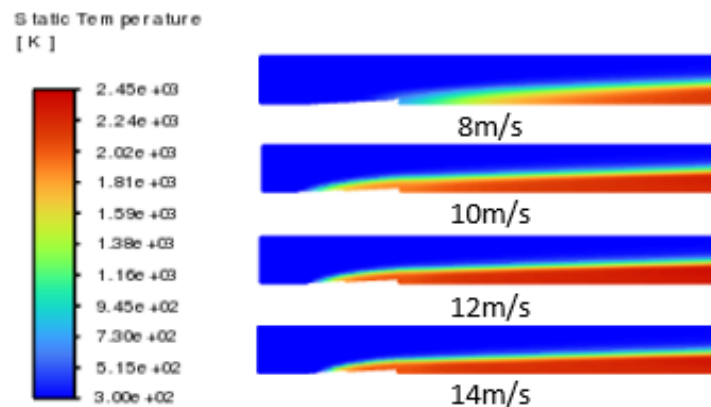
Inlet Velocity (m/s)	Outlet Temperature (K)		Percentage error (%)
	Present	Wan et al. 2012	
10	1325.79	1250	6.06
20	1619.84	1550	4.5

This study checks the accuracy of the simulation by comparing the outlet temperature results with previous research. At an inlet velocity of 10 m/s, the outlet temperature from this simulation was 1325.79 K, while the previous study recorded 1250 K, resulting in a percentage error of 6.06%. For 20 m/s, the outlet temperature reached 1619.84 K, compared to 1550 K in the reference study, with an error of 4.5%.

The difference in results is considered acceptable and can be explained by variations in model design. The previous study included 1 mm thick walls in the combustor geometry, which may have caused additional heat loss through conduction. In contrast, the model used in this study does not include wall thickness, which reduces heat loss and results in slightly higher outlet temperatures. Despite this, the close values indicate that the simulation results are reliable and valid for analyzing combustion and exergy performance in a miniature hydrogen-air combustor.

3.3.2 Temperature Contours

Fig. 3.3 shows the combustion intensity and temperature distribution within the miniature combustor shows significant variation.

**Fig. 3.3:** Temperature contour of ratio 0.2 1st

At 10 m/s and 12 m/s, the flame appears more stabilized and fully developed, with higher temperature zones extending downstream, indicating improved combustion. However, at 8 m/s and 14 m/s, the temperature is lower, and the flame is less developed or shifted, suggesting suboptimal mixing or quenching.

effects.

Fig. 3.4 above shows the temperature contour for bluff body ratio of 0.1 first design shows that at 8–12 m/s, the flame is stable with good heat distribution, indicating efficient combustion.

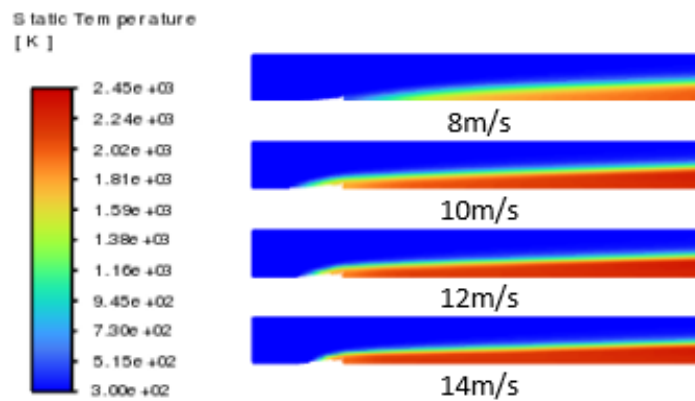


Fig. 3.4: Temperature Contour ratio 0.1 1st

At 14 m/s, the flame shifts further back and appears weaker, suggesting reduced thermal and exergy performance at higher velocity.

Fig. 3.5 shows the temperature contour for bluff body ratio 0.1 second design shows how the flame behaves at different inlet velocities from 8 m/s to 14 m/s. At 8 m/s, the flame is strong and stays near the bluff body.

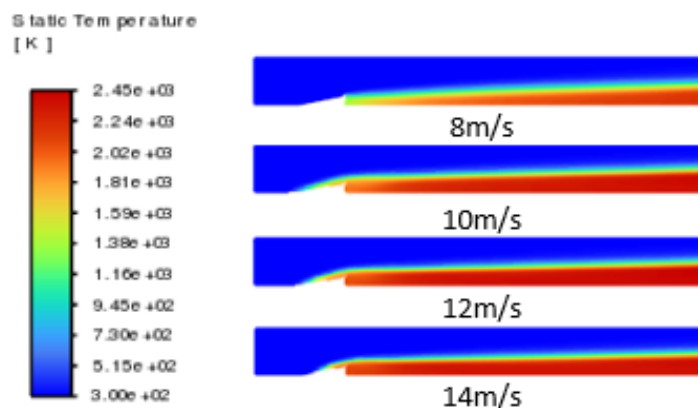


Fig. 3.5: Temperature contour ratio 0.1 2nd

As the velocity increases to 10 m/s and 12 m/s, the flame moves slightly downstream but remains stable, showing good combustion. However, at 14 m/s, the flame becomes more stretched and weaker, which may reduce combustion efficiency. This contour helps show how inlet velocity affects flame stability and heat distribution, which are important for understanding the exergy efficiency of the miniature combustor.

Fig. 3.6 shows the temperature contours show that as flow velocity increases, the temperature distribution becomes more uniform, indicating better heat dissipation.

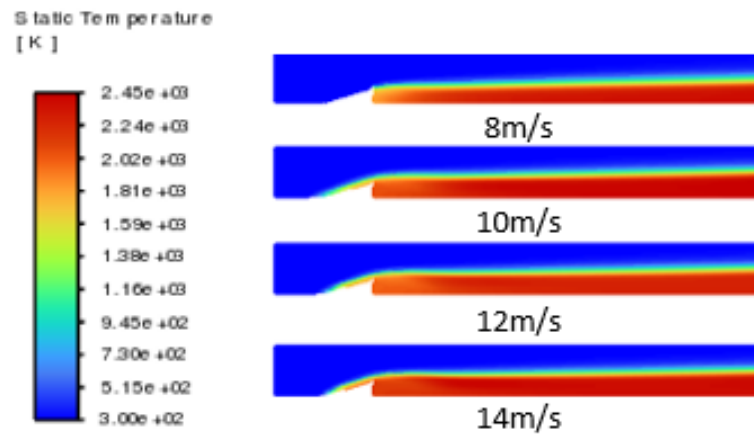


Fig. 3.6: Temperature contour ratio 0.1 3rd

This affects the combustion and exergy performance of the hydrogen/air mixture. This showed the same results as Fig. 3.4 and Fig. 3.5 in previous cases.

Fig. 3.7 shows that at a velocity of 8 m/s, the temperature is relatively uniform, but as the velocity increases to 14 m/s, the temperature near the bluff body rises significantly, creating a sharper gradient.

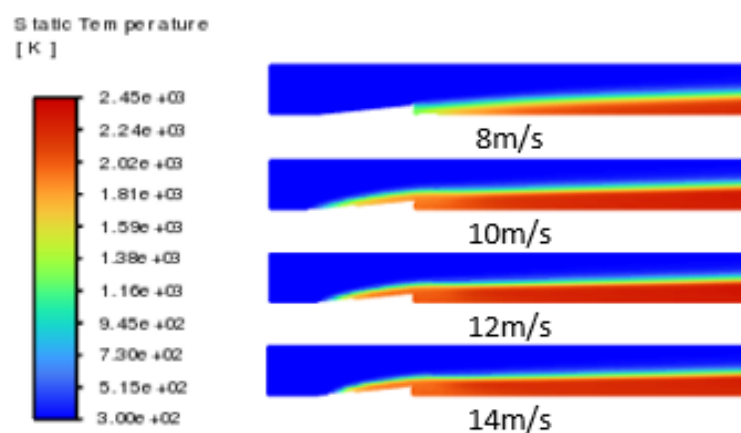


Fig. 3.7: Temperature contour ratio 0.2 2nd

Higher velocities result in more pronounced temperature differences between the body and the surrounding flow.

Fig. 3.8 shows that temperature contours show a decrease in temperature as velocity increases.

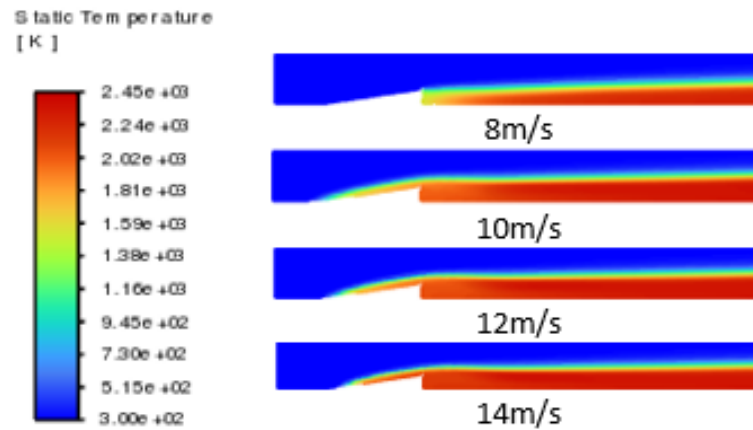


Fig. 3.8: Temperature contour ratio 0.2 3rd

At 8 m/s, the temperature is high near the bluff body but drops downstream. At 10 m/s and 12 m/s, the temperature extends further, indicating better combustion. At 14 m/s, the temperature drops again, suggesting inefficiency. Compared to Fig. 4.4, 10 m/s and 12 m/s show stable combustion, while 8 m/s and 14 m/s show lower temperatures, confirming optimal combustion at moderate velocities.

Fig. 3.9 shows that at 8m/s, the temperature distribution is quite uniform, with lower temperature regions near the combustor wall.

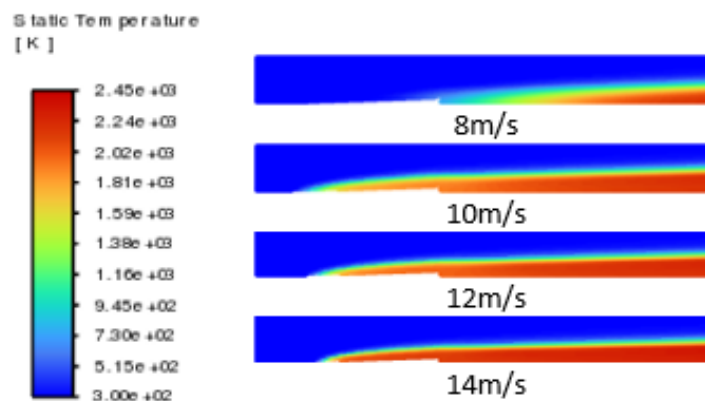


Fig. 3.9: Temperature contour ratio 0.3 1st

As the velocity increases to 10m/s and 12m/s, the temperature near the combustor wall rises, indicating improved combustion with more developed and stabilized flame fronts. At 14m/s, the temperature drops significantly, suggesting that the flame becomes less stable, potentially due to an inefficient mixing process. This behaviour highlights the impact of velocity on combustion efficiency and temperature development in the combustor.

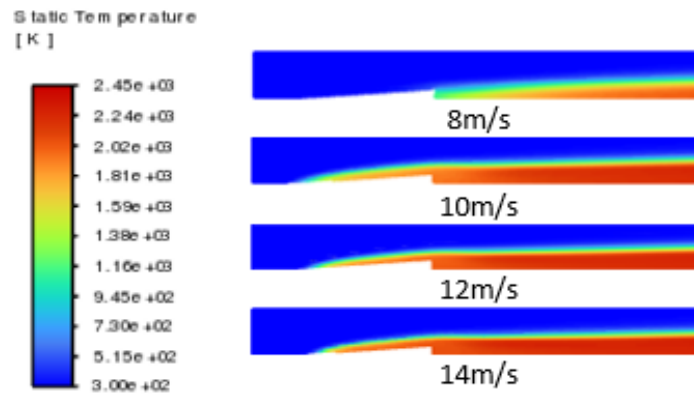


Fig. 3.10: Temperature contour ratio 0.3 2nd

The temperature contours show that at 8 m/s, the temperature is higher near the bluff body but drops quickly downstream. As velocity increases from 10 m/s to 12 m/s, the temperature distribution stabilizes, with a larger heated zone. At 14 m/s, the temperature is more uniform, indicating better combustion efficiency.

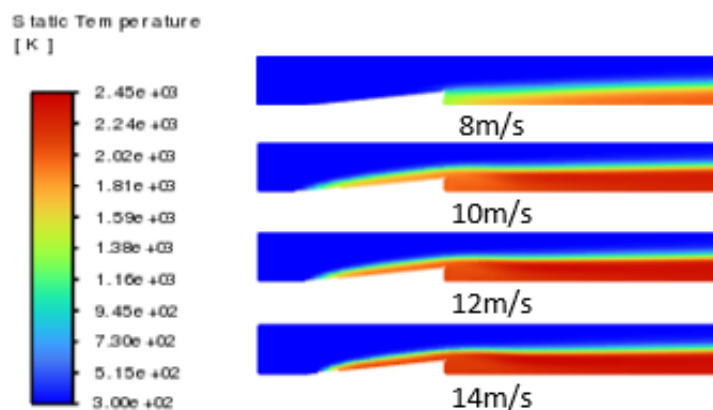


Fig. 3.11: Temperature contour ratio 0.3 3rd

At 8 m/s, the temperature is uniform with cooler regions near the wall. At 10 m/s and 12 m/s, the temperature rises near the wall, indicating better combustion and flame stabilization. However, at 14 m/s, the temperature drops, suggesting instability due to poor mixing or cooling effects from the higher velocity. This shows the impact of flow velocity on combustion efficiency.

Fig. 3.12 shows the ratio at 0.2 first design at 8 m/s, the flame is stable and concentrated near the bluff body.

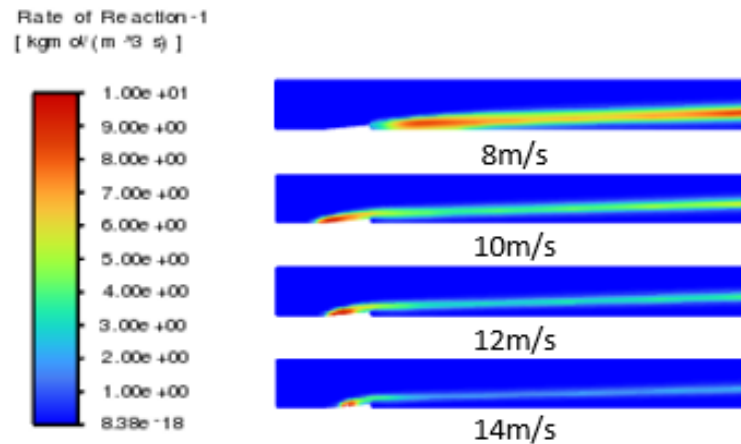


Fig. 3.12: Reaction contour ratio 0.1 1st

The reaction intensity increases and weakens slightly after reaching velocity at 10m/s. At 14 m/s, the flame becomes unstable and detached, leading to incomplete combustion. This indicates that higher velocities reduce flame stability and exergy efficiency, with optimal performance observed around 10 m/s.

This Fig. 3.13 shows the ratio at 0.2 first design at 8 m/s, the flame is stable and concentrated near the bluff body.

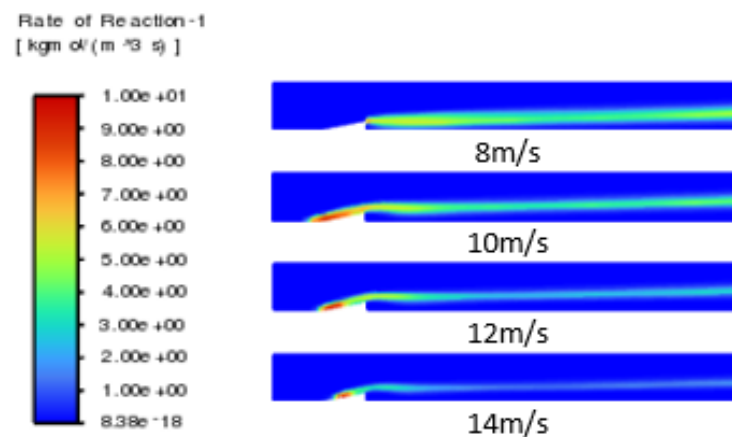


Fig. 3.13: Reaction contour ratio 0.1 2nd

The reaction intensity increases and weakens slightly after reaching velocity at 10m/s. At 14 m/s, the flame becomes unstable and detached, leading to incomplete combustion. This indicates that higher velocities reduce flame stability and exergy efficiency, with optimal performance observed around 10 m/s.

Fig. 3.14 shows the reaction contour at ratio 0.2 third design that the velocity at 8 m/s, the flame is stable and concentrated near the bluff body, indicating efficient combustion.

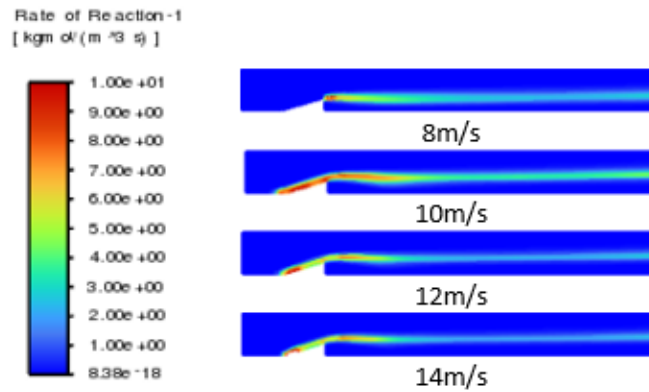


Fig. 3.14: Reaction contour ratio 0.1 3rd

As the velocity increases to 10 m/s and 12 m/s, the flame stretches downstream and weakens slightly, reducing reaction intensity. This trend is same as the reaction before. This indicates that higher velocities reduce flame stability and exergy efficiency.

Fig. 3.15 shows that at 8m/s, the reaction rate is low, indicating less efficient combustion.

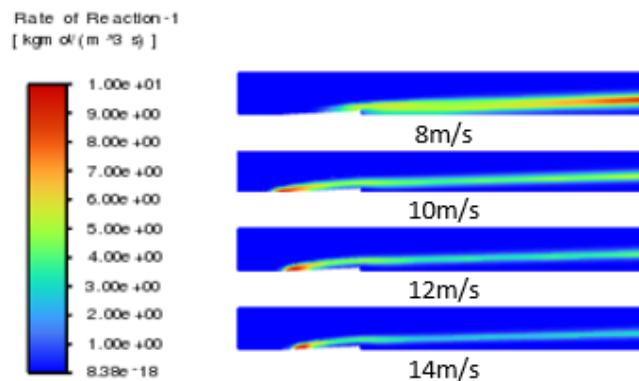


Fig. 3.15: Reaction contour ratio 0.2 1st

As the velocity increases to 10m/s and 12m/s, the reaction rate rises, suggesting improved combustion due to better mixing and more stable flame fronts. However, at 14m/s, the reaction rate plateaus, showing diminishing returns in combustion efficiency. Relating this to exergy, higher reaction rates imply better energy conversion, but once the rate stabilizes at higher velocities, the exergy efficiency may decrease, indicating less effective energy utilization.

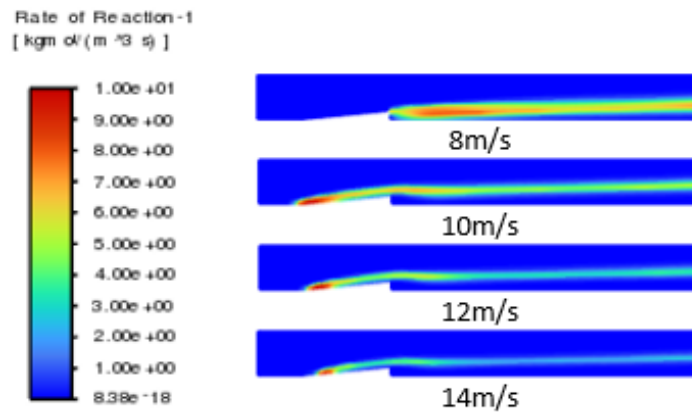


Fig. 3.16: Reaction contour ratio 0.2 2nd

The reaction rate contours show that at 8m/s, combustion is weak. As velocity increases to 10m/s and 12m/s, the reaction rate improves. However, at 14m/s, the rate levels off, indicating that higher velocity no longer significantly enhances combustion.

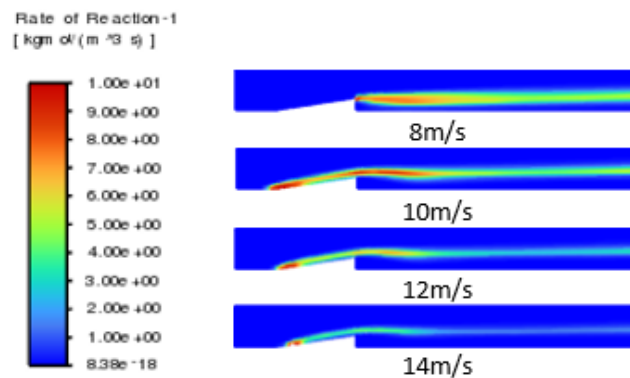


Fig. 3.17: Reaction contour ratio 0.2 3rd

As the velocity increases from 8m/s to 14m/s, the reaction zone expands and becomes more distributed, indicating improved mixing of hydrogen and air. At 8m/s, the reaction is concentrated in a small region, while at 10m/s and 12m/s, the reaction zone grows, reflecting better combustion. However, at 14m/s, the reaction becomes less intense, suggesting that high velocity may lead to flame instability or cooling effects, reducing combustion efficiency.

Fig. 3.18 shows that as the velocity increases, the reaction rate initially increases at 10 m/s and 12 m/s, showing more active combustion near the bluff body.

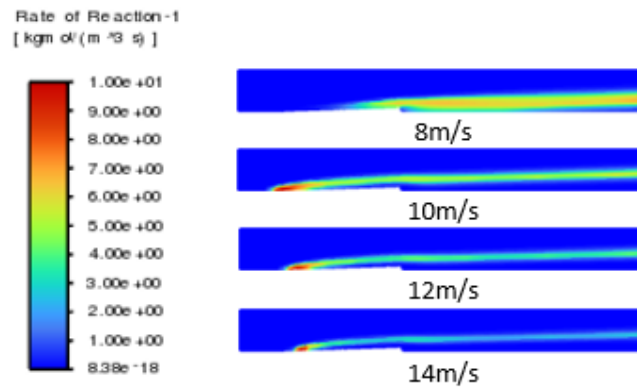


Fig. 3.18: Reaction contour ratio 0.3 1st

However, at 14 m/s, the reaction rate decreases significantly, suggesting that high velocities may disrupt the mixing process, leading to a less stable flame. Thus, the optimal reaction rate appears to occur at 10 m/s and 12 m/s, where the flame is more developed and combustion is more efficient.

Fig. 3.19 shows that the reaction contour shows that the hydrogen and air reaction rate is highest at 10 m/s and 12 m/s, with a more stable flame.

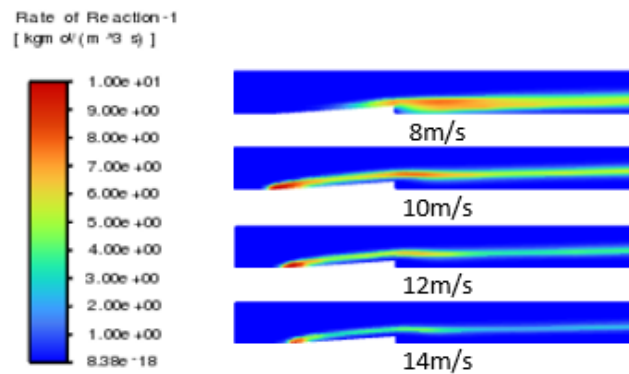


Fig. 3.19: Reaction contour ratio 0.3 2nd

At 14 m/s, the reaction rate decreases, indicating less efficient combustion due to disrupted mixing.

Fig. 3.20 shows that the reaction rate at 8 m/s in this figure shows a lower combustion intensity, like the findings in Fig. 4.16, where the reaction was less developed.

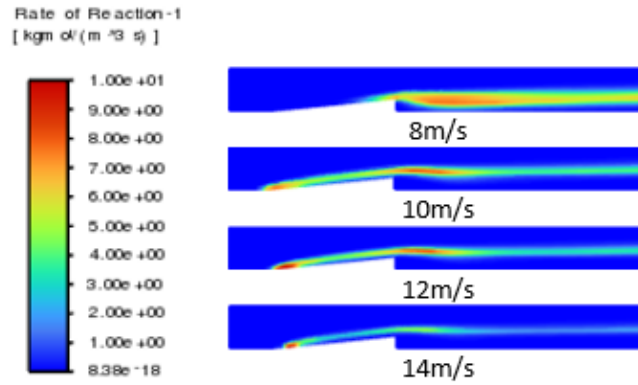


Fig. 3.20: Reaction contour ratio 0.3 3rd

At 10 m/s and 12 m/s, both figures show improved combustion with more developed flame fronts. However, at 14 m/s, as seen in both this Fig. 3.18 and Fig. 3.19, the reaction rate drops, indicating less stable combustion, likely due to higher velocity affecting the mixing pr

3.4 EXERGY GENERATION ANALYSIS

This section presented the exergy generation analysis from the combustion. According to the Thermodynamics' Second Law, the exergy efficiency is derived as below:

$$E_{X_{in}} = \dot{m}_{H_2} \times Q_{LHV} \quad (3.2)$$

where $E_{X_{in}}$, is the inlet exergy; Q_{LHV} , is the lower heating value of hydrogen; and \dot{m}_{H_2} is the mass flow rate of methane. The total exergy loss can be simplified as the outlet pressure is equal to the atmospheric pressure. The total exergy at the outlet is;

$$E_{X_{loss}} = \dot{m}_{exhaust} \times C_{P_{exhaust}} \times (T_{eg} - T_{ambient}) \quad (3.3)$$

$$E_{X_{eg}} = E_{X_{loss}} + \dot{m}_{inlet} \times T_{\infty} \times \left(C_{P_{outlet}} \ln \frac{T_{\infty}}{T_{eg}} \right) \quad (3.4)$$

where T_{eg} , is the exhaust gas temperature; T_{∞} , is the ambient temperature; \dot{m}_{inlet} , is the mass flow rate at inlet; $E_{X_{loss}}$, is the exergy loss at outlet; and $E_{X_{eg}}$, is the total exergy loss at the outlet.

$$E_{X_{des}} = E_{X_{in}} - E_{X_{eg}} \quad (3.5)$$

where $E_{X_{des}}$ is the exergy utilization during the combustion. The exergy efficiency as given as;

$$n_{exergy} = \left(1 - \frac{E_{X_{des}}}{E_{X_{in}}}\right) \times 100\% \quad (3.6)$$

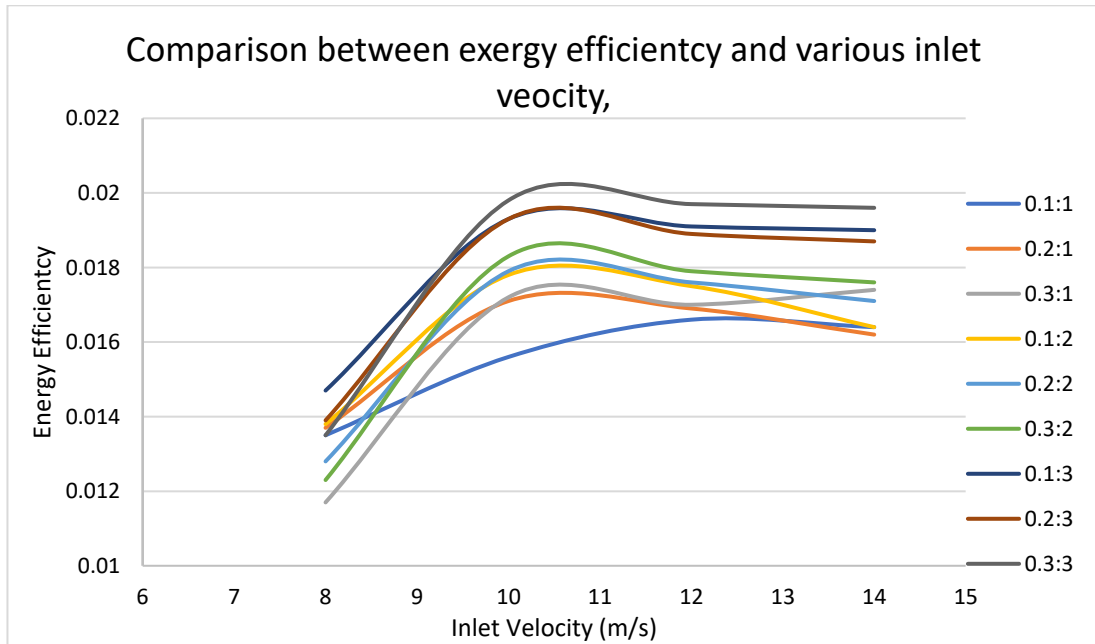


Fig. 3.21: Comparison on the exergy efficiency with various inlet velocities

Fig. 3.21, compares the exergy efficiency of the system at different inlet velocities (8 m/s, 10 m/s, 12 m/s, and 14 m/s) and various bluff body ratios (0.1, 0.2, and 0.3). The analysis shows that as the velocity increases from 8 m/s to 10 m/s, the exergy efficiency improves across all bluff body ratios. This indicates that the system becomes more efficient at converting energy into useful work as the velocity increases, suggesting that it can handle higher energy input without significant energy losses. However, as the velocity continues to rise from 10 m/s to 12 m/s and 14 m/s, a slight decrease in exergy efficiency is observed, particularly for the 0.1 and 0.2 bluff body ratios. This suggests that at higher

velocities, the system begins to lose efficiency, likely due to increased friction or turbulence, which leads to higher energy dissipation. As a result, the system is not able to maintain the same level of performance as it did at lower velocities. At the highest velocity of 14 m/s, the exergy efficiency further drops for most bluff body ratios, indicating that the system struggles to maintain efficiency at extreme velocities. This suggests that the system has an ideal velocity range beyond which its performance deteriorates, likely due to the system's inability to effectively convert energy at these higher speeds. Regarding the bluff body ratios, the 0.3 ratio provides the most stable exergy efficiency across different velocities, showing less fluctuation compared to the 0.1 and 0.2 ratios. This ratio appears to offer the best performance in terms of consistency, suggesting that a higher bluff body ratio may improve the system's overall stability and energy efficiency. Therefore, the ideal performance is likely achieved at a velocity of around 10 m/s with a bluff body ratio of 0.3.

3.5 CONCLUSION AND RECOMMENDATIONS

In this study, the exergy analysis of a premixed hydrogen/air miniature combustor was conducted to evaluate the effects of bluff body geometry and inlet velocity on combustion characteristics and exergy efficiency. The investigation revealed that the bluff body ratio of 0.3 provided the most favorable combustion performance. At inlet velocities of 10 m/s and 12 m/s, the flame was stable and well-developed, showing superior combustion efficiency. However, at higher velocities (14 m/s), the flame became weaker and more unstable, highlighting the detrimental effects of excessive velocity on combustion stability. Regarding inlet velocity, it was observed that lower velocities from 8 m/s to 10 m/s led to more stable flames, resulting in better heat distribution and improved exergy efficiency. As the velocity increased beyond 10 m/s, exergy efficiency slightly decreased, indicating that higher velocities disrupt the mixing process, leading to energy losses and reduced performance. The optimal velocity for maintaining high combustion and exergy efficiency was found to be 10 m/s, as it provided the best balance between flame stability and energy utilization. The exergy efficiency analysis showed that the 0.3 bluff body ratio consistently performed better across varying velocities, suggesting that a larger bluff body enhances energy conversion efficiency by providing more stable combustion. The results highlight the importance of balancing both the bluff body ratio and inlet velocity to optimize performance in miniature combustors. The findings suggest that for maximum efficiency, the ideal design would incorporate a bluff body ratio of 0.3 and an inlet velocity around 10 m/s. This research has broader implications for advancing clean energy solutions and supporting the achievement of Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). By optimizing combustion processes for better efficiency and reducing energy waste, this work contributes to the development of more

sustainable energy systems. Future studies could further explore the influence of other geometric designs and fuel mixtures to refine these findings and improve the overall efficiency of combustion systems in miniature combustors, paving the way for greener and more sustainable energy solutions. In future research, it would be beneficial to expand the study by investigating a wider range of bluff body geometries and additional fuel types, such as methane or natural gas. Although hydrogen was the focus of this study, examining alternative fuels could provide insight into how different fuel properties affect combustion efficiency and exergy performance in miniature combustors. Moreover, the inclusion of a broader spectrum of flow conditions, such as varying inlet pressure or different ambient temperatures, could yield a more comprehensive understanding of the combustor's performance across diverse operational environments. The current study primarily evaluates combustion at specific inlet velocities, but exploring the effects of transient flow conditions or fluctuating velocities could provide a deeper understanding of how real-world variations impact performance. Conducting experiments over a wider range of operational conditions—such as varying thermal loads or extended duration testing—would offer a clearer picture of the combustor's long-term reliability and its capability to maintain high exergy efficiency under dynamic conditions. Additionally, using real-time experimental data to complement the simulation results would enhance the validation of the model and ensure that it accurately reflects actual performance. Future studies could further improve exergy efficiency by exploring the implementation of advanced thermal management techniques, such as incorporating porous media or enhanced heat exchange surfaces within the combustor. These innovations could help minimize thermal losses, increase energy recovery, and enhance the overall performance of the combustor. Additionally, the optimization of the bluff body ratio and geometric configurations could be refined based on the insights gained from this study. Testing various materials for the combustor construction, such as advanced ceramics or composites, could also lead to better thermal resistance and performance at higher temperatures. Finally, the data collected from this study can be extended by investigating other exergy losses such as those related to friction or heat radiation. Analyzing the impact of these losses on the overall system's energy conversion efficiency will provide a more holistic view of the combustor's effectiveness. It is also recommended to simulate and compare the results from different numerical methods and solvers to verify the consistency of the findings. This comparative analysis could further refine the prediction accuracy of the exergy performance of hydrogen/air combustors.

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