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Effect of turbo cyclone vane angles on performance and emissions of a 1000 cc engine

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Abstract

The installation of a turbo cyclone in the intake manifold aims to increase airflow turbulence, thereby improving the air–fuel mixture process inside the combustion chamber. This study investigates the effects of turbo cyclone implementation on the performance, fuel consumption, and exhaust emissions of a 1000 cc engine. The cyclone was designed with six fixed vanes at angles of 30°, 45°, and 60°, and tested using two fuels: RON 90 and RON 92. Engine performance was measured with a dynamometer across 1000–6000 rpm, fuel consumption was evaluated using Specific Fuel Consumption (SFC), and exhaust emissions were analyzed with a gas analyzer. Results indicate that the 60° vane angle delivers the best overall performance, achieving a maximum power of 34.1 HP, peak torque of 57.4 Nm, and the lowest SFC of 93.33 g/kWh. Additionally, CO and HC emissions were reduced by up to 40% compared to the baseline (non-cyclone) condition. Among the tested fuels, RON 92 consistently provided better performance and lower emissions, highlighting its higher combustion efficiency. These findings demonstrate that the turbo cyclone (particularly at a 60° vane angle) effectively improves engine efficiency, enhances output, and reduces harmful emissions.

Keywords:
Turbo cyclone, engine performance, SFC, exhaust emission

1 Introduction

The advancement of modern automotive technology has driven manufacturers and researchers to continuously improve energy efficiency, engine performance, and reduce exhaust gas emissions to support environmental sustainability[1]. Conventional vehicles, particularly those produced before the year 2000, often experience performance degradation due to aging and suboptimal maintenance. These conditions lead to decreased combustion efficiency, increased fuel consumption, and exhaust emissions that exceed ideal thresholds. One of the contributing factors is the suboptimal mixing of air and fuel within the combustion chamber, resulting in incomplete combustion. The primary emissions produced by internal combustion engines include Carbon Monoxide (CO), Nitrogen Oxides (NOx), unburned Hydrocarbons (HC), and various other pollutant particulates [2]. Numerous researchers have introduced various innovations to improve combustion efficiency in internal combustion engines, one of which is through the use of a device known as the turbo cyclone.

The turbo cyclone, constructed from stainless steel, consists of several vanes mounted at specific angles relative to its vertical axis. A turbo cyclone is a type of air compression technology that functions by creating a more focused vortex of air as it passes through the device[3], It functions to convert laminar airflow into turbulent flow, thereby enhancing the intensity and duration of interaction between air and fuel in the combustion chamber[4]. This turbulence promotes better homogenization of the air–fuel mixture, which in turn facilitates more efficient combustion The resulting turbulence promotes better homogenization of the air–fuel mixture, which in turn facilitates more efficient combustion[5]. Additionally, the turbo cyclone has the potential to minimize pressure drop in the intake manifold, supporting the stability of intake air pressure. The optimization of the combustion process contributes to increased engine output (power and torque), improved fuel consumption efficiency, and reduced emissions of harmful gases such as CO, Hydrocarbons (HC), and Carbon Dioxide (CO_2) [6]. In practical applications, the turbo cyclone has been widely adopted as a modification solution for intake air systems, particularly in vehicles with small to medium displacement engines. With its compact design and installation that does not require major modifications to the engine system, the device is considered an efficient and economical option for improving engine performance. Its effectiveness is largely influenced by the vane angle configuration, internal geometric design, and installation position within the intake duct, all of which collectively affect flow patterns and fluid dynamics within the system.

Several previous studies have explored the use of turbo cyclones. The study conducted by Adi Jaka Satrya et al. [7] entitled *"Experimental Study of Turbo Cyclone Addition with Vane Angle Variation on the Performance of Four-Stroke Engines"*, showed that the use of a turbo cyclone with a 55° vane angle on a 150 cc engine increased engine performance, achieving 9.0 HP, 10.65 Nm torque, 1.479 L/h fuel consumption, along with reductions in CO and HC emissions. The 55° angle was considered the most effective in improving efficiency and reducing exhaust emissions. The study by Onky Pieter Tegar Mandiri et al. [8], titled *"Effect of 6-Vane Turbo Cyclone at 45° and Fuel Variation on the Performance of 110 cc Automatic Engines"*, concluded that a 45° vane turbo cyclone increased torque by up to 14.76%, power by 13.78%, and reduced Specific Fuel Consumption (SFC) by 17.66%. The best results were achieved using Pertamax fuel, indicating improved efficiency and engine performance. Another study by Syahrul Huda et al.[9] entitled *"Effect of Turbo Cyclone Installation on Four-Stroke Motorcycles on Fuel Consumption and Exhaust Emissions"*, found that installing a turbo cyclone on a Yamaha Jupiter MX 135 cc motorcycle improved fuel efficiency and reduced emissions. The installation after the carburetor yielded the best results, with an 8% reduction in fuel consumption, a 9% decrease in HC emissions, and a 1% increase in CO_2 levels, indicating more efficient combustion.

However, these three studies present some data-based limitations, as noted in the study by Adi Jaka Satrya et al. [7] used only one type of fuel and did not compare octane quality; the study by Onky Pieter Tegar Mandiri et al. [8] lacked statistical analysis to examine the interaction between variables, and the study by Syahrul Huda et al. [9] did not investigate variations in vane angle or fuel type, nor did it employ a standardized emission testing instrument. These gaps offer opportunities for more comprehensive follow-up research.

Based on the identified research gaps, this study aims to experimentally investigate the effect of varying turbo cyclone blade angles (30°, 45°, and 60°) on the performance of a 1000 cc gasoline engine, fuel consumption efficiency, and exhaust emissions, using two different fuel types (RON 90 and RON 92). Performance data were obtained through dynamometer testing, while exhaust gas emissions were measured using a gas analyzer, and fuel consumption was calculated using the SFC method. All test results were analyzed using the Design of Experiment (DOE) method to evaluate the significance of each variable's influence and their interactions.

The choice of a 1000 cc engine was made strategically, as this engine capacity is widely used in small to mid-size passenger vehicles commonly found in Asian markets, including Indonesia. A 1000 cc engine is considered representative of daily driving needs that prioritize fuel efficiency and low emissions. Therefore, testing on this engine is expected to yield relevant and applicable findings for the development of passive devices such as turbo cyclones to optimize combustion systems in conventional motor vehicles in a practical and environmentally friendly manner.

2 Research methodology

This study employs an experimental method to investigate the effects of turbo cyclone blade angle variation and fuel octane rating on engine performance, fuel efficiency, and exhaust emissions. This approach is conducted systematically to analyze the cause-and-effect relationships between variables through quantitative data under controlled conditions [10][11].

2.1 Material and equipment

The materials and equipment used in this study were carefully selected to ensure accurate and reliable measurements throughout the experimental process. The primary test unit was a four-stroke gasoline internal combustion engine. The turbo cyclone device was custom-fabricated with adjustable blade angles of 30°, 45°, and 60°, specifically designed to generate turbulent airflow within the intake manifold to enhance air-fuel mixing. Two types of commercial gasoline fuels were used in the tests, each with different octane ratings: RON 90 and RON 92. An engine dynamometer (Dynotest) was employed to accurately measure engine performance, providing real-time data on output power (horsepower) and torque (Newton-meters). Fuel consumption was measured using a fuel flow meter, enabling precise calculation of SFC in grams per kilowatt-hour. Additionally, a gas analyzer was used to measure the concentrations of major exhaust gas emissions, including CO, CO_2, HC, and oxygen (O_2). All engine parameters and test results were recorded and monitored using a digital data acquisition system to ensure consistency and facilitate comprehensive analysis.

2.2 Experimental design

The experimental setup in this study was designed using a full factorial approach, which includes all possible combinations of turbo cyclone blade angles (30°, 45°, and 60°) with two types of fuel: RON 90 and RON 92. This combination resulted in a total of six different test configurations. Each test was conducted under consistent and controlled operating conditions to ensure data reliability and repeatability. Before data collection, the engine was allowed to reach thermal stability to eliminate the influence of transient temperature fluctuations. For each configuration, the turbo cyclone unit was installed with the specified blade angle, and the corresponding type of fuel was supplied to the engine. The engine was operated at a constant throttle opening of 50% and steady engine speed, with data collected at engine speeds ranging from 1000 to 2000 RPM. The key performance parameters measured in each test included engine torque, power output, SFC, and exhaust gas composition. To enhance accuracy and ensure data consistency, each test was repeated three times, and the results were averaged for analysis.

2.3 Theoretical framework

This study is grounded in the fundamental principles of thermodynamics and internal combustion engine operation, particularly concerning engine performance and energy efficiency. To evaluate the impact of intake air turbulence induced by the turbo cyclone, key performance parameters such as power, torque, and SFC were analyzed.

2.3.1 Power

Power is the energy produced by an engine during a process per unit of time [12]. It serves as a measure of the engine's capability to generate useful work per unit of time, typically expressed in Horsepower (HP) or kilowatts (kW)[13]. Power reflects how efficiently an engine converts the chemical energy of fuel into mechanical energy. The output power can be calculated based on engine torque and rotational speed using Eq. (1).

$$Ne = \frac{T \times n}{716.2} \tag{1}$$

where Ne is power in kilowatts (kW), T is torque in Newton-meters (Nm), and n is engine speed in revolutions per minute (RPM).

2.3.2 Torque

Torque is a measure of an engine's ability to perform work [14]. It is a crucial parameter in determining vehicle acceleration, particularly at low to mid-engine speeds. Torque (Eq. (2)) is generated from the pressure exerted on the piston during the combustion process and is directly influenced by the efficiency of air–fuel mixing. An increase in intake air turbulence, such as that produced by a turbo cyclone, can enhance the homogeneity of the air–fuel mixture and combustion efficiency, potentially increasing torque output [15].

$$T = \frac{716.2 \times Ne}{n} \tag{2}$$

2.3.3 SFC

SFC is a parameter that indicates the fuel flow rate per unit of output power. SFC is standardized as it is independent of engine size, making it a reliable indicator of an engine's thermal efficiency in utilizing fuel to generate power under specific operating conditions[16]. SFC is expressed in units of grams per kilowatt-hour (g/kWh) and is calculated using Eq. (3) [17].

$$Sfc = \frac{m_f \times 10^3}{Ne} \tag{2}$$

where Sfc is Specific fuel consumption (g/kW.h), m_f is fuel mass flow rate (kg/s), and Ne is engine output power (KW)

2.4 Equipment setup

The description in Fig. 1 is as follows: 1. Experimental vehicle, 2. Turbo cyclone, 3. Intake manifold, 4. Dyno test (engine dynamometer), 5. Blower fan, 6. Dyno test computer monitor, and 7. Gas analyzer. Testing tool specifications (dynamometer and gas analyzer) can be seen in Table 1.

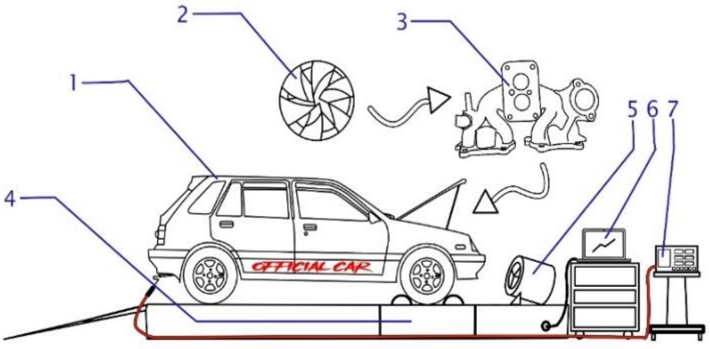


Fig. 1. Equipment setup

Table 1. Testing tool specifications

Instruments	Type	Range	Accuracy
Dynamometer	Dynojet 424x LC2 (Chassis Dyno)	0-2000 HP / 0-320 km/h	±1% FS (power)
Gas analyzer	HESHBON (HG - 520)	CO : 0 - 9.99 % HC : 0 - 9999 ppm CO2 : 0 - 20.0 % O2 : 0 - 25.00 % Lamda : 0 - 2.000	0.01 % res 1 ppm res 0.01 % res 0.01 % res 0.01 % res

3 Results and discussion

3.1 Power data results

Fig. 2 illustrates that engine power increases with rising RPM, reaching its peak at 5000 RPM. The combination of a 45° turbo cyclone blade angle and RON 92 fuel produced the highest power output, indicating optimal combustion efficiency. RON 92 delivers better performance compared to RON 90 due to its higher resistance to knocking and its support for more advanced ignition timing. Conversely, the 60° blade angle resulted in reduced power at higher RPMs, possibly due to excessive turbulence causing premature combustion. These findings are consistent with the study by Adi Jaka

Satrya et al. [7], which demonstrated increased power with a 55° blade angle on a 150 cc engine. Although the optimal angle differs, the effect of increased turbulence on power remains consistent, underscoring the importance of selecting a blade angle that aligns with the engine's characteristics.

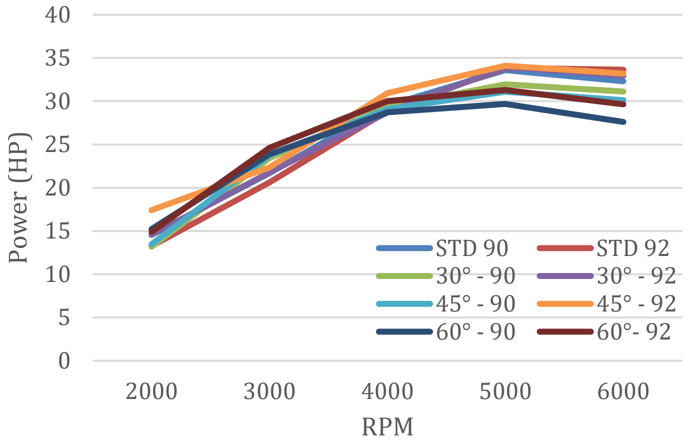
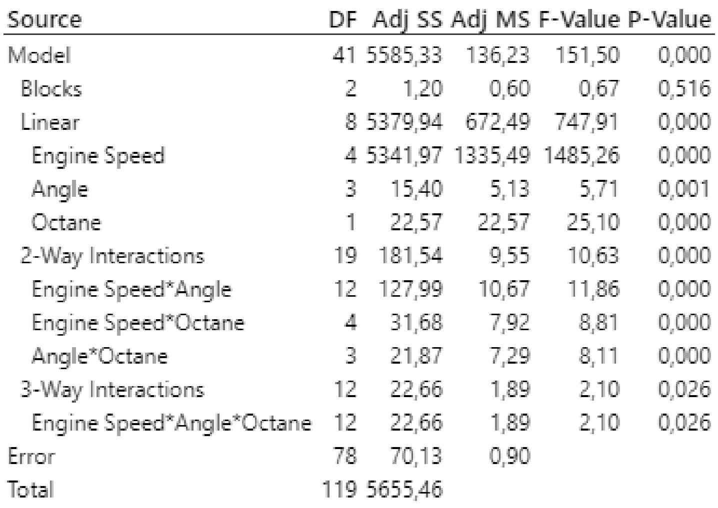


Fig. 2. Power results

The ANOVA analysis results (Fig. 3) indicate that the overall model is significant (P-value = 0.000). Engine speed, blade angle, and fuel octane rating all have a significant effect on the results, with engine speed being the most dominant factor (F-value = 1485.26). The two-way and three-way interactions between variables are also significant, indicating the presence of combined effects that must be taken into account. Meanwhile, the block factor is not significant (P-value = 0.516), suggesting it does not meaningfully affect the results. These findings highlight the importance of considering all variables and their interactions in optimizing engine performance.



Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	41	5585,33	136,23	151,50	0,000
Blocks	2	1,20	0,60	0,67	0,516
Linear	8	5379,94	672,49	747,91	0,000
Engine Speed	4	5341,97	1335,49	1485,26	0,000
Angle	3	15,40	5,13	5,71	0,001
Octane	1	22,57	22,57	25,10	0,000
2-Way Interactions	19	181,54	9,55	10,63	0,000
Engine Speed*Angle	12	127,99	10,67	11,86	0,000
Engine Speed*Octane	4	31,68	7,92	8,81	0,000
Angle*Octane	3	21,87	7,29	8,11	0,000
3-Way Interactions	12	22,66	1,89	2,10	0,026
Engine Speed*Angle*Octane	12	22,66	1,89	2,10	0,026
Error	78	70,13	0,90		
Total	119	5655,46			

Fig. 3. ANOVA test results on power

Fig. 4 shows the optimization results of engine power based on the DOE analysis. The maximum power of 34.1067 was achieved at the parameter combination of 5000 RPM, a 45° blade angle, and RON 92 fuel, with a desirability value of 0.9441, indicating a high degree of proximity to the optimal condition.

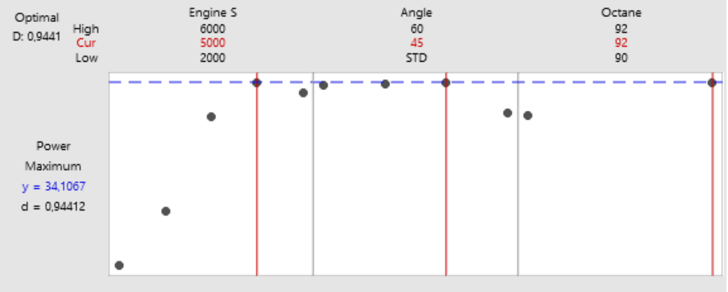


Fig. 4. Power statistics results

The graph shows that 5000 RPM produces the highest power compared to other RPM levels, while the 45° blade angle proves to be more efficient than both the standard and 60° angles. RON 92 fuel demonstrates the best performance, supporting more efficient combustion. Therefore, this parameter combination represents the most optimal configuration for maximizing engine power output based on the test results.

3.2 Torque data results

Fig. 5 shows the torque test results for various blade angle configurations and fuel types across different engine speeds. The maximum torque of 57.4 Nm was achieved at 3000 RPM with a 60° blade angle configuration and RON 92 fuel. In general, the highest torque occurred in the mid-RPM range (3000–4000 RPM) and then declined at higher RPMs, indicating that the engine's optimal efficiency lies within the mid-speed range. The use of RON 92 fuel consistently produced higher torque compared to RON 90, due to its greater resistance to knocking, allowing for more complete combustion. However, some irregularities were observed in certain configurations. One such instance was the 30° blade angle configuration with RON 92, which showed a significantly low torque value at 2000 RPM. This result deviates from the general trend, likely because the 30° blade angle produces suboptimal air turbulence at low engine speeds. As a result, the air–fuel mixture becomes less homogeneous, leading to incomplete combustion and reduced torque output. Overall, the combination of a 60° blade angle and RON 92 fuel provided the best torque performance in this test.

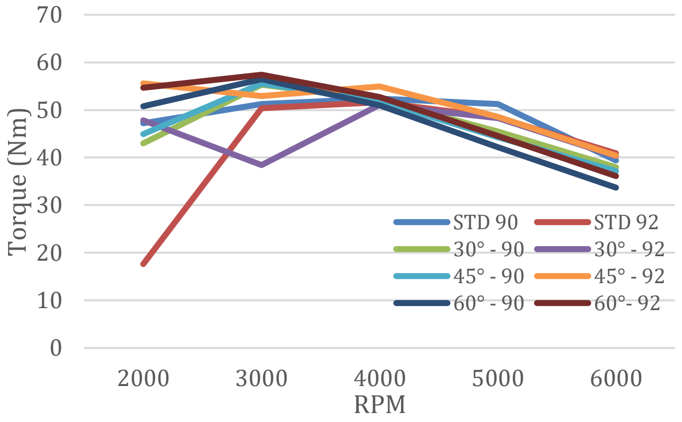
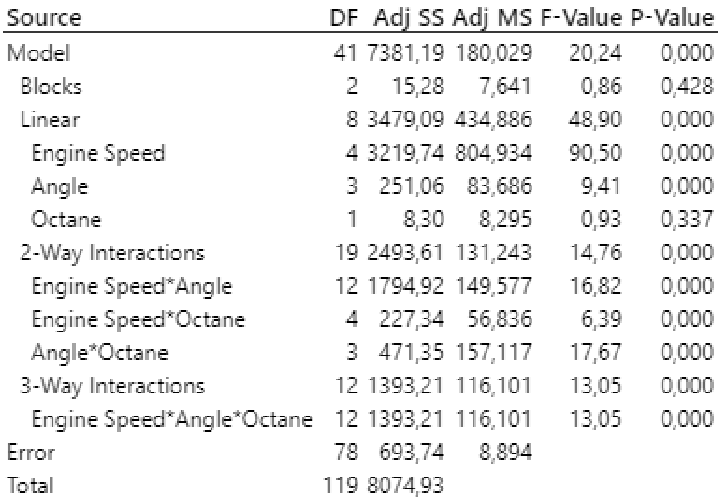


Fig. 5. Torque result

The ANOVA results (Fig. 6) indicate that the statistical model is significant overall (P-value = 0.000). The most influential factor is engine speed, with the highest F-value (90.50). Blade angle is also statistically significant, while octane rating shows no significant effect (P-value = 0.337). Two-way and three-way interactions between factors are significant, particularly the combinations of (Engine Speed, Angle) and (Angle, Octane), indicating that variable combinations also influence the outcomes. The blocks factor is not significant, meaning there is no substantial effect between experimental blocks.



Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	41	7381,19	180,029	20,24	0,000
Blocks	2	15,28	7,641	0,86	0,428
Linear	8	3479,09	434,886	48,90	0,000
Engine Speed	4	3219,74	804,934	90,50	0,000
Angle	3	251,06	83,686	9,41	0,000
Octane	1	8,30	8,295	0,93	0,337
2-Way Interactions	19	2493,61	131,243	14,76	0,000
Engine Speed*Angle	12	1794,92	149,577	16,82	0,000
Engine Speed*Octane	4	227,34	56,836	6,39	0,000
Angle*Octane	3	471,35	157,117	17,67	0,000
3-Way Interactions	12	1393,21	116,101	13,05	0,000
Engine Speed*Angle*Octane	12	1393,21	116,101	13,05	0,000
Error	78	693,74	8,894		
Total	119	8074,93			

Fig. 6. ANOVA test results on torque

Fig. 7 presents the results of the DOE analysis for torque optimization based on the variables of RPM, blade angle, and fuel octane rating (RON). The maximum torque of 57.40 Nm was achieved at 3000 RPM, with a blade angle of 60° and RON 92 fuel, resulting in a desirability value of 0.93342. The 3000 RPM setting produced the highest torque compared to both lower and higher RPMs. The 60° blade angle delivered slightly better performance than the standard angle, while variations in RON did not show a significant effect on torque output. It can be concluded that the optimal combination for achieving maximum torque is 3000 RPM, a 60° blade angle, and RON 92 fuel.

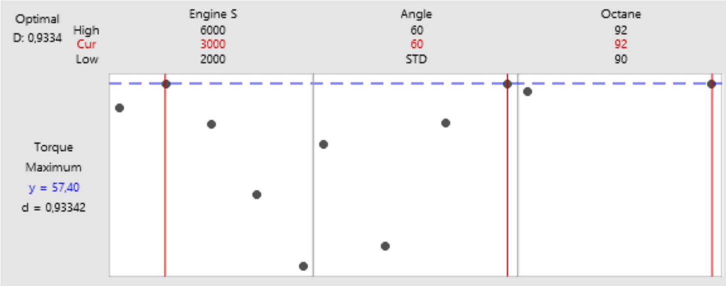


Fig. 7. Torque statistics results

3.3 CO exhaust gas emission data results (%)

Fig. 8 shows the CO exhaust emission results across various blade angle configurations and fuel types at different engine RPMs. The highest CO emission occurred at 2000 RPM with a 45° blade angle and RON 90 fuel, reaching approximately 8.5%, due to suboptimal air–fuel mixing resulting in incomplete combustion. In contrast, the 60°–RON 92 configuration produced the lowest CO emissions, around 1.5–2%, indicating more efficient combustion enabled by improved air turbulence and RON 92's resistance to knocking. As RPM increased from 3000 to 5000, CO emissions decreased across all configurations, attributed to enhanced combustion efficiency. At higher RPMs, differences among configurations became less pronounced. The extremely high emission value for the 45°–RON 90 configuration at 2000 RPM can be considered an outlier, likely caused by an overly rich fuel mixture and inadequate airflow. Overall, the combination of a 60° blade angle and RON 92 fuel proved to be the most effective in reducing CO emissions and enhancing engine combustion efficiency.

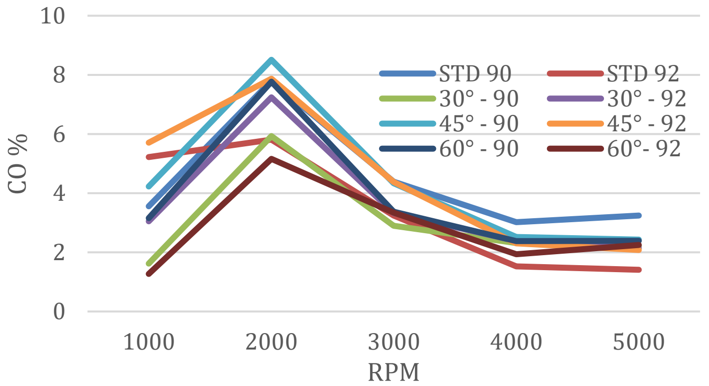
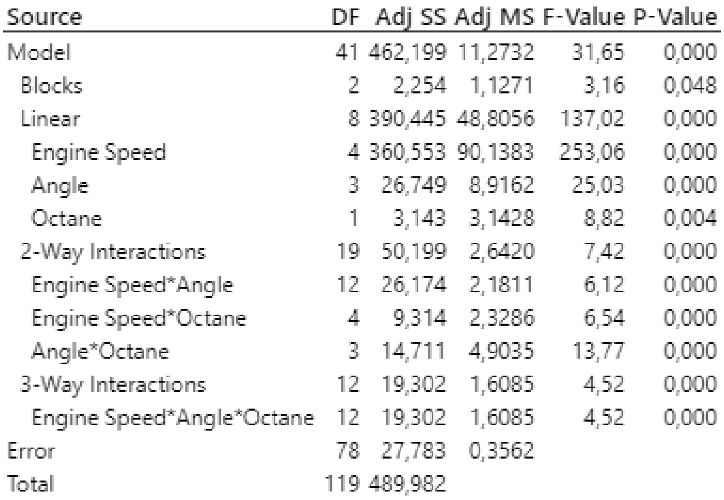


Fig. 8. Exhaust gas emission results (CO)

The ANOVA results shown in Fig. 9 indicate that the statistical model is significant overall, with a P-value = 0.000, suggesting that the tested variables collectively influence the response. The most influential main factor is Engine Speed, with an F-value of 253.06 (P-value = 0.000), followed by Angle and Octane, which are also statistically significant. Two-way interactions, such as (Engine Speed, Angle) and (Angle, Octane), as well as the three-way interaction (Engine Speed, Angle, Octane), also show significance, indicating that the effects among variables are complex and interdependent. The Blocks factor is also significant (P-value = 0.048), although its contribution is relatively minor compared to the other factors. The low Error value indicates that the variation in the data is well explained by the model.



Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	41	462,199	11,2732	31,65	0,000
Blocks	2	2,254	1,1271	3,16	0,048
Linear	8	390,445	48,8056	137,02	0,000
Engine Speed	4	360,553	90,1383	253,06	0,000
Angle	3	26,749	8,9162	25,03	0,000
Octane	1	3,143	3,1428	8,82	0,004
2-Way Interactions	19	50,199	2,6420	7,42	0,000
Engine Speed*Angle	12	26,174	2,1811	6,12	0,000
Engine Speed*Octane	4	9,314	2,3286	6,54	0,000
Angle*Octane	3	14,711	4,9035	13,77	0,000
3-Way Interactions	12	19,302	1,6085	4,52	0,000
Engine Speed*Angle*Octane	12	19,302	1,6085	4,52	0,000
Error	78	27,783	0,3562		
Total	119	489,982			

Fig. 9. ANOVA test results on exhaust gas emission (CO)

Fig. 10 presents the DOE analysis results for optimizing CO emissions based on the variables RPM, blade angle, and RON value. The lowest CO emission, measured at 1.2667%, was achieved with the combination of 1000 RPM, a 60° blade angle, and RON 92 fuel, yielding a desirability score of 0.97968. Low engine speed proved to be the most effective in reducing emissions, while the 60° blade angle generated more efficient airflow, thereby enhancing combustion quality. The use of RON 92 fuel also resulted in cleaner emissions compared to RON 90. Therefore, the combination of 1000 RPM, 60° blade angle, and RON 92 is the optimal condition for significantly minimizing CO emissions.

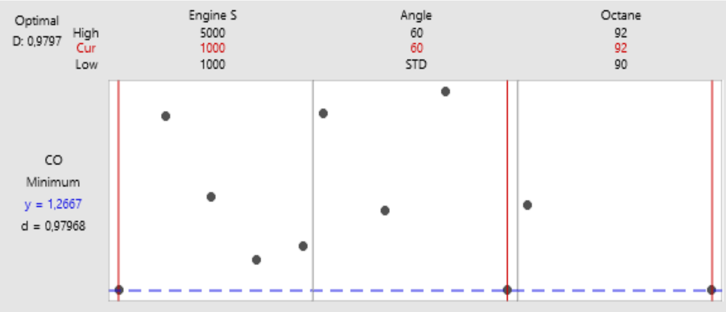


Fig. 10. CO emission statistics results

3.4 HC exhaust gas emission data results (ppm)

Fig. 11 illustrates the reduction of HC exhaust emissions with increasing engine speed (RPM). The highest emission was recorded at 2000 RPM with a 60° blade angle and RON 92 fuel, exceeding 800 ppm, likely due to incomplete combustion caused by excessively advanced ignition timing.

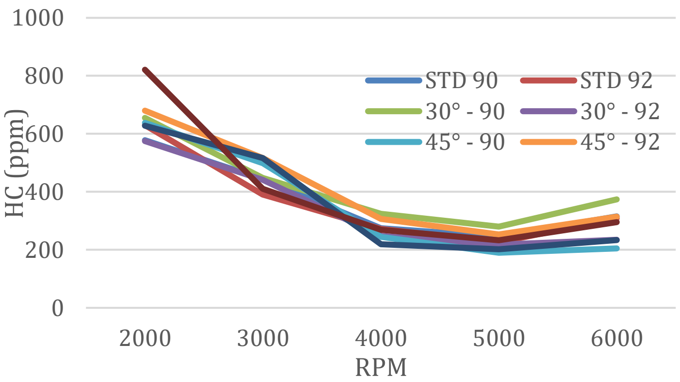
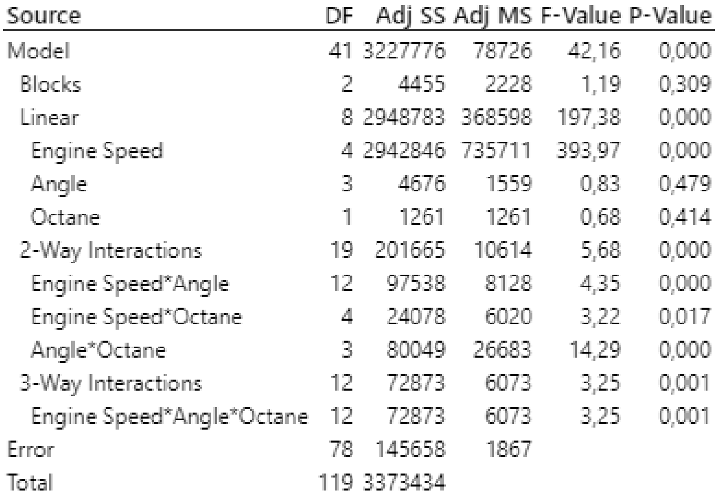


Fig. 11. Exhaust gas emission results (HC)

As RPM increased to 4000, all configurations showed a significant decrease in HC emissions, reflecting more efficient combustion due to a more homogeneous air–fuel mixture and faster combustion rates. The lowest emissions occurred at 5000 RPM, particularly with the 60° blade angle using both RON 90 and RON 92 fuels, falling below 200 ppm. However, at 6000 RPM, some configurations showed a slight increase in emissions, possibly due to insufficient combustion time at high engine speeds. Overall, the highest HC emissions occurred at low RPM with wide blade angles and high-octane fuel, while the most efficient combustion was achieved at 4000–5000 RPM. This highlights the importance of optimizing blade angle, fuel octane rating, and ignition timing to minimize HC emissions.

The ANOVA results in Fig. 12 indicate that the overall model is significant (P-value = 0.000), meaning that the analyzed variables affect the response. The most significant factor is Engine Speed, with a very high F-value (393.97) and a P-value of 0.000, indicating a dominant influence on the response. In contrast, the variables Angle and Octane are not statistically significant, with P-values of 0.479 and 0.414, respectively, suggesting that they do not individually contribute meaningfully to the response. However, two-way interactions such as (Engine Speed, Angle) P-value = 0.000 and (Angle, Octane) P-value = 0.000 show significant interactive effects. Similarly, the three-way interaction (Engine Speed, Angle, Octane) is also significant (P-value = 0.001), indicating that the combination of all three variables has a substantial impact on the outcome. The relatively low error value suggests that the model explains the data variation well.



Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	41	3227776	78726	42,16	0,000
Blocks	2	4455	2228	1,19	0,309
Linear	8	2948783	368598	197,38	0,000
Engine Speed	4	2942846	735711	393,97	0,000
Angle	3	4676	1559	0,83	0,479
Octane	1	1261	1261	0,68	0,414
2-Way Interactions	19	201665	10614	5,68	0,000
Engine Speed*Angle	12	97538	8128	4,35	0,000
Engine Speed*Octane	4	24078	6020	3,22	0,017
Angle*Octane	3	80049	26683	14,29	0,000
3-Way Interactions	12	72873	6073	3,25	0,001
Engine Speed*Angle*Octane	12	72873	6073	3,25	0,001
Error	78	145658	1867		
Total	119	3373434			

Fig. 12. ANOVA test results on exhaust gas emission (HC)

Fig. 13 presents the results of the DOE analysis for optimizing HC emissions based on the variables of RPM, blade angle, and fuel RON value. The lowest HC emission, measured at 189.67 ppm, was achieved with the combination of 1000 RPM, a blade angle of 45°, and RON 90 fuel, yielding a desirability score of 0.92270. Low RPM proved effective in reducing emissions by enabling more complete combustion. The 45° blade angle produced a more optimal airflow and fuel mixture compared to the standard or 60° angle. Additionally, RON 90 demonstrated the best performance in minimizing HC emissions under the test conditions. Therefore, the combination of 1000 RPM, a 45° blade angle, and RON 90 fuel represents the optimal configuration for minimizing hydrocarbon emissions.

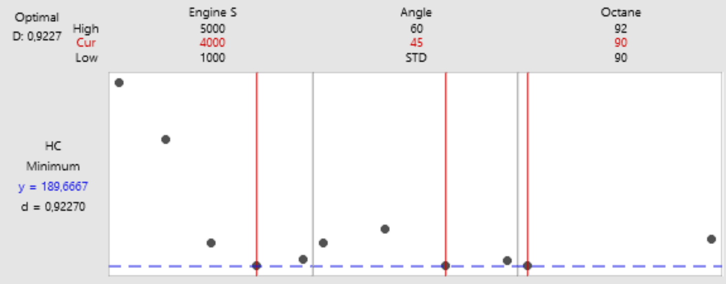


Fig. 13. HC emission statistics results

3.5 CO₂ exhaust gas emission data results (%)

Fig. 14 illustrates the trend of CO_2 exhaust emissions across various blade angle configurations and fuel types (RON 90 and RON 92). At 2000 RPM, CO_2 emissions ranged between 9–11%, with the highest value observed in the standard configuration using RON 92. At 3000 RPM, CO_2 emissions decreased across all configurations, indicating reduced combustion efficiency due to suboptimal air–fuel mixture. As RPM increased from 4000 to 6000, CO_2 emissions rose significantly, peaking at approximately 13.5% in both the standard and 60° configurations using RON 92. This increase reflects more complete combustion, as CO_2 is the primary byproduct of ideal hydrocarbon fuel combustion. It can be concluded that the highest CO_2 emissions occur at high engine speeds (5000–6000 RPM), indicating optimal combustion efficiency. Meanwhile, the drop in emissions at 3000 RPM suggests an imbalance in the air–fuel mixture. Blade angle variations and RON values influence emission patterns, but the main trend shows that increasing RPM promotes more efficient combustion.

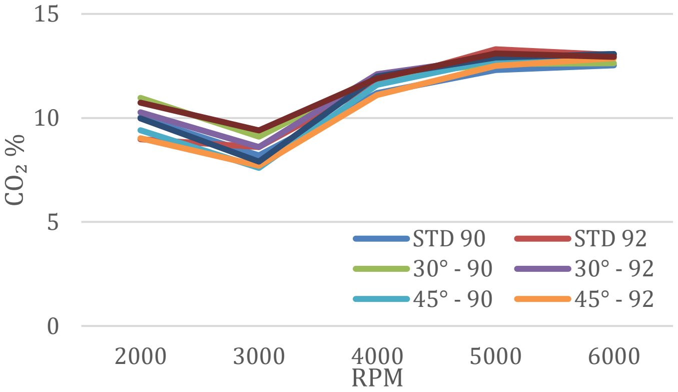
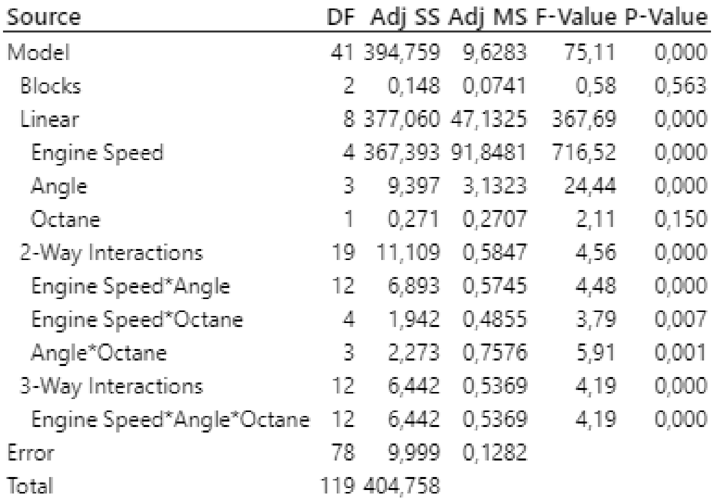


Fig. 14. Exhaust gas emission results (CO_2)

The ANOVA results presented in Fig. 15 indicate that the overall model is statistically significant (P-value = 0.000), meaning that the tested variables contribute meaningfully to the response variable. Individually, Engine Speed has the most dominant and significant effect (P-value = 0.000) on engine performance. The Angle variable also shows a significant influence (P-value = 0.000), whereas the Octane variable does not exhibit a statistically significant effect (P-value = 0.150). All two-way interactions (Engine Speed, Angle), (Engine Speed, Octane), and (Angle, Octane) are significant, with P-values less than 0.05, indicating that combinations of variables significantly affect the results. The three-way interaction (Engine Speed, Angle, Octane) is also significant (P-value = 0.000), suggesting a combined influence of all three factors on the response. With a low error value (9.999), the model is considered highly reliable in representing the effects of the experimental factors on the response.



Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	41	394,759	9,6283	75,11	0,000
Blocks	2	0,148	0,0741	0,58	0,563
Linear	8	377,060	47,1325	367,69	0,000
Engine Speed	4	367,393	91,8481	716,52	0,000
Angle	3	9,397	3,1323	24,44	0,000
Octane	1	0,271	0,2707	2,11	0,150
2-Way Interactions	19	11,109	0,5847	4,56	0,000
Engine Speed*Angle	12	6,893	0,5745	4,48	0,000
Engine Speed*Octane	4	1,942	0,4855	3,79	0,007
Angle*Octane	3	2,273	0,7576	5,91	0,001
3-Way Interactions	12	6,442	0,5369	4,19	0,000
Engine Speed*Angle*Octane	12	6,442	0,5369	4,19	0,000
Error	78	9,999	0,1282		
Total	119	404,758			

Fig. 15. ANOVA test results on exhaust gas emission (CO_2)

Fig. 16 presents the results of the DOE analysis for optimizing CO emissions based on the variables of RPM, blade angle, and fuel RON value. The lowest CO emission, recorded at 7.57%, was achieved with the combination of 1000 RPM, a 45° blade angle, and RON 90 fuel, yielding a desirability score of 0.97222. Low RPM allows for a longer oxidation time of CO into CO_2, thereby enhancing combustion efficiency. The 45° blade angle produces a more optimal airflow compared to other configurations, supporting more complete combustion. Additionally, RON 90 demonstrated the best performance in reducing CO emissions under the test conditions. It can be concluded that the combination of 1000 RPM, a 45° blade angle, and RON 90 fuel represents the optimal condition for minimizing CO emissions.

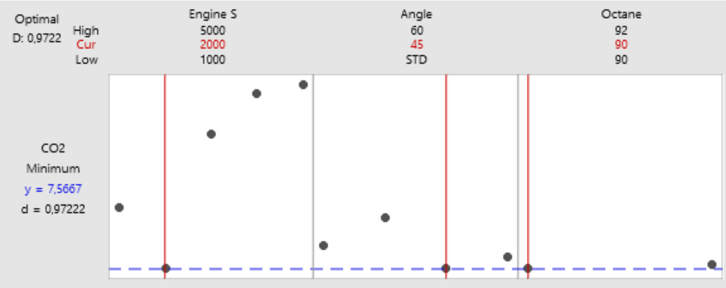


Fig. 16. CO_2 emission statistics results

3.6 SFC fuel consumption data results

Fig. 17 shows that the standard configuration using RON 90 fuel produced the highest SFC, approximately 195 g/kWh at 2000 RPM, indicating the lowest combustion efficiency. In contrast, the configuration with a 60° blade angle and RON 90 recorded the lowest SFC, around 90–100 g/kWh, reflecting more efficient combustion. Optimal efficiency was generally achieved at 3500 RPM, particularly in configurations with 45° and 60° blade angles using both RON 90 and RON 92 fuels. At 5000 RPM, SFC values increased again in most configurations, except those using larger blade angles and higher-octane fuels. These findings align with the study by Onky Pieter Tegar [8], which reported a 17.66% reduction in SFC after the implementation of a turbo cyclone, indicating that increased airflow turbulence consistently improves engine combustion efficiency.

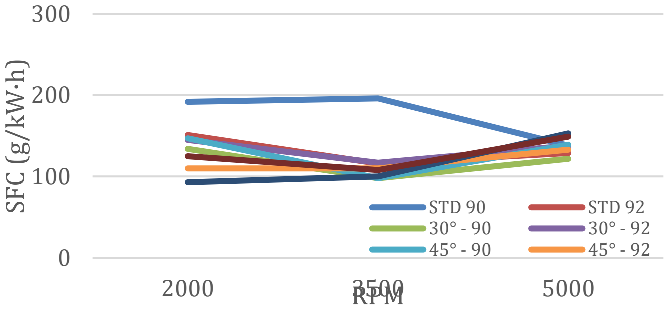
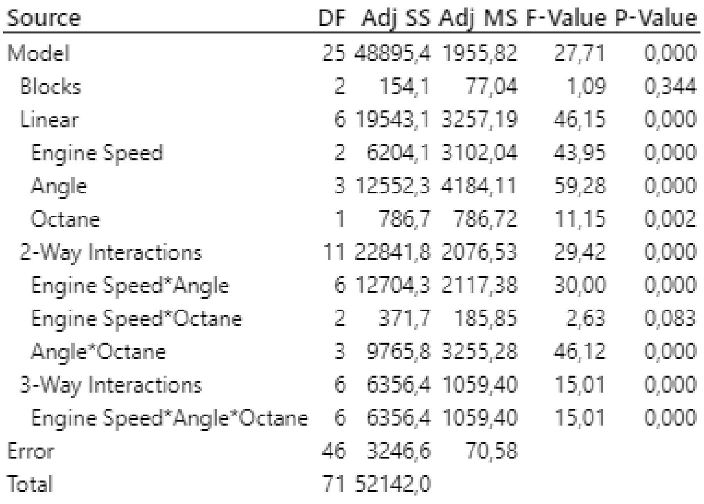


Fig. 17. SFC results

Based on the ANOVA results (Fig. 18), the overall model is significant (P-value = 0.000), indicating that the tested variables have a statistically significant effect on the response. The factors Engine Speed, Angle, and Octane each show significant individual effects on the output, with Angle being the most dominant factor (F = 59.28).



Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	25	48895,4	1955,82	27,71	0,000
Blocks	2	154,1	77,04	1,09	0,344
Linear	6	19543,1	3257,19	46,15	0,000
Engine Speed	2	6204,1	3102,04	43,95	0,000
Angle	3	12552,3	4184,11	59,28	0,000
Octane	1	786,7	786,72	11,15	0,002
2-Way Interactions	11	22841,8	2076,53	29,42	0,000
Engine Speed*Angle	6	12704,3	2117,38	30,00	0,000
Engine Speed*Octane	2	371,7	185,85	2,63	0,083
Angle*Octane	3	9765,8	3255,28	46,12	0,000
3-Way Interactions	6	6356,4	1059,40	15,01	0,000
Engine Speed*Angle*Octane	6	6356,4	1059,40	15,01	0,000
Error	46	3246,6	70,58		
Total	71	52142,0			

Fig. 18. ANOVA test results on SFC

The two-way interactions between Engine Speed*Angle and Angle*Octane are also significant, whereas the interaction between Engine SpeedOctane is not significant (P = 0.083), suggesting that the combination of engine speed and octane rating does not substantially contribute to changes in the response. The three-way interaction of (Engine Speed, Angle, Octane) is significant (P = 0.000), indicating that the combined influence of all three factors has a relevant impact on the experimental results. The relatively low error value suggests that the model provides good predictive accuracy.

Fig. 19 presents the optimization results of SFC using the DOE method with three variables: RPM, blade angle, and fuel RON value. The black dots represent experimental results, while the blue dashed line indicates the target minimum SFC of 93.33. A desirability value of 0.97953 indicates that the obtained configuration is very close to the optimal condition. The best result was achieved at a combination of 5000 RPM, a 60° blade angle, and RON 90 fuel. High RPM provides maximum combustion efficiency, the 60° blade angle supports optimal airflow, and RON 90 proves to be sufficiently efficient without requiring higher octane fuel. Thus, this combination represents the most efficient configuration for minimizing fuel consumption.

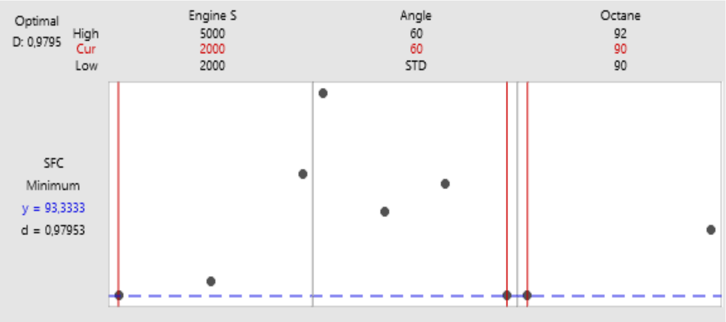


Fig. 19. SFC statistics results

3.7 Summary of test results

Engine performance testing is conducted using a variety of operational parameters to analyze their impact on engine output characteristics. The three main variables tested are engine speed, ignition angle, and fuel octane rating. The summary of the test results for all measured variables and parameters is presented in Table 2.

Table 2. Summary of test results

Variabel	Power (HP)	Torque (Nm)	Exhaust gas emission (%)			SFC (g/kWh)
			HC	CO	CO_2	
Engine speed	5000	3000	1000	4000	2000	2000
Angle	45	60	60	45	45	60
Octane	92	92	92	90	90	90

4 Conclusions

The results of this experiment confirm that the addition of a turbo cyclone to the intake manifold positively influences the performance of a 1000 cc engine. Increased airflow turbulence enhanced combustion efficiency, resulting in a maximum power of 34.1 HP at 6000 RPM, peak torque of 57.4 Nm at 3000 RPM, and improved fuel efficiency with the lowest specific fuel consumption (SFC) of 93.33 g/kWh. Exhaust emissions (especially CO and HC) were significantly reduced, indicating more complete combustion. Different vane angles produced varying effects. Firstly, the 60° vane angle gave the most balanced results, with the best fuel efficiency, torque, and CO emission reduction. Secondly, the 45° vane angle was most effective in reducing HC emissions. Thirdly, the 30° vane angle showed good performance at mid-range RPMs but lacked stability at higher RPMs.

The combination of a 60° vane angle with RON 92 fuel provided the best overall performance, while RON 90 achieved the highest fuel efficiency under certain configurations. However, the experiments were limited to controlled conditions, and the long-term durability of the cyclone components was not evaluated. Therefore, future research should examine operating conditions, loads, and component lifespan to support the broader application of this technology.

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