



Article

Thermal Performance Improvement of a Counter-Flow Double-Pipe Heat Exchanger Using a Twisted Turbulator

Eric Maspaitella¹, Nicolas Titahelu², Cendy Sophia Edwina Tupamahu³¹S1 Mechanical Engineering, Faculty of Engineering, Pattimura University^{2,3}Department of Mechanical Engineering, Faculty of Engineering, Pattimura University

DOI: 10.31004/jestm.v6i1.387

E-mail: ericmas82@gmail.com

ARTICLE INFORMATION

Volume 6 Issue 1
 Received: 18 January 2026
 Accepted: 20 February 2026
 Publish Online: 30 March 2026
 Online: at <https://JESTM.org>

Keywords

Double-pipe heat exchanger;
 effectiveness;
 pitch ratio;
 thermal performance;
 twisted turbulator;
 waste heat recovery

ABSTRACT

Internal combustion systems, such as 5 KVA generators, convert only part of fossil fuel energy into useful work, while the remaining energy is released as waste heat through exhaust gas, cooling systems, and mechanical losses. This study aims to improve the thermal performance of a double-pipe heat exchanger using a twisted turbulator by varying the pitch-to-diameter ratio, p/d , from 0.8 to 3.9. The experiment was conducted at the Thermodynamics and Heat Transfer Laboratory, Faculty of Engineering, Pattimura University, using five p/d variations, namely 0.8, 1.6, 2.4, 3.2, and 3.9. The operating conditions were maintained constant, with a hot fluid inlet temperature of 523.2 K, a cold fluid inlet temperature of 308.2 K, a cold fluid velocity of 1.0 m/s, and a hot fluid velocity of 5.0 m/s. The main components included a copper tube bank, steel pipe casing, thermocouples, flowmeter, pipe system, and valves. The performance parameters were evaluated using Reynolds number, Prandtl number, friction factor, Nusselt number, overall heat transfer coefficient, actual heat transfer rate, maximum heat transfer rate, and effectiveness. The results show that the best performance was obtained at $p/d = 0.8$, producing a cold fluid outlet temperature of 425.84 K, Nusselt number of 7.569, overall heat transfer coefficient of 0.2029 $W/m^2 \cdot K$, and effectiveness of 39.95%. The lower p/d ratio enhanced swirl flow, turbulence intensity, fluid mixing, and thermal boundary layer disruption. Therefore, $p/d = 0.8$ is recommended for improving the tested heat exchanger performance in small-scale waste heat recovery applications under laboratory operating conditions and design.

1. Introduction

Heat exchangers function to transfer thermal energy between two or more fluids separated by a solid material. In fossil-fueled internal combustion systems, effective thermal efficiency only reaches around 25–35%, with the remainder being lost as waste heat through exhaust gases, cooling systems, and friction. Waste heat recovery is therefore an important strategy to increase energy efficiency and reduce energy losses in thermal systems. The United States Department of Energy states that 20–50% of industrial energy input is lost as waste heat, which, if utilized, could reduce dependence on fossil fuels and reduce environmental impact. This is in line with the explanation of Jouhara et al. (2018), who stated that waste heat recovery technologies have significant potential to improve energy efficiency in industrial and combustion systems.

Waste heat from internal combustion engines such as 5 KVA generators is often underutilized, resulting in overall energy inefficiency. Various heat exchanger models have been developed for heat recovery applications, including H-fin tube heat exchangers, spiral heat exchangers, shell-and-tube heat exchangers, tube-bank heat exchangers, and inner turbulator types. Previous studies have shown that heat recovery from internal combustion engines can support energy efficiency and sustainable energy utilization (Digdoyo et al., 2021; Douadi et al., 2022). Waste heat can also be applied for practical thermal processes, such as drying and preheating, as demonstrated by Masud et al. (2020).

The main problem in conventional double-pipe heat exchangers is the low convective heat transfer rate, which limits the effectiveness of waste heat recovery from flue gases. This limitation is often caused by weak mixing, stable boundary layer formation, and limited heat transfer area. To overcome this problem, several geometric modifications and passive enhancement techniques have been investigated. El Maakoul et al. (2020) reported that surface interruptions in double-pipe heat exchangers can improve thermal performance. Luo and Song (2021) also showed that a twisted annulus in a double-tube heat exchanger can enhance heat transfer through stronger flow disturbance and better fluid mixing.

One of the passive heat transfer enhancement methods is the use of a twisted turbulator. A twisted turbulator can increase flow turbulence, create swirl flow, disturb the thermal boundary layer, and improve convective heat transfer. The performance of a twisted turbulator is strongly influenced by its geometric characteristics, especially the pitch-to-diameter ratio, p/d . A smaller p/d ratio generally produces stronger swirl intensity and better thermal mixing, while a larger p/d ratio produces weaker disturbance. Recent studies have also shown that turbulator geometry has a significant effect on the hydrothermal performance of counter-flow double-tube heat exchangers (Tavousi et al., 2024).

Variations in the pitch-to-diameter ratio of twisted turbulators have not been widely explored specifically for double-pipe heat exchanger configurations connected to small-scale generator exhaust systems. Although previous studies have investigated several forms of heat exchanger enhancement, limited experimental data are available on the effect of p/d variation in a double-pipe heat exchanger for 5 KVA generator waste heat recovery. This creates a research gap, especially in determining the most effective p/d configuration for improving outlet temperature, Nusselt number, overall heat transfer coefficient, and effectiveness.

This study designs and tests a double-pipe heat exchanger with twisted turbulators on a copper tube bank and steel casing. The p/d ratio is varied from 0.8 to 3.9 to optimize the thermal performance of a 5 KVA generator set. The main objectives are to measure the effect of p/d on cold fluid outlet temperature, Nusselt number, overall heat transfer coefficient, actual heat transfer rate, maximum heat transfer rate, and heat exchanger effectiveness, while comparing the performance with a configuration without a turbulator. The novelty of this study lies in the application of twisted turbulator p/d variation to a local 5 KVA generator set with a double-pipe heat exchanger configuration. The results are expected to support the development of simple waste heat recovery systems for small-scale industrial and local power generation applications.

2. Literature Review

Waste heat recovery is an important topic in mechanical engineering because many thermal systems release a large amount of unused energy to the environment. Jouhara et al. (2018) reviewed waste heat recovery technologies and applications and emphasized

that unused thermal energy can be recovered to improve energy efficiency. Douadi et al. (2022) also explained that engine waste heat recovery requires proper heat exchanger selection, working fluid consideration, and system configuration to obtain useful thermal energy.

Internal combustion engine exhaust gases are among the most important sources of waste heat. Digdoyo et al. (2021) reviewed the utilization of internal combustion engine waste heat and stated that exhaust gas recovery can be used as part of sustainable energy development. In practical applications, recovered waste heat can be used for drying and heating processes. Masud et al. (2020) experimentally investigated a waste-heat-based food drying system and showed that waste heat can be converted into useful thermal energy.

Double-pipe heat exchangers are commonly used in laboratory-scale and small-scale thermal systems because they are simple, compact, and easy to fabricate. The counter-flow arrangement is generally preferred because it can provide better temperature distribution and heat transfer performance compared with parallel flow. El Maakoul et al. (2020) studied performance enhancement in finned annulus double-pipe heat exchangers using surface interruptions and found that geometric modification can improve thermal performance. Luo and Song (2021) investigated a double-tube heat exchanger with a novel twisted annulus and reported that twisted geometry can improve thermal performance by increasing flow disturbance.

Several heat exchanger designs have been developed for waste heat recovery applications. Fetuga et al. (2023) conducted a numerical analysis of waste heat recovery shell-and-tube heat exchangers with different tube configurations under counter-flow conditions. Their findings showed that tube arrangement and flow configuration significantly affect heat transfer performance. Tang et al. (2022) investigated thermal-hydraulic characteristics in a finned tube heat exchanger for flue gas waste heat recovery and showed that geometric modification can enhance heat transfer but must be balanced with flow resistance.

Spiral heat exchangers and other compact heat exchangers have also been studied for waste heat recovery applications. Mokhtar et al. (2023) experimentally characterized a spiral heat

exchanger for wastewater heat recovery and showed that heat exchanger geometry strongly affects recovery performance. Although the working fluid and heat source differ from generator exhaust gas, the study confirms the importance of selecting appropriate heat exchanger geometry for low-grade heat recovery.

Passive heat transfer enhancement is widely used because it can improve heat transfer without requiring complex additional systems. Twisted tapes, turbulators, fins, and surface interruptions are examples of passive enhancement devices. Tavousi et al. (2024) investigated novel turbulators in a counter-flow double-tube heat exchanger using nanofluids and found that turbulator configuration can significantly influence hydrothermal performance. Salameh et al. (2023) also showed that the thermal performance of concentric counter-flow tube heat exchangers can be improved by using different nanofluids, indicating that both geometry and working fluid properties influence heat transfer enhancement.

The Nusselt number, overall heat transfer coefficient, actual heat transfer rate, maximum heat transfer rate, and effectiveness are commonly used parameters to evaluate heat exchanger performance. In turbulator-based systems, a higher Nusselt number generally indicates better convective heat transfer. However, heat transfer enhancement should not only be evaluated from thermal performance but also from hydraulic characteristics, such as pressure drop and friction factor. This is important because stronger turbulence may increase heat transfer but may also increase pumping power requirements.

From the reviewed literature, it can be concluded that heat exchanger geometry, flow configuration, and passive enhancement devices significantly affect thermal performance. However, the specific effect of twisted turbulator p/d variation in a counter-flow double-pipe heat exchanger using a 5 KVA generator exhaust source has not been sufficiently discussed. Therefore, this study contributes experimental data on five p/d variations and evaluates their effects on temperature, Nusselt number, overall heat transfer coefficient, heat transfer rate, and effectiveness.

3. Research Methodology

3.1 Research Design

This research is quantitative research with an experimental approach to test the thermal performance of a double-pipe heat exchanger equipped with a twisted turbulator on a 5 KVA generator set. This type of research emphasizes direct testing through variations

in the pitch-to-diameter ratio, p/d , from 0.8 to 3.9 to measure total heat transfer rate, cold fluid outlet temperature, Nusselt number, overall heat transfer coefficient, and effectiveness. The experimental approach is suitable for obtaining empirical data from engineering devices under controlled conditions, as supported by general experimental research principles (Sugiyono, 2021; Creswell & Creswell, 2023).

The independent variable in this study is the pitch-to-diameter ratio, p/d , of the twisted turbulator. The tested p/d ratios are 0.8, 1.6, 2.4, 3.2, and 3.9. The dependent variables include cold fluid outlet temperature, hot fluid outlet temperature, Nusselt number, overall heat transfer coefficient, actual heat transfer rate, maximum heat transfer rate, and heat exchanger effectiveness. The controlled variables include hot fluid inlet temperature, cold fluid inlet temperature, hot fluid velocity, cold fluid velocity, heat exchanger length, pipe material, and counter-flow arrangement.

3.2 Experimental Setup

The experimental setup consisted of a 5 KVA generator set, a double-pipe heat exchanger, a twisted turbulator, thermocouples, flowmeters, connecting pipes, valves, and supporting instruments. The hot fluid was exhaust gas from the generator, while the cold fluid flowed through the heat exchanger as the receiving fluid. The system was arranged in a counter-flow configuration to increase the mean temperature difference between the hot and cold fluids.

The heat exchanger consisted of a copper tube bank and a steel pipe casing. Copper was selected because of its high thermal conductivity, while steel was used as the outer casing due to its mechanical strength and availability. The twisted turbulator was inserted inside the heat exchanger flow passage to increase swirl flow and turbulence intensity. The p/d ratio was defined as the ratio between the turbulator pitch, p , and the turbulator diameter or characteristic tube diameter, d . The p/d values tested in this study were 0.8, 1.6, 2.4, 3.2, and 3.9.

The hot fluid inlet temperature was maintained at 523.2 K, and the cold fluid inlet temperature was maintained at 308.2 K based on

the measured experimental data. The cold fluid velocity was set at 1.0 m/s, while the hot fluid velocity was set at 5.0 m/s. Temperature measurements were taken at the inlet and outlet of both hot and cold sides. The experiment was conducted at the Thermodynamics and Heat Transfer Laboratory, Faculty of Engineering, Pattimura University, starting in June 2024. The experimental design and data collection followed systematic research procedures for engineering experiments (Emzir, 2022; Sudaryono, 2021).

3.3 Experimental Procedure

The experimental procedure was carried out in several stages. First, the heat exchanger system, generator, pipes, valves, thermocouples, and flowmeters were inspected to ensure that the system was ready for operation. Second, the measuring instruments were checked and calibrated to reduce measurement errors. Third, the 5 KVA generator was operated until the exhaust gas temperature reached stable conditions. Fourth, the cold fluid was circulated through the heat exchanger at a constant velocity of 1.0 m/s. Fifth, the twisted turbulator was installed with a selected p/d ratio, and the system was operated until steady-state conditions were reached.

After stable conditions were achieved, temperature and velocity data were recorded. The same procedure was repeated for each p/d ratio. The results were then processed to calculate the heat transfer parameters. The data were also compared with the heat exchanger configuration without a turbulator to evaluate the effect of the twisted turbulator on effectiveness. To improve data reliability, each test condition should be repeated, and the average values should be used for analysis. Instrument uncertainty and measurement error should also be considered in future testing to strengthen the validity of the results.

3.4 Data Reduction

Data analysis techniques involve calculating the Reynolds number, Prandtl number, friction factor, Nusselt number, overall heat transfer coefficient, actual heat transfer rate, maximum heat transfer rate, and effectiveness. These parameters are commonly used in heat exchanger performance analysis and have also been applied in previous studies on double-pipe heat exchangers and waste heat recovery systems (El Maakoul et al., 2020; Fetuga et al., 2023; Tavousi et al., 2024).

The Reynolds number is calculated using:

$$Re = \frac{\rho V D}{\mu}$$

where Re is the Reynolds number, ρ is fluid density, V is fluid velocity, D is hydraulic diameter, and μ is dynamic viscosity.

The Prandtl number is calculated using:

$$Pr = \frac{\mu C_p}{k}$$

where Pr is the Prandtl number, C_p is specific heat, and k is thermal conductivity.

The Nusselt number is calculated using:

$$Nu = \frac{hD}{k}$$

where Nu is the Nusselt number and h is the convective heat transfer coefficient.

The overall heat transfer coefficient is calculated using the thermal resistance concept:

$$\frac{1}{U} = \frac{1}{h_h} + \frac{\Delta x}{k_w} + \frac{1}{h_c}$$

where U is the overall heat transfer coefficient, h_h is the hot-side heat transfer coefficient, h_c is the cold-side heat transfer coefficient, Δx is wall thickness, and k_w is wall thermal conductivity.

The logarithmic mean temperature difference for counter-flow arrangement is calculated using:

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1 / \Delta T_2)}$$

where:

$$\Delta T_1 = T_{h,i} - T_{c,o}$$

$$\Delta T_2 = T_{h,o} - T_{c,i}$$

where Q_{actual} is the actual heat transfer rate and A is the heat transfer area.

The maximum heat transfer rate is calculated using:

$$Q_{max} = C_{min}(T_{h,i} - T_{c,i})$$

where Q_{max} is the maximum heat transfer rate and C_{min} is the minimum heat capacity rate.

The heat exchanger effectiveness is calculated using:

$$\varepsilon = \frac{Q_{actual}}{Q_{max}} \times 100\%$$

where ε is the heat exchanger effectiveness.

4. Results and Discussion

4.1 Inlet and Outlet Fluid Temperature

The inlet and outlet fluid temperature data obtained from the test results on variations in the pitch-to-diameter ratio, p/d, are presented in Table 1. These data are the results of direct measurements during the heat exchanger testing process with variations in turbulator configurations.

Table 1. Experimental Measurement Data for Each p/d Variation

p/d	Th,i (K)	Tc,i (K)	Vc,i (m/s)	Vh,i (m/s)	Th,o (K)	Tc,o (K)
0.8	523.2	308.2	1.0	5.0	361.99	425.84
1.6	523.2	308.2	1.0	5.0	366.06	411.38
2.4	523.2	308.2	1.0	5.0	369.21	405.68
3.2	523.2	308.2	1.0	5.0	371.00	404.50
3.9	523.2	308.2	1.0	5.0	371.94	403.22

The relationship between the p/d ratio and the fluid outlet temperature shows that the cold fluid outlet temperature decreases as the p/d ratio increases. The highest cold fluid outlet temperature was obtained at p/d = 0.8, with a value of 425.84 K. Meanwhile, the lowest cold fluid outlet temperature was obtained at p/d = 3.9, with a value of 403.22 K.

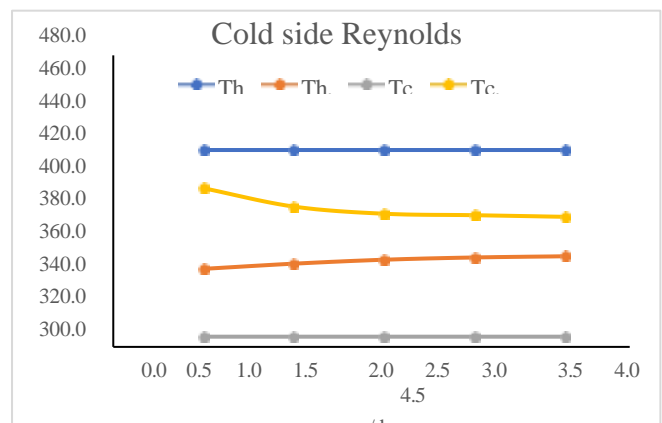


Figure 1. Graph of the effect of p/d on temperature output data

This result indicates that a smaller p/d ratio improves heat transfer between the hot and cold fluids. At p/d = 0.8, the twist pitch is more compact, causing stronger swirl flow and more intensive mixing. The stronger mixing reduces the thermal boundary layer thickness and increases the temperature gradient between the fluid and the heat transfer surface. This mechanism is consistent with Luo and Song (2021), who reported that twisted geometry improves heat transfer through flow disturbance, and Tavousi et al. (2024), who found that turbulator configuration influences hydrothermal performance in counter-flow double-tube heat exchangers.

The hot fluid outlet temperature also supports this trend. At p/d = 0.8, the hot fluid outlet temperature was 361.99 K, which is lower than the values obtained at larger p/d ratios. A lower hot fluid outlet temperature indicates that more heat was transferred from the hot fluid to the cold fluid. Therefore, the temperature data confirm that p/d = 0.8 provides the most effective heat transfer condition among the tested configurations.

4.2 Heat Transfer Characteristics Based on Nusselt Number

The Nusselt number values obtained from the calculation results for each p/d variation are presented in Table 2. These values were obtained by processing temperature data and fluid flow parameters on the hot side of the heat exchanger.

Table 2. Results of Nusselt Number Calculations on the Hot Side

p/d	Re _h	Pr _h	f _h	Nu _h
0.8	11718.5	0.0007405	0.00533459	7.569
1.6	9202.8	0.0007395	0.00379019	4.825
2.4	8711.1	0.0007388	0.00298491	3.895
3.2	8441.9	0.0007384	0.00251106	3.361
3.9	8383.3	0.0007382	0.00217885	3.027

The results show that the Nusselt number decreases as p/d increases. The highest Nusselt number was obtained at p/d = 0.8, with a value of 7.569, while the lowest value was obtained at p/d = 3.9, with a value of 3.027. This trend indicates that a smaller p/d ratio produces better convective heat transfer.

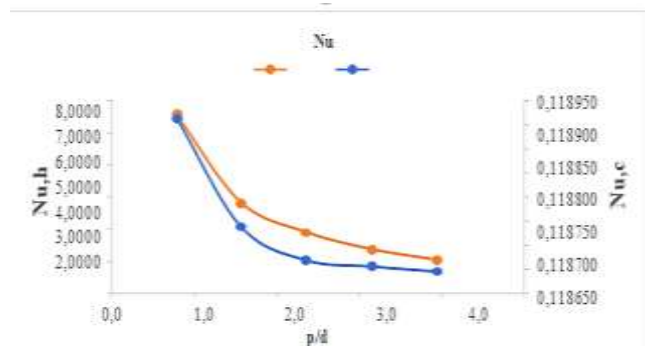


Figure 2. Graph of the effect of p/d on the Nusselt number

The increase in Nusselt number at p/d = 0.8 is caused by stronger swirl flow and higher turbulence intensity. The twisted turbulator forces the flow to rotate and creates secondary flow, which increases fluid mixing and reduces thermal resistance near the wall. As a result, the convective heat transfer coefficient increases. This finding is in line with El Maakoul et al. (2020), who showed that geometric modification can improve heat transfer performance, and Tavousi et al. (2024), who showed that turbulator configuration affects hydrothermal behavior.

The Reynolds number also decreases as p/d increases. This shows that the flow characteristics are influenced by turbulator geometry. A smaller p/d ratio creates stronger disturbance and increases interaction between the fluid and the heat transfer surface. However, the Prandtl number values in Table 2 are relatively small and should be carefully verified using accurate fluid properties and correct units. This verification is important to improve the technical quality of the calculation.

4.3 Overall Heat Transfer Coefficient

The overall heat transfer coefficient values obtained from the calculation results for each p/d variation are presented in Table 3. These values are calculated based on the heat transfer parameters on the hot side and cold side of the heat exchanger.

Table 3. Results of Overall Heat Transfer Coefficient Calculation

p/d	L (m)	λ _w or k _w (W/m·K)	h _h (W/m ² ·K)	h _c (W/m ² ·K)	U (W/m ² ·K)
0.8	2.0	387	8.429	0.032	0.2029
1.6	2.0	387	5.295	0.032	0.1966
2.4	2.0	387	4.227	0.031	0.1940
3.2	2.0	387	3.624	0.031	0.1933
3.9	2.0	387	3.254	0.031	0.1926

The highest overall heat transfer coefficient was obtained at $p/d = 0.8$, with a value of $0.2029 \text{ W/m}^2\cdot\text{K}$. The value then decreased slightly as p/d increased, reaching $0.1926 \text{ W/m}^2\cdot\text{K}$ at $p/d = 3.9$. This result confirms that a smaller p/d ratio improves the overall heat transfer process.

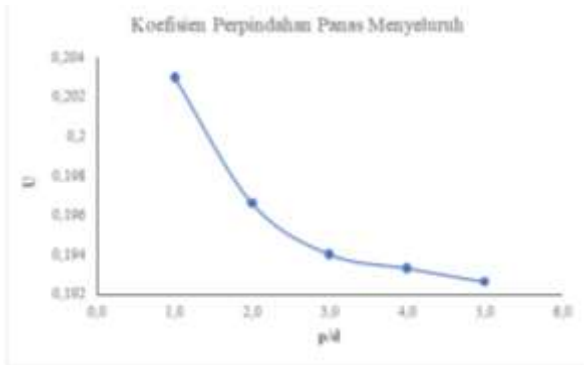


Figure 3. Graph of the effect of p/d on the overall heat transfer coefficient

The increase in U at $p/d = 0.8$ is related to the higher hot-side heat transfer coefficient generated by stronger turbulence. However, the change in U is relatively small compared with the change in Nusselt number. This may indicate that the total heat transfer process is affected not only by hot-side convection but also by other thermal resistances, such as cold-side convection and wall conduction. Since copper has high thermal conductivity, the wall resistance is expected to be relatively small. Therefore, convective resistance may dominate the overall heat transfer process.

The unit notation in this table has been corrected to $\text{W/m}\cdot\text{K}$ for thermal conductivity and $\text{W/m}^2\cdot\text{K}$ for heat transfer coefficients. This correction is important because incorrect unit notation can lead to misinterpretation of the results.

4.4 Actual and Maximum Heat Transfer

The actual heat transfer and maximum heat transfer values obtained from the calculation results for each p/d variation are presented in Table 4 and Table 5. These values are calculated based on fluid temperature data and heat transfer parameters obtained during the testing process.

Table 4. Calculation Results for Actual Heat Transfer

p/d	U (W/m ² ·K)	A (m ²)	ΔT_{lm} (K)	Q _{actual} (W)
0.8	0.2029	0.1595	40.964	1.326
1.6	0.1966	0.1595	51.063	1.601
2.4	0.1940	0.1595	55.600	1.720
3.2	0.1933	0.1595	57.070	1.760
3.9	0.1926	0.1595	58.194	1.788

The results show that Q_{actual} increases as p/d increases. At $p/d = 0.8$, Q_{actual} was 1.326 W , while at $p/d = 3.9$, Q_{actual} increased to 1.788 W . This trend is influenced by the increase in logarithmic mean temperature difference at higher p/d ratios. Although the overall heat transfer coefficient was highest at $p/d = 0.8$, the ΔT_{lm} value at this condition was lower than that of larger p/d ratios.

Table 5. Calculation Results for Maximum Heat Transfer

p/d	\dot{m} (kg/s)	C_p (kJ/kg·K)	ΔT (K)	Q _{max} (W)
0.8	0.115	0.949	30.360	3.319
1.6	0.119	0.945	44.820	5.045
2.4	0.121	0.944	50.520	5.751
3.2	0.121	0.943	51.700	5.899
3.9	0.121	0.943	52.980	6.060

The maximum heat transfer also increases as p/d increases. This increase is mainly influenced by changes in the temperature difference used in the Q_{max} calculation. Since heat exchanger effectiveness is calculated from the ratio between Q_{actual} and Q_{max} , the increase in Q_{actual} does not automatically result in higher effectiveness if Q_{max} increases more significantly.

The unit of C_p has been written as $\text{kJ/kg}\cdot\text{K}$ to avoid confusion. If C_p is calculated in $\text{J/kg}\cdot\text{K}$, the values should be rechecked. Consistent unit notation is necessary to ensure accurate interpretation of the heat transfer calculation.

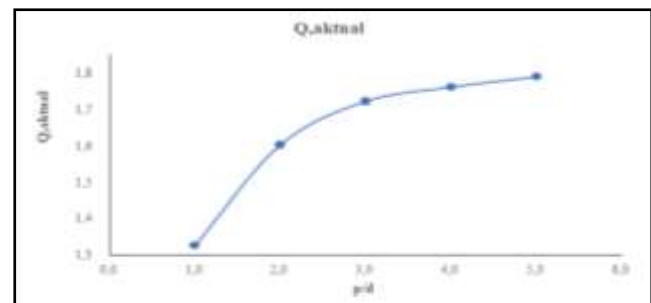


Figure 4. Graph of the effect of p/d on actual heat transfer

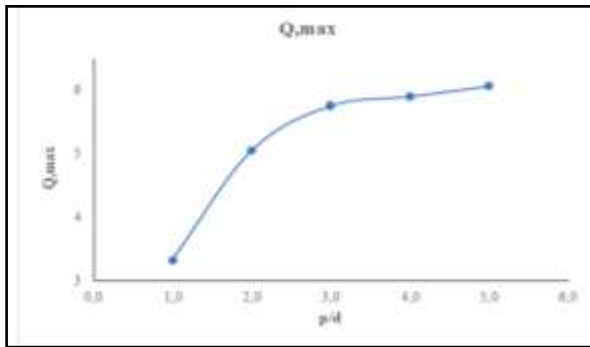


Figure 5. Graph of the effect of p/d on maximum heat transfer

The relationship between the p/d ratio to the actual heat transfer and maximum heat transfer is shown in Figure 4. and Figure 5. The graph shows the change in heat transfer value at each p/d variation, which illustrates the effect of variations in turbulator configuration on the heat transfer performance of the heat exchanger.

4.5 Heat Exchanger Effectiveness

Heat exchanger effectiveness describes the ratio between actual heat transfer and the maximum possible heat transfer. The effectiveness values for different p/d ratios are shown in Table 6.

Table 6. Heat Exchanger Effectiveness Calculation Results

p/d	Q _{actual} (W)	Q _{max} (W)	Effectiveness (%)
0.8	1.326	3.319	39.95
1.6	1.601	5.045	31.74
2.4	1.720	5.751	29.92
3.2	1.760	5.899	29.83
3.9	1.788	6.060	29.50

The highest effectiveness was obtained at p/d = 0.8, with a value of 39.95%. The effectiveness decreased to 31.74% at p/d = 1.6 and continued decreasing until it reached 29.50% at p/d = 3.9. These results show that the lowest p/d ratio provided the most effective heat exchanger performance.

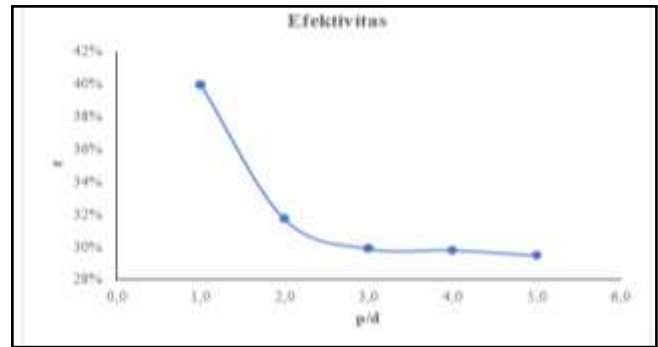


Figure 6. Graph of the effect of p/d on effectiveness

The higher effectiveness at p/d = 0.8 is caused by the stronger swirl flow and higher turbulence intensity generated by the twisted turbulator. The compact pitch increases the interaction between the fluid and the heat transfer surface, enhances mixing, and reduces the thermal boundary layer thickness. These mechanisms improve the heat transfer process from the hot fluid to the cold fluid.

Although Q_{actual} increases at larger p/d ratios, effectiveness decreases because Q_{max} increases more significantly. This explains why p/d = 0.8 still gives the best effectiveness even though its Q_{actual} value is lower than those of larger p/d ratios. This finding supports the use of a smaller p/d ratio for improving the effectiveness of the tested heat exchanger configuration.

4.6 Comparison Between Twisted Turbulator and No-Turbulator Configuration

The comparison of heat exchanger performance between the use of a twisted turbulator and without a turbulator is important to evaluate the effect of the turbulator on heat transfer performance. Based on the comparison results, the use of a twisted turbulator produces higher effectiveness compared with the heat exchanger without a turbulator under the same test conditions.

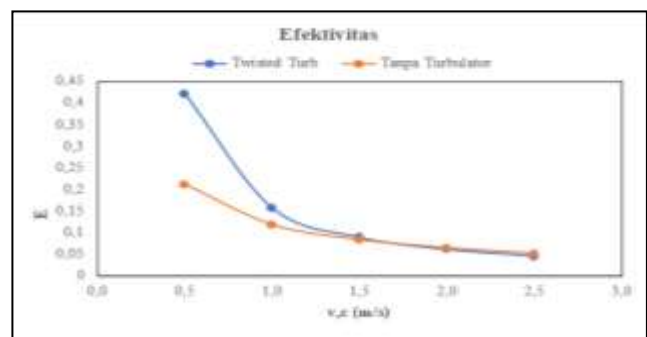


Figure 7. Comparison of the effectiveness of a twisted turbulator and without a turbulator

The increase in effectiveness indicates that the twisted turbulator can improve turbulence and fluid mixing inside the heat exchanger. Without a turbulator, the flow tends to be more stable, and the thermal boundary layer is more difficult to disrupt. With a twisted turbulator, the flow becomes more disturbed and rotational, increasing the heat transfer intensity.

However, the no-turbulator data should be presented more clearly in numerical form, not only through a graph. A comparison table should include the values of outlet temperature, Nusselt number, overall heat transfer coefficient, Q_{actual} , Q_{max} , and effectiveness for the no-turbulator configuration. This will allow the percentage improvement caused by the twisted turbulator to be calculated more accurately.

In addition, pressure drop should be considered in future studies. A smaller p/d ratio may improve heat transfer but may also increase flow

5. Conclusion

This study shows that variations in the pitch-to-diameter ratio, p/d , of a twisted turbulator significantly affect the thermal performance of a double-pipe heat exchanger. The tested p/d ratios were 0.8, 1.6, 2.4, 3.2, and 3.9. The results show that the lowest p/d ratio produces the best heat exchanger effectiveness.

The optimum configuration was obtained at $p/d = 0.8$, with a cold fluid outlet temperature of 425.84 K, hot fluid outlet temperature of 361.99 K, Nusselt number of 7.569, overall heat transfer coefficient of 0.2029 W/m²·K, and effectiveness of 39.95%. This improvement confirms the role of the twisted turbulator in enhancing swirl flow, turbulence intensity, fluid mixing, and convective heat transfer.

The effectiveness decreases as p/d increases. At $p/d = 3.9$, the effectiveness decreased to 29.50%. This indicates that a larger p/d ratio produces weaker flow disturbance and lower thermal effectiveness. Therefore, $p/d = 0.8$ is recommended as the most effective configuration for the tested double-pipe heat exchanger system.

The practical implication of this study is the potential use of a twisted turbulator double-pipe heat exchanger for small-scale waste heat recovery applications, especially in local generator systems. However, the study is limited

to laboratory testing under constant temperature and flow rate conditions. The effects of real generator load fluctuations, long-term material degradation, heat loss, corrosion, and pressure drop were not fully investigated.

Future research should include uncertainty analysis, pressure drop measurement, CFD simulation, and field testing on continuously operating generators. Further studies may also investigate the use of nanofluids or other working fluids to improve heat transfer performance, as suggested by Salameh et al. (2023) and Tavousi et al. (2024).

References

- Creswell, J. W., & Creswell, J. D. (2023). *Research design: Qualitative, quantitative, and mixed methods approaches* (6th ed.). SAGE Publications. <https://doi.org/10.1007/978-3-031-64050-4>
- Digdoyo, A., Surawan, T., Djamruddin, D., Yuniati, E., Ardiyan, D., & Saputra, A. (2021). Review: Utilization of waste heat from internal combustion engines as renewable energy through exhaust gas recovery process. *Technology of Renewable Energy Development*, 130–144.
- Douadi, O., Ravi, R., Faqir, M., & Essadiqi, E. (2022). A conceptual framework for waste heat recovery from compression ignition engines: Technologies, working fluids & heat exchangers. *Energy Conversion and Management X*, 16, 100309. <https://doi.org/10.1016/j.ecmx.2022.100309>
- Emzir. (2022). *Qualitative research methodology: Sampling techniques, data analysis, and applications*. Pustaka Setia. <https://doi.org/10.5281/zenodo.6802990>
- El Maakoul, A., Feddi, K., Saadeddine, S., Ben Abdellah, A., & El Metoui, M. (2020). Performance enhancement of finned annulus using surface interruptions in double-pipe heat exchangers. *Energy Conversion and Management*, 210, 112710. <https://doi.org/10.1016/j.enconman.2020.112710>
- Fetuga, I. A., Olakoyejo, O. T., Abolarin, S. M., Gbegudu, J. K., Onwuegbusi, A., & Adelaja, A. O. (2023). Numerical analysis of thermal performance of waste heat recovery shell and tube heat exchangers on counter-flow with different tube configurations. *Alexandria*

- Engineering Journal, 64, 859–875.
<https://doi.org/10.1016/j.aej.2022.09.017>
- Jouhara, H., Khordehghah, N., Almahmoud, S., Delpech, B., Chauhan, A., & Tassou, S. A. (2018). Waste heat recovery technologies and applications. *Thermal Science and Engineering Progress*, 6, 268–289.
<https://doi.org/10.1016/j.tsep.2018.04.017>
- Luo, C., & Song, K. W. (2021). Thermal performance enhancement of a double-tube heat exchanger with novel twisted annulus formed by counter-twisted oval tubes. *International Journal of Thermal Sciences*, 164, 106892.
<https://doi.org/10.1016/j.ijthermalsci.2021.106892>
- Masud, M. H., Ananno, A. A., Ahmed, N., Dabnichki, P., & Salehin, K. N. (2020). Experimental investigation of a novel waste heat based food drying system. *Journal of Food Engineering*, 281, 110002.
<https://doi.org/10.1016/j.jfoodeng.2020.110002>
- Mokhtar, Z., Vanden Berghe, J., & Blondeau, J. (2023). Experimental characterization of a spiral heat exchanger for waste water heat recovery from partially filled sewage pipes. *Case Studies in Thermal Engineering*, 52, 103770.
<https://doi.org/10.1016/j.csite.2023.103770>
- Salameh, T., Alkasrawi, M., Olabi, A. G., Al Makky, A., & Abdelkareem, M. A. (2023). Experimental and numerical analysis of heat transfer enhancement inside concentric counter flow tube heat exchanger using different nanofluids. *International Journal of Thermofluids*, 20, 100432.
<https://doi.org/10.1016/j.ijft.2023.100432>
- Sugiyono. (2021). Quantitative, qualitative, and R&D research methods. Alfabeta.
<https://doi.org/10.5281/zenodo.5812846>
- Sudaryono. (2021). Scientific research methods: Quantitative, qualitative, and development approaches. Graha Ilmu.
<https://doi.org/10.5281/zenodo.4728241>
- Tavousi, E., Perera, N., Flynn, D., Hasan, R., & Rahman, M. (2024). Effect of novel turbulators on the hydrothermal performance of counterflow double tube heat exchanger using nanofluids. *International Journal of Heat and Fluid Flow*, 107, 109427.
<https://doi.org/10.1016/j.ijheatfluidflow.2024.109427>
- Tang, S., Xie, X., Zhao, Z., & Ding, L. (2022). Investigation of thermal-hydraulic characteristics in a novel finned tube heat exchanger for flue gas waste heat recovery. *Case Studies in Thermal Engineering*, 39, 102392.
<https://doi.org/10.1016/j.csite.2022.102392>
- Salameh, T., Alkasrawi, M., Olabi, A. G., Al Makky, A., & Abdelkareem, M. A. (2023). Experimental and numerical analysis of heat transfer enhancement inside concentric counter flow tube heat exchanger using different nanofluids. *International Journal of Thermofluids*, 20, 100432. doi:10.1016/j.ijft.2023.100432
- Tang, S., Xie, X., Zhao, Z., & Ding, L. (2022). Investigation of thermal-hydraulic characteristics in a novel finned tube heat exchanger for flue gas waste heat recovery. *Case Studies in Thermal Engineering*, 39, 102392. doi:10.1016/j.csite.2022.102392
- Tavousi, E., Perera, N., Flynn, D., Hasan, R., & Rahman, M. (2024). Effect of novel turbulators on the hydrothermal performance of counterflow double tube heat exchanger using nanofluids. *International Journal of Heat and Fluid Flow*, 107, 109427.
[doi:10.1016/j.ijheatfluidflow.2024.109427](https://doi.org/10.1016/j.ijheatfluidflow.2024.109427)