

Optimization of Helical Coil Heat Exchanger as a Waste Recovery System for Efficient Fuel Consumption

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Abstract

The study endeavors to harness waste heat from the exhaust gas of a diesel engine through the utilization of a helical coil heat exchanger (HCHE), with the overarching goal of enhancing engine efficiency. Employing SolidWorks CAD software and SolidWorks Flow Simulation, the HCHE was meticulously modeled and simulated to optimize its design parameters. The HCHE design incorporated a coil length of 30 millimeters, an inside diameter of 4mm, and an outside diameter of 5mm. Through systematic variation of coil pitch at operational speeds of 1500, 2000, and 2500 revolutions per minute, the optimization process aimed to identify the most efficient configuration. Remarkably, the simulation results indicated that a coil pitch of 20mm yielded optimal performance. Notably, the simulation revealed a significant increase in the temperature of diesel fuel, from 15.6°C to 32.5°C, resulting in a corresponding decrease in density from 832 kg/m³ to 820.491 kg/m³. This thermal enhancement led to an average reduction in volume consumption of 10%, consequently translating to a proportional decrease in fuel consumption. Furthermore, the simulation analysis indicated a resulting pressure drop of 5.3075 kPa, well within the acceptable threshold of 20.77 kPa. This underscores the safety and efficacy of the 20mm coil pitch configuration in mitigating pressure drop issues within the fuel line. These findings validated the effectiveness of the helical coil heat exchanger design, closely aligning with expectations. Moreover, the exchanger's performance was linked to diesel fuel temperature dynamics. Further exploration of parameters influencing heat recovery is recommended for future research and technological advancements.

1. Introduction

The diesel engine stands as a cornerstone of various industries, including automotive and energy production. Yet, despite its ubiquity, its efficiency remains a challenge. Modern diesel engines boast a maximum efficiency of around 40%, implying that a staggering 60% of the fuel's energy dissipates as heat. Within this loss, 30% dissipates into the exhaust gas, while the remaining 30% dissipates through the engine's cooler or radiator (Jadhao & Thombare, 2013). To put this into perspective, only a quarter of the energy derived from the fuel stored within the tank is effectively utilized for productive tasks, such as propelling the vehicle forward or powering essential accessories like air conditioning see Fig. 1. This inefficiency not only impacts individual vehicle

performance but also contributes to the larger global concern of fuel demand and consumption driven by the widespread use of internal combustion engines (Saiful & Shenk, 2010).

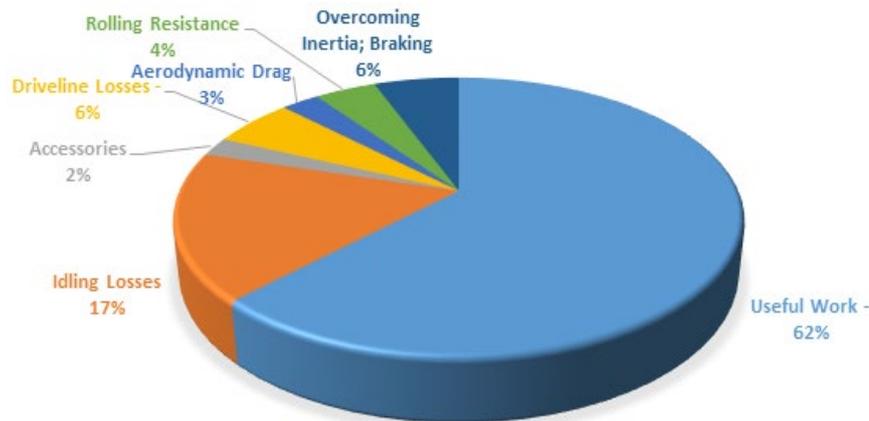


Fig. 1 Partition of work in a diesel engine

In the realm of engineering, optimizing the recovery of waste heat from diesel engines, particularly from the exhaust line, is a significant endeavor. While complete recovery remains elusive, substantial portions of this heat can be reclaimed through various methodologies. Among these, the employment of an exhaust heat exchanger (EHE) emerges as a prevalent and efficacious solution (Raja & Navaneetha Krishnan, 2014). Design and implementation of the EHE are pivotal in maximizing heat recovery efficiency. Helical coil heat exchangers, renowned for their versatility and effectiveness, are extensively utilized for this purpose across diverse applications. By optimizing the helical coil configuration, heat transfer rates can be enhanced, thereby augmenting overall heat recovery efficiency (Hatima et al., 2014). The significance of harnessing waste heat from the exhaust line cannot be overstated, considering it constitutes a substantial portion of the input energy. As such, diesel engine exhaust gases present a viable alternative heat source with multifaceted potential applications, including supplementary power generation and enhancing overall engine efficiency.

This research endeavors to address several key objectives aimed at optimizing engine performance and reducing environmental impact:

1. **Heat Recovery:** The primary focus is on reclaiming heat lost through the exhaust pipe, harnessing it as a supplementary source of thermal energy. By capturing this heat, which typically ranges between 150°C to 200°C, through a specialized heat exchanger, the aim is to utilize it for productive purposes within the engine system.

2. **Emission Reduction:** A secondary objective is to mitigate the emission of undesirable by-products resulting from fuel combustion. By enhancing combustion efficiency through heat recovery, the production of harmful emissions such as carbon monoxide can be minimized. This not only improves air quality but also contributes to broader environmental conservation efforts, including the mitigation of global warming effects.

3. **Fuel Efficiency:** Another critical goal is to curtail fuel consumption, a pivotal factor in both economic and environmental considerations. By optimizing engine performance through heat recovery, the research aims to reduce the amount of fuel required to achieve a given level of output. This not only translates to cost savings for operators but also contributes to overall energy conservation objectives by decreasing reliance on finite fuel resources.

By addressing these specific objectives, the research endeavors to contribute to the advancement of sustainable engine technologies, fostering a balance between performance optimization, environmental stewardship, and energy efficiency. Through innovative approaches such as heat recovery and emission reduction strategies, the aim is to pave the way for a more sustainable and resilient future in the transportation and energy utilization sectors.

1.1 Significance of Study

The significance of this study lies in its elucidation of techniques to enhance engine efficiency through the implementation of a heat exchanger system, coupled with the reheating of fuel via connection to the fuel pipe, thereby reducing fuel consumption. With global energy demands projected to surge by 50% by 2035, and the

depletion of fossil fuel resources accelerating, there is an urgent need for innovative solutions to mitigate energy consumption and environmental impact. Fuel oil remains a primary energy source, particularly in the transportation sector. By integrating a heat exchanger into both the fuel and exhaust systems of automobiles, substantial reductions in fuel consumption, ranging from 10% to 25%, can be achieved. Additionally, this approach facilitates more efficient fuel combustion within the engine, thereby mitigating the production of harmful by-products associated with combustion processes.

In summary, this study offers practical solutions to pressing challenges in energy consumption and environmental sustainability within the transportation sector. By leveraging innovative technologies such as heat exchangers, it aims to drive efficiency improvements and foster a more sustainable trajectory for energy utilization and environmental stewardship.

2. Methodology

The primary objective of this research is to recover heat lost in the exhaust pipe and utilize it to enhance engine efficiency, as elucidated by Willard Pulkrabek (1997). With combustion temperatures in engine cylinders reaching exceedingly high values, efficient heat management becomes imperative to prevent engine overheating and mitigate energy wastage. By harnessing this rejected heat through a heat exchanger system, the study aims to maximize energy utilization and minimize environmental impact.

2.1 Heat Recovery and Transfer

Heat, as a form of energy, naturally flows from warmer to cooler surfaces until thermal equilibrium is reached. Recovering heat from the exhaust pipe presents challenges and opportunities in heat transfer mechanisms. Leveraging principles of conduction and convection, the research explores methods to efficiently transfer heat from exhaust gases to other components, such as the fuel system, using various heat exchanger configurations.

The choice of heat exchanger design is critical in optimizing heat recovery efficiency. Spiral and counter-flow heat exchangers are identified as potential candidates for their ability to facilitate effective heat exchange between fluids of different temperatures while minimizing energy losses. Helically coiled exchangers, in particular, offer advantages such as higher film coefficients, enhanced pressure drop utilization, and robustness in handling extreme temperature differentials.

2.2 Thermal Insulation

Effective thermal insulation plays a pivotal role in maintaining temperature differentials necessary for efficient heat transfer. By selecting appropriate insulating materials and configurations, the research aims to minimize heat loss or gain along the fuel pipeline, thereby maximizing the temperature differential available for heat recovery. Factors such as ambient conditions and service requirements are considered in designing thermal insulation systems to optimize energy conservation and operational efficiency.

2.3 Fuel Efficiency and Consumption

Fuel efficiency directly impacts fuel consumption, making it a key consideration in engine performance optimization. By reheating fuel before combustion, volumetric efficiency can be enhanced due to the expansion of fuel at higher temperatures. This process not only reduces fuel consumption but also mitigates emissions of undesirable combustion by-products, contributing to environmental sustainability.

The research paradigm encompasses the systematic process of knowledge acquisition, application, and output generation. Beginning with theoretical inputs on heat transfer modes and heat exchanger principles, the research progresses through practical experimentation and analysis. Computation and simulation techniques are employed to anticipate and address potential challenges, ensuring a robust and informed research methodology. The output of the research culminates in data-driven insights and recommendations for enhancing engine efficiency and reducing environmental impact.

3. Design Consideration

Design, graphical, and tabular data were used to show the comparisons of the results. The following are the analyses of the data made after the experimentation. With the same properties as those other liquids, the volume of diesel fuel gradually expands as the temperature turns a degree higher. The rate of expansion can be determined by the so-called coefficient of thermal expansion. A distinctive value of the thermal expansion coefficient for diesel fuel is $0.00083/^\circ\text{C}$.

Table 1 Diesel fuel properties

Parameters	Units	Limits
Cetane Number	-	51.0 minimum
Cetane Index	-	40.0 minimum
Density at 15 °C	Kg/m ³	820 to 845
Freezing Point	°C	-6
Boiling Point	°C	315
Ignition Point	°C	315
Flash Point	°C	55
Viscosity @40°C	mm ² /sec	2.00 to 4.50
Specific Heat	kJ/ kg – k	1.8
Thermal Conductivity (k)	W/ m – k	1.51
API°	-	34.97

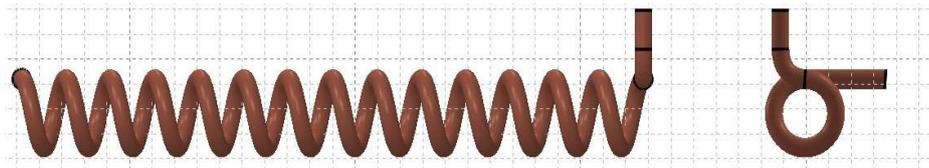


Fig. 2 Design of helical coil

Fig. 2 shows the helical coil heat exchanger. It has an advantage compared to tube-in-tube heat exchangers. It handles high temperatures and extreme temperature differentials without high induced stresses or costly expansion joints. It has a high-pressure capability and the ability to fully clean the service fluid flow area. The geometric dimensions of the helical coil. It includes the inside diameter of the helical coil (I.D.), outside diameter of the coil (O.D), free length, mean diameter, and pitch of the coil. The following four important dimensionless numbers are also in the design of the coil Reynolds number, Darcy’s friction factor, the number of turns of coil, and density conversion factor (Purandare, Pramod & Lele, 2016).

3.1 Pressure Drop in the Fuel Line & Brake Specific Fuel Consumption

Fuel pressure is likely the most serious factor in the fuel injection system, so much so that only up to 20.7786 kPa change in fuel pressure can often cause noticeable drivability problems, hence, the pressure drop of the fuel line is an essential factor to consider (Kumar et. al, 2014). The double spiral flows in curved or bent tubes. The primary characteristic of flow through a bend is the presence of a radial pressure gradient made by the centrifugal force acting on the fluid. It creates a double spiral flow field shown schematically. Jayant S. (2015) stated that the total pressure drop is the sum of two components namely; First, the result of friction in a straight pipe equivalent length which depends mainly on the Reynolds number (i.e. depends on pipe roughness); and the result of losses due to change of direction, normally expressed in terms of a bend loss coefficient, depends mainly on the curvature ratio and the bend angle. The engine minimum brake specific fuel consumption (BSFC) relative to Engine Speed. The minimum BSFC is the optimized BSFC based on varying compression ratios and engine speed (Ujjiwal K. Saha, 2010).

3.2 Dimension of Coil

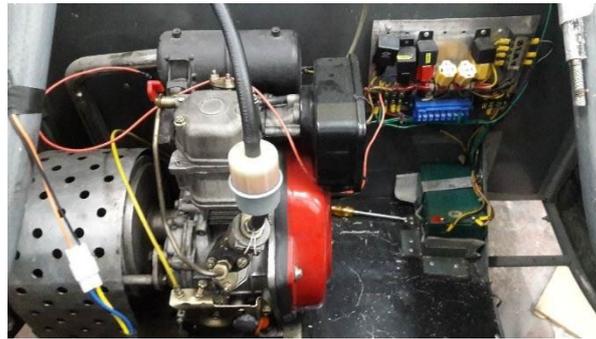
From the literature, it was revealed that the helical coil for the heat exchanger is the most suitable for limited space and economic constraints. It also increases the exposure area and transit time of heat transfer for the coil. Table 2 shows the dimensional parameters of the helical coil. A copper coil was used as a heat exchanger for its higher thermal conductivity. It has an exhaust pipe outside and inside diameter of 27mm and 30 mm, inner and outer diameter of the coil of 4mm and 5mm.

Table 2 Actual dimensional parameters of helical coil

Dimensional Parameters	Dimension
Outer Diameter of Exhaust Pipe	30 mm
Inner Diameter of Exhaust Pipe	27 mm
Thickness of Exhaust Pipe	1.5 mm
Outer Diameter of Coil	5 mm
Inner Diameter of Coil	4 mm
Thickness of Coil	0.5 mm

3.3 Experimental Set-Up

Fig. 3 shows the actual test run set up, where a tachometer is used to adjust the rotational speed of the engine. Five trials are performed based on the pitch and rotational speed of the engine. Each trial takes 30 minutes to execute per pitch per rotational speed of the engine for 30 minutes per trial. After the collection and computation of fuel consumption per rpm in the actual test, the brake-specific fuel consumption is compared to determine the optimum pitch of the coil.

**Fig. 3** 7 Hp diesel engine set-up

4. Results and Discussion

The study endeavors to harness waste heat from the exhaust gas of a diesel engine through the utilization of a helical coil heat exchanger (HCHE), with the overarching goal of enhancing engine efficiency. Findings validated the effectiveness of the helical coil heat exchanger design, closely aligning with expectations.

4.1 Brake-Specific Fuel Consumption

Table 3 shows the results on average fuel consumption based on five trials per pitch for every rotational speed of 1500 rpm, 2000 rpm, and 2500 rpm that was used to compute the brake-specific fuel consumption on each coil. In The result of the computation of brake-specific fuel consumption as shown in Table 3 by each pitch considering the variation of the engine the 20 mm pitch terms produced the lowest average fuel consumption which also reflected the brake-specific fuel consumption (BSFC) as shown in Fig. 4.

Table 3 Average computation of brake specific fuel consumption (BSFC)

Pitch (mm)	BSFC (g/kW - hr)		
	1500 rpm	2000 rpm	2500 rpm
16	258.77	320.68	376.04
18	254.29	313.04	371.04
20	249.80	305.84	366.28
22	253.06	316.28	383.26
24	256.32	326.73	400.24
26	259.58	337.17	417.22

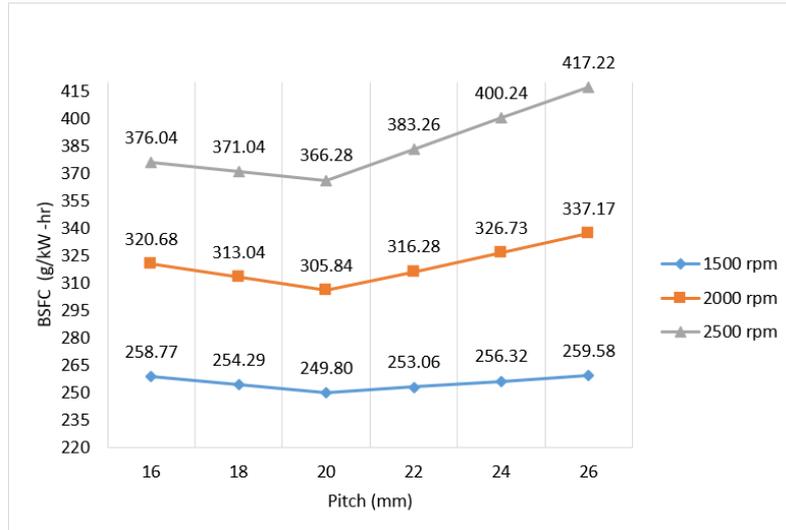


Fig. 4 Brake specific fuel consumption based on rpm and pitch of coil

Based on the results of the optimization process, 20mm is the optimum pitch of the coil. It concerns brake-specific fuel consumption, which provided a change in temperature of fuel from an initial temperature of 15.6 °C to 32.5 °C that affects the density of fuel from initial density based on the initial condition of 832 kg/m³ to 820.491 kg/m³. The change in density is affected by the change in temperature concerning the volumetric thermal expansion of the diesel fuel.

Fig. 5 shows the comparison of BSFC with and without the heat exchanger. It shows the difference in terms of performance based on BSCF with and without the heat exchanger considering the rotational speed of 1500 rpm, 2000 rpm, and 2500 rpm. Based on the results, a 20mm pitch coil is the optimum pitch for a helical coil heat exchanger for a 7 HP diesel engine.

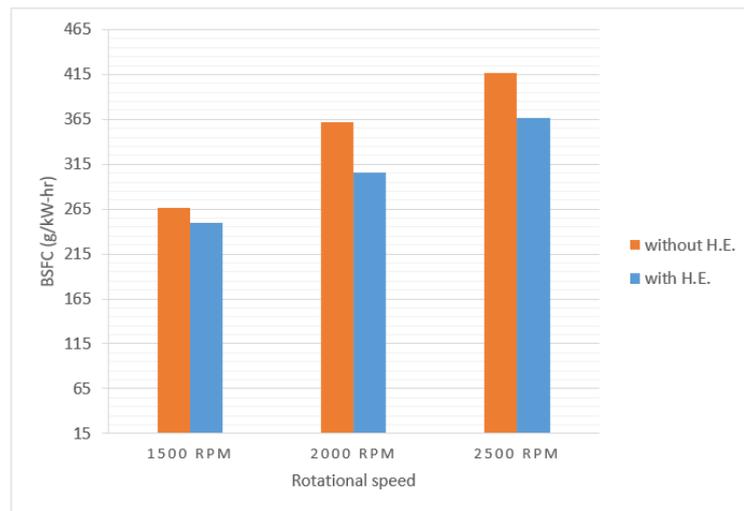


Fig. 5 Comparison of BSFC with & without heat exchanger based on the optimum pitch of coil

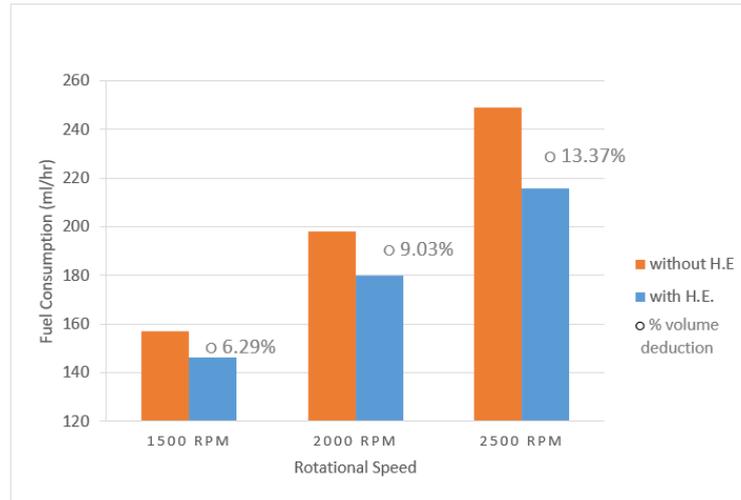


Fig. 6 Comparison of BSFC with & without heat exchanger based on the optimum pitch of coil

To quantify the impact of the heat exchanger installation on fuel consumption, the study computes the percent volume decrease in fuel consumption with the heat exchanger compared to without. This analysis reveals significant reductions in fuel consumption across different engine speeds, with computed percent volume decreases of 6.29%, 9.03%, and 13.37% for engine speeds of 1500 rpm, 2000 rpm, and 2500 rpm, respectively. Moreover, the average percent decrease in volume consumption is calculated to be 10%, indicating a consistent and substantial improvement in fuel efficiency facilitated by the optimized heat exchanger.

This reduction in fuel consumption is reflected in the brake-specific fuel consumption (BSFC) with and without the heat exchanger, underscoring the tangible benefits of integrating the optimized heat exchanger into the engine system. Overall, the engineering approach employed in this study provides a robust framework for evaluating and optimizing fuel consumption through the implementation of heat exchanger technologies, with clear implications for enhancing engine efficiency and performance.

4.2 Pressure Drop Simulation

The change in density of fuel affects the mass flow rate of the fuel. It is because of the expansion of volume in the coil and the mass flow rate of the 20mm pitch considering the rotational speed of 1500 rpm, 2000 rpm, and 2500 rpm are 0.033529, 0.04105, and 0.04916 gram per sec which is the lowest value compared to the other pitch of the coil as shown in table 4. The change in density of fuel affects the mass flow rate of the fuel. It is because of the expansion of volume in the coil and the mass flow rate of the 20mm pitch considering the rotational speed of 1500 rpm, 2000 rpm, and 2500 rpm are 0.033529, 0.04105, and 0.04916 gram per sec which is the lowest value compared to the other pitch of the coil as shown in table.

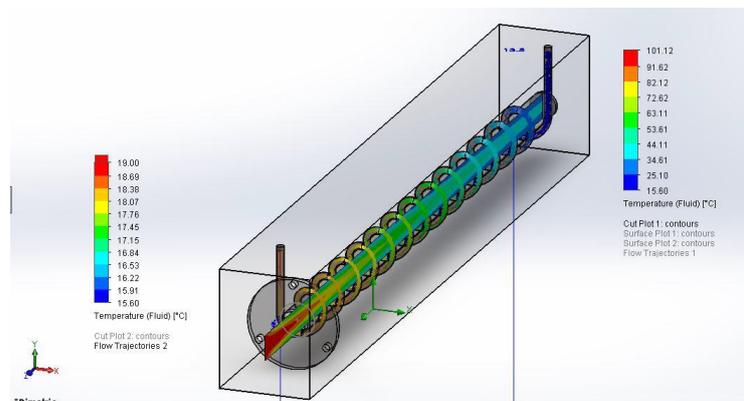


Fig. 7 Pressure drop simulation analysis

Fig. 7 shows the simulation analysis using SOLIDWORKS. The simulation process considers initial parameters to determine the pressure drop on coils such as the standard temperature of fuel 15.6 °C, exhaust gas temperature ranging from 150 °C up to 200 °C, and the optimum pitch of the coil is 20mm based on BSFC. The simulation result of CFD and FEA analysis of 20mm pitch provides a 5.3075 kPa pressure drop on the coil.

Table 4 The computed value of the actual density of fuel considering the temperature

Pitch	Mass flow rate (g/sec)			Temperature °C	Density kg/m ³
	1500rpm	2000rpm	2500rpm		
16	0.03457	0.04278	0.05020	38.24	816.5834
18	0.03401	0.04187	0.04963	36.8	817.5515
20	0.03353	0.04105	0.04916	32.5	820.491
22	0.03400	0.04192	0.05150	31.16	821.3658
24	0.03448	0.04279	0.05384	29.83	822.271
26	0.03496	0.04366	0.05619	28.495	823.1805

5. Conclusion

The identification of the optimum pitch of the coil at 20mm based on brake-specific fuel consumption (BSFC) represents a critical milestone in the study. BSFC is a key performance indicator for engine efficiency, directly correlating with the amount of fuel consumed per unit of power produced. The fact that the 20mm pitch coil configuration resulted in the lowest BSFC indicates that it achieves the most efficient heat transfer and fuel utilization within the engine system. This finding not only validates the effectiveness of the helical coil heat exchanger design but also provides valuable insights for future optimization efforts aimed at further enhancing engine performance and fuel efficiency.

The simulation results indicating a resulting pressure drop of 5.3075 kPa are significant in assessing the safety and viability of the heat exchanger design within the fuel line. Pressure drop is a critical parameter in fluid flow systems, with excessive drops potentially leading to operational issues or component failure. The fact that the simulated pressure drops fall well within the tolerable limit of 20.77 kPa demonstrates that the heat exchanger design effectively balances heat transfer efficiency with minimal impact on fuel flow dynamics. This ensures smooth and stable operation of the engine system, affirming the safety and reliability of the heat exchanger implementation.

The high correlation of 80.05% between the experimental pressure drop value and the mathematically computed value further strengthens the validity of the study's findings. Experimental validation is crucial in engineering analyses, providing empirical evidence to verify theoretical predictions and simulation results. The close agreement between experimental and computed values demonstrates the accuracy and reliability of the computational models and methodologies employed in the study. This enhances confidence in the predictive capabilities of the engineering approach, facilitating informed decision-making in heat exchanger design and optimization processes.

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Author Contribution

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

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