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THE VOLUMETRIC EFFICIENCY OF A SINGLE-CYLINDER SPARK-IGNITION ENGINE AS AFFECTED BY AIR INTAKE TEMPERATURE AND HUMIDITY

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ABSTRACT

Nowadays, there are an increasing demand for energy efficiency and emission reduction by the internal combustion engine. It can be achieved by improving the volumetric efficiency of spark ignition engine. The air intake temperature and humidity give an impact to the volumetric efficiency. Thus, the goal of this study is to investigate the impacts of air intake temperature and humidity on the volumetric efficiency of a single cylinder spark ignition engine. This study was facilitated using Altair HyperStudy. It was executed by full factorial design of experiments (DOE). The effects of engine speed, air intake temperature, and humidity towards the volumetric efficiency was assessed based on one-dimensional engine simulation. The ANOVA analysis showed a positive correlation between engine speed and volumetric efficiency. There is a negative effect found for the air intake temperature. However, a negligible impact of humidity obtained in this study. The optimal configuration for achieving a maximum volumetric efficiency of 0.97 was identified at 4500 RPM, 26 degrees Celsius, and 68.0% humidity. It is suggested by the results that while engine speed has a significant impact on volumetric efficiency, temperature and humidity also play important roles in optimizing engine performance. These insights are valuable for designing and operating more efficient and environmentally friendly engines.

Keywords: *Volumetric Efficiency, Air Intake Temperature, Humidity, Spark Ignition Engine*

1.0 INTRODUCTION

The increasing requirement for energy efficiency and emission reduction to be achieved by internal combustion engine has triggered extensive facet to optimize engine performance. Among these strategies, the control of air intake temperature and humidity was found to be a vital factor because it impacts the volumetric efficiency of spark ignition engine. The volumetric efficiency of an internal combustion engine represents its capability to effectively draw air-fuel mixture into the combustion chamber. Volumetric efficiency directly affects engine power output and fuel consumption [1]–[5]. Volumetric efficiency is a property of an engine that measures the engine's ability to fill its cylinder with air and fuel mixture during the intake stroke. Volumetric efficiency is another key factor of internal combustion engine because it depends on the engine performance and air to fuel efficiency. It is defined as the air amount an engine takes in relative to the maximum amount it could draw in, in an ideal situation. There are several factors that influence the volumetric efficiency, and air intake temperature and humidity are only some of the examples. The analyses how these factors influence volumetric efficiency could bring the efforts to design better combustion engines and improve engine performance.

Typically, higher intake temperatures lead to reduced air density, which translates into less air entering the cylinder and, subsequently, lower volumetric efficiency. B. Chen et al. [6] studied the thermal balance of turbocharged gasoline direct injection engines with intake air humidification and stated that high intake air temperatures adversely affect volumetric efficiency due to the lower air density. The findings by S. Jo et al. [7] also indicated that intake-air temperatures impact the emission characteristics of engines, affecting the volumetric efficiency as well. Specifically, the researchers found that high temperatures had a negative effect on the engines' operation, with volumetric efficiency reduced by the increased intake air temperature. According to H. Park et al. [8], similar effects of temperature on the mentioned parameter can be observed for the stoichiometric and lean combustion modes in boosted spark-ignition engines using syngas as fuel, finding that higher intake temperatures lead to lower volumetric efficiency due to the reduced mass of air entering the engine. This trend is also elucidated by several other studies, a higher temperature imposed also reduces volumetric efficiency further [1], [9]–[12].

Another factor that notably affects the volumetric efficiency is the humidity of the air intake due to its effect on air density and combustion characteristics. According to J.R. Serrano et al. [13], who researched the impact of natural and forced charge air humidity on compression-ignition engines, increased humidity improves volumetric efficiency through better charge cooling and air density. As a result, better volumetric efficiency contributes to better engine operation and lower emissions. At the same time, the study conducted by Golzari et al. [14] on the effect of water injection, which increases humidity, in the boosted downsized gasoline direct injection engines also had a similar result, indicating that the addition of water to the intake air positively affected volumetric efficiency through cooler and denser intake air charge. Thus, water injection affecting volumetric efficiency through air charge density is an effective means of raising the performance of the engine. D. Soysal et al. [15]. have also concluded that water addition improved the volumetric efficiency, because of the higher air density and the lower intake air temperature. Moreover, M. Hsueh et al. [16] studied water vapor addition to the spark-ignition engines and found that the increase of air humidity improved the volumetric efficiency because of the cooling effect of water vapor. This agreement was supported by J. Khatri et al. [17], who found that the increase of the relative humidity improves the volumetric efficiency, thus, affecting the use of water injection. Thereby, the common conclusion found in the reviewed literature is that the water addition and increase in the air intake humidity improve the volumetric efficiency of the engines because of the air-cooling effect, increase of its density, and reduction in the air temperature.

However, most of these studies have focused on the individual effects of air intake temperature and humidity, with little attention given to their combined effects. The combined effects of air intake temperature and humidity on volumetric efficiency are complex, as they interact to influence air density and combustion characteristics. J. Wan et al. [18] studied water injection applications for spark ignition engines and devised a technique to obtain a better volumetric efficiency by cooling the intake air charge and humidifying it. Such a technique requires proper control of the spark plug parameters and the humidity levels. Similarly, Y. Li et al. [19] also established the effect of the control parameters as in respect of spark plug applications and humidity on the volumetric efficiency under different intake temperature ranges. It was also reported by M. Araki et al. [20] that both air temperature and air humidity could greatly affect the volumetric efficiency of wall-wet port-fuel-injected engines. It can also be seen from the work by D.D. Rocha et al. [21] that varying water the injection control parameters, which adjust the intake air temperature and humidity. Furthermore, J. Zareei et al. [22] also showed that varying the ignition timing and excess air ratio in direct injection hydrogen-CNG engines could optimize variations in humidity and temperature. These results show that both intake air moisture and temperature must be considered in organic rankine cycle systems operating under varying conditions; in other words, varying these two factors impacts the volume efficiency more than other methods. Thus, it is clear that the literature shows that varying air intake humidity and temperature has been shown to lead to significant improvements in volumetric efficiency.

Even though extensive research has been conducted on the effects of air intake temperature and humidity on volumetric efficiency that has already taken place further investigation is needed to identify the correlation effect of both parameters toward volumetric efficiency. On top of that, finding related studies that would discuss the effects on a single cylinder spark ignition engine is rather difficult and therefore limited. In light of such considerations, the primary goal of the present study is investigating the impacts of air intake temperature and humidity on the volumetric efficiency of a single cylinder spark ignition engine. The results of the study will help make an input to the process of optimizing the functioning of engines and designing more efficient and environmentally friendly engines.

2.0 METHODOLOGY

2.1 Simulation Model

This study was carried out based on one-dimensional engine simulation as shown as Figure 1. The study was conducted to analyze the fluid dynamics and thermal characteristics within the intake piping and various components of an engine system. The flow model encompassed the concurrent resolution of the continuity, momentum, and energy equations in a one-dimensional framework, implying that all variables were averaged along the flow direction. Volumetric efficiency (VE) was assessed to evaluate the effectiveness of the engine's breathing capability, which is contingent upon the volume of the intake charge passing through the intake system [23]. It was calculated by dividing the actual mass of air ingested by the engine by the theoretical air mass intake based on displacement volume, as demonstrated in Equations 1 and Equation 2 [24].

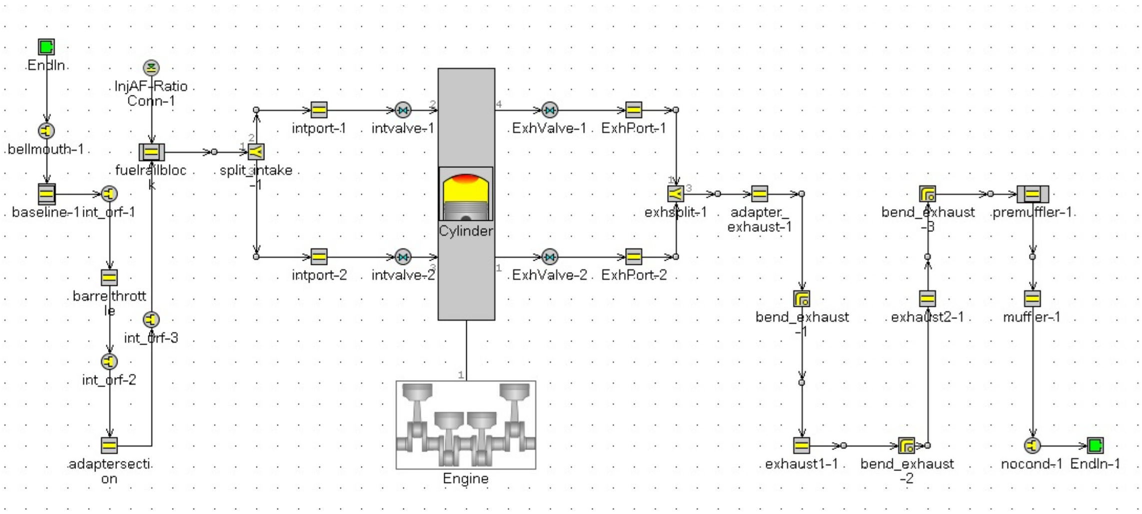


Figure 1: One-dimensional Engine Simulation Setup

$$VE = \frac{\dot{m}_{air,actual}}{\dot{m}_{air,ideal}} \quad (1)$$

$$\dot{m}_{air,ideal} = \frac{P_{atm} \times V_{disp}}{RT_{air}} \left[\frac{RPM}{2}\right] \quad (2)$$

The engine specifications utilized in this study are detailed in Table 1. Before conducting the analysis, the baseline engine configuration was validated against the findings of V. Mariucci et al. [25]. The model calibration process included iterative adjustments of parameters such as in-cylinder temperature and ignition timing, aiming to achieve a robust correlation with experimental data. The calibration results for volumetric efficiency are shown in Table 2.

Table 1: Specifications of the single-cylinder engine [25]

No	Name	Specification
1	Engine Bore	89 cm
2	Engine Stroke	79.5 cm
3	Connecting Rod Length	13.81 cm
4	Engine Compression Ratio	10.5:1
5	Engine Clearance Volume	47.10 cm3
6	Intake Valve Lift	0.914 cm
7	Exhaust Valve Lift	0.937 cm
8	Intake Valve Timing Open	308.0 CAD
9	Intake Valve Timing Duration	286.0 CAD
10	Exhaust Valve Timing Open	86.5 CAD
11	Exhaust Valve Timing Duration	326.0 CAD

Table 2: The calibration of volumetric efficiency for the baseline engine

Engine Speed (RPM)	V. Mariucci [25]	Simulation	Error (%)
1000	87	87	0.00
2000	91	90	1.09
2500	100	95	5.00
3000	105	103	1.90
3500	100	102	2.00
4000	98	97	1.02
4500	95	93	2.11
5000	90	88	2.22
5500	80	78	2.50

2.2 Design Exploration

The design exploration for this study was facilitated using Altair HyperStudy. The process was executed through the establishment of the setup model, design of experiments (DOE), approximation, and optimization. Following the establishment of the setup model, the subsequent step involved selecting design factors specific to this particular model. Details of the parameter designs as listed in Table 3. The range for engine speed is between 2500 RPM to 4500 RPM [26]. The air intake temperature is 26 degree Celsius up to 34 degree Celsius. Meanwhile the air humidity was range from 68% until 92%. A comprehensive analysis has been undertaken to examine the effects of all parameters towards the volumetric efficiency of the spark ignition single cylinder engine. Thus, the amount of volumetric efficiency, was solved by the one-dimensional gas dynamics. The full factorial method was executed in the DOE setup. Thus, 75 runs were solved to determine the volumetric efficiency. Following the conclusion of the DOE study, the run matrix of the computed response was tallied. The selected curve fitting method chosen was Least Square Regression (LSR) with squared method. The optimized configuration to obtain the optimum volumetric efficiency was carried out using Global Response Surface Methodology (GRSM).

Table 3: Parameter design for full factorial analysis

Parameter	Unit	Level 1	Level 2	Level 3	Level 4	Level 5
Engine Speed	RPM	2500	3500	4500	-	-
Temperature	Celsius	26	28	30	32	34
Humidity	Percentage	68	74	80	86	92

3.0 RESULTS AND DISCUSSION

3.1 Linear Effect Analysis

The analysis of each parameter design's effect and their interactions on volumetric efficiency is undertaken. Figure 2 demonstrates the linearly positive impact of all the parameter designs on the volumetric efficiency. It indicates that engine speed has a significant positive correlation with volumetric efficiency. As engine speed increases from 2500 RPM to 4500 RPM, the volumetric efficiency rises sharply from about 0.91 to 0.96. This phenomenon occurs because higher engine speed improves the dynamic pressure of the intake air, enhancing the cylinder's ability to fill with the air-fuel mixture. The increased momentum of the incoming air at higher speeds overcomes the restrictions and losses in the intake system, thus increasing the volumetric efficiency. Conversely, the slight negative correlation (-0.013) between temperature and volumetric efficiency was obtained. Higher temperatures cause a minor reduction in volumetric efficiency, dropping from approximately 0.94 to 0.93. The humidity hardly changes volumetric efficiency. However, it remains relatively constant around 0.94, regardless of the humidity level. The stability of volumetric efficiency can be explained by the fact that while increasing the humidity levels more water vapor is made part of the intake air. However, the amount of vapor is not that substantial, to permanently decrease volumetric efficiency. Moreover, being equal to humidity's effect, the reduction of air density due to the raised humidity is negligible compared to the impact of temperature and an engine rotation speed. It is clear that among the three factors considered, engine speed is the greatest influencer of volumetric efficiency.

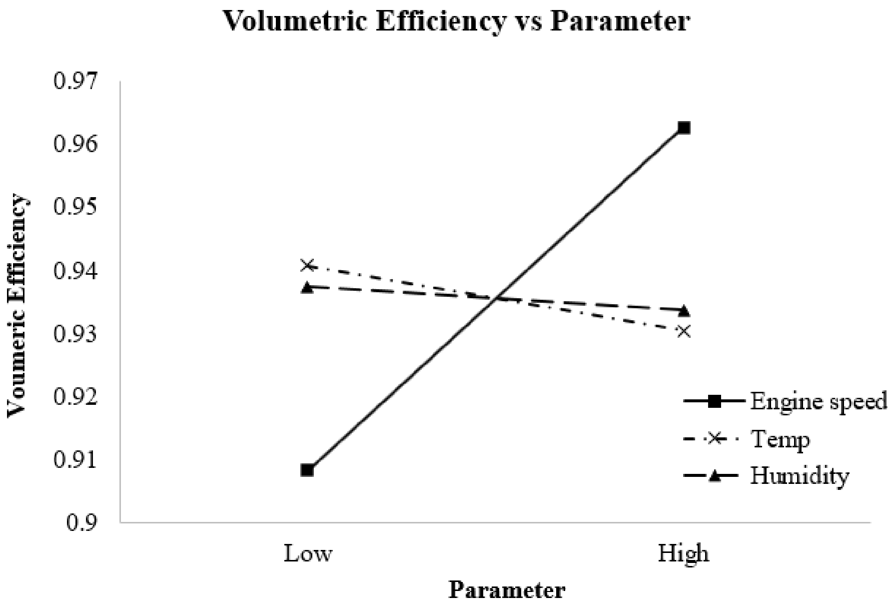


Figure 2: Effect of Volumetric Efficiency Against Parameter Designs

3.2 Analysis of Variance

The Analysis of Variance (ANOVA) was used to study whether Engine Speed, Temperature, and Humidity have an impact on the response measured as shown in Table 4. ANOVA is a technique of statistical analysis designed to determine if there is a statistically significant variation between the means of three or more groups. In this study, there is reliable evidence that Engine Speed and Temperature affect the response. In the case of Engine Speed, the effect is because the p value is 5.60e-44. The value of the test statistics demonstrates that the outcomes differ significantly when different speeds of the engine operation are simulated. Temperature also finds a significant influence, highlighting the importance of ambient temperature conditions in influencing the measured response. On the other hand, the factor of Humidity did not show a significant effect because the p-value 0.142 greater that 0.05 on the outcome variable in this analysis. This means that varying the exposure to an increased or decreased level of humidity in the specified range would change the measured response by some small amount. Despite ANOVA, the regression equation was obtained in this study as shown in Equation 3. This equation describes how well the parameter designs predicts the volumetric efficiency under specific conditions.

Table 4: Volumetric Efficiency Analyzed by ANOVA

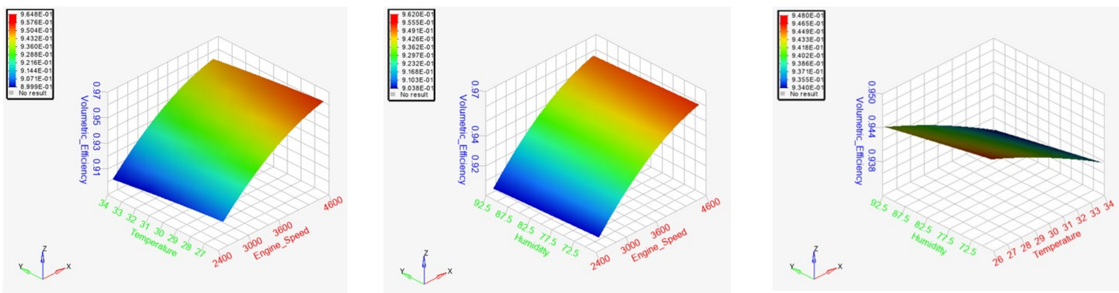
Parameters	Degree of Freedom (DOF)	Sum of Squares	Mean Squares	F-value	p-value
Engine Speed, S	2	0.0383513	0.0191756	602.18221	5.60e-44
Temperature, T	2	0.0010149	5.07e-04	15.936219	2.11e-06
Humiditty, H	2	1.28e-04	6.39e-05	2.0051698	0.1425207
Error	68	0.0021654	3.18e-05		
Total	74	0.0416593			

$$VE = 0.758 + 8.774 \times 10^{-5}S + 8.755 \times 10^{-4}T + 1.194 \times 10^{-4}H - 8.643 \times 10^{-9}S^2 - 3.622 \times 10^{-5}T^2 - 2.152 \times 10^{-7}H^2 \quad (3)$$

where,
VE for Volumetric Efficiency
S for Engine Speed, in RPM
T for Temperature, in the unit of Celsius
H for Humidity, in percentage

3.3 Response Surface Analysis

Figure 3a demonstrates the impact of the engine speed and temperature on the volumetric efficiency of the single-cylinder spark ignition engine, with the assumption that humidity equals 80%. There is a strong positive relationship between the engine speed and the volumetric efficiency. The higher engine speed allows more air to be moved into the cylinder. In return, it helps to fill the cylinders better with the air-fuel mixture. It is due to the increase intake air momentum, overcoming the restrictions within the intake system and decreasing the filling losses. On the contrary, the plot indicates a negative correlation with temperature. This relationship is explained by the fact that, at higher temperatures, the air density decreases, meaning that there are fewer oxygen molecules for the given volume. Therefore, the overall quantity of the air-fuel mixture drawn inside the cylinder is diminished, and the engine's air density is not high enough to fill the cylinder. The associated decrease in volumetric efficiency remains small which is 0.52% reduction. Apart from being important, the difference is also showed that as increasing the engine speed and controlling the temperature of the intake air through intercooling or related techniques will distinctly improve the volumetric efficiency up to 6.66%. As a result, the fuel efficiency of the car will be enhanced, and its engine will perform better, ultimately featuring a higher power.



(a) (b) (c)

Figure 3: Volumetric Efficiency Response Surface Versus (a) Temperature and Engine Speed, (b) Humidity and Engine Speed, and (c) Humidity and Temperature

The relationship of engine speed, humidity and volumetric efficiency of a single-cylinder, spark ignition engine under the constant temperature of 30 degrees Celsius was shown in Figure 3b. The surface plot shows the changes in the volumetric efficiency. Based on this figure, it demonstrated that the engine speed and the humidity have a considerable impact on volumetric efficiency. The general observations suggest that the increase in engine speed results in the increase of volumetric efficiency and this tendency is more significant at higher rate when the efficiency reaches its maximum. On the contrary, lower figures of humidity correspond to lower volumetric efficiency. The rationale behind this is based on the fact that at higher engine speed, the velocity of the intake air also increases, thus improving the cylinder filling and intake air and fuel mixture preparation. Additionally, higher engine speed (4500 rpm) decreases the period during which the transfer of heat to the cylinder walls is possible, decreasing heat loss and maintaining high efficiency. Higher humidity is related to the introduction of more water vapor in the intake air that is aspirated by the engine. As water vapor does not contain oxygen available for combustion, the combustion efficiency of the engine decreases and its performance deteriorates. In addition, although water vapor has a cooling effect in that it is evaporated and the intake is cooled as a result, this process provides a slight cooling effect and is not sufficient to offset the disadvantages of the reduced availability of oxygen. From the figure, it can be deduced that lower humidity levels and higher engine speed perfectly optimize the volume efficiency of an engine. This will be important for engine tuning and the general control of the environment around the engine.

From the Figure 3c, the relationship between humidity, temperature, and volumetric efficiency in a single-cylinder spark ignition engine running at a constant engine speed of 3500 RPM is presented. The analysis in this plot shows that the volumetric efficiency decreases slightly from 0.944 – 0.938 (0.64%) with an increase in humidity. The decrease is due to water vapor, which is present in the higher concentration in the intake air decreasing the amount of oxygen required for combustion. Consequently, the combustion efficiency will decrease. Water vapor affects the intake charge's temperature due to evaporative cooling while a temperature increase reduces oxygen availability through a decline in air density. The influence of reduced oxygen availability greatly surpasses evaporative cooling, rendering water vapor's volume effects irrelevant. Therefore, high relative humidity is the reason for the noticeable efficiency decrease. Volumetric efficiency is less affected by temperature variation within the specified boundaries. However, a high temperature results in less air being taken in by the engine, which reduces combustion oxygen availability. Still, the temperature range of 26 to 34 degrees Celsius suggests that the engine is operating within an optimal temperature range and is not greatly affected by the increase in temperature. It also demonstrated that volumetric efficiency at an engine speed of 3500 RPM is greatly affected by humidity and less by temperature. The reason for humid air being less effective in engine operation is the reduction in oxygen percentage through water vapor, which fills the portion of the air that contains no oxygen, thus reducing the total oxygen availability. The effectiveness of water vapor's cooling property is limited to humidity being able to cool down the air, but the amount of cooling is insignificant to the effect of reducing volumetric efficiency generated by decreased oxygen availability. The temperature increase has relatively less effect 0.64% due to the optimal temperature range.

Once the volumetric efficiency response has been completed, the optimization procedure was executed. It was implemented in this study to search for the optimum configuration between engine speed, temperature and humidity. The optimum configuration is a result of a considerable amount of fine-tuning of parameters required for internal combustion engines to perform at the maximum possible level of volumetric efficiency. The evaluation was carried out based on the regression equation obtained in the analysis. Based on this evaluation setup, the algorithm computation end with the converge analysis. The optimum configuration suggested is 4500 RPM of engine speed, 26 degree Celsius of temperature, and the humidity is 68.0%. The volumetric efficiency on this optimum configuration is 0.97. It is clear that the volumetric efficiency is a result of multiple factors and directly determines the quality of the overall performance. The engine speed is a direct indicator of how much power is being produced. The chosen engine speed is the best for avoiding overloading of an engine. As for the quality, it is determined by the intake air density modulated by the temperature. The current temperature is one of the optimal measures as it ensures the assigned density while not overheating the engine, maintaining its nominal state. The humidity also contributes to the proper mixture of air and fuel that guarantees complete combustion and stable performance. Thus, it is possible to conclude that the presented configuration allows obtaining the highest volumetric efficiency, meaning that cylinders are filled completely and the fuel is burned at near perfect levels.

4.0 CONCLUSION

It is evident after the examination of engine speed, temperature, and humidity impacts on the volumetric efficiency of internal combustion engines that the influence of speed is the most significant at present. The increase of engine speed raises intake air's dynamic pressure, which creates optimal cylinder filling with the air-fuel mixture, thus significantly increasing the usage of cylinder capacity. At the same time, temperature has an insignificant negative correlation. This means that when the temperature increases, air density becomes lower, that leads to a slight decrease from 0.944 to 0.938 in the efficiency of the engine. On the contrary, humidity also shows no correlation, which means that the change in this parameter in the examined range does not impact the volumetric efficiency. It is also important to note the existing opposite effects of temperature and speed as well as those of temperature and humidity on the parameters under consideration. Therefore, it is possible to conclude that while all the factors under examination have an impact on efficiency, the influence of speed is the most sustainable and has the highest rate. The observed interactions between temperature and speed of the engine and temperature and humidity show that these parameters are related in a complex way. Internal combustion engines' highest performance and oxygen efficiency depend on the optimal engine speed and regulation of the intake air temperature. The optimum configuration that was obtained in this study is suggested at 4500 RPM of engine speed, 26 degree Celsius of temperature, and the humidity is 68.0% that obtained the maximum volumetric efficiency of 0.97. Therefore, any further research could examine these interactions to obtain nuanced information to improve the design and operation of engines to increase its sustainability and performance.

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