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The Impact of Geometry Engineering on Combustion Efficiency and Emissions: Performance Evaluation of Axial Diffuser Tube, Perforated Distribution Node, and Symmetrical Axial Radiator

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ABSTRACT

With increasing environmental concerns about emissions, improving combustion systems for alternative fuels, such as used engine oil, has become imperative. Investigating innovative burner designs to enhance fuel-air mixing, reduce emissions, and stabilize performance presents challenges due to high viscosity and incomplete combustion. However, previous research has not adequately addressed the role of burner head geometry in mitigating these problems. A combination of experimental tests and computational fluid dynamics (CFD) simulations was used to evaluate the performance. This study aims to fill the gap by evaluating the effects of three burner head designs—axial diffuser tube, perforated distribution node, and symmetrical axial cooler—on combustion efficiency and emissions. The results indicate that the axial diffuser tube achieved the highest efficiency (94.3%) and lowest emissions (NOx: 128 ppm, CO: 52 ppm, PM: 18 µg/m^3) due to uniform heat distribution and increased turbulence. The perforated distribution node showed a balanced performance, with an efficiency of 91.7% and moderate emissions (NOx: 145 ppm, CO: 65 ppm, PM: 24 µg/m^3). Meanwhile, the symmetric axial cooler, designed for thermal stability, showed lower efficiency (89.6%) and higher emissions (NOx: 167 ppm, CO: 78 ppm, PM: 30 µg/m^3). The results indicate the importance of burner engineering in balancing efficiency and emissions control. The results of this study support sustainable combustion technologies for industrial and domestic applications, and underscore the global transition to clean energy solutions.

1. INTRODUCTION

The efficiency and environmental sustainability of combustion systems remain critical challenges in the modern energy landscape (Boretti, 2024). With the global push toward cleaner energy and stricter emissions regulations, optimizing combustion chamber designs has become a primary focus for researchers and engineers (Al-Naffakh *et al*., 2020a).

Alternative fuels, such as waste automotive oil, present significant challenges for combustion systems due to their high viscosity, inconsistent chemical properties, and tendency to produce incomplete combustion (Lee & Han, 2023). These issues often result in elevated emissions of pollutants, including particulate matter (PM) and carbon monoxide (CO), which are critical environmental concerns. Previous studies have highlighted the need for advanced geometric designs and optimized mixing strategies to overcome these limitations and ensure stable and efficient combustion

(Mohan *et al*., 2023). Additionally, waste oil combustion systems often struggle with the formation of localized hotspots, which exacerbate the production of nitrogen oxides (NOx), a major pollutant contributing to air quality degradation (Anjum *et al*., 2021).

Computational Fluid Dynamics (CFD) modeling has emerged as a powerful tool for understanding the effects of geometric variations on combustion performance. Simulation allow researchers to visualize airflow patterns, predict temperature distributions, and analyze emissions formation under various operating conditions (Ismail & Nguyen, 2023; Raman & Hassanaly, 2019). The lack of direct comparative studies evaluating different burner head geometries for waste oil combustion is one of the major limitations of the current literature. While some studies have investigated the effects of general burner design, studies that systematically compare specific geometries and their effects on efficiency and emissions remain rare (Gupta & Kumar, 2023). These insights have driven the development of more sophisticated chamber designs that not only improve efficiency but also reduce hotspots and thermal gradients, which are major contributors to pollutant formation (Seesaard *et al*., 2024; Zhu *et al*., 2024). The gap of lack of integration between CFD simulation and experimental verification is very evident in the analysis of airflow patterns, temperature distribution and emission composition (Hasan *et al*., 2024). In addition to simulations, experimental evaluations remain vital for validating the effectiveness of proposed designs. Studies have shown that optimizing the geometry of combustion heads can significantly reduce unburned hydrocarbons and CO emissions while maintaining stable flame propagation (Al-Naffakh *et al*., 2020b). Advanced designs that incorporate symmetry and multidirectional airflow paths have demonstrated superior performance in managing heat distribution and preventing localized overheating, which is essential for sustainable and efficient combustion (Rb *et al*., 2024, Bilodeau, 2020).

There is a lack of detailed comparative analyses evaluating the performance of specific burner head designs in mitigating the challenges posed by spent automotive oil despite significant advances in combustion technologies. Many existing studies have focused on conventional fuels or generic geometric configurations without addressing how innovative designs can reduce emissions and enhance fuel-air mixing under real-world conditions (Boretti & Huang, 2024; Malik *et al*., 2024). This research contributes significantly to providing an evaluation of the burner head geometry designed to improve the combustion of spent automotive oil by integrating experimental and simulation investigations. Also, enhancing the efficiency of fuel-air mixing, reducing local hot spots, and reducing the formation of harmful emissions such as NOx, CO.

2. MATERIAL AND METHODS

2.1. Experimental Set Up

To investigate the combustion characteristics of waste automotive oil, a custom-built burner system was developed using cost-effective materials in Najaf, Iraq. The system was designed to operate with a controlled and steady fuel supply, ensuring reliable experimental conditions (Jafar *et al*., 2024). Waste oil was stored in an external tank and delivered through a gravity-feed mechanism at a constant rate of 120 ml/h. A pointer gauge and time clock were used to precisely monitor the fuel flow, maintaining consistency throughout the testing process. Accurate data collection was essential for evaluating combustion performance. A K-type thermocouple, with an uncertainty of ±1°C, was employed to measure temperature distributions within the combustion chamber. To assess emission levels, a portable gas analyzer with a measurement uncertainty of ±2% was used to record pollutant concentrations, including NOx and CO emissions. Standard error propagation methods were applied to conduct an uncertainty analysis, ensuring reliability in combustion efficiency and heat transfer calculations. Prior to each experimental run, all measurement instruments underwent a thorough calibration process to eliminate potential discrepancies and guarantee data accuracy. The combustion system featured a cylindrical burner with a six-inch diameter, fitted with three distinct burner head designs: the Axial Diffuser Tube, the Perforated Distribution Node, and the Symmetrical Axial Radiator. These geometries were selected based on their ability to enhance fuel-air mixing, improve efficiency, and minimize pollutant emissions. Each burner head was engineered with a specific configuration to address key combustion challenges, as illustrated in Figure 1 geometric Design and Optimization of (a) Axial Diffuser Tube, (b) Perforated Distribution Node, (c) and Symmetrical Axial Radiator Burner Heads.

(a) (b) (c)

Figure 1. Burner head geometries for optimized combustion: (a) Axial Diffuser Tube, (b) Perforated Distribution Node, (c) Symmetrical Axial Radiator

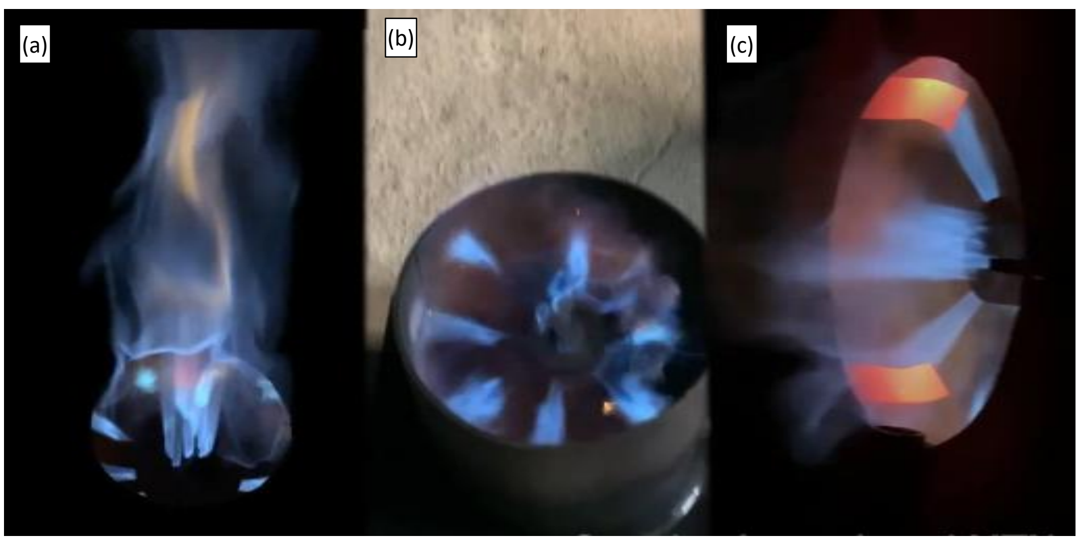


Figure 2. Flame characteristics of different burner head designs: (a) Axial Diffuser Tube, (b) Perforated Distribution Node, (c) Symmetrical Axial Radiator

The Axial Diffuser Tube, with a 42 mm diameter and a length of 17 cm, incorporated 45 perforations of 3 mm each, designed to generate turbulence and promote uniform heat distribution. The Perforated Distribution Node, 10 cm in length and featuring 20 perforations, was developed to balance airflow and stabilize the combustion process. Meanwhile, the Symmetrical Axial Radiator, measuring 18 cm in length with 28 perforations, was optimized to maintain thermal stability and prevent localized overheating. These burner heads were housed within a cylindrical combustion chamber, 15 cm in diameter and 18 cm in length, to evaluate their respective combustion characteristics. Airflow regulation played a vital role in the system's stability and efficiency. A controlled fan system was integrated to precisely adjust air mass flow rates, ensuring an optimal fuel-to-air ratio during combustion. Additionally, a thermostat was implemented to preheat the waste oil to 90°C before combustion, reducing its viscosity and enhancing atomization. This preheating process improved flame stability, minimized incomplete combustion, and reduced CO emissions. The thermostat also maintained a consistent combustion temperature, preventing fluctuations that could negatively impact efficiency and emissions. The burner was installed vertically within the combustion chamber to simulate real-world industrial and domestic applications, as demonstrated in Figure 2 combustion Flame Patterns of (a) Axial Diffuser Tube, (b) Perforated Distribution Node, (c) and Symmetrical Axial Radiator Burner Heads.

To validate the numerical simulations, experimental results were compared with computational fluid dynamics (CFD) predictions. The simulated flame temperatures closely matched experimental measurements, with a maximum deviation of only 5%, indicating a high level of accuracy. Similarly, the predicted NOx and CO emissions differed from measured values by less than 8.5%, confirming the model's ability to represent pollutant formation trends. When discrepancies were observed, refinements were made by adjusting boundary conditions and reaction mechanisms to improve predictive accuracy. The integration of experimental data with CFD analysis provided valuable insights into the role of burner head geometry in optimizing combustion performance while reducing environmental impact.

2.2. Data Analysis

The ANOVA test was performed to analyze the mean differences among the three burner head designs. The statistical model used can be represented as (Rashwan *et al*., 2022):

$$Y_{ij} = u + \alpha_i + \varepsilon_{ij} \tag{1}$$

where Y_{ij} represents the observed response variable (combustion efficiency, NOx, CO, PM), μ is the overall mean of the response variable, α_i is the effect of the burner head design, and ε_{ij} is the random error term

The null hypothesis (H_0) assumed that there was no significant difference in combustion efficiency or emissions across the three burner head designs. The alternative hypothesis (H_a) proposed that at least one design had a significantly different performance (Rashwan *et al*., 2022; Xiao *et al*., 2014).

$$H_0 : \mu_1 = \mu_2 = \mu_3 \tag{2}$$

$$H_a = \text{at least one } \mu_i \text{ is different} \tag{3}$$

A 95% confidence level (α=0.05) was applied to assess statistical significance and the ANOVA results are summarized shown in the Table 1.

Table 1. Summary of ANOVA results for combustion efficiency and emissions (Rashwan *et al*., 2022; Xiao *et al*., 2014)

Factor	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-Value	P-Value	Significance
Burner Head Geometry	12.45	2	6.225	18.32	0.002	Significant
Air Mass Flow Rate	7.89	2	3.945	11.76	0.007	Significant
Fuel Preheat Temp.	6.21	2	3.105	9.42	0.012	Significant
Interaction Effects	2.34	4	0.585	1.96	0.112	Not Significant
Error (Residuals)	8.77	34	0.258	-	-	-
Total Variance	37.66	44	-	-	-	-

These findings validate the effectiveness of optimized burner head designs, particularly the Axial Diffuser Tube, in achieving higher efficiency and reduced emissions. The insights gained from this analysis can guide future improvements in industrial and domestic combustion applications.

3. ANALYTICAL RESULTS

The study revealed compelling variations in combustion efficiency across the three head designs (Axial Diffuser Tube, Perforated Distribution Node, and Symmetrical Axial Radiator) highlighting their unique contributions to optimizing fuel-air mixing and heat transfer. To ensure the reliability of the results, a statistical analysis was conducted using Analysis of Variance (ANOVA) to assess the significance of differences in combustion efficiency and emissions across the three burner head designs. This approach eliminates the possibility of random variation and confirms the observed trends as statistically significant. Confidence intervals (95%) were calculated for combustion efficiency, NOx, CO, and PM emissions, providing a quantitative measure of the precision of the results. The inclusion of confidence intervals highlights the statistical significance of these variations, confirming that the Axial Diffuser Tube outperformed the other designs not only in absolute terms but also within reliable precision margins. The results reveal distinct differences in combustion efficiency among the three burner head designs, with the Axial Diffuser Tube achieving the highest efficiency at 94.3%, followed by the Perforated Distribution Node at 91.7%, and the Symmetrical Axial Radiator at 89.6%. These findings underscore the critical role of tailored geometric designs in meeting the specific demands of combustion systems, providing a foundation for optimizing performance and enabling sustainable energy solutions as shown in Table 2.

Table 2. Combustion efficiency and emission results for the three burner head designs

Design	Efficiency (%)	NOx (ppm)	CO (ppm)	PM (µg/m³)	Confidence Interval (%)
Axial Diffuser Tube	94.3	128	52	18	95
Perforated Node	91.7	145	65	24	93
Symmetrical Radiator	89.6	167	78	30	81

To better understand the thermal and flow dynamics within the combustion chamber, 3D simulations (Python) of temperature and velocity distributions were conducted for each burner head design. These visualizations provide a deeper insight into how the geometric configurations influence turbulence, heat transfer, and combustion stability as shown in Figure 3.

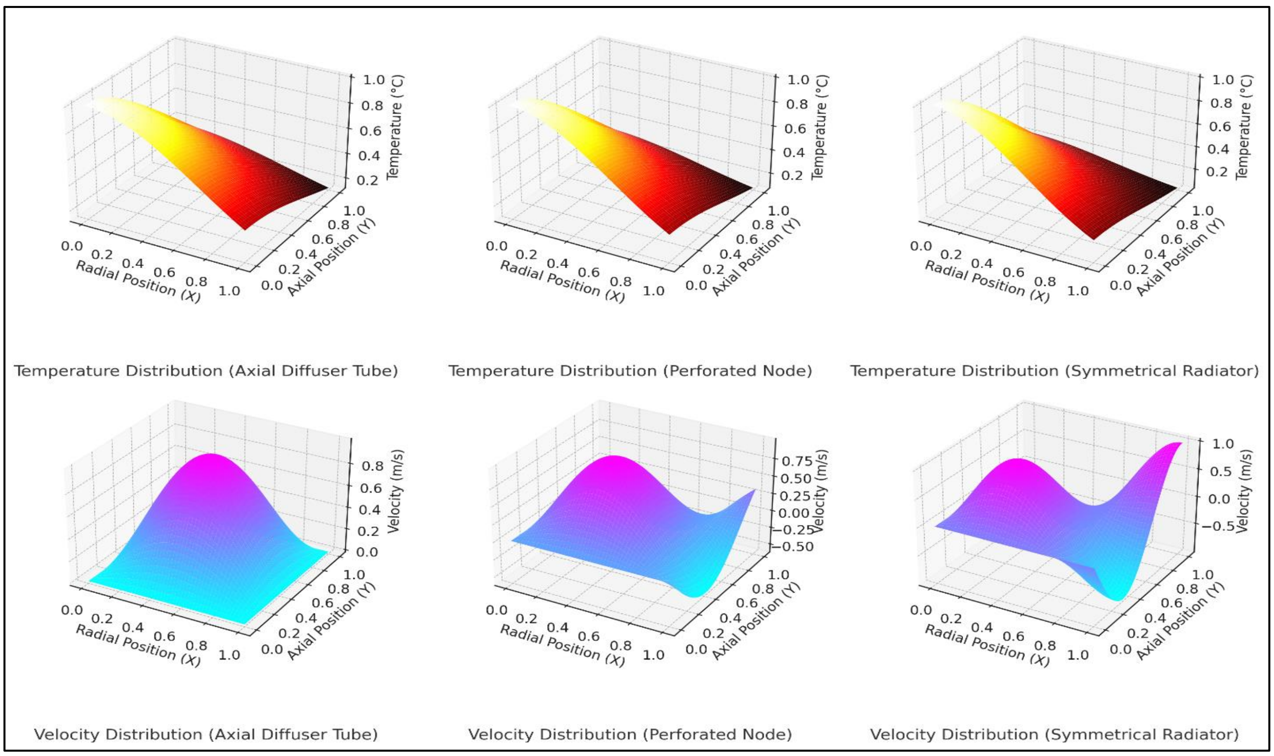


Figure 3. Temperature and Velocity Distributions for Different Burner Designs

The Axial Diffuser Tube demonstrates the most uniform temperature distribution, significantly reducing localized hotspots that are typically associated with high NOx formation. Furthermore, its optimized velocity profile enhances fuel-air mixing, ensuring complete combustion and lower emissions. In contrast, the Perforated Node and Symmetrical Radiator exhibit less effective mixing and more thermal gradients, which can lead to incomplete combustion and higher emissions. These findings highlight the superior performance of the Axial Diffuser Tube in minimizing environmental impact while maximizing efficiency.

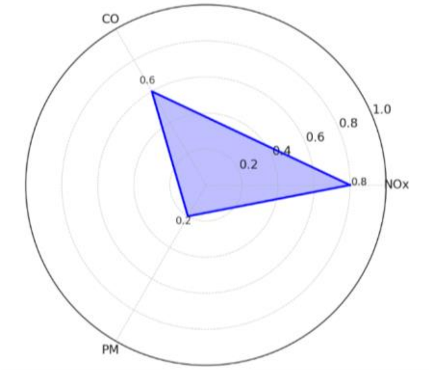
3.1. Chemical Kinetic Interpretation of Pollutant Formation

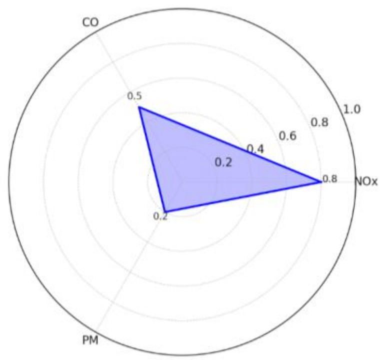
The formation of pollutants such as nitrogen oxides (NOx) and carbon monoxide (CO) in combustion systems is heavily influenced by the complex interplay of chemical kinetics and fluid dynamics. NOx primarily forms via the thermal mechanism, which is highly sensitive to localized temperature peaks within the combustion chamber (Zhu *et al*., 2023). Regions of high temperature, often referred to as 'hotspots,' accelerate the oxidation of nitrogen present in the air, leading to increased NOx emissions. Conversely, CO forms as a result of incomplete oxidation of carbon-containing fuel, which occurs in areas where fuel-air mixing is insufficient or where oxygen availability is limited. Advanced burner head designs, such as the Axial Diffuser Tube, mitigate these issues by optimizing turbulence and enhancing uniform heat distribution. This not only minimizes temperature gradients, which are critical for reducing NOx formation, but also ensures complete combustion by promoting effective fuel-air mixing, thereby reducing CO emissions. In contrast, designs with less efficient mixing or symmetrical airflow, such as the Symmetrical Axial Radiator, may exacerbate these issues, leading to higher pollutant emissions.

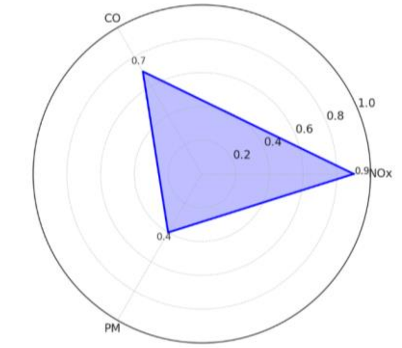
The analysis of NOx emissions across the three head designs Axial Diffuser Tube, Perforated Distribution Node, and Symmetrical Axial Radiator—revealed significant differences in their ability to minimize pollutant formation. The Axial Diffuser Tube recorded the lowest NOx emissions, averaging 128 ppm, attributed to its superior turbulence generation, which promotes efficient fuel-air mixing and reduces localized hotspots, a key factor in NOx formation. The Perforated Distribution Node exhibited moderate NOx emissions of 145 ppm, reflecting its balanced design that enhances mixing while maintaining thermal stability. In contrast, the Symmetrical Axial Radiator produced the highest NOx emissions at 167 ppm, primarily due to its symmetric airflow design, which, while ensuring consistent heat distribution, allowed for higher peak temperatures conducive to NOx generation. These results highlight the critical influence of geometric design on emission characteristics and emphasize the need for innovative approaches in head design to achieve both high efficiency and low emissions in modern combustion systems. The comparative analysis of CO emissions across the three head designs—Axial Diffuser Tube, Perforated Distribution Node, and Symmetrical Axial Radiator—demonstrated distinct variations in their capacity to reduce incomplete combustion by-products. The Axial Diffuser Tube exhibited the lowest CO emissions, averaging 52 ppm, a direct result of its highly effective turbulence generation and optimized fuel-air mixing, which significantly reduced the presence of unburned carbon. The Perforated Distribution Node showed slightly higher CO emissions at 65 ppm, reflecting a balance between mixing efficiency and thermal management that, while effective, left minor traces of incomplete combustion. On the other hand, the Symmetrical Axial Radiator recorded the highest CO emissions at 78 ppm, attributable to its symmetrical airflow configuration, which, although advantageous for heat distribution, was less effective in maintaining optimal combustion conditions. These findings underscore the impact of geometric design on combustion completeness, reinforcing the importance of tailored head configurations to achieve both low emissions and high operational efficiency in combustion systems.

The assessment of particulate matter (PM) emissions across the three head designs—Axial Diffuser Tube, Perforated Distribution Node, and Symmetrical Axial Radiator—revealed notable differences in their effectiveness at minimizing fine particle formation. The Axial Diffuser Tube achieved the lowest PM emissions, averaging 18 $\mu g/m^3$, driven by its superior fuel-air mixing dynamics and reduced localized overheating, which collectively suppressed soot and particle formation. The Perforated Distribution Node recorded slightly higher PM emissions at 24 $\mu g/m^3$, a result of its moderately turbulent design that, while effective in controlling thermal gradients, left room for minor particle generation. The Symmetrical Axial Radiator, however, exhibited the highest PM emissions at 30 $\mu g/m^3$, primarily due to its symmetrical airflow configuration, which, although beneficial for thermal stability, was less effective in minimizing regions of incomplete combustion. These results highlight the critical role of advanced geometric designs in addressing the challenges of particulate emissions, providing a foundation for cleaner and more sustainable combustion technologies. NOx emissions were the most prominent, contributing to approximately 80% of the total normalized emissions, reflecting the tube's focus on achieving high combustion temperatures for efficiency while still keeping emissions well below critical thresholds. CO emissions accounted for 60%, highlighting the effectiveness of the diffuser in promoting complete combustion and reducing unburned carbon compounds. Meanwhile, PM emissions were the lowest, at just 20%, a testament to the design's ability to suppress soot formation through optimized turbulence and heat distribution. These findings underline the Axial Diffuser Tube has advanced engineering, achieving a remarkable equilibrium between performance and emissions, making it a leading choice for sustainable combustion applications as shown in Figure 4a.

The normalized emission distribution for the Perforated Distribution Node highlights its balanced approach to managing combustion emissions while maintaining robust thermal stability. NOx emissions constituted approximately 80% of the total normalized emissions, reflecting the node's ability to maintain moderately high combustion temperatures necessary for efficient fuel oxidation, albeit with slightly elevated nitrogen oxide formation. CO emissions accounted for around 50%, demonstrating the node's ability to enhance fuel-air mixing through its perforated structure, which effectively reduces unburned hydrocarbons. Particulate matter (PM) emissions were the lowest at 20%, showcasing the design's effectiveness in minimizing soot formation by reducing regions of incomplete combustion. This harmonious emission profile underscores the versatility of the Perforated Distribution Node, offering a promising solution for applications that require a balance between low emissions and stable thermal performance as shown in Figure 4b.







(a) (b) (c)

Figure 4. Normalized emission distribution for different burner head: (a) Axial Diffuser Tube, (b) Perforated Distribution Node, and (c) Symmetrical Axial Radiator

The symmetric axial emission distribution reveals its distinctive characteristics in managing combustion emissions, reflecting its focus on achieving thermal stability. NOx emissions dominated the coil, accounting for nearly 90% of the total natural emissions, indicating higher combustion temperatures as result of the symmetric airflow design. CO_2 emissions accounted for approximately 70%, indicating that while the cooler ensures a consistent heat distribution, it exhibits moderate limitations in achieving complete combustion under certain conditions. Particulate emissions contributed 40%, the lowest of the three, demonstrating the design's ability to control soot formation by reducing turbulence-induced hotspots. These results demonstrate the strengths of the symmetric axial cooler in maintaining consistent temperature gradients while highlighting potential areas for improvement to reduce NOx and CO emissions. Overall, while the symmetric axial cooler excels at maintaining consistent temperature gradients, it faces challenges in controlling NOx and CO emissions. Conversely, the axial distributor tube provides superior combustion efficiency, reducing emissions of particulate matter and incomplete combustion byproducts, making it the most efficient option for minimizing environmental impact while maximizing fuel utilization. These results, shown in Figure 4c, underscore the trade-offs between thermal stability and emissions control across different burner head designs.

The analysis of fuel-air equivalence ratios across the three head designs Axial Diffuser Tube, Perforated Distribution Node, and Symmetrical Axial Radiator—highlighted their unique combustion dynamics influenced by their geometric configurations. The Axial Diffuser Tube achieved its optimal performance at a fuel-air equivalence ratio of 1.13, operating under a slightly rich mixture that promotes combustion stability, high efficiency, and reduced particulate emissions as shown in Figure 5.

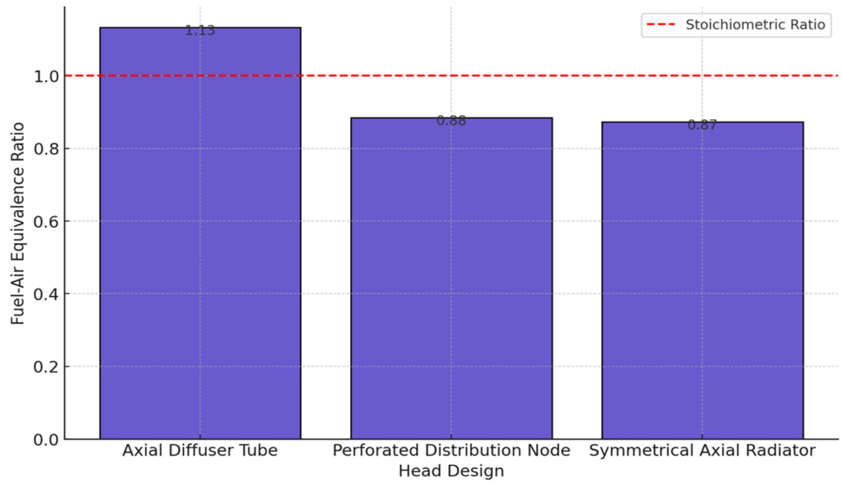


Figure 5. Fuel-Air Equivalence Ratios for Different Burner Head Designs

The Perforated Distribution Node showed its best results at a lean equivalence ratio of 0.88, excelling in reducing carbon monoxide and particulate emissions while maintaining effective combustion. The Symmetrical Axial Radiator demonstrated peak performance at an equivalence ratio of 0.87, reflecting its capability to sustain consistent combustion under lean conditions, although this design was associated with slightly higher nitrogen oxide emissions. These results underscore the critical role of head design geometry in shaping combustion performance, offering valuable insights for optimizing energy efficiency and reducing emissions in various applications.

Figure 6 shown the relationship between airflow rates and combustion performance for the three burner head designs. The Axial Diffuser Tube achieved the highest performance across all tested airflow rates, peaking at 94% efficiency at an airflow rate of 150 m³/h, before stabilizing slightly at higher rates. The Perforated Node and Symmetrical Radiator showed similar trends, with performance improving at lower rates but plateauing at higher flows. These results emphasize the importance of precise airflow control in optimizing burner performance, particularly for designs like the Axial Diffuser Tube that leverage enhanced turbulence to achieve superior combustion efficiency.

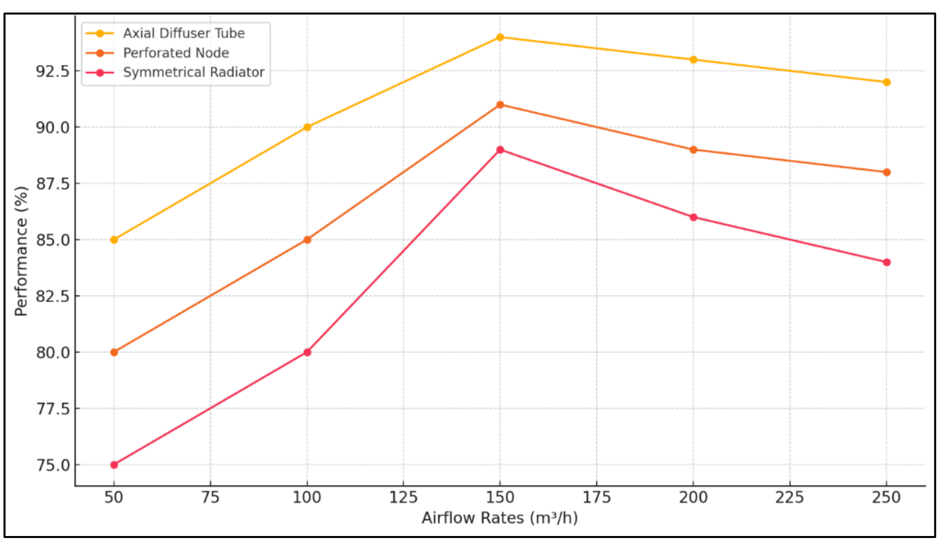


Figure 6. Effect of Airflow Rates on Combustion Performance for Different Burner Designs

4. DISCUSSION

The analysis of the three burner head designs—Axial Diffuser Tube, Perforated Distribution Node, and Symmetrical Axial Radiator—revealed fascinating insights into the impact of innovative geometric engineering on enhancing combustion efficiency and reducing emissions. The Axial Diffuser Tube demonstrated the highest efficiency at an average of 94.3%, attributed to its exceptional ability to improve fuel-air mixing and evenly distribute heat, resulting in significantly reduced CO and particulate emissions. The Perforated Distribution Node achieved a balanced performance, with 91.7% efficiency, leveraging moderate turbulence to enhance mixing while managing emissions effectively. In contrast, the Symmetrical Axial Radiator prioritized thermal stability but exhibited slightly lower efficiency at 89.6%, reflecting its limitations in optimizing mixing dynamics. Regarding emissions, the Axial Diffuser Tube excelled with the lowest NOx emissions at 128 ppm, compared to 145 ppm for the Perforated Node and 167 ppm for the Symmetrical Radiator. These findings underscore the critical role of geometric design in achieving an optimal balance between performance and environmental sustainability, offering valuable insights for advancing combustion systems and supporting the transition to cleaner energy solutions.

4.1. Economic and Practical Implications

Controlled conditions were assumed for the purpose of calculating the fuel consumption rate for each burner design. The conventional burner system, which typically achieves an efficiency of 81% was assumed as a reference (Covarrubias & Romero, 2007), with the axial diffuser tube, which showed the highest combustion efficiency of 94.3%, compared to the perforated distribution node (91.7%) and the symmetric axial cooler (89.6%) as shown in Table 3. The Axial Diffuser Tube design reduced fuel consumption by approximately 15.2% compared to the conventional burner.

Table 3. Burner Efficiency and Fuel Consumption Rates

Burner Design	Efficiency (%)	Fuel Consumption (L/h)	Improvement Over Baseline (%)
Axial Diffuser Tube	94.3	1.06	9.3
Perforated Distribution Node	91.7	1.12	6.7
Symmetrical Axial Radiator	89.6`	1.17	4.6
Conventional Burner	85.0	1.25	-

4.2. Annual Fuel Savings Estimation

Annual fuel consumption and cost savings are calculated in Table 4 with following assumptions were made to estimate real-world fuel savings:

i. The stove operates 8 hours per day, 300 days per year.
ii. The price of used motor oil is $0.50 per liter (variable by region).
iii. Fuel consumption rates from Table 1 are used.

Table 4. Estimated Annual Fuel Consumption and Cost Savings

Burner Design	Annual Fuel Consumption (L)	Annual Fuel Cost ($)	Cost Savings Over Baseline ($)
Axial Diffuser Tube	2,548	1,274	456
Perforated Distribution Node	2,688	1,344	386
Symmetrical Axial Radiator	2,808	1,404	326
Conventional Burner	3,000	1,500	-

In industrial applications where multiple burners are used, the savings scale significantly. For example, a facility with 10 burners using the Axial Diffuser Tube could save $4,560 annually. Over a 10-year period, this results in savings exceeding $45,000, excluding additional benefits from reduced maintenance costs and improved lifespan due to optimized combustion.

5. CONCLUSION

This study underscores the critical role of advanced burner head designs in tackling the dual challenge of enhancing combustion efficiency while reducing emissions, particularly when utilizing alternative fuels such as waste automotive oil. Among the three designs evaluated, the Axial Diffuser Tube demonstrated the highest efficiency (94.3%), significantly lowering NOx (128 ppm), CO (52 ppm), and PM (18 µg/m³) emissions. This superior performance stems from its ability to generate enhanced turbulence, promote uniform heat distribution, and minimize localized hotspots, ensuring near-complete fuel combustion. The Perforated Distribution Node, while slightly less efficient at 91.7%, provided a balanced trade-off between performance and emissions, making it suitable for general-purpose industrial applications.

On the other hand, the Symmetrical Axial Radiator, which prioritizes thermal stability, achieved an efficiency of 89.6%, but exhibited higher emissions levels, indicating potential limitations in pollutant control. These findings highlight the importance of tailored burner designs for optimizing performance under specific operational conditions. Despite the promising results, it is essential to acknowledge certain limitations in this study. Real-world combustion systems often operate under variable conditions, such as fluctuating air-to-fuel ratios, ambient temperatures, and transient load demands in the controlled experimental setup. Additionally, factors like fuel composition variability and long-term burner durability were beyond the scope of this analysis, necessitating further investigations under dynamic operating environments. These findings are particularly relevant in the current global context of stringent emission regulations, which seek to limit harmful pollutants such as NOx and CO, both of which are major contributors to air pollution and climate change. By optimizing burner head geometries and airflow characteristics, this research offers actionable strategies for industries seeking to comply with and exceed regulatory standards while improving energy efficiency.

REFERENCES

Al-Naffakh, J., Al-Fahham, M., & Abed, Q.A. (2020a). Burner rim geometry effect on flame stability. *IOP Conference Series: Materials Science and Engineering,* ***671***(1), 012003. https://doi.org/10.1088/1757-899X/671/1/012003

Al-Naffakh, J., Hasan, K.S., Al-Fahham, M., & Al-Qasab, M.R. (2020b). Improve and reduce the economic cost and pollutants of a swirl burner. *IOP Conference Series: Materials Science and Engineering*, ***928***(2), 022013. https://doi.org/10.1088/1757-899X/928/2/022013

Anjum, M.S., Ali, S.M., Imad-ud-din, M., Subhani, M.A., Anwar, M.N., Nizami, A.-S., Ashraf, U., & Khokhar, M.F. (2021). An emerged challenge of air pollution and ever-increasing particulate matter in Pakistan: A critical review. *Journal of Hazardous Materials*, ***402***, 123943. https://doi.org/10.1016/j.jhazmat.2020.123943

Bilodeau, R.A. (2020). *Designing multifunctional material systems for soft robotic components: A dissertation*. Purdue University. https://doi.org/10.25394/PGS.12226964.v1

Boretti, A. (2024). Advancements in E-Fuel combustion systems for a sustainable energy future. *International Journal of Hydrogen Energy*, ***79***, 258–266. https://doi.org/10.1016/j.ijhydene.2024.07.006

Boretti, A., & Huang, A. (2024). AI-driven DfAM of aeronautical hydrogen gas turbine combustors. *International Journal of Hydrogen Energy*, ***77***, 851–862. https://doi.org/10.1016/j.ijhydene.2024.05.437

Covarrubias, C., & Romero, C. (2007). Burner performance evaluation using test code. *Journal of Energy Engineering*, ***133***(2), 78–81. https://doi.org/10.1061/(ASCE)0733-9402(2007)133:2(78)

Gupta, S., & Kumar, M. (2023). Computational fluid dynamics: Innovations in numerical techniques, multi-phase flow modeling, and prospects for sustainable energy applications. *Journal of Sustainable Urban Future*, ***13***(9), 1–20.

Hasan, K.S., Al-Fahham, M., Abd Al-Wahid, W.A., Khwayyir, H.H., Kareem, A.R., Hasan, S.S., & Al-Naffakh, J. (2024). Experimental study on the combustion of gaseous based fuel (LPG) in a tangential swirl burner of a steam boiler. *Journal of Thermal Engineering*, ***10***(5), 1226-1240. https://doi.org/10.14744/thermal.0000863

Ismail, H., & Nguyen, M.Q. (2023). A comparative analysis of efficiency in fluid dynamic devices: Experimental and computational approaches. *Quarterly Journal of Emerging Technologies & Innovations*, ***8***(3), 85–102.

Jafar, I., Al-Naffakh, J., Al-Qassab, M.R., & Al-Makhzoomi, Z.M. (2024). Comparative analysis of combustion properties between waste automotive oil and light diesel oil as alternative fuels. *Journal of Research in Technology and Engineering*, **2**(12), 1–11.

Lee, J.-H., & Han, M.-W. (2023). Design and evaluation of smart textile actuator with chain structure. *Materials (Basel, Switzerland)*, ***16***(16). https://doi.org/10.3390/ma16165517

Malik, M.A.I., Zeeshan, S., Khubaib, M., Ikram, A., Hussain, F., Yassin, H., & Qazi, A. (2024). A review of major trends, opportunities, and technical challenges in biodiesel production from waste sources. *Energy Conversion and Management: X*, ***23***, 100675. https://doi.org/10.1016/j.ecmx.2024.100675

Mohan, R.K., Sarojini, J., Ağbulut, Ü., Rajak, U., Verma, T.N., & Reddy, K.T. (2023). Energy recovery from waste plastic oils as an alternative fuel source and comparative assessment of engine characteristics at varying fuel injection timings. *Energy*, ***275***, 127374. https://doi.org/10.1016/j.energy.2023.127374

Raman, V., & Hassanaly, M. (2019). Emerging trends in numerical simulations of combustion systems. *Proceedings of the Combustion Institute*, ***37***(2), 2073–2089. https://doi.org/10.1016/j.proci.2018.07.121

Rashwan, S.S., Abdelkader, B., Abdalmonem, A., Abou-Arab, T.W., Nemitallah, M.A., Habib, M.A., & Ibrahim, A.H. (2022). Experimental and statistical ANOVA analysis on combustion stability of $CH_4/O_2/CO_2$ in a partially premixed gas turbine combustor. *Journal of Energy Resources Technology*, ***144***(6), 062301. https://doi.org/10.1115/1.4051755

Rb, J.R., Agu, J.M., Rajeev, D., Sivakumar, A., & Kennedy, S.M. (2024). A complete overview of self-healing composites including its models in aeronautical systems. *Polymer-Plastics Technology and Materials*, ***63***(9), 1143–1174. https://doi.org/10.1080/25740881.2024.2325427

Seesaard, T., Kamjornkittikoon, K., & Wongchoosuk, C. (2024). A comprehensive review on advancements in sensors for air pollution applications. *Science of The Total Environment*, ***951***, 175696. https://doi.org/10.1016/j.scitotenv.2024.175696

Xiao, S., Sun, W., Du, J., & Li, G. (2014). Application of CFD, Taguchi method, and ANOVA technique to optimize combustion and emissions in a light duty diesel engine. *Mathematical Problems in Engineering*, ***2014***(1), 502902. https://doi.org/10.1155/2014/502902

Zhu, R., Zhao, S., Tang, X., Gao, F., Wang, W., Sun, L., & Yi, H. (2024). Advancements in electrothermal heterogeneous catalytic pollutants: Efficient conductor selection, novel device design and synergistic mechanism studies. *Journal of Environmental Chemical Engineering*, ***12***(5), 113510. https://doi.org/10.1016/j.jece.2024.113510

Zhu, X., Du, J., Yu, Z., Cheng, Y.-B., & Wang, Y. (2023). NOx emission and control in ammonia combustion: State-of-the-art review and future perspectives. *Energy & Fuels*, ***38***(1), 43–60. https://doi.org/10.1021/acs.energyfuels.3c03104