UNIVERSITI TEKNOLOGI MARA

INVESTIGATION ON THE EFFECT OF AIR INTAKE TEMPERATURE AND HUMIDITY ON VOLUMETRIC EFFICIENCY, BRAKE POWER AND BRAKE TORQUE OF A SINGLE CYLINDER SPARK IGNITION ENGINE

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MSc

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ABSTRACT

The performance of spark-ignition (SI) engines operating in tropical climates is significantly influenced by variations in ambient air conditions, particularly intake air temperature and relative humidity. Elevated intake temperature reduces air density, while high humidity decreases oxygen concentration in the intake charge, directly affecting volumetric efficiency (VE) and overall engine performance. Despite extensive research on combustion optimization, limited studies have quantitatively examined the combined effects of temperature and humidity under realistic tropical intake conditions using validated simulation techniques. This study investigates the influence of intake air temperature and relative humidity on the volumetric efficiency of a 500-cc single-cylinder spark-ignition engine operating on petrol. A one-dimensional engine model was developed using GT-Power and validated against experimental data, showing a maximum deviation of 3.8% between simulated and measured brake torque, confirming model reliability. The intake temperature was varied from 26°C to 34°C and relative humidity from 68% to 92%, across engine speeds ranging from 2500 rpm to 4500 rpm. Design of Experiments (DOE) and Response Surface Methodology (RSM) were employed to evaluate interaction effects and to determine optimal intake conditions. The results demonstrate that increasing intake temperature from 26°C to 34°C reduced volumetric efficiency by approximately 5.42%, primarily due to reduced air density. Increasing relative humidity from 68% to 92% caused an additional VE reduction of approximately 2.16% due to oxygen displacement effects. Under combined hot-humid conditions at 4500 rpm, the maximum volumetric efficiency reduction reached 7.83% compared to baseline conditions. ANOVA results revealed that intake temperature contributed 64.37% of the total variation in volumetric efficiency, indicating it as the dominant influencing parameter, while relative humidity contributed 21.84%. Optimization analysis predicted an optimal intake condition at 26.8°C and 70.5% relative humidity, achieving a maximum volumetric efficiency of 87.62%, with a model prediction accuracy of $R^2 = 0.962$. This study provides quantitative evidence of the compounded degradation of SI engine breathing performance under tropical intake conditions and establishes a foundation for climate-adaptive engine calibration strategies to improve performance consistency in hot and humid environments.

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LIST OF ABBREVIATIONS

Abbreviations

0D	0 dimensional
1D	1 dimensional
AFR	Air fuel ratio
BP	Brake power
BT	Brake torque
CFD	Computational fluid dynamics
DOE	Design of experiments
IAT	Intake air temperature
ICE	Internal combustion engine
IVC	Intake valve closing
IVO	Intake valve opening
LSR	Least squares regression
MLSR	Moving least squares regression
RBF	Radial basis function
RPM	Revolution per minute
RSM	Responses surface modelling
SI	Spark ignition
VE	Volumetric efficiency
VVL	Variable valve lift

VVT	Variable valve timing

CHAPTER 1
PRELIMINARY WORK

1.1 Introduction

This chapter introduces the contextual background and motivation for this research, which investigates the influence of intake-air temperature and humidity on engine performance parameters namely volumetric efficiency, brake power, and brake torque in single-cylinder spark-ignition engines. This chapter systematically outlines the problem statement, identifies critical research gaps, formulates hypotheses, and defines the specific objectives of the study using simulation-based methods.

1.2 Background of Study

Small-displacement spark-ignition (SI) engines play a critical role in powering two-wheelers and light-duty machinery, particularly across tropical and developing economies. Their appeal lies in mechanical simplicity, cost-effectiveness, and ease of maintenance which are essential in Southeast Asia, Africa, and Latin America where two-wheelers constitute a primary mode of transportation (Zhang et al., 2022), (Zheng et al., 2021) . However, ambient environmental conditions, notably intake-air temperature and humidity, have a marked influence on the combustion process and overall engine efficiency. In tropical climates characterized by elevated ambient temperature and moisture levels, these variations significantly impair engine volumetric efficiency (VE), brake power, and torque output (Ye et al., 2021), (Jalalifar et al., 2020) .

Volumetric efficiency reflects an engine's capability to ingest the ideal air-fuel charge per intake cycle. Its deterioration due to increased air temperature and moisture can limit combustion energy and reduce mechanical output (Som et al., 2024), (Khan et al., 2021). Brake power and torque, crucial indicators of engine performance and drivability, also drop under hot-humid conditions. High intake temperatures reduce air density and volumetric throughput, while elevated humidity displaces oxygen, slowing

combustion and increasing cycle inefficiencies (Abdelmalek et al., 2020; Kim et al., 2020; Orozco et al., 2021). These adverse effects are particularly acute duit laain small engines due to their limited thermal mass and lack of complex intake systems (Olufisayo et al., 2025), (Fu et al., 2026).

While the effects of intake-air conditions have been studied in larger, multi-cylinder automotive engines, limited research exists for small single-cylinder platforms prevalent in low-income regions. Previous studies have often examined weather-related variables such as temperature and humidity separately, and their integration into vehicle or engine performance models remains limited. Additionally, few studies leverage high-fidelity simulation tools such as GT-Power to investigate environmental effects across speed ranges typical for commuter motorcycles, particularly 2,500–4,500 r/min (Done et al., 2022; Khan et al., 2021; Osei et al., 2025; Salih & Delvescovo, 2018).

To address this gap, this study utilises GT-Power simulation to evaluate and optimise the coupled effects of intake-air temperature and humidity on engine performance metrics. This computational approach enables full-span operating condition modelling, delivering a detailed picture of performance sensitivity to climate variations. Ultimately, the findings are intended to support robust calibration strategies for improving fuel economy and emission compliance in hot-humid regions (Cheruyiot et al., 2015; Ghaffarpasand et al., 2021; Navarro et al., 2013).

1.3 Problem Statement

Small-displacement spark-ignition (SI) engines, widely used in motorcycles and portable machinery, operate under a wide range of ambient environmental conditions. In tropical climates, characterized by high temperatures and relative humidity, intake-air properties significantly influence engine performance. Increased intake-air temperature reduces air density, while elevated humidity lowers oxygen concentration, resulting in diminished volumetric efficiency (VE), brake power, and brake torque (Jalalifar et al., 2020; Som et al., 2024; Ye et al., 2021). This degradation affects both fuel economy and combustion stability, leading to operational inefficiencies, especially during peak ambient conditions.

Despite existing literature exploring intake-air effects on SI engine performance, there remains a critical lack of systematic investigations that evaluate both temperature and humidity together across multiple engine speeds (Abdelmalek et al., 2020; Khan et al., 2021; Zhang et al., 2022). Existing studies often isolate either temperature or humidity in static conditions and focus predominantly on multi-cylinder engines. These approaches do not capture the complex real-world operating environments of single-cylinder engines found in urban mobility solutions throughout Southeast Asia, Africa, and Latin America (Zheng et al., 2021), (Kim et al., 2020).

Accordingly, high-fidelity simulations using GT-Power offer a viable method for investigating intake-air influence across realistic speed ranges while enabling scenario-based optimizations (Olufisayo et al., 2025), (Fu et al., 2026). However, prior work seldom integrates performance simulations with parameter optimization tailored to climate-sensitive calibration strategies. As a result, the operational and environmental adaptability of small engines remains poorly understood (Ghaffarpasand et al., 2021) and insufficiently optimized, necessitating a more robust simulation-driven study framework.

1.4 Research Gap

While several studies have addressed the effects of intake-air temperature or humidity independently, comprehensive evaluations of their combined influence remain limited particularly for small, single-cylinder SI engines operating in hot and humid environments. Such gaps hinder the development of predictive models applicable to lightweight mobility platforms. For instance, (Som et al., 2024) highlighted VE reductions under humidity changes, but without considering temperature co-variations.

Additionally, the engine performance behaviour over full operational speed ranges remains insufficiently explored in the literature. Most works rely on fixed or nominal speeds, overlooking dynamic load conditions typical of commuter and portable-engine use cases (Khan et al., 2021), (Olufisayo et al., 2025). This lack of

speed-dependent performance mapping under environmental stressors limits the applicability of existing intake-air control strategies.

Finally, few studies propose simulation-based optimisation frameworks that determine the ideal intake-air temperature and humidity conditions for maximizing VE, brake power, and brake torque. Although GT-Power (Gamma Technologies) has been validated for thermodynamic simulations, and GT-Power–Matlab/Simulink coupling has been applied for engine intake-system optimisation, its potential in climate-robust calibration remains underutilized (Cheruyiot et al., 2015; Jiang et al., 2022; Olufisayo et al., 2025). Accordingly, this study aims to address this by integrating GT-Power (Gamma Technologies) with multivariable optimisation to support reliable engine calibration under tropical duty cycles.

1.5 Hypothesis

H1: Intake-air temperature and humidity jointly influence engine performance, significantly affecting VE, brake power, and brake torque under tropical conditions.

H2: There exists an optimal combination of intake-air temperature and humidity for each engine speed that maximizes engine performance.

H3: GT-Power simulation can accurately model intake-air influence and support performance optimisation across speed ranges.

1.6 Research Objective

i. To evaluate the effect of varying intake-air temperature and humidity on the volumetric efficiency, brake power, and brake torque of a single-cylinder SI engine across its operational speed range using GT-Power simulation.
ii. To analyse the interaction of intake-air parameters with engine speed to determine their impact on performance trends under tropical climate scenarios.

iii. To optimise the configuration of intake-air temperature and humidity for maximum engine performance using a simulation-based approach.

1.7 Scope of Study

This research presents a simulation-based investigation into the effects of intake-air temperature and humidity on the performance characteristics of a single-cylinder spark-ignition (SI) engine, specifically focusing on volumetric efficiency, brake power, and brake torque. A one-dimensional engine model is developed using GT-Power software to capture the thermodynamic behavior and airflow dynamics of the engine under varying intake conditions. To support statistical evaluation and optimisation, Altair HyperStudy is employed to implement a comprehensive Design of Experiment (DOE) framework, along with advanced analytical techniques.

The scope of the study is delineated as follows:

i. The simulation is conducted on a 4-valve spark-ignition engine designed to mimic one cylinder of the Jaguar 3.0L V6 X200 engine.
ii. The simulation is validated using secondary experimental reference data.
iii. The speed range from 2500 RPM to 4500 RPM were selected to simulate the optimal engine operating condition.
iv. Intake-air temperature is varied within a range of 26°C to 34°C to simulate thermal conditions commonly encountered in tropical climates.
v. Relative humidity levels are adjusted between 68% and 92%, capturing the environmental extremes of high-humidity regions.
vi. A full-factorial DOE is executed using Altair HyperStudy to systematically assess the main and interaction effects of engine speed, intake-air temperature, and humidity on the selected performance metrics.
vii. Optimisation is carried out using response surface modelling (RSM) and analysis of variance (ANOVA) to identify the intake-air conditions that yield optimal engine performance.

This study is confined to the influence of intake-air parameters on engine performance in steady-state operation. It does not encompass fuel type variation, or advanced combustion strategies. The findings are intended to support climate-adaptive calibration strategies for lightweight engines operating in hot and humid environments.

1.8 Thesis Layout

This thesis is organized into five chapters to systematically present the research process and findings. Chapter 1 introduces the study by presenting the research background, highlighting the problem statement, identifying the research gap, and formulating the research hypotheses and objectives. It also defines the scope of the study and outlines the overall structure of the thesis.

Chapter 2 provides a comprehensive review of existing literature related to intake-air parameters and their effects on the performance of spark-ignition engines. The review identifies significant contributions and limitations within prior studies, thereby establishing the context and justification for the present research.

Chapter 3 describes the research methodology in detail. It covers the development of the one-dimensional engine simulation model using GT-Power software and outlines the configuration and boundary conditions applied. This chapter also explains the use of Altair HyperStudy for the Design of Experiment (DOE), statistical modelling, and optimisation processes.

Chapter 4 presents the results obtained from the simulation and statistical analysis. It includes a thorough discussion of the influence of intake-air temperature and humidity on volumetric efficiency, brake power, and brake torque. Trends, interactions, and optimisation outcomes are analysed using appropriate plots and statistical metrics.

Finally, Chapter 5 concludes the thesis by summarising the main findings and contributions of the study. It also provides recommendations for future research, particularly in extending the simulation framework to include experimental validation or alternative engine configurations under varying environmental conditions.

1.9 Summary

In summary, this study seeks to advance the understanding of environmental influences specifically intake-air temperature and humidity on the performance of small-displacement SI engines. Through systematic GT-Power simulation across varying engine speeds and climatic conditions, the outcomes are expected to contribute to the development of climate-resilient, performance-optimized engine configurations for light-duty applications.

CHAPTER 2
LITERATURE REVIEW

2.0 Introduction

Volumetric efficiency (VE) is a fundamental performance indicator in internal combustion engines (ICEs) which is reflecting the engine's capability to induct and retain air in the cylinder during the intake stroke. In spark ignition (SI) engines, volumetric efficiency plays a critical role in determining power output, fuel economy, combustion stability, and exhaust emissions (Gumus, 2011), (Harazi et al., 2024). The quantity of air admitted governs the amount of fuel that can be burned efficiently. Thus, even small variations in volumetric efficiency can significantly influence engine behaviour.

Engine breathing characteristics are influenced not only by design parameters such as intake geometry, valve timing, and combustion chamber shape, but also by environmental conditions, particularly intake air temperature and humidity. In real-world operation, engines operate under continuous varying ambient conditions that affect the air density, oxygen availability, and thermophysical properties of the intake charge (Hoseinifar et al., 2023).

While extensive research has addressed volumetric efficiency from design and operational perspectives, comparatively fewer studies have investigated environmental factors especially the combined effect of temperature and humidity using modern simulation tools such as GT-POWER. This chapter reviews the theoretical background, influencing factors, environmental effects, modelling approaches, and simulation-based studies relevant to volumetric efficiency, culminating in identifying research gaps addressed by the present work.

2.1 Spark Ignition (SI) Engine Performance and Volumetric Efficiency

Spark Ignition (SI) engines are internal combustion engines in which a spark rather than compression alone initiates the combustion of a pre-mixed air–fuel mixture. The performance of SI engines depends heavily on the ability to draw in the maximum possible mass of air in each intake stroke. More air provides more oxygen and thus more potential for fuel combustion. The metric often used to assess this is known as volumetric efficiency (VE). It is defined as the ratio of the actual mass of air inducted per cycle to the theoretical maximum mass that could be inducted, based on displacement and ambient conditions.

Spark ignition engines convert chemical energy into mechanical work through controlled flame propagation initiated by a spark. Performance metrics typically include torque, power, brake thermal efficiency, specific fuel consumption, and emissions (Korakianitis et al., 2011). However, all these outputs fundamentally depend on the mass of air inducted into the cylinder. Volumetric efficiency is defined as shown in equation (2.1).

$$VE = \frac{\text{Actual mass of air inducted}}{\text{Theoretical mass of air at ambient conditions}} \tag{2.1}$$

A high volumetric efficiency implies effective cylinder filling, allowing more fuel to be burned and higher power to be produced (Talati et al., 2022). In naturally aspirated engines, volumetric efficiency typically ranges between 70–95%, whereas boosted engines may exceed 100% due to pressurised intake systems.

Volumetric efficiency is influenced by many factors: ambient air conditions (temperature, pressure, humidity), the design of the intake system (runner length, cross-section, valve timing and lift), engine speed (RPM), load, and flow dynamics in the intake manifold/cylinder. Losses occur through flow restriction, throttling, reversion, heat transfer between the incoming air and hot engine surfaces, and incomplete filling, especially at high RPM when there is less time to fill the cylinder.

In single-cylinder SI engines, these factors often have more pronounced effects. Since no balancing of cylinders, intake pulsations can be stronger, and temperature/humidity fluctuations in the intake air may be less damped. Thus, when ambient intake conditions vary, the volumetric filling is less stable and making single cylinder engines a good test bed to isolate and study how environmental variables affect VE (Chang et al., 2017).

Numerous studies have highlighted that volumetric efficiency is not constant across the engine operating range. It varies significantly with engine speed, throttle position, and intake pressure dynamics (Harazi et al., 2024; Jemni et al., 2021; Rimkus et al., 2022). Moreover, transient effects such as pressure wave tuning and valve overlap can temporarily enhance or reduce cylinder filling (Sawant et al., 2018). In small single-cylinder engines, volumetric efficiency fluctuations tend to be more pronounced due to stronger pulsating flow effects and limited intake runner tuning opportunities (Talati et al., 2022). This makes single-cylinder SI engines particularly sensitive to intake air conditions and suitable for focused volumetric efficiency investigations.

Recent research supports these dependencies in an experimental setup, increasing the intake air temperature for a single-cylinder SI engine operating at various speeds showed a marked decline in volumetric efficiency, with corresponding reductions in torque and increases in fuel consumption and exhaust temperature (Purayil et al., 2025). The study emphasizes that temperature has a first-order effect on air density and mass flow, which cascades into performance metrics.

2.2 Factors Affecting Volumetric Efficiency

2.2.1 Overview on Volumetric Efficiency

Volumetric efficiency (VE) is a central performance metric for spark-ignition (SI) engines because it directly governs how much oxygen mass enters the cylinder each cycle and therefore sets the upper limit for fuel energy that can be converted to work. Multiple interacting factors determine VE such ambient conditions (temperature, pressure, humidity), intake-system geometry (runner length/diameter, plenum volume), valve events (timing, overlap, lift), gas-dynamic phenomena (inertial charging, wave

tuning, Helmholtz resonance) and operating point (engine speed and load). Since VE is inherently a transient and strongly coupled quantity it depends on time-varying pressures, flow inertia, heat transfer and valve. Events small changes in one factor (for example intake runner length or intake temperature) can cascade into measurable changes in filling, combustion phasing, torque and emissions (Anaclerio et al., 2024; Talati et al., 2022).

In single-cylinder engines especially, pulsations and local flow disturbances are less damped than in multi-cylinder engines, so the sensitivity of VE to intake geometry and ambient conditions tends to be greater. Thus, accurately predicting and measuring VE requires attention to both the quasi-steady (mean mass flow vs. throttle) and dynamic (wave and inertial) components of the intake process. Recent reviews emphasise that improving VE is rarely about a single "silver-bullet" change; rather, it is achieved by co-optimising intake geometry, valve strategy and when possible controlling intake conditions (temperature, humidity) to the operating regime of interest (Aljohani et al., 2026; Jain et al., 2020). Based on the above discussion, the main factors affecting volumetric efficiency are summarised in Table 2.1.

Table 2.1
Summary of The Main Factors Affecting Volumetric Efficiency in Spark-Ignition Engines.

Factor	Main Parameters / Mechanism
Intake air temperature	Intake temperature affects air density based on the ideal gas relationship. At constant pressure, higher temperature reduces air density.
Air humidity	Water vapour displaces dry air and reduces oxygen partial pressure. It also changes the thermal behaviour of the intake charge due to its higher specific heat capacity.
Intake manifold geometry and wave dynamics	Runner length, runner diameter, plenum volume, inertial charging, wave tuning, and Helmholtz resonance affect intake flow behaviour.
Valve timing, lift, and overlap	Intake valve opening, intake valve closing, valve lift, and valve overlap determine the available time and flow area for air induction.

Factor	Main Parameters / Mechanism
Engine speed and load	Engine speed affects intake duration, while load affects throttle position, manifold pressure, and pressure drop.
Combined interaction of factors	VE is affected by the interaction of ambient condition, intake geometry, valve events, gas-dynamic behaviour, engine speed, and load.

2.2.2 Intake Air Temperature

Air intake temperature is arguably the most direct ambient factor affecting VE because of its immediate impact on air density (Ideal Gas Law: $\rho = p/RT$). At constant absolute pressure, a rise in intake temperature reduces air density and therefore the mass of oxygen ingested per cycle. For naturally aspirated SI engines this effect is linear to first order: a 10 °C rise in intake temperature reduces density and oxygen mass by roughly 3–4% at standard conditions, which typically reduces torque and power proportionally if fuelling is not adjusted (Cinar et al., 2015; Nazmi Naufal Khaifullizan et al., 2021). However, the overall effect on engine performance is nuanced because intake temperature also interacts with evaporation of fuel (important for port-injection systems), flame speed, ignition delay and knock tendency. In some cases, higher intake temperatures can improve vaporisation of heavier fuels and reduce wall wetting, slightly improving mixture formation and combustion stability despite a loss in charge mass (Teoh et al., 2021). Higher intake temperatures tend to promote faster evaporation of injected fuel (important for port injection and for spray penetration in direct injection), which can improve mixture homogeneity and reduce wall wetting losses at low loads (Jo et al., 2020). However, in certain injection strategies faster evaporation can move mixture distribution toward local rich or lean pockets, changing knock tendencies. Intake temperature changes the temperature gradients between charge and cylinder walls; this shift heat transfer losses and can alter indicated efficiency. Overall, the net effect of intake air temperature (IAT) on brake thermal efficiency is therefore the result of competing mechanisms: loss of charge mass (negative), improved vaporisation/combustion (positive), and changed heat transfer/knock behaviour. These mechanisms explain why experiments often show nuanced results: sometimes small

rises in thermal efficiency despite lower volumetric filling, or changes in specific emissions even when volumetric efficiency falls (Jo et al., 2020).

It was reported that raising intake air temperature across a range of 15-75 °C leads to measurable declines in volumetric efficiency while improving thermal efficiency under some conditions (due to reduced heat losses and changes in combustion behaviour (Hamzah et al., 2023). In another regionally relevant study, the investigation on the effect of intake air temperature on a 1.3 L passenger car engine was carried out (Nazmi Naufal Khaifullizan et al., 2021). They showed that engine performance of both torque and power was superior when intake temperatures were lower (~35-40 °C) compared to elevated intake temperatures (~65-70 °C), as shown in Figure 2.1. While the fuel consumption worsened as temperature increased. Numerous studies confirm this effect showed that rise in intake air temperature resulted in a noticeable reduction in engine torque and volumetric efficiency (Jo et al., 2020). Similarly, observed that intake air heating degraded performance but reduced HC and CO emissions (Cinar et al., 2015). Experimentally demonstrated that increasing intake air temperature from 30°C to 60°C caused a significant decline in volumetric efficiency and brake power in a single-cylinder SI engine (Som et al., 2024).

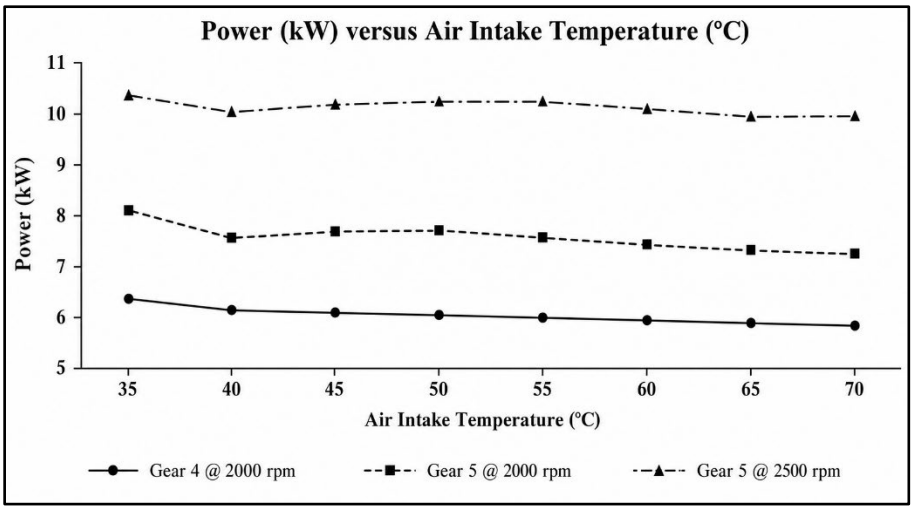


Figure 2.1 Graph of Power (kW) Against Air Intake Temperature (Nazmi Naufal Khaifullizan et al., 2021)

Temperature also interacts with other phenomena which elevated intake air temperatures can increase the temperature of incoming charge, raising the propensity for knock, altering flame speed, and changing combustion phasing. Thus, intake

temperature has both direct mechanical/thermodynamic effects (via density) and indirect effects on combustion chemistry and thermal cycles.

However, intake temperature also affects fuel vaporisation and mixture preparation. Warmer air improves fuel atomisation, which can enhance combustion stability at low loads (Sun et al., 2022). This dual effect explains why moderate intake heating is sometimes applied in cold-start conditions.

2.2.3 Humidity of air

Humidity affects VE through two primary mechanisms. First, water vapor displaces dry air constituents and therefore reduces oxygen partial pressure in the intake charge at constant total pressure as shown in Figure 2.2. Second, water vapor's thermophysical properties (notably higher specific heat) change the thermal history of the incoming charge during compression and heat exchange with cylinder walls, which can alter combustion timing and flame propagation as illustrated in Figure 2.3. At a macroscopic level, humid air therefore reduces the chemically-active oxygen mass available for combustion (all else equal) but also tends to slow combustion and reduce peak temperatures with consequential reductions in NO_x formation (Serrano et al., 2023; Soysal et al., 2022).

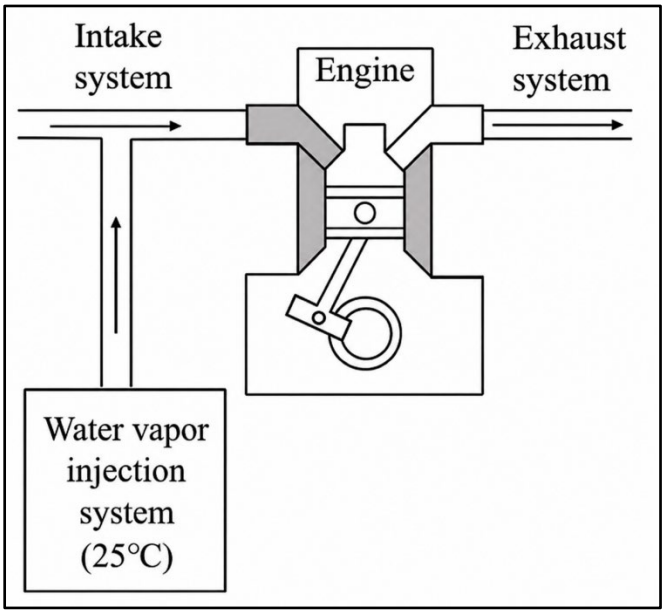


Figure 2.2 Schematic of Mechanism For The Water Vapor Injection System (Teoh et al., 2021).

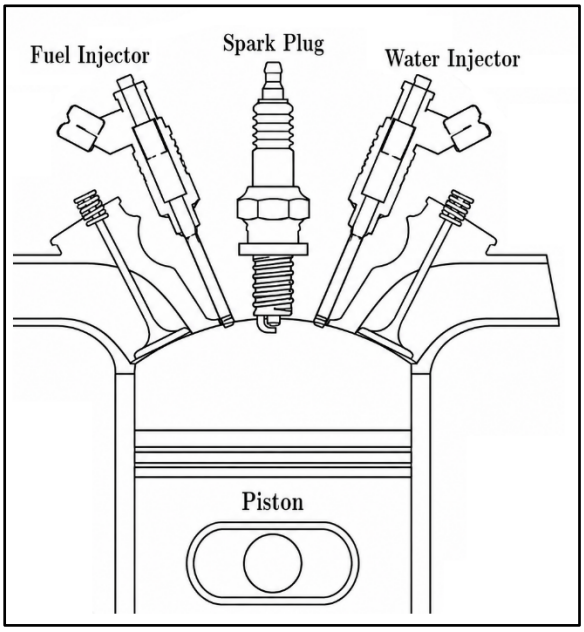


Figure 2.3 Schematic of Mechanism For The Water Vapour Changes The Thermal History of The Charge Due to Heat Absorption (Wei et al., 2016)

The magnitude and sign of humidity's effect on VE can be context dependent. Several experimental studies on both SI and compression-ignition engines report that increasing humidity reduces NO_x significantly but produces only modest penalties in fuel consumption and power under moderate loads; however, at high speeds and loads the slowed combustion and reduced oxygen can raise BSFC (brake specific fuel consumption) and reduce torque slightly (Hsueh et al., 2021; Serrano et al., 2023). From a modelling perspective, accounting for humidity requires including water vapor in intake composition (reducing O_2 partial pressure) and updating thermodynamic properties used in control corrections. Standards and correction maps often include humidity or wet-bulb corrections for engine testing, but many calibration strategies still simplify humidity effects a simplification that can lead to small but systematic errors in performance prediction, especially outside temperate climates. For engines intended to operate in tropical environments, explicit inclusion of humidity in both experimental protocols and predictive models is recommended.

Experimental work has been demonstrated that humidified intake air slightly reduces engine power but significantly lowers NO_x emissions due to reduced peak flame temperatures (Hsueh et al., 2021). Similar trends were observed a reduction in

combustion temperature and pressure under high humidity conditions (Serrano et al., 2023). Another study focusing on small off-road SI engines showed that humidity effects on both observed and power-corrected performance are often underestimated; higher relative humidity can reduce power output more than what standard correction methods (Adrian Olmos Jr, Steven Griffin, Gary Price, Nathan Beilke, 2021).

Relative humidity can affect emission formation, knock tendency, and combustion stability in addition to pure volumetric filling. These combined effects mean that humidity is more than a background condition, it also can play a role especially when ambient conditions or intake control are not tightly managed. From a volumetric efficiency perspective, humidity slightly reduces effective oxygen-based volumetric efficiency, even if the total air volume inducted remains similar. This is particularly important when analysing engines in humid tropical climates. Despite its importance, humidity has historically received less attention than temperature, especially in simulation-based studies, largely due to modelling complexities associated with moist air thermophysical properties.

2.2.4 Intake Manifold Geometry and Wave Dynamics

Intake manifold geometry such as runner length, runner diameter, plenum volume and the presence (or absence) of swirl or tumble features has strongly affected VE via wave dynamics and flow resistance. Two dominant phenomena are relevant is inertial (ram) charging, where the momentum of the intake flow continues to fill the cylinder beyond the instantaneous piston movement, and second is resonant (wave) tuning, where pressure waves in the intake tract are timed (by runner length and plenum design) to arrive at the valve just as it opens or closes, generating beneficial pressure peaks that augment filling at specific RPM ranges (Helmholtz and acoustic resonance tuning). Variable-length manifolds exploit these effects by changing effective runner length to shift the tuned RPM band, improving VE across a wider RPM range (Nejatzadegan et al., 2025; Silva et al., 2019; Talati et al., 2022).

Experimental and CFD studies document significant VE gains from carefully tuned intake systems. For example, variable-length manifolds and runner tuning have produced VE increases of several percent (typical reports: 5–15% improvement in

targeted RPM bands) and corresponding torque increases; the exact gains depend on the engine geometry and the RPM band of interest (Anaclerio et al., 2024; Harazi et al., 2024). For single-cylinder engines, the effect can be even more pronounced because the lack of multiple cylinder pulsation averaging makes the single runner's resonance more influential on instantaneous filling (Harazi et al., 2024).

On the flip side, achieving broad-band improvements is challenging fixed geometries offer good gains at tuned rpm ranges but degrade off-peak; variable systems add weight, cost and control complexity. Advances in low-cost variable geometry intake designs and active intake control (e.g., simple butterfly valves to switch runner length) show promise for small engines where packaging constraints are tight (Talati et al., 2022). Overall, intake geometry remains one of the most effective and well-studied levers for improving VE when done in concert with valve timing and cam profile choices.

2.2.5 Valve Timing, Lift and Overlap

Valve events such as the timing of intake valve opening (IVO), intake valve closing (IVC), valve lift magnitude and valve overlap determine the temporal window for cylinder filling and therefore directly set the quasi-steady and dynamic charge mass. Variable valve timing (VVT) and variable valve lift (VVL) systems change these events in real time to adapt cylinder breathing to engine speed and load. The literature shows consistent volumetric efficiency improvements from VVT/VVL: by advancing/retarding IVC or changing lift, engines can reduce pumping losses at low load and exploit inertial charging at higher RPM to improve VE and torque across the map (Shaikh et al., 2025; Wang et al., 2021).

Several experimental papers report VE increases in the order of 3–8% across targeted RPM ranges when appropriate VVT/VVL strategies are applied. The improvements in brake torque and fuel consumption follow accordingly (Gülcan et al., 2024; Rimkus et al., 2022). The mechanism is intuitive at low speeds, early closing or reduced overlap reduces reversion and pumping losses; at high speeds, late intake closing and higher lift preserve flow momentum and exploit wave tuning, thereby improving high-RPM filling. Nonetheless, implementing VVT/VVL in small single-

cylinder engines is nontrivial because of space, cost and control constraints yet modern electromechanical actuators and simple switching systems (two-step cam switching) provide feasible paths for research-level implementations.

2.2.6 Engine Speed and Load

Engine speed is a primary dynamic factor where VE is not constant with RPM because of the interplay between intake time, inertial filling, and wave effects. Typically, VE increases with speed up to a band where resonance or inertial charging is positive, then falls at very high RPM when flow losses and valve timing limitations dominate. Load influences the throttle position (and hence pressure drop across the throttle), the effective mass flow, and the intake manifold pressure; at part load the throttle reduces mass flow nonlinearly, increasing pumping losses and reducing VE at a given speed. Engine operating strategies therefore must consider both speed and load to optimise filling (Jemni et al., 2021; Talati et al., 2022).

From a control and experimental perspective, this means VE maps are two-dimensional (speed × load) rather than simple functions of RPM. Many studies use design-of-experiments or full factorial testing (speed × temperature × humidity) to quantify how VE changes across operating space; these reveal significant nonlinearities and interactions (Harazi et al., 2024; Som et al., 2024). Practical engine calibration therefore benefits from high-resolution VE mapping and the use of adaptive control strategies that adjust valve timing, boost, or intake conditioning to maintain best filling across the map.

2.3 Combined Effect of Air Temperature and Humidity

While air intake temperature and humidity each influence volumetric efficiency and overall engine performance in their own ways, real-world ambient conditions rarely vary one parameter at a time. In most environmental conditions especially in tropical and subtropical climates, temperature and humidity change simultaneously and interactively (Hoseinifar et al., 2023). Because both parameters influence charge density, oxygen availability, combustion heat transfer, and in-cylinder kinetics, their

coupled effect on volumetric efficiency is complex and necessitates integrated study. This subchapter reviews the theoretical basis, experimental evidence, and modelling work on the combined effects, focusing on how temperature and humidity together modulate engine breathing and performance.

Since the temperature and humidity individually affect volumetric efficiency, their interactions with engine speed and load are critical. Engine speed (RPM) influences volumetric efficiency because at higher speeds, the time available for intake and filling is reduced; inertia and flow dynamics in the intake manifold become more significant, leading to increased flow losses or incomplete filling. Thus, the adverse effects of high intake air temperature or high humidity are magnified at high RPM.

Load also plays a role: under part-load or throttled conditions, the throttle introduces pressure drop, further reducing mass flow; the temperature of the incoming air can alter charge heating, mixture stratification, etc. High load conditions may lessen relative losses in some cases but increase demands on the intake system's ability to respond quickly to changes in ambient intake conditions.

The investigation on the effects of vehicle speed and engine load on real-world motor vehicle emissions using on-road measurements in a highway tunnel has been carried out (Kean et al., 2003). The study demonstrates that carbon monoxide (CO) and nitrogen oxides (NOx) emissions are strongly influenced by the combined effects of vehicle speed and engine load, rather than by either parameter alone. Uphill driving, representing higher engine load conditions, produced significantly higher CO and NOx emissions compared to downhill driving, even when normalized per unit of fuel consumed. In particular, CO emissions showed a sharp increase at higher speeds under high-load conditions, attributed to fuel enrichment strategies employed by engines to protect components and maintain power output.

A key contribution of this study is its identification of the limitations of speed-only emission models. It show that specific power (a proxy for engine load) provides a more physically meaningful representation of real-world driving conditions, highlighting the need to incorporate load-based parameters into emission modeling frameworks. Furthermore, while CO and NOx increased with load, non-methane

hydrocarbons (NMHC) exhibited contrasting behavior, with higher fuel-normalized emissions observed under low-load downhill conditions, suggesting different dominant formation mechanisms.

The study also reveals that distance-based emission factors are far more sensitive to driving conditions than fuel-based factors, indicating that traditional inventory approaches may significantly misrepresent emissions under varying traffic and load scenarios. Although the work is limited to light-duty vehicles and does not include detailed combustion or engine control analysis, it provides strong empirical evidence that accurate emission prediction requires a coupled consideration of speed and engine load. This finding is particularly relevant for simulation-based engine and combustion studies, where realistic operating conditions must be represented to achieve reliable emission predictions.

2.3.1 Thermodynamic Interaction Between Temperature and Humidity

The combined effect of air temperature and humidity on volumetric efficiency is rooted in basic gas mixture physics. Humid air at higher temperature contains more water vapor (higher saturation pressure), which displaces dry air constituents, especially oxygen, at a given total pressure. Simultaneously, higher temperature reduces overall air density. Therefore, the combined presence of high humidity and high temperature produces a compounded reduction in oxygen mass per unit charge, far greater than either factor in isolation (Taghavifar & Anvari, 2019).

If dry air at 25 °C and 50% relative humidity contains a certain oxygen mass, raising temperature to 40 °C while increasing humidity to 80% does not just change one variable; it simultaneously lowers air density and dilutes oxygen concentration. The effect on accessible oxygen is multiplicative rather than additive, because mass density and composition are both altered. These combined changes can reduce the maximum achievable fuel mass per intake stroke, reduce achievable torque and power, and necessitate recalibration of control systems such as fuel injection and ignition timing (Chang et al., 2017).

Thermodynamic models that integrate both temperature and humidity often using psychrometric relationships and ideal gas corrections show that the combined losses in air mass flow and oxygen availability are most severe at high temperature/high humidity extremes, typical of tropical afternoon conditions. This suggests that volumetric efficiency maps and corrections used for temperate climates may significantly overestimate performance in such conditions (Hoseinifar et al., 2023).

Several recent engine studies have attempted to observe or quantify how varying both temperature and humidity influence volumetric efficiency and performance. For instance, the study carried out to determine the effect of temperature (TEMP) and relative humidity (RH) and their interaction on traffic emissions. (Jamriska et al., 2008). The study demonstrates that air temperature and relative humidity significantly influence traffic-related exhaust particle emissions. Particle number concentration was mainly governed by traffic flow and wind speed, while temperature and humidity showed secondary but important effects. An inverse relationship was observed between temperature and particle concentration, whereas higher relative humidity led to increased particle concentration. The influence of these parameters was also particle-size dependent, with temperature dominating smaller particles and humidity becoming more influential for larger particles. These findings highlight the importance of environmental conditions, particularly temperature and humidity, in affecting combustion behaviour and emission characteristics.

Recent study to examine the influence of ambient temperature and humidity on vehicle exhaust emissions using the International Vehicle Emissions (IVE) model also being reported (Hoseinifar et al., 2023). The results revealed that exhaust emissions are highly sensitive to environmental conditions, particularly temperature and relative humidity. It was found that as ambient temperature increases from –7 °C to 20 °C, emissions of CO, NO_x, and CH_4 decrease, while SO_x, PM, CO_2, and N_2O remain largely unchanged. However, beyond a critical temperature of 20 °C, emissions of all investigated pollutants and greenhouse gases increase significantly, indicating a threshold behaviour in temperature–emission relationships. This suggests that rising average temperatures due to climate change are likely to intensify vehicular emissions, thereby contributing to a reinforcing climate feedback loop.

With respect to humidity, the study showed that SO_x, PM, CO_2, and N_2O emissions are relatively insensitive to changes in relative humidity, whereas increasing humidity leads to higher CO and CH_4 emissions and reduced NO_x emissions. Consequently, CO and CH_4 emissions tend to be higher during wet seasons, while NO_x emissions are more prominent during dry conditions. Overall, the findings highlight the critical role of meteorological parameters in shaping vehicular emission behaviour and emphasize the need to account for ambient temperature and humidity in environmental and transportation policy planning.

2.3.2 Impact on Combustion Quality and Emissions

Beyond pure breathing and oxygen availability, the combined effects of temperature and humidity influence combustion dynamics in ways that feed back into volumetric efficiency and effective cylinder filling. High intake temperature reduces charge density, while high humidity changes flame speed and heat release patterns. When these conditions coincide, the quality of combustion is altered: moist, warm air reduces flame propagation speed and increases ignition delay relative to dry, cooler air. This shift in combustion timing often results in a later peak pressure location (i.e., closer to or even past top dead centre), which reduces the mechanical work extracted per cycle even if cylinder filling is otherwise adequate. In other words, even if volumetric efficiency were unchanged, the effective combustion efficiency which contributes to brake torque and power is lowered.

It was reported that ambient temperature and humidity have been shown to exert a significant influence on combustion behaviour and heat release characteristics in advanced engine concepts (Chang et al., 2017). In a study on spark-assisted compression ignition (SACI) engines, increasing the intake air temperature was found to advance combustion phasing and increase the maximum pressure rise rate, indicating a faster and more auto-ignition-dominated heat release process, which consequently led to higher NO_x emissions due to elevated in-cylinder temperatures. Conversely, increasing ambient humidity retarded combustion phasing and reduced the pressure rise rate, reflecting a slower heat release process caused by the thermal and chemical dilution effects of water vapour. Higher humidity also increased combustion instability and fuel consumption while reducing NO_x formation. These findings highlight the

strong sensitivity of heat release dynamics to intake air conditions and emphasise the need to account for both temperature and humidity in engine performance and control strategies, even for conventional spark ignition engines.

An investigation on gasoline-fuelled compression ignition engines under isobaric combustion show that intake air temperature strongly influences efficiency and combustion losses (Aljohani et al., 2026). At moderate peak cylinder pressure (PCP), lower intake temperatures (around 25 °C) yielded higher efficiency compared to elevated temperatures (80 °C), primarily due to reduced thermal losses. As PCP increased to 150 bar, efficiency became less sensitive to intake temperature, indicating that combustion was increasingly pressure-dominated.

These findings highlight that while ambient intake temperatures favour efficiency and stability, higher temperatures reduce charge density and increase thermal losses. The role of intake temperature is therefore critical in balancing efficiency, emissions, and combustion stability, especially when combined with strategies such as multiple injections and EGR.

2.4 Methods and Experimental Approaches to Evaluate Volumetric Efficiency

The evaluation of volumetric efficiency and its dependency on intake conditions especially air temperature and humidity require carefully designed experimental setups, accurate sensing systems, robust data acquisition strategies, and rigorous analytical or computational methods. This section reviews experimental and modelling approaches used in the literature to investigate VE and related performance metrics, highlighting the tools, techniques, and methodological scope employed in recent studies. Included are practical methods for controlling environmental conditions, measuring critical variables, and simulating engine behaviour each with advantages and limitations.

2.4.1 Experimental Methods

Most experimental investigations into volumetric efficiency and intake condition effects employ either engine test rigs with environmental control capabilities or engine dynamometer systems equipped with advanced sensors and instrumentation. typical laboratory test rig consists of a single-cylinder or multi-cylinder engine mounted on a dynamometer, allowing controlled variation of speed, load, and intake conditions (Lu & Zhu, 2025; Sawant et al., 2018). For intake temperature and humidity studies, the intake air is commonly conditioned using an environmental control chamber or heater/humidifier unit preceding the throttle body. This approach was used to manipulate intake temperature and humidity in a systematic manner while measuring output performance and emissions (Chang et al., 2017). Environmental chambers provide the advantage of precise control over ambient variables, but they require careful calibration and insulation to prevent heat soak or unexpected moisture condensation inside air ducts. Dynamometers are paired with air handling units that provide pre-conditioned intake air typically achieved through heat exchangers or vapor injection systems coupled with sensors. For example, the controlled steam injection system to vary intake humidity while operating the engine at several fixed speeds and loads has been used in the previous study (Hsueh et al., 2021). The strength of this setup lies in replicating real operating conditions under repeatable laboratory control, giving high fidelity to performance characterization.

2.4.2 Analytical and Computational Modelling Methods

2.4.2.1 *Zero- Dimensional and Quasi-Steady Models*

The 0-D models treat the engine filling process in aggregate, using mass continuity and ideal gas relations to estimate air charge based on intake pressure, temperature, and throttle position. These analytical models are easy to implement and fast to compute, making them popular for engine control unit (ECU) calibration. However, they lack detailed spatial flow information and cannot capture dynamic effects such as intake pulsations or wave resonance. Other comparison of dimensional as shown in Table 2.2.

2.4.2.2 *One-Dimensional Gas–Dynamic Models*

The 1-D gas-dynamic models model pressure waves, flow inertia, and acoustic effects along the intake manifold. Tools like GT-Power and Ricardo Wave are widely used to simulate intake and exhaust dynamics, enabling prediction of volumetric efficiency across a range of RPMs and intake conditions. These models incorporate friction, heat transfer, and shock losses, making them more predictive than 0-D approaches.

A recent application of this approach had illustrated how 1-D modelling can optimize the geometry of an intake manifold of an internal combustion engine in order to predict the influence of intake duct length on VE, torque and horsepower, matching experimental results to within a few percentage points (Silva et al., 2019).

2.4.2.3 *Computational Fluid Dynamics (CFD)*

CFD provides high-fidelity spatial resolution of flow, temperature, and turbulence within the intake manifold and cylinder. When coupled with combustion models (e.g., flamelet models or Direct Numerical Simulation in limited regions), CFD can capture localized effects of temperature gradients and humidity distribution on flow separation, swirl, and mixture formation.

CFD studies often use boundary conditions derived from 1-D models or measured data to reduce computational cost. The main limitation of CFD is its high computational cost and sensitivity to turbulence modeling assumptions especially at higher Reynolds numbers prevalent in engine flows. Nevertheless, CFD remains essential for detailed investigations of intake geometry effects, local heat transfer, and transient phenomena that influence VE (Nejatzadegan et al., 2025; Onyegirim et al., 2025).

Table 2.2
Comparative Evaluation of Methods Reveals Trade-Offs Between Accuracy, Cost, Complexity, and General Applicability.

Method	Advantages	Limitations
0D Models	Fast, easy to implement, compatible with ECU calibration	Overly simplified, neglects dynamics and spatial effects
1D Gas-dynamic	Captures wave effects, inertia, resonance	Cannot resolve turbulence and local temperature fields
CFD	High spatial resolution; detailed flow/temperature insight	Computationally expensive; model assumptions influence results
Engine Dynamometer Tests	High control over speed and load; real engine behavior	Equipment cost; environmental control complexity
Environmental Chambers	Precise ambient control	High cost and potential heat/mass transfer errors
Steam/Humidifier Systems	Fine humidity control	Risk of condensation and sensor errors

2.5 Use of GT-POWER in Volumetric Efficiency Studies

Engine simulation plays a pivotal role in modern internal combustion engine research and development. Among the available tools, GT-POWER has become the industry standard used by OEMs and major engine manufacturers to predict and analyse

engine performance, including power, torque, airflow characteristics, volumetric efficiency, fuel consumption, pumping losses, and turbocharger matching (Khanyi et al., 2025). Its strength lies in integrating one-dimensional gas dynamics with empirical and analytical submodels for flow, heat transfer, turbulence, and combustion, enabling both steady-state and transient simulations with high fidelity.

GT-POWER's breadth of modelling capabilities makes it especially suitable for evaluating how environmental and design parameters such as intake air temperature and humidity affect internal combustion processes and performance metrics like volumetric efficiency. The following sections review how GT-POWER has been used in past research, and specifically studies that incorporate intake condition variations or similar environmental effects.

In an effort to quantify how geometry of an intake manifold of an internal combustion engine influences volumetric efficiency and performance, the GT-POWER one-dimensional simulation platform was employed in the study (Silva et al., 2019). It is to optimise the geometry of an engine intake manifold with the aim of maximising volumetric efficiency across a wide engine speed range. By using a numerical optimisation method, the researchers determined the optimal intake runner lengths for engine speeds between 1000 and 6000 rpm. The results showed that shorter intake runners significantly improved volumetric efficiency at higher engine speeds, while longer runners were more beneficial at lower speeds. Based on these findings, a variable-geometry intake manifold was proposed, which demonstrated improved volumetric efficiency, torque, and power output, along with reduced brake-specific fuel consumption. The study highlights the strong influence of intake system design on volumetric efficiency and confirms the suitability of GT-POWER as a reliable tool for intake optimisation and engine performance analysis.

Another study demonstrated the capability of one-dimensional engine simulation, particularly GT-POWER, in accurately predicting and improving volumetric efficiency through intake valve and swirl optimisation (Jain et al., 2020). Using a validated 1D model, the authors analysed the effects of intake valve timing, lift, duration, and swirl ratio on the volumetric efficiency of a single-cylinder diesel engine. The simulation results showed that optimising valve events, combined with a 25%

reduction in swirl and a 10% improvement in flow coefficient, produced a 5–15% increase in volumetric efficiency across a wide engine speed range as shown in Figure 2.4. The findings highlight GT-POWER's effectiveness as a predictive and design tool for analysing gas exchange processes and guiding strategies to enhance volumetric efficiency through valve and flow management. Thus, it is demonstrated that the effectiveness of GT-POWER in simulating and improving volumetric efficiency through intake system design optimisation in a four-cylinder gasoline engine (Talati et al., 2022). A novel variable-length intake manifold was proposed and analysed using a validated one-dimensional GT-POWER model under steady-state wide-open throttle conditions. The simulation successfully captured the thermo-fluid and gas exchange behaviour associated with different intake lengths and throttle configurations. Compared with the stock intake manifold, the optimised design achieved a 6.33% increase in volumetric efficiency, along with notable improvements in brake torque, brake thermal efficiency, and heat release rate. The results highlight GT-POWER's strong capability as a predictive tool for analysing intake system modifications and their impact on volumetric efficiency and overall engine performance.

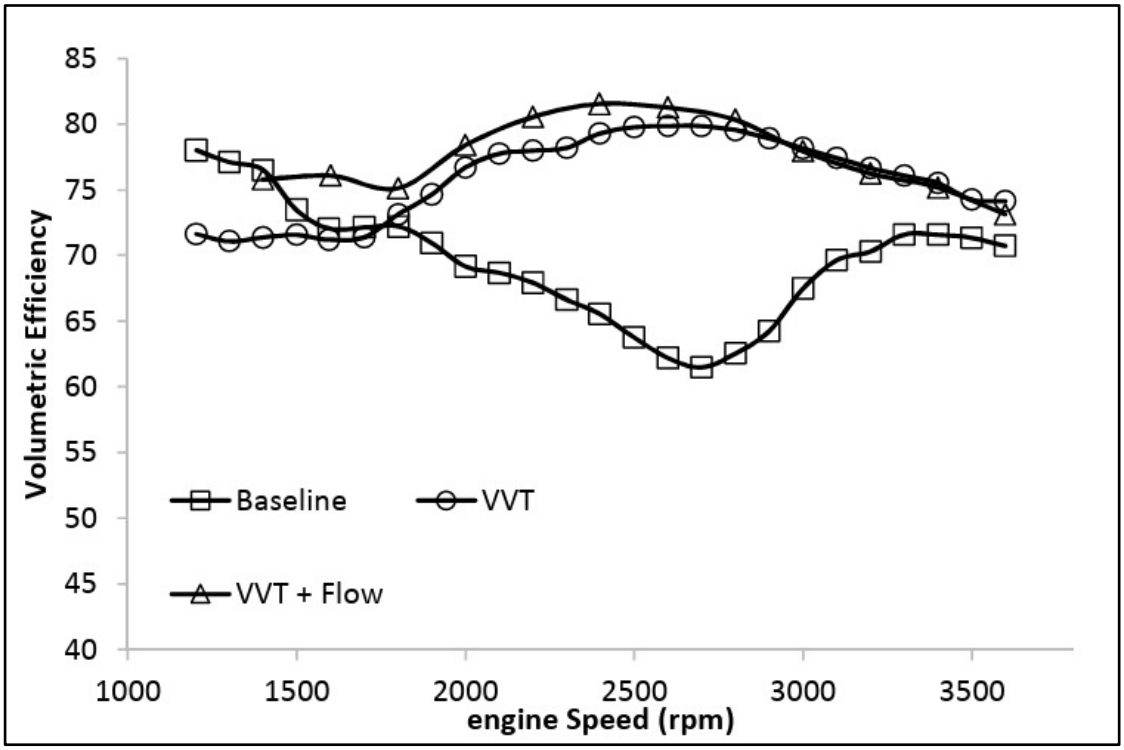


Figure 2.4 Comparison of Engine Speed Vs Volumetric Efficiency for Baseline and Optimised Combination Using GT-POWER. (Jain et al., 2020)

GT-POWER is a powerful and widely used simulation platform for engine performance prediction, including volumetric efficiency, especially when environmental conditions vary. Past studies have successfully used GT-POWER to quantify the effects of intake air temperature and, to a lesser extent, humidity, on engine performance metrics. While direct research on humidity effects within GT-POWER remains relatively limited, recent work shows that intake humidity can be incorporated into simulations by adjusting intake gas composition and boundary conditions enabling studies that more closely mirror experimental conditions.

2.6 Summary and Research Gap

This chapter has reviewed and synthesized existing studies related to volumetric efficiency in spark ignition (SI) engines, with particular focus on the effects of intake air temperature, humidity, and their combined influence. Volumetric efficiency is widely recognised as a fundamental performance parameter that governs the breathing capability of an engine and directly affects power output, fuel consumption, and emissions.

The literature clearly establishes that intake air temperature exerts a dominant influence on volumetric efficiency by controlling air density and oxygen mass flow into the cylinder. A rise in intake temperature leads to a reduction in air density, thereby decreasing the amount of oxygen available for combustion and resulting in lower torque and power. These trends have been consistently observed across experimental investigations, analytical studies, and numerical simulations for naturally aspirated and boosted SI engines.

In contrast, intake air humidity primarily affects volumetric efficiency indirectly by altering the composition of intake air and displacing oxygen with water vapour. Although the direct effect of humidity on volumetric efficiency is generally smaller than that of temperature, humidity plays a critical role in modifying combustion characteristics, flame propagation, heat transfer, and emissions. Higher humidity levels are frequently associated with reduced NO_x emissions due to lower peak combustion temperatures but may also lead to a slight deterioration in combustion efficiency and brake output.

Importantly, the review highlights that air temperature and humidity rarely vary independently in real operating environments. Instead, they often change simultaneously, especially in tropical climates where high temperature is commonly accompanied by high humidity. Recent studies indicate that their combined effect on volumetric efficiency and engine performance is nonlinear and compounded, resulting in more pronounced degradation in engine breathing and output than when either factor is considered alone. This finding underscores the limitations of traditional correction models that treat temperature and humidity as independent variables.

From a methodological perspective, the literature demonstrates a wide range of approaches used to study volumetric efficiency and intake condition effects, including experimental engine test rigs, environmental chambers, and numerical modelling techniques such as zero-dimensional thermodynamic models, one-dimensional gas dynamic simulations, and computational fluid dynamics (CFD). Among these, one-dimensional engine simulation tools particularly GT-POWER have emerged as powerful platforms for predicting engine airflow, volumetric efficiency, and performance under various operating and boundary conditions.

GT-POWER has been extensively used in industry and academia to model intake and exhaust flow dynamics, predict torque and power characteristics, and optimise intake and valve timing configurations. More recent studies have demonstrated its capability to simulate the effects of intake air temperature and, to a lesser extent, humidity by modifying gas properties and boundary conditions. These capabilities make GT-POWER especially suitable for parametric investigations of environmental effects on volumetric efficiency, offering flexibility and repeatability that are difficult to achieve through experiments alone.

Overall, the literature provides strong evidence that intake air temperature and humidity significantly influence volumetric efficiency and engine performance. However, the manner in which these effects are represented, particularly in simulation-based frameworks, remains incomplete and fragmented. Despite the breadth of existing studies, several important research gaps have been identified that motivate the present work.

i. Limited Focus on Single-Cylinder SI Engines in Simulation-Based Studies

Most simulation studies involving volumetric efficiency and intake condition effects have focused on multi-cylinder automotive engines. Single-cylinder SI engines, which are widely used in motorcycles, portable generators, and small utility vehicles, have received comparatively less attention in simulation-based investigations. Due to their simpler geometry and stronger cyclic flow variations, single-cylinder engines are more sensitive to intake boundary conditions, making them particularly suitable for detailed parametric studies. There is a lack of comprehensive GT-POWER-based investigations dedicated specifically to single-cylinder SI engines under varying air temperature and humidity conditions.

ii. Insufficient Integration of Temperature and Humidity Effects in GT-POWER Studies

While numerous studies using GT-POWER have examined the influence of intake air temperature on engine performance, far fewer have incorporated humidity as an explicit modelling parameter. Moreover, most available works consider temperature and humidity separately rather than investigating their combined and interactive effects on volumetric efficiency. This represents a significant gap, as real-world ambient conditions involve simultaneous variations of both parameters.

iii. Limited Simulation-Based Studies on Humidity Effects

The effect of intake air humidity has traditionally been explored through experimental studies, with relatively limited adoption in engine simulation frameworks. Within GT-POWER applications, humidity is often neglected or simplified through standard air assumptions. There remains a lack of systematic simulation-based research that explicitly models moist air composition and evaluates its impact on airflow, volumetric efficiency, and engine breathing characteristics.

iv. Lack of Parametric Studies Under Tropical Climate Conditions

Most existing GT-POWER simulations are based on standard or temperate ambient conditions. There is a notable shortage of simulation studies that replicate tropical climate conditions, characterised by high temperature and high humidity, despite their prevalence in many regions including Southeast Asia. This gap limits the

applicability of current engine performance predictions to such environments and restricts the development of climate-adaptive engine design and calibration strategies.

v. Absence of Dedicated GT-POWER Frameworks for Volumetric Efficiency as the Primary Performance Metric

Many GT-POWER studies treat volumetric efficiency as a secondary output while focusing on torque, fuel consumption, or emissions. There is a lack of studies that position volumetric efficiency as the central performance parameter and systematically investigate how it varies with intake air temperature and humidity through controlled simulation-based parametric analysis.

CHAPTER 3
METHODOLOGY

3.1 Introduction

This chapter presents the research methodology adopted to investigate the influence of intake-air temperature and relative humidity on the performance of a single-cylinder spark-ignition (SI) engine. The methodology is structured to systematically quantify the effects of selected environmental and operating parameters on key engine performance responses, namely volumetric efficiency, brake torque, and brake power. A simulation-based approach is employed to ensure controlled variation of parameters and repeatable evaluation of performance under representative tropical operating conditions.

The overall research strategy integrates one-dimensional engine simulation, statistical design of experiments, response surface modelling, and optimisation techniques. This structured framework ensures that the research objectives outlined in Chapter 1 are addressed in a rigorous and traceable manner, while minimising experimental uncertainties and resource limitations typically associated with physical engine testing.

3.1.1 Overview of Research Methodology

The research methodology adopted in this study is based on a numerical simulation and statistical analysis framework as shown in Figure 3.1. A validated one-dimensional engine model of a single-cylinder SI engine is developed using GT-Power to simulate the air-handling, combustion, and performance characteristics of the engine. The simulation model allows independent control of intake-air temperature, relative humidity, and engine speed, which are selected as the primary input variables due to their significant influence on intake air density, combustion quality, and overall engine performance.

A full-factorial Design of Experiments (DOE) approach is implemented to systematically evaluate the individual and combined effects of the selected input parameters. The resulting simulation data are analysed using Response Surface Modelling (RSM) to establish regression models that describe the relationships between the input variables and engine performance responses. Statistical tools, including analysis of variance (ANOVA) and coefficient of determination (R^2), are employed to assess the significance and predictive accuracy of the developed models.

Subsequently, a multi-objective optimisation procedure is conducted to identify optimal operating conditions that maximise engine performance under tropical intake-air conditions. The integration of simulation, statistical modelling, and optimisation provides a comprehensive and efficient methodology for achieving the research objectives.

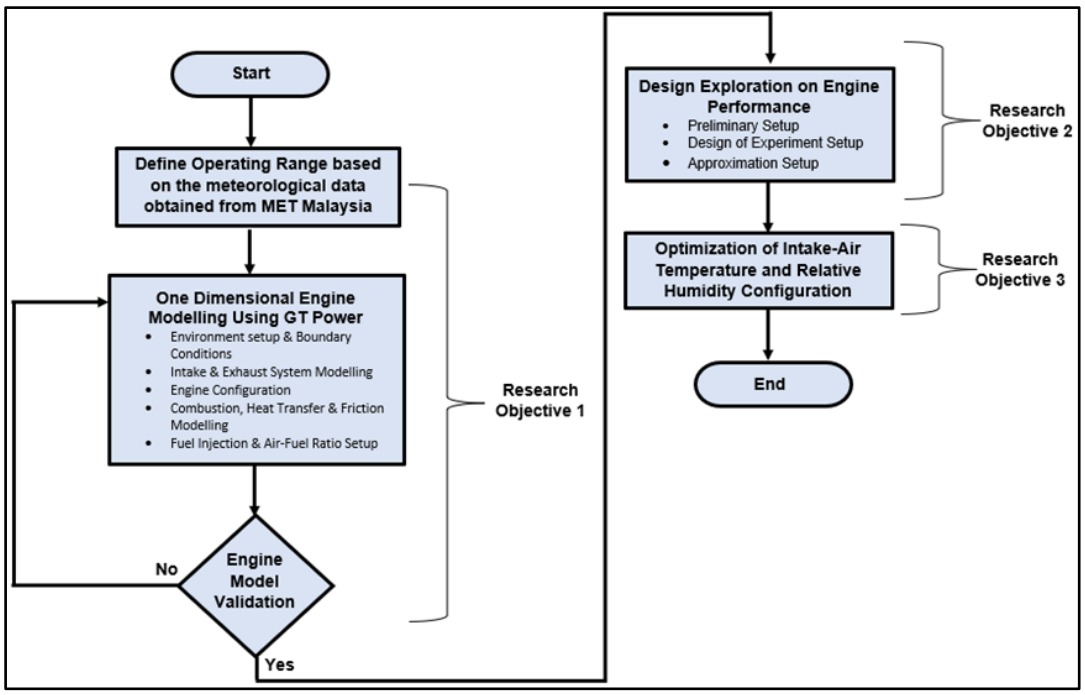


Figure 3.1 Research Methodology Framework

3.1.2 Research Workflow and Methodological Framework

The research workflow is designed to ensure logical progression from problem definition to performance optimisation. The methodological framework begins with the identification and the selection of relevant input parameters based on tropical

environmental conditions. These parameters are then incorporated into the development of the GT-Power engine simulation model.

Following model development, calibration and validation procedures are performed to ensure that the simulation outputs exhibit acceptable agreement with reference performance data. Once the GT-Power model is validated, the established simulation setup is used as the baseline engine model for the DOE study. The DOE matrix is generated in Altair HyperStudy, and each design point is executed by running the corresponding GT-Power simulation case with the specified intake-air temperature, relative humidity, and engine speed settings. The resulting response outputs are then extracted from GT-Power and recorded back into HyperStudy for systematic data compilation and subsequent statistical analysis.

The generated dataset is subsequently analysed using RSM to evaluate linear effects, interaction effects, and nonlinear response behaviour of the engine performance metrics. Based on the established response surfaces, optimisation studies are carried out to determine optimal combinations of intake-air temperature, relative humidity, and engine speed. The final stage of the methodology involves interpreting the results in the context of tropical engine operation and drawing conclusions that directly address the research objectives.

3.2 Definition of Operating Conditions and Input Parameters

The operating conditions and input parameters employed in this study were defined to reflect realistic environmental and operational scenarios encountered by small single-cylinder spark-ignition (SI) engines operating in tropical climates. The selection of intake-air temperature, relative humidity, and engine speed was based on regional meteorological observations, typical engine usage characteristics, and the requirements of a simulation-based investigation using GT-Power integrated with statistical design and optimisation tools.

The selected ranges and discrete input levels ensure comprehensive coverage of the observed climatic variability while maintaining balanced sampling suitable for

Design of Experiments (DOE) and Response Surface Modelling (RSM). This approach enables systematic evaluation of individual effects, interaction effects, and nonlinear trends on engine performance parameters.

3.2.1 Selection of Intake-Air Temperature and Relative Humidity Ranges

The selection of intake-air temperature and relative humidity ranges in this study was guided by meteorological observations representative of the Malaysian region and supported through descriptive statistical justification. The meteorological data obtained from METMalaysia (2019) are summarised in Table 3.1. These environmental variables were selected because they directly influence intake-air thermophysical properties, including density and oxygen availability, which subsequently affect cylinder filling behaviour and volumetric efficiency

Table 3.1
Average Temperature and Humidity in Malaysia for 2019

State	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
	Temperature (˚C)	Humidity (%)	Temperature (˚C)	Humidity (%)	Temperature (˚C)	Humidity (%)	Temperature (˚C)	Humidity (%)	Temperature (˚C)	Humidity (%)	Temperature (˚C)	Humidity (%)	Temperature (˚C)	Humidity (%)	Temperature (˚C)	Humidity (%)	Temperature (˚C)	Humidity (%)	Temperature (˚C)	Humidity (%)	Temperature (˚C)	Humidity (%)	Temperature (˚C)	Humidity (%)
Johor	29	78	30	75	30	72	**31**	73	**31**	73	29	79	29	77	30	73	29	72	30	73	29	78	28	84
Melaka	29	75	29	73	30	72	30	73	30	72	29	77	29	78	29	76	28	74	29	73	28	79	28	81
Negeri Sembilan	29	80	30	77	30	76	30	80	30	76	29	81	29	78	29	76	29	73	29	79	29	83	28	84
Wilayah Persekutuan	30	72	**31**	71	**31**	69	**31**	73	**31**	70	30	74	30	72	30	69	30	**68**	30	73	30	75	29	76
Selangor	29	77	30	76	30	75	30	78	30	75	29	77	29	76	29	74	28	73	29	76	28	78	28	79
Pahang	28	78	28	78	29	74	30	75	**31**	75	30	79	29	80	29	81	28	80	29	78	28	84	**26**	85
Perak	27	77	28	76	29	74	29	79	30	77	28	81	27	83	27	80	**26**	80	**26**	86	**26**	85	**26**	84
Penang	28	75	30	75	30	72	**31**	72	30	73	30	76	29	77	30	75	28	76	28	79	28	79	28	79
Kedah	28	78	30	73	**31**	69	**31**	74	30	76	29	80	29	79	29	78	28	79	29	80	28	82	28	78
Perlis	28	77	30	73	**31**	69	**31**	73	**31**	74	29	76	29	75	29	75	28	77	28	79	28	81	28	77
Kelantan	27	83	27	80	28	76	30	76	30	76	29	79	29	78	29	78	27	80	28	79	27	83	**26**	82
Terengganu	27	81	27	80	28	76	30	74	30	72	29	78	29	80	29	80	27	81	28	78	28	82	**26**	82
Sabah	29	72	29	70	29	71	30	72	**31**	69	30	74	29	75	29	72	28	72	28	76	28	77	28	80
Sarawak	28	88	28	88	29	83	30	83	**31**	80	30	83	29	80	30	77	29	77	28	87	28	88	27	**92**

Meteorological data indicate that ambient air temperature varies within a relatively narrow range of 26°C to 31°C, with values frequently clustering near the upper bound. This observation provides the basis for defining the lower and mid-range intake-air temperature conditions adopted in the simulation. To represent realistic engine operating scenarios, the temperature range was conservatively extended beyond the observed ambient maximum to 34°C. This extension is methodologically justified to account for intake-air heating effects associated with engine heat soak, under-hood thermal accumulation, and reduced cooling airflow during prolonged or low-speed operation. Accordingly, the intake-air temperature range adopted in this study was defined as 26°C to 34°C.

In contrast, relative humidity exhibits a wider variability under tropical climatic conditions. Meteorological observations show that relative humidity ranges from 68% to 92%, indicating consistently high moisture content and meaningful relative humidity fluctuations. Based directly on these recorded values, the relative humidity range adopted in the simulation was defined as 68% to 92%, with no extrapolation beyond the measured ambient limits. This approach ensures that the relative humidity conditions investigated remain representative of the natural operating environment.

To support a statistically robust Design of Experiments (DOE) framework and enable regression-based Response Surface Modelling (RSM), both temperature and relative humidity were discretised into uniformly spaced levels across their respective ranges. Intake-air temperature was defined at five levels: 26, 28, 30, 32, and 34°C, while relative humidity was defined at five levels: 68%, 74%, 80%, 86%, and 92%. Uniform discretisation ensures balanced sampling of the design space, reduces bias toward dominant ambient conditions, and improves the stability of regression development and ANOVA-based factor significance evaluation.

3.2.2 Engine Speed Operating Range

The engine speed range was selected to represent typical operating conditions of small single-cylinder SI engines used in light-duty applications such as motorcycles

and portable power units. These engines commonly operate within a moderate speed range during steady-state and urban usage.

In this study, engine speed was varied between 2500 rpm and 4500 rpm. The lower limit represents low-speed operation where intake flow inertia and cylinder filling efficiency are limited, while the upper limit corresponds to higher-speed conditions where dynamic intake effects become more pronounced. This speed range enables assessment of speed-dependent performance characteristics as well as interaction effects with intake-air temperature and relative humidity.

3.3 One-Dimensional Engine Modelling Using GT-Power

A one-dimensional (1-D) engine simulation approach was adopted in this study to evaluate the effects of intake-air temperature and relative humidity on the performance of a single-cylinder spark-ignition (SI) engine. GT-Power was selected due to its established capability in predicting gas exchange, combustion, and engine performance characteristics with reasonable computational efficiency. The 1-D modelling approach enables systematic parametric analysis while maintaining sufficient physical fidelity for performance-oriented investigations.

3.3.1 Overview of GT-Power Simulation Framework

GT-Power is a one-dimensional (1-D) engine simulation software within the GT-Suite platform that solves the conservation equations of mass, momentum, and energy along discretised flow paths representing the intake and exhaust systems. The engine model is developed using interconnected components that represent physical elements such as cylinders, pipes, valves, injectors, and boundary conditions, enabling prediction of time-dependent gas dynamics including pressure wave propagation, mass flow behaviour, and heat transfer effects. In the present study, the GT-Power simulation framework comprises an intake boundary, intake piping, cylinder and valve train components, exhaust piping, and an exhaust boundary to evaluate the influence of intake-air temperature and relative humidity on the breathing characteristics of a single-

cylinder spark-ignition engine at controlled operating speeds. Figure 3.2 illustrates the one-dimensional engine simulation framework adopted in this study. Each simulation case is conducted under steady-state conditions, and the solver computes cycle-resolved pressure, temperature, and mass-flow variations to predict key performance responses such as volumetric efficiency, brake torque, and brake power for direct comparison across different combinations of intake-air conditions and engine speed.

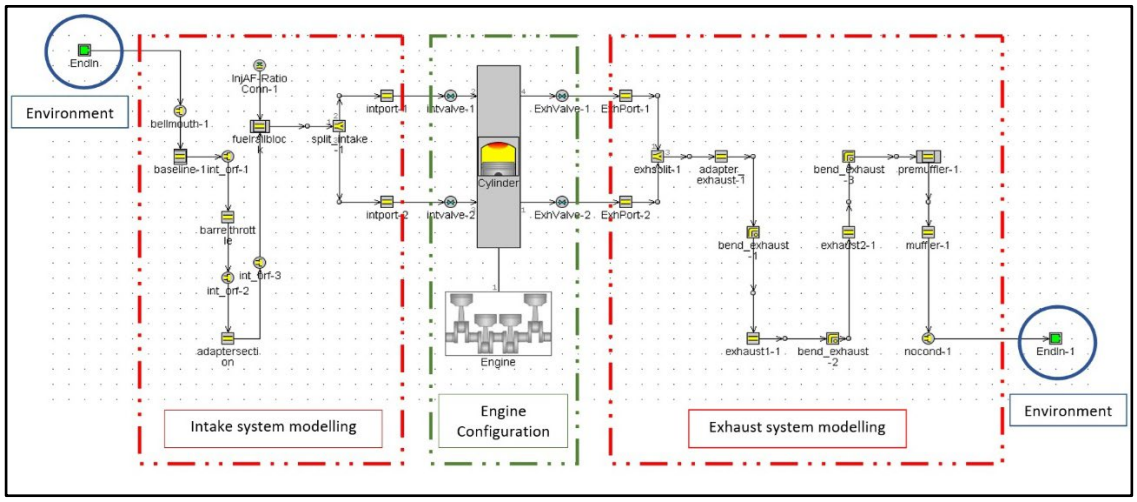


Figure 3.2 Workflow GT-Power

3.3.2 Environment Setup and Boundary Conditions

To ensure consistency, repeatability, and controlled comparison across all simulation cases, several assumptions and boundary conditions were applied. All simulations were conducted under steady-state operating conditions, and transient effects were not considered. Ambient pressure was fixed at 1 bar, representing naturally aspirated engine operation. While the temperature and relative humidity will be setup as design variable.

The intake air (N_2 is 76.7% and O_2 is 23.3%) was assumed to be homogeneous, with temperature and relative humidity uniformly prescribed at the intake boundary. Fuel properties were defined using the Indolene-combustion fuel model available in the GT-Power reference library, representing gasoline fuel characteristics. Combustion, heat transfer, and friction models were maintained constant for all cases, and no changes

were made to engine geometry or hardware configuration throughout the parametric study.

These assumptions ensure that any observed variations in volumetric efficiency, brake torque, and brake power are attributable solely to changes in intake-air temperature, relative humidity, and engine speed.

3.3.3 Intake and Exhaust System Modelling

The intake and exhaust flow paths were constructed using one-dimensional pipe network elements to represent gas transport between the boundaries and the cylinder. Straight duct section was modelled using the Pipe object. The pipe element, key geometric and physical properties, including diameter, length, and surface roughness, were specified to account for wave propagation, flow resistance, frictional losses, and gas dynamic effects along the flow path. The inlet and outlet boundary conditions were defined using the EndEnvironment object, where ambient pressure and intake-air properties were prescribed.

In the present study, the intake system consists of an inlet boundary at which intake-air temperature and relative humidity are specified, followed by intake piping and valve connection elements leading to the cylinder as shown in Figure 3.3. Initial flow conditions were assigned using the FStateInit template to define the starting temperature, pressure, and mixture composition within the pipe network, while junction and branching sections were modelled using the FsplitGeneral object to enable multiple flow connections where required. Similarly, the exhaust system comprises exhaust valve components, exhaust piping, and an outlet boundary representing atmospheric discharge, with exhaust boundary conditions maintained constant throughout the study as shown in Figure 3.4. This modelling configuration enables the simulation to capture the influence of intake-air conditions on cylinder filling behaviour, gas exchange efficiency, and overall engine breathing characteristics.

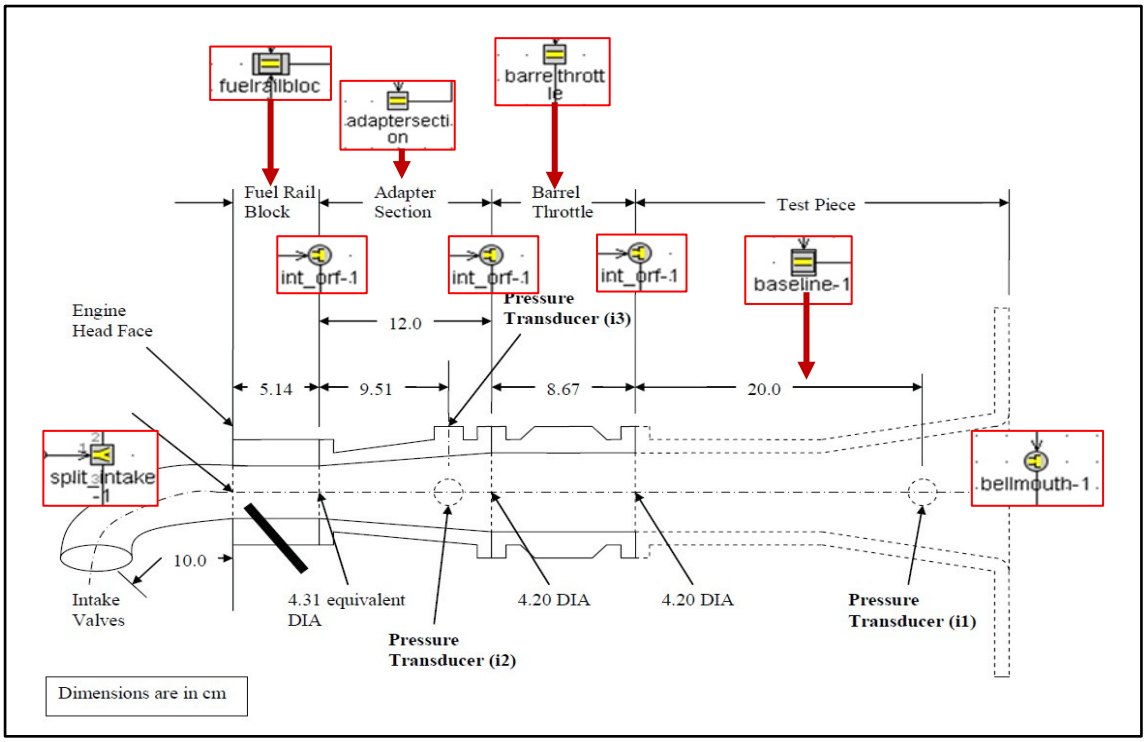


Figure 3.3 Intake System Modelling

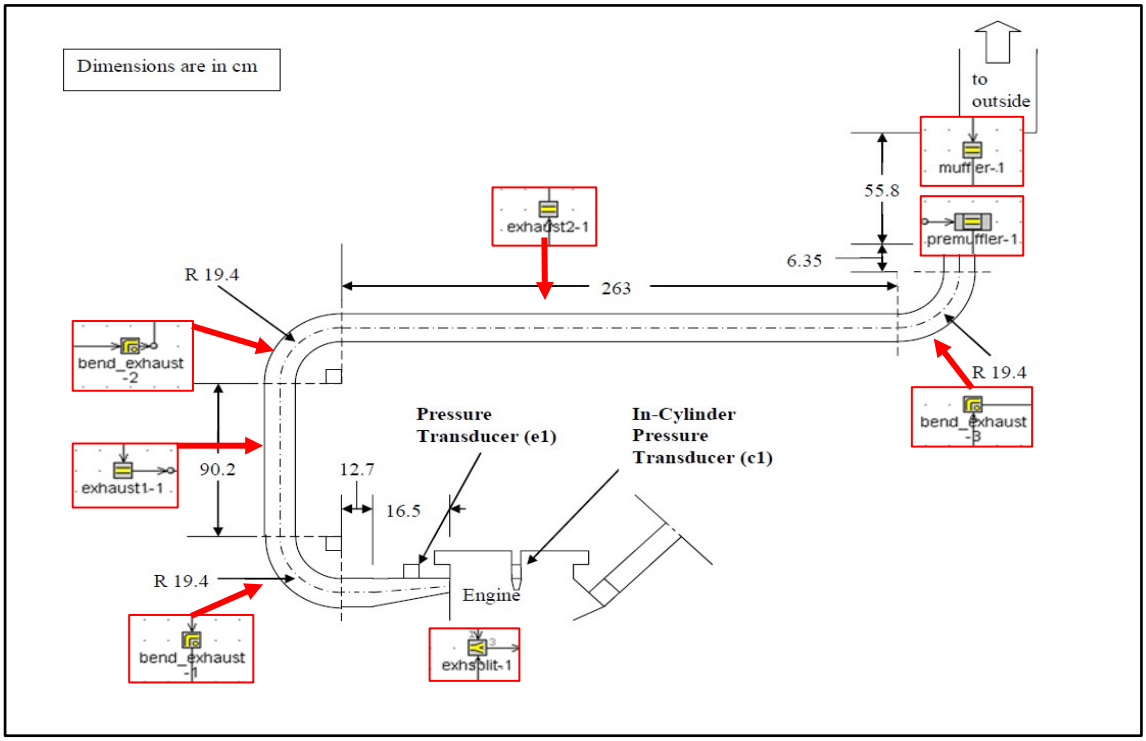


Figure 3.4 Exhaust System Modelling

3.3.4 Single-Cylinder Spark-Ignition Engine Configuration

A naturally aspirated, four-stroke, single-cylinder spark-ignition (SI) engine model was developed in GT-Power using standard engine component templates. The engine is represented by core objects that define cylinder thermodynamics, crank-train kinematics, and valve flow connections. The cylinder, modelled using the EngCylinder object, defines the combustion chamber volume, compression ratio, and thermodynamic state of the working fluid throughout the engine cycle. Valve timing events, including intake and exhaust valve opening and closing, were specified based on representative engine characteristics, while the crank-train component, represented by the EngineCrankTrain object, governs engine rotational speed and cycle timing. These components were linked using predefined connection templates to ensure correct cylinder indexing and cycle synchronisation, with valve-train elements controlling mass flow into and out of the cylinder. Where detailed manufacturer data were unavailable, standard assumptions consistent with small-displacement SI engines were adopted. The engine geometry and base operating parameters were maintained constant for all simulation cases to ensure that observed performance variations are attributable primarily to changes in intake-air temperature, relative humidity, and engine speed. The engine specifications utilized in this study are detailed in Table 3.2.

Table 3.2
Specifications of The Single-Cylinder Engine (Mariucci, 2006)

No	Name	Specification
1	Engine Bore	8.9 cm
2	Engine Stroke	7.95 cm
3	Connecting Rod Length	13.81 cm
4	Engine Compression Ratio	10.5:1
5	Engine Clearance Volume	47.10 cm^3
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

3.3.5 Combustion, Heat Transfer, and Friction Modelling

Combustion within the cylinder was modelled using a spark-ignition turbulent combustion approach in GT-Power, where the rate of heat release is defined as a function of crank angle to reproduce representative in-cylinder pressure and temperature histories. The combustion model was implemented using the EngCylCombSITurb object, with combustion phasing and burn duration specified based on the baseline engine configuration. To ensure a controlled parametric investigation, all combustion-related settings were maintained consistently across simulation cases so that performance variations could be attributed primarily to changes in intake-air temperature, relative humidity, and engine speed.

Heat transfer between the working gas and the cylinder walls was modelled using the EngCylHeatTr convective heat-transfer template, while the cylinder wall thermal boundary conditions were assigned using the EngCylTWall model. These heat transfer settings were applied uniformly across all cases to maintain consistency in thermal behaviour throughout the simulation runs. Mechanical friction losses were represented using the friction model embedded within the EngineCrankTrain object, referenced through the EngFrictionCF template, which accounts for speed-dependent mechanical losses in terms of friction mean effective pressure (FMEP). Maintaining consistent combustion, heat transfer, and friction modelling assumptions across all simulations ensures that the observed changes in volumetric efficiency and engine performance outputs are predominantly driven by the selected intake-air conditions and operating speed variations.

3.3.6 Fuel Injection and Air–Fuel Ratio Setup

Fuel injection was modelled using a port-fuel injection configuration, where fuel is introduced upstream of the intake valve. The injection system was implemented using the InjAF-RatioConn template, which allows the specification of injector characteristics and air–fuel ratio (AFR) control. Fuel properties were defined using the Indolene-combustion fuel model available in the GT-Power reference library to represent typical

gasoline behaviour, thereby ensuring consistent fuel thermophysical properties across all simulation runs as shown in Table 3.3.

Table 3.3
Fuel Properties

Attributes	**Unit**	**Value**
Lower Heating Value	kJ/kg	43000
Critical Temperature	K	568.8
Critical Pressure	bar	24.9
Air Fuel Ratio	-	12.5 : 1

To eliminate mixture strength as a confounding variable, the AFR was maintained at a constant stoichiometric condition for all simulation cases. The injected fuel mass flow rate was adjusted automatically by the solver to preserve the specified AFR under varying intake-air density conditions associated with changes in intake-air temperature and relative humidity. This approach ensures that observed changes in engine performance are primarily attributable to variations in intake-air conditions and engine speed, rather than changes in mixture composition.

3.4 Model Calibration and Validation Strategy

Model calibration and validation were conducted to ensure that the developed one-dimensional (1-D) GT-Power engine model provides reliable, stable, and physically representative predictions of engine performance. Since the present work is simulation-based and does not involve extensive experimental testing, calibration was required to establish confidence in the baseline model prior to conducting parametric variation studies. Baseline simulation outputs were examined using GT-Post, and calibration was performed based on established spark-ignition (SI) engine behaviour and benchmark performance characteristics reported in the literature. The validation strategy was designed to confirm that the model produces realistic output magnitudes and consistent performance trends across the selected operating conditions.

The calibration and validation processes were completed prior to the Design of Experiments (DOE) and optimisation stages to ensure that subsequent statistical analyses were performed using a credible and numerically stable baseline engine model.

3.4.1 Calibration Parameters and Tuning Approach

In this study, calibration refers to the systematic tuning of selected uncertain GT-Power sub-model parameters to establish a stable and physically representative baseline engine model. In contrast, validation refers to evaluating the credibility of the calibrated model by comparing its predicted outputs with independent reference data reported in the literature, ensuring that the simulated magnitudes and trends are realistic over the intended operating range.

GT-Power is a comprehensive engine simulation platform that requires numerous input parameters, some of which are difficult to obtain experimentally without detailed manufacturer specifications or extensive engine testing. Therefore, when complete engine data are unavailable, model calibration is commonly performed through systematic adjustment of key influential parameters to improve prediction reliability. In this study, calibration of the baseline intake configuration was performed to establish a credible reference model prior to evaluating the effects of intake-air temperature and relative humidity.

Model calibration was carried out by tuning selected sub-model parameters that significantly influence in-cylinder thermodynamics, gas exchange behaviour, and overall engine breathing characteristics. The objective of calibration was to obtain realistic predictions of volumetric efficiency, brake torque, and brake power across the investigated engine speed range.
The key calibration parameters adopted in this study include:

i. In-cylinder temperature (TEMP_CYL, speed-dependent)
ii. Initial cylinder temperature (TEMP_INIT, speed-dependent)
iii. Crank angle of start of combustion (CAB, speed-dependent)
iv. Engine friction (friction, constant)

v. Convection heat transfer multiplier (CONVEC_M, constant)

Calibration was conducted iteratively by adjusting these parameters within physically acceptable limits until the baseline model demonstrated stable convergence and consistent performance trends with respect to engine speed. Once satisfactory baseline behaviour was achieved, the tuned parameters were fixed and maintained constant throughout the DOE simulations. This approach ensures that variations in predicted performance responses are attributable primarily to changes in intake-air temperature, relative humidity, and engine speed, rather than to changes in calibration settings.

3.4.2 Heat Transfer and Initial Condition Calibration

The parameters TEMP_CYL and CONVEC_M govern heat transfer between the in-cylinder gas and the cylinder wall. These parameters primarily affect the magnitude of volumetric efficiency and brake performance curves, while the overall trend remains largely unchanged. Increasing TEMP_CYL or CONVEC_M increases the in-cylinder gas temperature, which reduces air density and subsequently decreases volumetric efficiency and brake power. In this study, CONVEC_M was set to 1.0, and TEMP_CYL was defined as a speed-dependent array based on the baseline calibration procedure.

The parameter TEMP_INIT defines the initial cylinder temperature at the start of the simulation cycle. Although TEMP_INIT does not significantly change the overall performance trend, it influences predicted magnitudes through its effect on in-cylinder pressure and gas dynamic behaviour during the intake process. As TEMP_INIT increases, the in-cylinder pressure rises, affecting intake wave propagation and reflection. Under favourable timing, reflected compression waves may enhance cylinder filling, resulting in increased volumetric efficiency.

3.4.3 Combustion Phasing and Friction Calibration

Combustion phasing was controlled through the crank angle of start of burn (CAB), which influences peak cylinder pressure timing and the effective work transfer during the engine cycle. If combustion begins too early, additional compression work may be imposed on the piston near the end of the compression stroke. Conversely, late combustion initiation reduces peak cylinder pressure and limits expansion work output. Therefore, CAB was calibrated as a speed-dependent parameter to achieve physically consistent brake performance behaviour across the investigated operating range.

Mechanical friction losses were represented using the EngFrictionCF template. The friction setting was defined as 0.4 bar, which lies within the recommended range suggested in GT-Power modelling guidelines. This parameter mainly affects the magnitude of brake power output through its influence on brake mean effective pressure (BMEP), torque, and brake power. To ensure consistent comparison across simulation cases, the friction parameter was maintained constant throughout the study.

3.4.4 Ambient and Fuel Settings

Baseline ambient conditions were specified as 1 bar and 300 K, representing naturally aspirated operation under standard conditions. Fuel properties were defined using the Indolene-combustion fuel object available in the GT-Power library, representing gasoline-like characteristics. The fuel heating value and density were set to 43,000 kJ/kg and 750 kg/m³, respectively, to maintain consistency in combustion energy input throughout the simulation runs.

3.4.5 Reference Data and Model Validation

Model validation was performed by correlating the baseline simulation outputs against the findings of V. Mariucci et al. (Mariucci, 2006). As shown in Table 3.4, the baseline model results exhibited a difference of less than 5% compared with Mariucci's experimental baseline geometry, indicating good agreement and supporting the

accuracy of the GT-Power simulation setup. The objective of this validation was not to replicate a specific engine configuration exactly, but to ensure that the developed model demonstrates realistic output magnitudes, correct torque–speed and power–speed trends, and physically consistent behaviour under varying operating conditions.

Table 3.4
Validation Result for Baseline Intake

Engine Speed, RPM	Volumetric efficiency, % (Experiment) Mariucci, 2006	Volumetric efficiency, % (Simulation)	Difference, %
1000	87.0	86.4	0.7
1500	93.0	92.2	0.9
2000	85.0	84.0	1.2
2250	85.5	84.6	1.1
2500	92.0	91.6	0.4
2750	91.0	90.0	1.1
3000	103.5	103.5	0.0
3250	100.0	99.5	0.5
3500	101.0	102.2	1.2
3750	111.0	106.8	3.8
4000	100.0	100.0	0.0
4250	95.0	93.9	1.2
4500	98.5	96.8	1.7
4750	100.5	101.4	0.9
5000	95.0	96.7	1.8
5250	85.0	85.6	0.7
5500	81.0	81.6	0.7

Validation quality was further assessed based on trend consistency, physical plausibility, numerical stability, and acceptable agreement with reference performance values. The model was evaluated to confirm that predicted variations in volumetric efficiency, brake torque, and brake power across the operating speed range are consistent with established spark-ignition (SI) engine performance characteristics. In

addition, the model response to intake-air temperature and relative humidity variations was verified to remain physically reasonable, including the expected reduction in intake-air density at elevated temperatures and the influence of relative humidity on intake-air composition.

Stable convergence and repeatable outputs were achieved across the full range of operating conditions considered in this study. Upon satisfying these validation requirements, the GT-Power model was deemed sufficiently accurate and reliable for executing the DOE-based simulation runs and supporting the subsequent statistical modelling and optimisation analyses.

3.5 Design Exploration on Engine Performance

In this study, the design exploration of intake-air temperature, relative humidity, and engine speed was carried out using the Altair HyperStudy framework as the primary design exploration and optimisation platform. A validated GT-Power one-dimensional engine simulation model was employed to evaluate the influence of intake-air temperature, relative humidity, and engine speed on volumetric efficiency, brake torque, and brake power. The investigation was aimed at understanding how variations in intake-air conditions and operating speed affect engine breathing and brake performance, and subsequently identifying the operating combination that provides improved engine performance.

The design exploration was implemented using a sequential methodology comprising:

i. Preliminary Setup
ii. Design of Experiment Setup
iii. Approximation Setup
iv. Optimization Setup

3.5.1 Preliminary Setup

A GT-Power simulation model was developed to represent the single-cylinder spark-ignition engine operating under naturally aspirated conditions. The model was validated to establish a credible baseline configuration before performing parametric variation studies. In this study, intake-air temperature, relative humidity, and engine speed were parameterised to enable systematic variation of the selected design variables.

The selection of design variables was guided by the research objectives and the operating conditions defined in sub-chapter 3.2. Three factors were selected as primary input variables due to their direct influence on intake-air density, cylinder filling behaviour, and combustion performance. The selected parameter levels are summarised in Table 3.5.

Table 3.5
Parameter Design for Full Factorial Analysis

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

3.5.2 Design of Experiment (DOE) Setup

Design of Experiments (DOE) is a systematic analytical approach in which controlled variations are applied to selected input parameters to quantify their influence on system responses. The outcomes of DOE facilitate identification of dominant factors and interaction effects governing system behaviour. Furthermore, the response data generated from DOE are used to develop an approximation (surrogate) model, which provides an efficient representation of the system response for subsequent statistical evaluation and optimisation.

Various DOE strategies are available in engineering applications, including Full Factorial, Fractional Factorial, Plackett–Burman, Central Composite, Box–Behnken, Latin Hypercube, Hammersley, and user-defined experimental designs. In this study, a full factorial DOE method was adopted to ensure complete coverage of the design space. A 5 × 5 × 3 full factorial design consisting of 75 design combinations was employed as shown in Table 3.6. Each design combination was analysed using the GT-Power solver to obtain the corresponding engine performance responses.

The response outputs recorded for each DOE run were:

i. Volumetric efficiency (VE)
ii. Brake torque (BT)
iii. Brake power (BP)

Table 3.6
DOE Combination Test (5 x 5 x 3 Full Factorial Design)

Run	Intake-air Temperature	Relative Humidity	Engine Speed
1	Low	Low	Low
2	Low	Low	Mid
3	Low	Low	High
4	Low	Mid	Low
5	Low	Mid	Mid
6	Low	Mid	High
7	Low	High	Low
8	Low	High	Mid
9	Low	High	High
10	Mid	Low	Low
11	Mid	Low	Mid
12	Mid	Low	High
13	Mid	Mid	Low
14	Mid	Mid	Mid
15	Mid	Mid	High
16	Mid	High	Low
17	Mid	High	Mid

18	Mid	High	High
19	High	Low	Low
20	High	Low	Mid
21	High	Low	High
22	High	Mid	Low
23	High	Mid	Mid
24	High	Mid	High
25	High	High	Low
26	High	High	Mid
27	High	High	High
28	Low	Low	Low
29	Low	Low	Mid
30	Low	Low	High
31	Low	Mid	Low
32	Low	Mid	Mid
33	Low	Mid	High
34	Low	High	Low
35	Low	High	Mid
36	Low	High	High
37	Mid	Low	Low
38	Mid	Low	Mid
39	Mid	Low	High
40	Mid	Mid	Low
41	Mid	Mid	Mid
42	Mid	Mid	High
43	Mid	High	Low
44	Mid	High	Mid
45	Mid	High	High
46	High	Low	Low
47	High	Low	Mid
48	High	Low	High
49	High	Mid	Low
50	High	Mid	Mid

51	High	Mid	High
52	High	High	Low
53	High	High	Mid
54	High	High	High
55	Low	Low	Low
56	Low	Low	Mid
57	Low	Low	High
58	Low	Mid	Low
59	Low	Mid	Mid
60	Low	Mid	High
61	Low	High	Low
62	Low	High	Mid
63	Low	High	High
64	Mid	Low	Low
65	Mid	Low	Mid
66	Mid	Low	High
67	Mid	Mid	Low
68	Mid	Mid	Mid
69	Mid	Mid	High
70	Mid	High	Low
71	Mid	High	Mid
72	Mid	High	High
73	High	Low	Low
74	High	Low	Mid
75	High	Low	High

3.5.3 Approximation Setup

The response data obtained from the DOE analysis were used to develop a mathematical representation of the system behaviour expressed as a function of the selected design variables. This representation, commonly referred to as a response surface model (RSM), provides an efficient means of describing the relationship between the input parameters and the corresponding responses. Once established, the

response surface model can be used as a surrogate for the GT-Power simulation model, allowing rapid prediction of responses for new combinations of design variables without repeatedly executing full simulations.

Altair HyperStudy provides several response surface fitting techniques, including Least Squares Regression (LSR), Moving Least Squares Regression (MLSM), HyperKriging (HK), and Radial Basis Function (RBF). In this study, a Least Squares Regression (LSR) approach with a full quadratic formulation was adopted to minimise the cumulative squared error between predicted responses and the corresponding DOE simulation outputs.

The predictive accuracy of the developed regression models was evaluated using the coefficient of determination (R^2). Values of R^2 close to unity indicate strong agreement between the fitted models and simulation data, reflecting good model fidelity. In this study, high R^2 values were obtained for the volumetric efficiency, brake torque, and brake power models, confirming that the developed response surfaces accurately represent the underlying GT-Power simulation results.

In addition, Analysis of Variance (ANOVA) was performed to evaluate the statistical significance of the main factors and their interaction effects on the engine performance responses. Factors with p-values less than 0.05 (95% confidence level) were considered statistically significant contributors to response behaviour.

3.5.4 Optimization Setup

Optimisation analysis was conducted to determine the optimal combination of design variables that enhances engine performance by maximising selected objective functions while satisfying the prescribed operating constraints. In this study, the optimisation problem was formulated using intake-air temperature, relative humidity, and engine speed as the design variables. The optimisation objectives were defined as the maximisation of:

i. Volumetric efficiency (VE)

ii. Brake torque (BT)
iii. Brake power (BP)

Optimisation can be performed either by directly executing the simulation model at each iteration or by using an approximation model developed from DOE results. In this study, a fit-based optimisation approach was adopted to reduce computational effort. Accordingly, the response surface models developed during the approximation stage were used as surrogate models for evaluating the optimisation objectives.

During the optimisation process, candidate design configurations were generated within the predefined design space, and the corresponding performance responses were evaluated using the surrogate models. The optimisation procedure was continued iteratively until convergence criteria were satisfied, based on stabilisation of objective function values or attainment of the maximum allowable number of iterations.

Upon convergence, the optimal intake-air temperature, relative humidity, and engine speed configuration was identified as the design that maximises the selected engine performance responses. The predicted optimum solution was subsequently verified using the GT-Power simulation model to confirm the performance improvement and validate the reliability of the optimisation results.

3.6 Summary of Research Methodology

This chapter has presented a structured and simulation-based research methodology developed to investigate the effects of intake-air temperature and relative humidity on the performance of a single-cylinder spark-ignition engine operating under tropical conditions. The methodology integrates one-dimensional engine modelling, statistical design of experiments, response surface modelling, and optimisation techniques to ensure a systematic and repeatable analysis.

A one-dimensional GT-Power engine model was developed to simulate the gas exchange, combustion, and performance characteristics of the engine. Realistic

operating ranges for intake-air temperature, relative humidity, and engine speed were defined based on meteorological data and engineering considerations. The model was calibrated and validated using reference performance characteristics to ensure physically consistent behaviour prior to parametric analysis.

A Design of Experiments approach was implemented using Altair HyperStudy to systematically vary the selected input parameters and generate a comprehensive dataset of engine performance responses. Statistical analysis and response surface modelling were subsequently employed to quantify the influence of individual factors and interaction effects on volumetric efficiency, brake torque, and brake power. The developed regression models demonstrated strong predictive capability and provided a reliable basis for performance evaluation.

Finally, an optimisation study was conducted to identify optimal intake-air and operating conditions within realistic constraints, enabling assessment of performance trade-offs under tropical environments. The adopted methodology ensures that the analysis is statistically robust, computationally efficient, and directly aligned with the research objectives. The results obtained using this methodology are presented and discussed in detail in the following chapter.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the main analytical phase of the study by evaluating the influence of intake-air temperature and relative humidity on the performance of a naturally aspirated spark-ignition engine using GT-Power simulation outputs. The analysis focuses on three key performance responses: volumetric efficiency (VE), brake power (BP), and brake torque (BT) that is evaluated over the investigated engine speed range. These responses were selected because they are directly affected by changes in intake-air properties which govern cylinder filling, combustion potential, and brake output under practical operating conditions.

The results presented in this chapter are based on simulation cases defined using meteorological conditions representative of Malaysia's tropical climate. Intake-air temperature is varied from 26°C to 34°C. Meanwhile, the relative humidity is varied from 68% to 92%, in accordance with the simulation workflow. The results are analysed across low and high engine speed conditions to capture speed-dependent effects on airflow dynamics, combustion behaviour, and brake performance.

In order to ensure consistency with the proposed methodology, the results are presented using a structured approach comprising DOE-based trend evaluation, response surface model (RSM) interpretation, and optimisation within the defined operating limits. Temperature and humidity effects are first discussed independently to establish their primary influence, followed by combined assessment to identify interaction behaviour and practical performance implications. The chapter concludes by identifying the most favourable intake-air conditions that maximise VE and improve BP and BT stability.

4.2 Model Validation

Model validation was carried out to evaluate the reliability of the developed GT-Power simulation model before conducting the DOE-based parametric analysis. In this study, the baseline simulation results were compared with the experimental baseline intake data reported by Mariucci (2006), as previously presented in Table 3-4. The validation focused on volumetric efficiency because this parameter directly represents the air-induction capability of the engine and strongly influences the prediction of brake torque and brake power.

Figure 4.1 shows the comparison between the experimental and simulated volumetric efficiency over the engine speed range from 1000 rpm to 5500 rpm. In general, the GT-Power simulation follows the experimental trend closely. The model captures the variation of volumetric efficiency at low, medium, and high engine speeds, including the increase in volumetric efficiency around the mid-speed range and the reduction at higher engine speeds. This agreement indicates that the developed model is able to reproduce the baseline intake behaviour with reasonable accuracy.

The percentage difference between the experimental and simulation results ranges from 0.0% to 3.8%, with an average difference of approximately 1.05%. The maximum difference occurs at 3750 rpm, where the experimental volumetric efficiency is 111.0%, while the simulation predicts 106.8%. Although this speed point shows the largest deviation, the difference remains below 5%. Therefore, the overall agreement is considered acceptable for a one-dimensional engine simulation model.

The small difference between the experimental and simulated results may be attributed to several factors, including simplification of the one-dimensional intake geometry, assumptions in boundary conditions, and the limited availability of detailed experimental engine parameters. Nevertheless, the simulated results remain physically consistent with spark-ignition engine behaviour. The model demonstrates realistic volumetric efficiency magnitudes and follows the expected speed-dependent trend.

Since volumetric efficiency governs the inducted air mass, the validation outcome provides confidence that the GT-Power model can reasonably predict engine

breathing behaviour under different intake-air temperature and relative humidity conditions. In addition, the model produced stable and repeatable outputs throughout the selected operating range. Therefore, the validated GT-Power model was considered suitable for the subsequent DOE analysis and for evaluating the effects of intake-air temperature and humidity on volumetric efficiency, brake power, and brake torque.

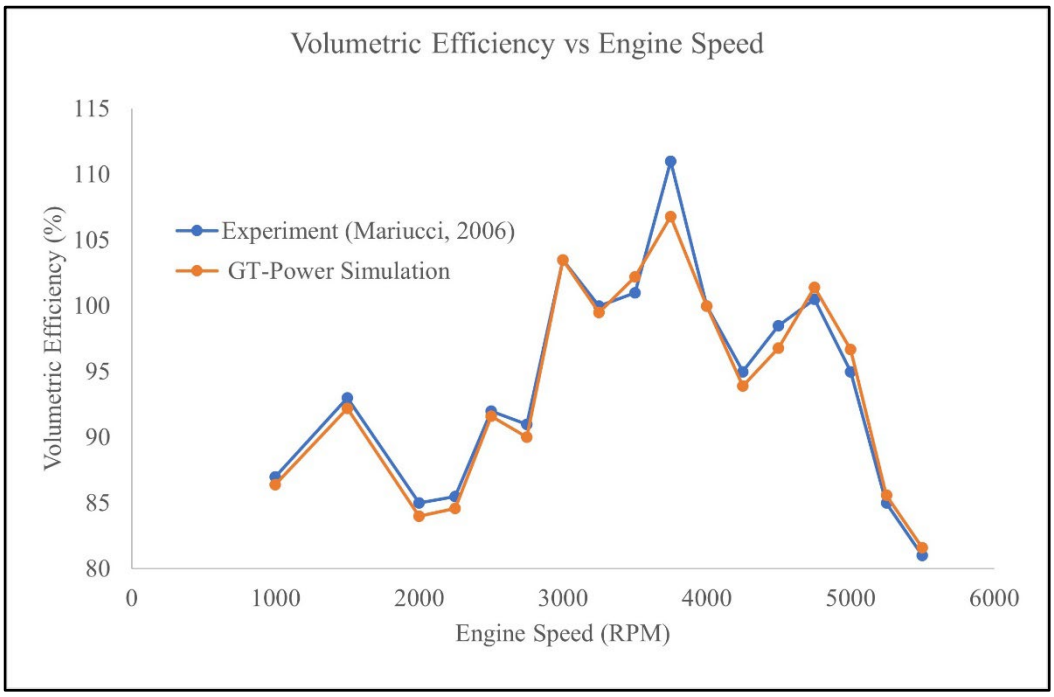


Figure 4.1 Model Validation Based on Volumetric Efficiency

4.3 Performance Analysis of Volumetric Efficiency (VE)

4.3.1 DOE Analysis on Volumetric Efficiency (VE)

In this section, the volumetric efficiency (VE) results obtained from the GT-Power simulation are presented and discussed based on the Design of Experiments (DOE) approach. The results were generated using the full factorial design implemented in the Altair HyperStudy framework. The main objective of this analysis is to evaluate how intake-air temperature, relative humidity, and engine speed influence the volumetric efficiency of a naturally aspirated spark ignition engine under tropical operating conditions. The investigated engine speeds were selected at 2500 rpm, 3500 rpm, and 4500 rpm. Meanwhile, intake-air temperature was varied from 26°C to 34°C

and relative humidity was varied from 68% to 92% to represent realistic meteorological conditions in Malaysia.

Based on the full factorial DOE design, a total of 75 simulation runs were executed. It consists of different combinations of engine speed, temperature, and humidity levels. The complete run matrix and corresponding VE responses are presented in Table 4.1. In the first set of simulations (Run 1 to Run 5), the engine speed was fixed at 2500 rpm and the intake-air temperature was maintained at 26°C while the humidity was varied from 68% to 92%. The results show that VE remained approximately constant at 0.92. It indicated that humidity produces a relatively small effect on VE at low engine speed when the intake temperature is maintained at its minimum level.

To evaluate the effect of intake-air temperature at the same engine speed, the temperature was increased progressively from 26°C to 34°C while maintaining the same humidity range. At 2500 rpm, VE decreased from 0.92 at 26°C (Run 1–Run 5) to approximately 0.89 at 34°C (Run 21–Run 25). This trend indicates that intake-air temperature has a stronger influence on VE than humidity under low-speed operation where the reduction in air density at higher temperature limits the inducted air mass and reduces cylinder filling effectiveness.

In the second engine speed level at 3500 rpm (Run 26 to Run 50), VE values were generally higher than those at 2500 rpm. At 26°C, VE was approximately 0.94 across the investigated humidity range (Run 26–Run 30). Similar behaviour was observed at 28°C, 30°C, and 32°C where VE remained close to 0.94 (Run 31–Run 45). Interestingly, at 34°C, VE increased slightly to approximately 0.95 (Run 46–Run 50). This indicates that the mid-speed operating condition demonstrates improved volumetric efficiency compared with low-speed operation which may be associated with enhanced intake inertia and improved breathing characteristics at higher engine speed.

In the final engine speed level at 4500 rpm (Run 51 to Run 75), the highest VE values were recorded. At 26°C, VE reached approximately 0.97 across the humidity range (Run 51–Run 55). When temperature was increased to 28°C, VE reduced slightly

to 0.96 (Run 56–Run 60). Further increases in temperature to 30°C and 32°C produced VE values around 0.96, with a small reduction observed at 32°C and 92% humidity (Run 70). At 34°C, VE decreased to approximately 0.95 across all humidity levels (Run 71–Run 75). Overall, the results show that engine speed is the dominant factor increasing VE, while intake-air temperature introduces a mild reduction at high speed. The influence of humidity remains comparatively smaller within the investigated range.

This DOE results demonstrate that volumetric efficiency increases with engine speed from 2500 rpm to 4500 rpm. The intake-air temperature produces a noticeable reduction in VE at low speed, whereas its effect becomes less pronounced at higher speed. Relative humidity shows minimal variation in VE compared with the other variables.

Table 4.1
Engine Speed Selection

Run	Engine Speed	Temperature	Relative Humidity	Volumetric Efficiency
1	2500	26	68	0.92
2	2500	26	74	0.92
3	2500	26	80	0.92
4	2500	26	86	0.92
5	2500	26	92	0.92
6	2500	28	68	0.91
7	2500	28	74	0.91
8	2500	28	80	0.91
9	2500	28	86	0.91
10	2500	28	92	0.91
11	2500	30	68	0.91
12	2500	30	74	0.91
13	2500	30	80	0.91
14	2500	30	86	0.90
15	2500	30	92	0.90
16	2500	32	68	0.90
17	2500	32	74	0.90
18	2500	32	80	0.90

19	2500	32	86	0.90
20	2500	32	92	0.90
21	2500	34	68	0.90
22	2500	34	74	0.89
23	2500	34	80	0.89
24	2500	34	86	0.89
25	2500	34	92	0.89
26	3500	26	68	0.94
27	3500	26	74	0.94
28	3500	26	80	0.94
29	3500	26	86	0.94
30	3500	26	92	0.94
31	3500	28	68	0.94
32	3500	28	74	0.94
33	3500	28	80	0.94
34	3500	28	86	0.94
35	3500	28	92	0.94
36	3500	30	68	0.94
37	3500	30	74	0.94
38	3500	30	80	0.94
39	3500	30	86	0.94
40	3500	30	92	0.94
41	3500	32	68	0.94
42	3500	32	74	0.94
43	3500	32	80	0.94
44	3500	32	86	0.94
45	3500	32	92	0.94
46	3500	34	68	0.95
47	3500	34	74	0.95
48	3500	34	80	0.95
49	3500	34	86	0.95
50	3500	34	92	0.95
51	4500	26	68	0.97

52	4500	26	74	0.97
53	4500	26	80	0.97
54	4500	26	86	0.97
55	4500	26	92	0.97
56	4500	28	68	0.97
57	4500	28	74	0.96
58	4500	28	80	0.96
59	4500	28	86	0.96
60	4500	28	92	0.96
61	4500	30	68	0.96
62	4500	30	74	0.96
63	4500	30	80	0.96
64	4500	30	86	0.96
65	4500	30	92	0.96
66	4500	32	68	0.96
67	4500	32	74	0.96
68	4500	32	80	0.96
69	4500	32	86	0.96
70	4500	32	92	0.95
71	4500	34	68	0.95
72	4500	34	74	0.95
73	4500	34	80	0.95
74	4500	34	86	0.95
75	4500	34	92	0.95

The effects of engine speed, intake-air temperature, and relative humidity on volumetric efficiency were analysed to identify the dominant contributors to engine breathing performance. Figure 4.2 shows that engine speed exhibits a strong positive influence on volumetric efficiency, indicating that it is the most influential factor within the investigated range. As engine speed increases from 2500 rpm to 4500 rpm, the volumetric efficiency increases markedly from approximately 0.91 to 0.96, which is consistent with improved intake inertia and enhanced cylinder filling at higher rotational speed. At elevated engine speed, the increased momentum of the incoming charge

reduces the relative impact of intake flow restrictions and pumping losses, resulting in improved volumetric efficiency.

In contrast, intake-air temperature shows a slight negative effect on volumetric efficiency. Increasing temperature leads to a small reduction in volumetric efficiency, with values decreasing from approximately 0.94 to 0.93, which can be attributed to the reduction in intake-air density at higher temperatures and the corresponding decrease in inducted air mass. Relative humidity produces the smallest variation in volumetric efficiency across the investigated range. The results remain relatively stable, indicating that the humidity effect is secondary compared with engine speed and temperature. Although higher humidity increases the water vapour content in the intake charge, the associated reduction in oxygen concentration and air density is comparatively small within the selected humidity range. Overall, the results confirm that engine speed is the dominant parameter governing volumetric efficiency, while temperature introduces a mild reduction and humidity has a comparatively limited influence.

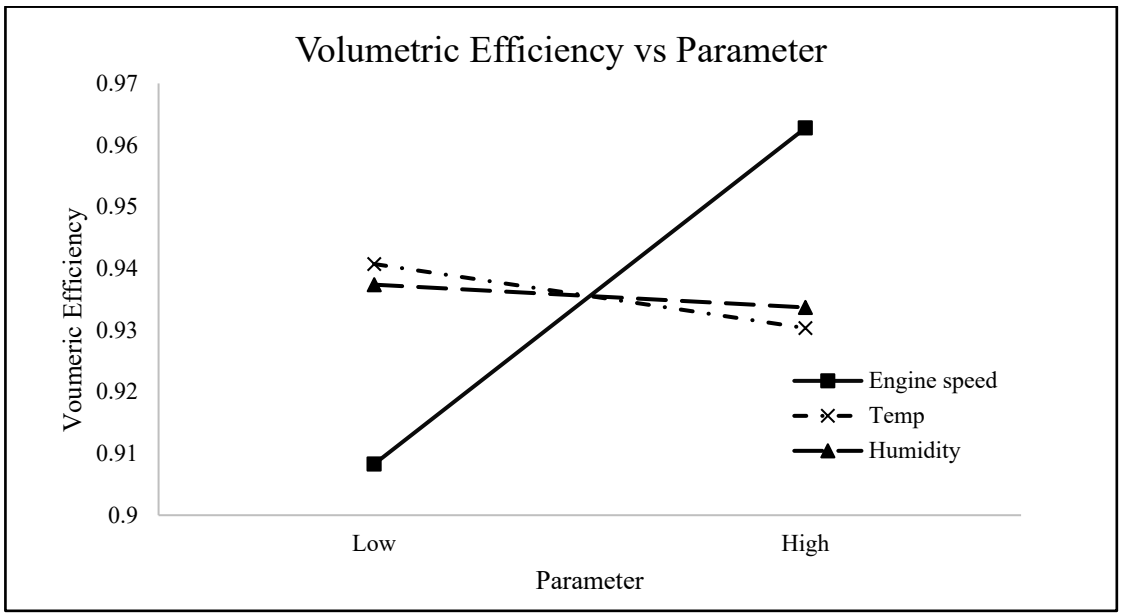


Figure 4.2 Linear Effect Analysis on Volumetric Efficiency

4.3.2 Response Surface Model (RSM) Analysis on Volumetric Efficiency (VE)

In order to develop a predictive model for volumetric efficiency, the DOE response matrix obtained from the GT-Power simulations was approximated using a response surface modelling (RSM) approach. The purpose of this approximation is to

generate a mathematical expression that represents volumetric efficiency as a function of the selected design variables, namely engine speed, intake-air temperature, and relative humidity. The response surface model acts as a surrogate model that enables efficient prediction of volumetric efficiency behaviour across the investigated operating range and supports subsequent optimisation analysis within the Altair HyperStudy framework.

In the present study, the Least Squares Regression (LSR) method available in Altair HyperStudy was adopted to construct the approximation model. Several regression forms were evaluated to identify the most suitable fitting model for volumetric efficiency. The quality of each regression model was assessed using the coefficient of determination, R-squared (R^2), which quantifies the agreement between the predicted and observed volumetric efficiency values. In general, an R^2 value closer to 1.0 indicates improved model adequacy and stronger predictive capability for the investigated dataset.

The approximation fitting comparisons for volumetric efficiency are summarised in Table 4.2. The linear regression model produced an R^2 value of 0.91, indicating that approximately 91% of the variability in volumetric efficiency can be explained by a first-order approximation. To improve the fitting accuracy, higher-order models were also examined. The squared regression model achieved the highest R^2 value of 0.94, while the cubic model produced an R^2 value of 0.93. Based on this comparison, the squared regression model was selected as the most suitable approximation for volumetric efficiency because it provides the best overall agreement with the DOE results. This model is subsequently used for response surface interpretation and optimisation within the defined operating bounds.

Table 4.2
Approximation Fitting Comparisons Based on Regression Model

Regression Model	**Volumetric Efficiency**
	R-Squared (R^2)
Least Square Regression with Linear Model	0.91
Least Square Regression with Squared Model	0.94
Least Square Regression with Cubic Model	0.93

In addition, Analysis of Variance (ANOVA) was performed to evaluate the statistical significance of engine speed, intake-air temperature, and relative humidity on volumetric efficiency. The ANOVA results are summarised in Table 4.3 where statistical significance is assessed at a 95% confidence level ($\alpha = 0.05$). Based on the p-values obtained, engine speed has the strongest and most statistically significant influence on volumetric efficiency ($p = 5.60 \times 10^{-44}$, $F = 602.18$). This indicates that the volumetric efficiency response varies significantly with changes in engine speed within the investigated range. Intake-air temperature also shows a statistically significant effect on volumetric efficiency ($p = 2.11 \times 10^{-6}$, $F = 15.94$), confirming that temperature variations within the selected operating limits contribute measurably to changes in cylinder filling performance.

In contrast, relative humidity does not exhibit a statistically significant main effect on volumetric efficiency for the investigated humidity range ($p = 0.1425 > 0.05$, $F = 2.01$). This suggests that, although humidity may introduce minor variations in volumetric efficiency, its contribution is comparatively small and is not statistically distinguishable from experimental error within the current dataset.

Following the significance evaluation, a regression model was developed to represent volumetric efficiency as a function of the investigated parameters. The resulting regression equation is presented in equation (4.1) and provides a predictive relationship between volumetric efficiency and the input variables within the defined bounds. In this model, VE represents volumetric efficiency, RPM represents engine speed, Temp denotes intake-air temperature (°C), and Humidity denotes relative humidity (%).

Table 4.3
Volumetric Efficiency Analysed 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

Humidity, H	2	1.28e-04	6.39e-05	2.0051698	0.1425207
Error	68	0.0021654	3.18e-05		
Total	74	0.0416593			

$$VE = \begin{array}{l} 0.758 + (8.774e\text{-}05)\ S + (8.7554e\text{-}04)\ T + (-1.193e\text{-}04)\ H \\ + (-8.643e\text{-}09)\ S^2 + (-3.6222e\text{-}5)\ T^2 + (-2.152e\text{-}07)\ H^2 \end{array} \quad (4.1)$$

Figure 4.3 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.

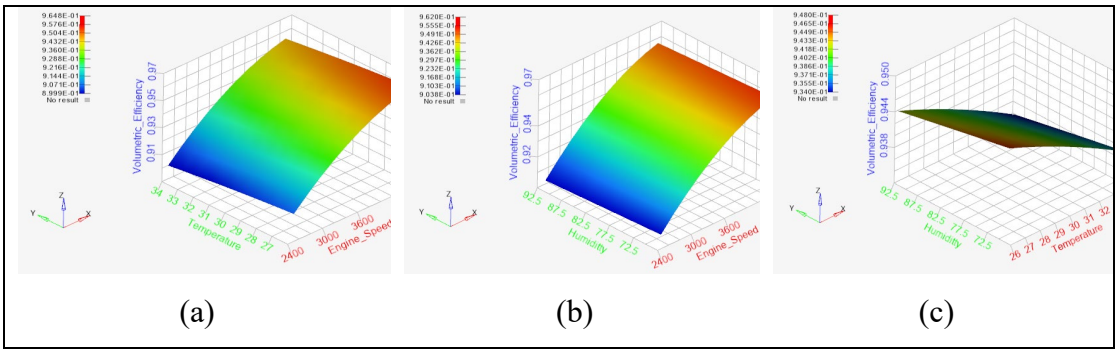


Figure 4.3 Volumetric Efficiency Response Surface Versus (a) Temperature and Engine Speed, (b) Humidity and Engine Speed, and (c) Humidity and Temperature

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 4.3(a). 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 4.3(b), 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.

4.3.3 Effect of Intake-Air Temperature on VE at Wet Condition (92% RH)

Figure 4.4 presents the relationship between volumetric efficiency and intake air temperature under wet conditions, where the relative humidity was maintained at approximately 92%. Across the examined temperature range (26 °C to 34 °C), a consistent downward trend is observed, signifying that volumetric efficiency deteriorates as the intake air becomes hotter. This indicates that temperature is the

dominant factor influencing volumetric efficiency, even in the presence of elevated humidity levels.

At low engine speed, volumetric efficiency exhibits a relatively sharp decline with increasing temperature. Specifically, the efficiency decreases from around 0.92 at 26 °C to approximately 0.89 at 34 °C. This behaviour is primarily attributed to the reduction in air density at higher temperatures, which reduces the overall air mass inducted per cycle. Since volumetric efficiency is a measure of the breathing capacity of the engine, the effect is more pronounced at lower speed because the dynamic ramming effect is weaker, and the filling process is heavily dependent on the static density of the intake charge.

In contrast, at high engine speed, the decline in volumetric efficiency is less severe, with values decreasing only from about 0.97 to 0.95 over the same temperature range. The reduced sensitivity at higher speeds can be explained by the contribution of dynamic pressure effects and turbulence inside the intake system, which partially compensate for the loss in density. The strong airflow and inertia of the intake charge at higher speeds help sustain better cylinder filling despite the elevated temperature.

From a thermodynamic perspective, the high humidity level introduces additional water vapor into the intake charge, which during vaporization absorbs latent heat and provides a cooling effect that could potentially improve volumetric efficiency. However, in this case, the thermal influence of rising temperature overrides the cooling benefit of water vapor, resulting in a net decrease in volumetric efficiency. This highlights the fact that although humid air can marginally mitigate thermal losses, its effect is limited under significantly high intake temperatures.

Therefore, volumetric efficiency consistently decreases with increasing temperature under wet conditions, with the impact being more significant at low engine speed. The results confirm that intake air temperature is a critical factor governing volumetric efficiency, while high humidity plays only a secondary role. Thus, cooler intake conditions remain more favourable for maintaining high volumetric efficiency, even in a humid environment.

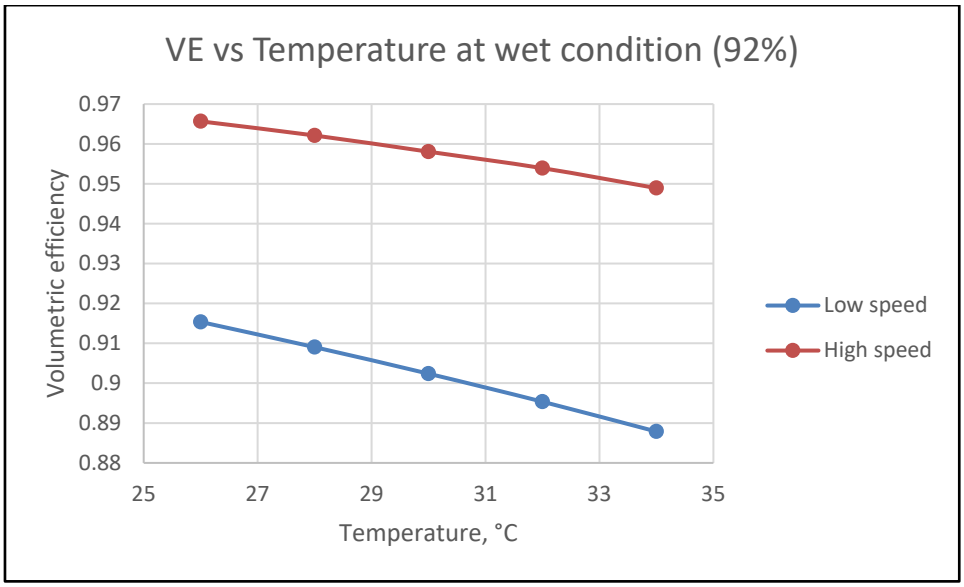


Figure 4.4 Volumetric Efficiency Vs Temperature at Wet Condition (92%)

4.3.4 Effect of Intake-Air Temperature on VE at Dry Condition (68% RH)

Figure 4.5 presents the variation of volumetric efficiency (VE) with intake air temperature under dry atmospheric conditions at 68% relative humidity. A clear declining trend of VE is observed as the intake temperature rises from 26 °C to 34 °C, confirming that higher thermal loading negatively affects the air–fuel induction process. Fundamentally, this reduction is attributed to the decrease in air density with increasing temperature, as predicted by the ideal gas law. Since volumetric efficiency directly depends on the mass of air trapped within the cylinder during the intake process, any reduction in density lowers the actual charge mass relative to the theoretical displacement volume.

At low engine speed, the VE reduction is more significant. The values decrease from approximately 0.92 at 26 °C to about 0.90 at 34 °C, representing a noticeable drop of nearly 2%. This decline reflects the absence of dynamic intake pressure recovery at low speeds, meaning the engine is primarily dependent on natural aspiration. As the intake temperature rises, the charge air becomes less dense, leading to insufficient cylinder filling. Furthermore, the lower turbulence at reduced speeds limits the effectiveness of mixture motion, thereby accentuating the impact of rising intake temperatures.

In contrast, high engine speed operation shows a smaller reduction in VE, ranging from 0.97 at 26 °C to around 0.96 at 34 °C. The relatively smaller decline can be attributed to the ram effect generated at higher piston velocities, where the momentum of the incoming charge partly compensates for the density loss caused by higher temperature. Additionally, at higher speeds, enhanced turbulence inside the cylinder promotes better volumetric efficiency, even though thermal effects remain unfavourable.

When compared to the wet condition case, the VE under dry conditions is consistently lower at similar temperatures. This indicates that humidity contributes a secondary role in sustaining VE. In humid conditions, water vapor present in the intake air undergoes partial evaporation, which absorbs latent heat and produces a mild cooling effect. This cooling helps retain a slightly higher air density and offsets part of the efficiency loss caused by higher intake temperatures. In dry conditions, however, this latent heat absorption effect is absent, and the intake charge is more directly exposed to thermal degradation. As a result, engines operating under dry conditions exhibit greater sensitivity to rising ambient temperature, which translates into more noticeable performance deterioration.

Thus, volumetric efficiency under dry conditions decreases progressively with intake temperature, with the decline being more severe at low engine speeds. The lack of humidity-driven cooling effects makes dry air more vulnerable to density reduction, thereby reducing the inducted charge mass. These findings emphasize the importance of intake air management, where charge cooling strategies such as intercooling or water injection may be particularly effective in mitigating volumetric efficiency losses in dry, high-temperature operating environments.

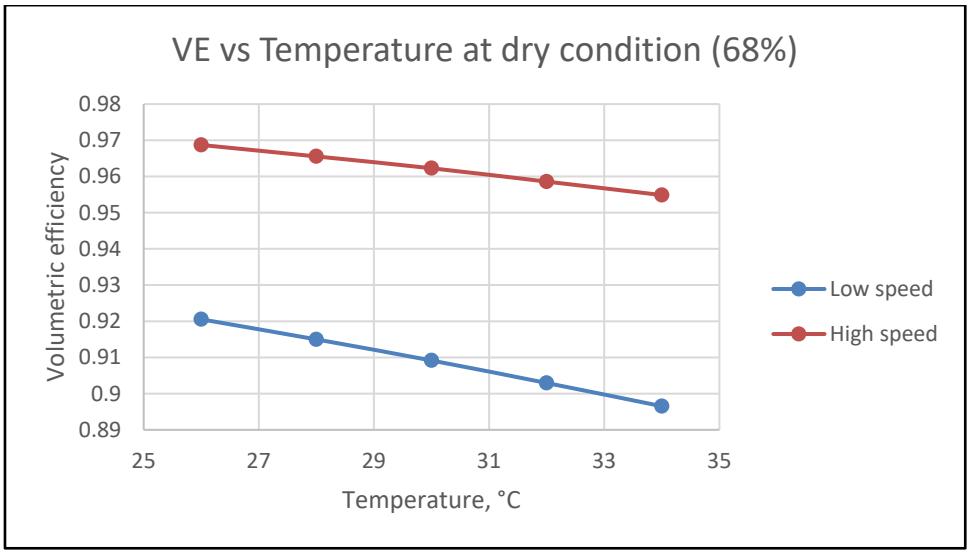


Figure 4.5 Volumetric Efficiency Vs Temperature at Dry Condition (68%)

4.3.5 Effect of Relative Humidity on VE at Cold Condition (26 °C)

Figure 4.6 illustrates the variation of volumetric efficiency (VE) with different humidity levels at a constant intake temperature of 26 °C, representing cold operating conditions. The results reveal a slight but consistent decline in VE as the humidity increases from 68% to 92% for both low-speed and high-speed engine operations. This behavior is fundamentally linked to the displacement of oxygen molecules in the intake charge by water vapor. Since water vapor has a lower molecular weight compared to dry air, increasing humidity reduces the partial pressure of oxygen and consequently lowers the mass of oxygen available for combustion within the same cylinder volume. This leads to a gradual reduction in volumetric efficiency.

At low engine speed, the volumetric efficiency decreases more noticeably, dropping from approximately 0.920 at 68% humidity to around 0.915 at 92% humidity. The reduction, though modest, indicates that lower intake momentum at reduced piston velocities makes the engine more sensitive to charge dilution caused by water vapor. Additionally, limited turbulence at low speed restricts mixing, exacerbating the impact of humidity on effective charge density.

In contrast, high engine speed operation maintains a consistently higher VE across the humidity range, declining only from about 0.969 at 68% to 0.966 at 92%.

The ram effect at higher piston velocities enhances charge induction, partially compensating for the displacement of oxygen by water vapor. Furthermore, increased turbulence at higher speeds promotes better mixing of air, fuel, and water vapor, thereby reducing the negative impact of humidity.

It is important to note that at cold intake temperature (26 °C), the influence of humidity on VE is less pronounced compared to higher temperature conditions. This is because lower intake temperature ensures a higher baseline air density, which mitigates the relative impact of water vapor dilution. Nonetheless, the general trend confirms that elevated humidity consistently reduces volumetric efficiency by lowering the oxygen fraction in the intake mixture.

By increasing humidity at constant low temperature results in a gradual decline in volumetric efficiency, with the effect being more significant at low speed than at high speed. Although the magnitude of reduction is relatively small under cold conditions, the findings highlight the inherent sensitivity of naturally aspirated engines to intake air composition.

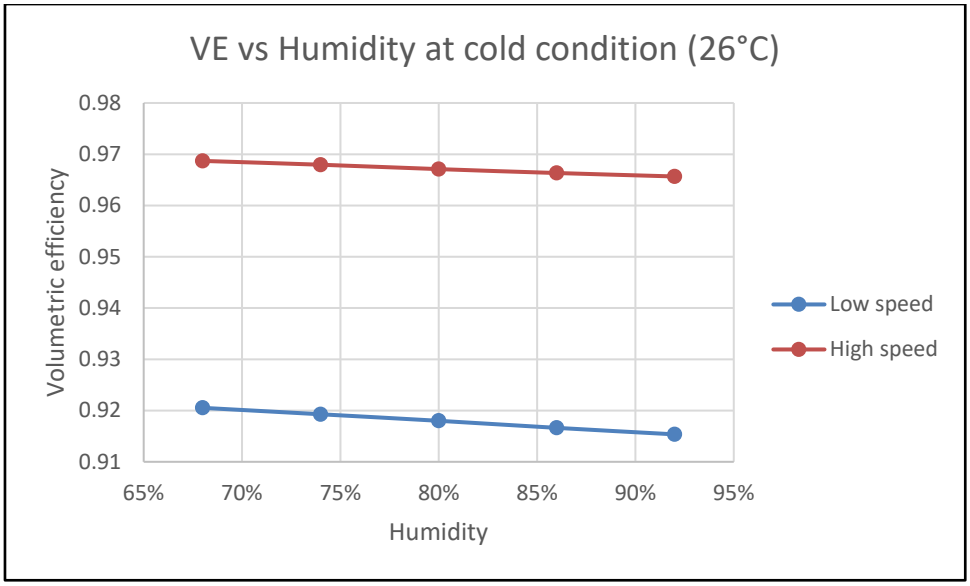


Figure 4.6 Volumetric Efficiency Vs Humidity at Cold Condition (26 °C)

4.3.6 Effect of Relative Humidity on VE at Hot Condition (34°C)

Figure 4.7 presents the relationship between volumetric efficiency (VE) and relative humidity at an intake temperature of 34 °C. The results reveal a distinct decreasing trend in VE as humidity increases from 68% to 92% for both low-speed and high-speed operations. This decline is primarily associated with the combined effects of high ambient temperature and increased water vapor concentration in the intake air, both of which reduce the oxygen availability for combustion.

At low engine speed, VE falls from approximately 0.897 at 68% humidity to around 0.889 at 92% humidity. Although the absolute difference appears small, the percentage loss is significant for a naturally aspirated engine where intake air quality directly governs performance. At low piston speeds, the intake momentum is relatively weak, and the ram effect is minimal, which means the intake process depends heavily on the natural density of the ambient air. Since hot air is already less dense, and increasing humidity displaces oxygen with water vapor, the engine experiences compounded air dilution. This explains the steeper decline in VE at lower speeds under hot and humid conditions.

For high engine speed, the VE decreases from about 0.955 at 68% humidity to 0.948 at 92%. Despite the downward trend, the effect of humidity is less pronounced than at low speed. This can be attributed to stronger intake momentum and turbulence at higher piston velocities, which promote better cylinder filling and mixing. The ram effect at higher speeds partially offsets the oxygen displacement caused by water vapor, enabling the engine to maintain relatively higher VE compared to low-speed operation. However, the decline still demonstrates that the combined influence of high temperature and humidity cannot be fully compensated, even at higher engine speeds.

From a thermodynamic perspective, the reduction in VE at hot and humid conditions arises because both temperature and water vapor content reduce the intake air's mass density. According to the ideal gas law, the density of the intake charge is inversely proportional to its absolute temperature. At 34 °C, the baseline density is already low compared to cooler conditions, which amplifies the effect of any additional moisture. Furthermore, as relative humidity increases, the partial pressure of water

vapor rises, displacing nitrogen and oxygen molecules in the intake air. Since oxygen is essential for combustion, its reduced proportion directly limits the volumetric efficiency.

When compared with the cold condition (26 °C), the decline in VE with increasing humidity is clearly more severe at 34 °C. This indicates that temperature and humidity act synergistically in reducing engine breathing efficiency. At higher temperatures, the intake air has less capacity to retain oxygen, and when coupled with high humidity, the available oxygen concentration decreases further, leading to more noticeable deterioration in VE.

In practical terms, these findings highlight the performance challenges of spark-ignition engines operating in hot and humid climates such as tropical regions. Engines in such environments are likely to experience reduced breathing efficiency, particularly under part-load and low-speed conditions where intake momentum is limited. This emphasizes the importance of intake air cooling strategies, such as intercooling or water–methanol injection, as well as adaptive control systems that can adjust the air–fuel ratio to mitigate the combined effects of temperature and humidity.

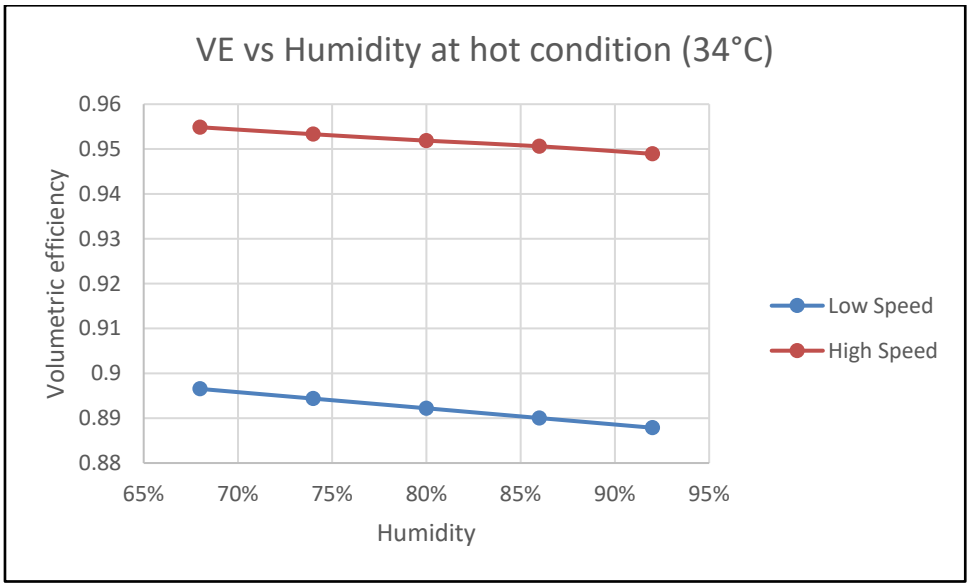


Figure 4.7 Volumetric Efficiency Vs Humidity at Hot Condition (34 °C)

4.4 Performance Analysis of Brake Power (BP)

4.4.1 DOE Analysis on Brake Power (BP)

In this section, the brake power results obtained from the GT-Power simulation are presented and discussed based on the Design of Experiments (DOE) approach. The results were generated using the design exploration capability provided by the Altair HyperStudy framework, as described in Chapter 3. The main objective of this analysis is to investigate the influence of engine speed, intake-air temperature, and relative humidity on brake power output under tropical operating conditions. The engine speed was evaluated at 2500 rpm, 3500 rpm, and 4500 rpm. Meanwhile, intake-air temperature was varied from 26°C to 34°C and relative humidity was varied from 68% to 92% to represent realistic atmospheric conditions.

Based on the full factorial DOE design, a total of 75 simulation runs were executed, covering all combinations of engine speed, temperature, and humidity levels. The run matrix and corresponding brake power responses are presented in Table 4.4. In the first set of simulations (Run 1 to Run 5), the engine speed was fixed at 2500 rpm and intake-air temperature was maintained at 26°C while humidity was varied from 68% to 92%. The brake power decreased slightly from 7.08 kW (Run 1) to 6.91 kW (Run 5), indicating that increasing humidity produces a small reduction in brake power at low speed and low temperature.

The evaluation on the effect of intake-air temperature at the same engine speed, temperature was increased from 26°C to 34°C while maintaining the same humidity range. At 2500 rpm and 68% humidity, brake power decreased from 7.08 kW at 26°C (Run 1) to 6.64 kW at 34°C (Run 21). Similarly, at 92% humidity, brake power decreased from 6.91 kW at 26°C (Run 5) to 6.36 kW at 34°C (Run 25). This trend shows that increasing intake-air temperature reduces brake power, which is attributed to reduced intake charge density and lower inducted air mass, thereby limiting the combustion energy release and brake output.

In the second engine speed level at 3500 rpm (Run 26 to Run 50), brake power values increased significantly compared with 2500 rpm. At 26°C, brake power

decreased from 9.43 kW at 68% humidity (Run 26) to 9.23 kW at 92% humidity (Run 30). At 34°C, brake power decreased from 9.36 kW at 68% humidity (Run 46) to 8.99 kW at 92% humidity (Run 50). These results indicate that the humidity effect remains relatively small but becomes more noticeable when intake-air temperature increases, resulting in a compounded reduction in brake power.

In the final engine speed level at 4500 rpm (Run 51 to Run 75), the highest brake power values were recorded. At 26°C, brake power decreased from 11.45 kW at 68% humidity (Run 51) to 11.02 kW at 92% humidity (Run 55). When intake-air temperature increased to 34°C, brake power further decreased from 10.44 kW at 68% humidity (Run 71) to 9.67 kW at 92% humidity (Run 75). This confirms that brake power is strongly influenced by engine speed, while intake-air temperature and humidity introduce additional penalties that reduce brake output, particularly at high speed where the demand for inducted air mass is higher.

Overall, the DOE results demonstrate that engine speed is the dominant factor governing brake power, where brake power increases substantially from the low-speed to high-speed operating condition. Intake-air temperature produces a consistent reduction in brake power across all engine speeds, while relative humidity contributes a smaller reduction within the investigated range. The combined influence of higher temperature and higher humidity results in the lowest brake power output, particularly at 4500 rpm. Further evaluation of the main effects and interaction behaviour will be carried out using response surface modelling in the subsequent section.

Table 4.4
Brake Power Response

Run	Engine Speed	Temperature	Relative Humidity	Brake Power (kW)
1	2500	26	68	7.08
2	2500	26	74	7.04
3	2500	26	80	7.00
4	2500	26	86	6.95
5	2500	26	92	6.91
6	2500	28	68	6.98
7	2500	28	74	6.94

8	2500	28	80	6.89
9	2500	28	86	6.84
10	2500	28	92	6.79
11	2500	30	68	6.88
12	2500	30	74	6.82
13	2500	30	80	6.77
14	2500	30	86	6.71
15	2500	30	92	6.66
16	2500	32	68	6.76
17	2500	32	74	6.57
18	2500	32	80	6.64
19	2500	32	86	6.58
20	2500	32	92	6.51
21	2500	34	68	6.64
22	2500	34	74	6.57
23	2500	34	80	6.50
24	2500	34	86	6.43
25	2500	34	92	6.36
26	3500	26	68	9.43
27	3500	26	74	9.38
28	3500	26	80	9.33
29	3500	26	86	9.28
30	3500	26	92	9.23
31	3500	28	68	9.44
32	3500	28	74	9.38
33	3500	28	80	9.32
34	3500	28	86	9.26
35	3500	28	92	9.20
36	3500	30	68	9.43
37	3500	30	74	9.36
38	3500	30	80	9.29
39	3500	30	86	9.22
40	3500	30	92	9.15

41	3500	32	68	9.40
42	3500	32	74	9.32
43	3500	32	80	9.25
44	3500	32	86	9.17
45	3500	32	92	9.09
46	3500	34	68	9.36
47	3500	34	74	9.28
48	3500	34	80	9.19
49	3500	34	86	9.09
50	3500	34	92	8.99
51	4500	26	68	11.45
52	4500	26	74	11.35
53	4500	26	80	11.24
54	4500	26	86	11.12
55	4500	26	92	11.02
56	4500	28	68	11.25
57	4500	28	74	11.12
58	4500	28	80	10.99
59	4500	28	86	10.86
60	4500	28	92	10.73
61	4500	30	68	11.01
62	4500	30	74	10.86
63	4500	30	80	10.71
64	4500	30	86	10.56
65	4500	30	92	10.41
66	4500	32	68	10.74
67	4500	32	74	10.57
68	4500	32	80	10.40
69	4500	32	86	10.23
70	4500	32	92	10.06
71	4500	34	68	10.44
72	4500	34	74	10.25
73	4500	34	80	10.06

74	4500	34	86	9.87
75	4500	34	92	9.67

The effects of engine speed, intake-air temperature, and relative humidity on brake power were analysed to identify the dominant contributors to engine output performance. Figure 4.8 shows that engine speed has a strong positive influence on brake power, indicating that it is the most influential factor within the investigated range. As engine speed increases from 2500 rpm to 4500 rpm, brake power increases markedly from approximately 6.9 kW to 10.8 kW, which is consistent with the higher rate of work output produced at increased engine speed. This behaviour is expected because higher engine speed increases the number of power cycles per unit time, leading to a higher brake power output when combustion and airflow remain stable.

In contrast, intake-air temperature exhibits a slight negative effect on brake power. Increasing temperature results in a small reduction in brake power, which can be attributed to reduced intake-air density and a lower inducted air mass, thereby limiting the available oxygen for combustion and reducing the effective brake output. Relative humidity also shows a mild negative influence on brake power, although its effect is comparatively smaller than engine speed. The reduction in brake power at higher humidity levels is associated with the increased water vapour content in the intake air, which slightly reduces oxygen concentration and alters the combustion process. Overall, the results confirm that engine speed is the dominant parameter governing brake power, while intake-air temperature and humidity contribute secondary reductions within the investigated operating range.

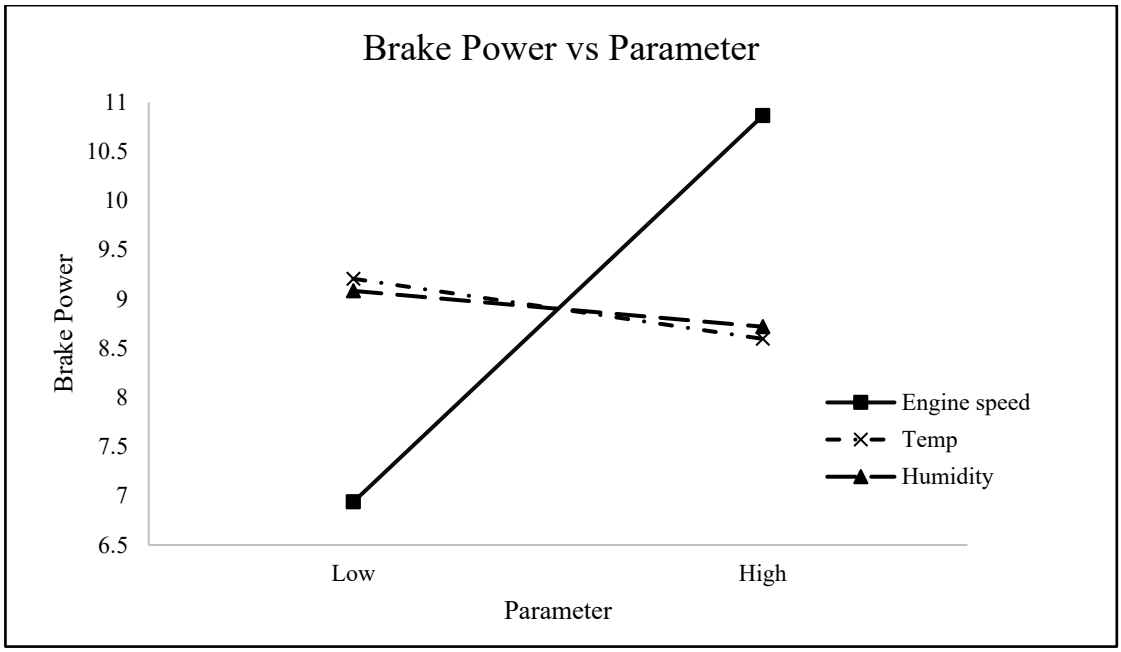


Figure 4.8 Linear Effect Analysis on Brake Power

4.4.2 Response Surface Model (RSM) Analysis on Brake Power (BP)

The approximation fitting comparisons for brake power are summarised in Table 4.5, where the regression model quality is evaluated using the coefficient of determination, R-squared (R^2). The linear regression model produced an R^2 value of 0.96, indicating that the selected input parameters can explain approximately 96% of the brake power variability using a first-order approximation. To improve the fitting accuracy, higher-order regression models were also examined. Both the squared and cubic regression models achieved an R^2 value of 0.99, demonstrating excellent agreement between the predicted and simulated brake power values.

Based on these results, the squared regression model was selected as the approximation model for brake power because it provides the highest fitting accuracy while maintaining a simpler mathematical form compared with the cubic model. This selected model is subsequently used for response surface interpretation and optimisation analysis within the defined operating bounds. The high R^2 value confirms that the developed approximation model is sufficiently accurate to support prediction and optimisation of brake power within the investigated parameter range.

Table 4.5
Approximation Fitting Comparisons Based on Regression Model

Regression Model	Brake Power
	R-Squared (R^2)
Least Square Regression with Linear Model	0.96
Least Square Regression with Squared Model	0.99
Least Square Regression with Cubic Model	0.99

The ANOVA results for brake power are summarised in Table 4.6, where statistical significance is evaluated at a 95% confidence level ($\alpha = 0.05$). Based on the p-values obtained, engine speed, intake-air temperature, and relative humidity all exhibit statistically significant effects on brake power within the investigated operating range. Engine speed is the most dominant factor, with an F-value of 3273.53 and a p-value of 2.55×10^{-68}, confirming that brake power varies significantly with engine speed. This behaviour is consistent with engine performance fundamentals, where increasing speed increases the rate of work output and results in higher brake power. Intake-air temperature also shows a statistically significant influence on brake power ($F = 58.22$, $p = 1.85 \times 10^{-15}$), indicating that temperature variations contribute measurably to brake power changes, primarily through their effect on intake charge density and inducted air mass. In addition, relative humidity demonstrates a statistically significant effect ($F = 20.59$, $p = 1.02 \times 10^{-7}$). Although its influence is smaller than engine speed and temperature, the statistical significance suggests that humidity variations within the selected range produce measurable changes in brake power, likely due to reduced oxygen availability and dilution effects associated with increased water vapour content in the intake mixture.

Following the significance evaluation, a regression model was developed to represent brake power as a function of the investigated parameters. The resulting regression equation is presented in equation (4.2) and provides a predictive relationship between brake power and the input variables within the defined bounds. In this model, BP represents brake power, RPM represents engine speed, Temp denotes intake-air temperature (°C), and Humidity denotes relative humidity (%). Overall, the ANOVA outcomes are consistent with the DOE trend observations and the linear effect analysis, where brake power increases strongly with engine speed while intake-air temperature

and relative humidity introduce secondary reductions. The ranking of influence based on the F-values confirms that engine speed is the dominant contributor and followed by temperature and humidity. Thus, it supports the response behaviour observed across the full factorial dataset. Consequently, the developed regression model provides a statistically justified basis for response surface interpretation and subsequent optimisation of brake power within the investigated operating range.

Table 4.6
Brake Power Analysed by ANOVA

Parameters	Degree of Freedom (DOF)	Sum of Squares	Mean Squares	F-value	p-value
Engine Speed, S	2	197.87285	98.936426	3273.5275	2.55e-68
Temperature, T	2	3.5192713	1.7596356	58.221383	1.85e-15
Humidity, H	2	1.2444880	0.6222440	20.588300	1.02e-07
Error	68	2.0551766	0.0302232		
Total	74	204.69179			

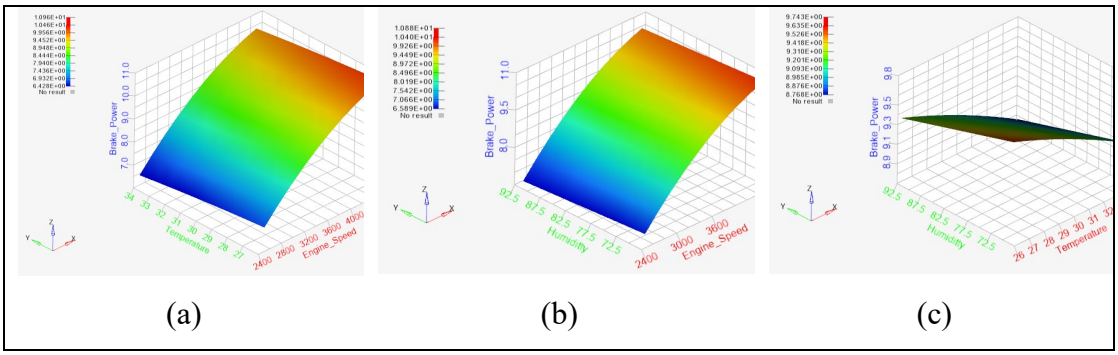
$$BP = \begin{aligned} &-3.040 + (0.006)\,S + (0.065)\,T + (-0.015)\,H + \\ &(-5.592e\text{-}07)\,S^2 + (-0.002)\,T^2 + (5.246)\,H^2 \end{aligned} \quad (4.2)$$

Figure 4.9(a) shows the combined influence of engine speed and intake-air temperature on brake power, with relative humidity fixed at 80%. A strong positive relationship is observed between engine speed and brake power, where increasing engine speed increases brake power significantly across the investigated range. This trend is expected because brake power is directly related to the rate of useful work output, and higher engine speed increases the number of combustion cycles per unit time. In contrast, intake-air temperature exhibits a negative correlation with brake power. As temperature increases from 26°C to 34°C, brake power decreases slightly at all engine speeds. This reduction is attributed to the lower intake-air density at higher temperature, which reduces the inducted air mass and limits oxygen availability for combustion, thereby reducing brake output. The surface plot confirms that temperature

acts as a secondary factor that reduces brake power, while engine speed remains the dominant contributor.

Figure 4.9(b) presents the response surface of brake power as a function of engine speed and relative humidity, with intake-air temperature maintained at 30°C. The surface indicates that brake power increases substantially with engine speed, consistent with the dominant trend observed in the DOE results. However, a mild decreasing trend in brake power is observed as relative humidity increases from 68% to 92%, particularly at higher engine speeds. This behaviour can be explained by the increased water vapour content in humid intake air, which reduces the effective oxygen concentration and contributes to charge dilution. Although water vapour may provide limited evaporative cooling, the reduction in oxygen availability and combustion potential dominates within the investigated range, resulting in a net reduction in brake power. Therefore, the surface suggests that higher brake power is achieved at high engine speed and lower humidity conditions.

Figure 4.9(c) illustrates the interaction between relative humidity and intake-air temperature on brake power at a constant engine speed of 3500 rpm. The surface shows that brake power decreases as both humidity and temperature increase, confirming the combined negative influence of hot and humid intake conditions. The reduction with temperature is associated with lower intake charge density, while the reduction with humidity is linked to reduced oxygen availability due to increased water vapour fraction. Compared with the strong influence of engine speed, the humidity–temperature interaction produces a smaller but measurable reduction in brake power. Overall, the response surfaces confirm that brake power is maximised under conditions of high engine speed, low intake-air temperature, and low relative humidity, which is consistent with the DOE trends and the ANOVA ranking reported earlier.



(a) (b) (c)

Figure 4.9 Brake Power Response Surface Versus (a) Temperature and Engine Speed, (b) Humidity and Engine Speed, and (c) Humidity and Temperature

4.4.3 Effect of Intake-Air Temperature on BP at Wet Condition (92%)

Figure 4.10 presents the variation of brake power with intake-air temperature under wet atmospheric conditions, where the relative humidity was maintained at approximately 92%. A gradual reduction in brake power is observed as the intake temperature increases from 26 °C to 34 °C for both low-speed and high-speed operating conditions. This trend indicates that higher intake-air temperature has a negative influence on engine power output, even when the intake charge contains a high level of moisture.

At low engine speed, brake power decreases slightly from approximately 7.1 kW at 26 °C to about 6.9 kW at 34 °C. Although the reduction is relatively small, the trend remains consistent. This behaviour is mainly attributed to the reduction in intake-air density at higher temperatures. As the air temperature increases, the mass of air inducted into the cylinder per cycle decreases. Consequently, the amount of oxygen available for combustion is reduced, resulting in lower combustion energy and a corresponding decrease in brake power.

At high engine speed, brake power remains considerably higher than at low speed, ranging from approximately 11.45 kW at 26 °C to around 11.0 kW at 34 °C. The higher brake power at increased engine speed is expected because more combustion cycles occur per unit time, and the intake flow momentum is greater. However, despite this advantage, the downward trend with increasing temperature is still evident. This

confirms that the negative effect of reduced air density cannot be fully compensated by the higher airflow velocity and dynamic intake effects at high speed.

Under wet conditions, the presence of water vapour in the intake air may provide a mild cooling effect through latent heat absorption. This effect can slightly reduce the thermal penalty associated with hot intake air. However, at 92% relative humidity, the intake charge also contains a higher fraction of water vapour, which displaces part of the dry air and reduces the oxygen concentration available for combustion. Therefore, the combined effect of high temperature and high humidity leads to a reduction in the effective air–fuel combustion capacity.

Based on this finding, the brake power decreases progressively with increasing intake-air temperature under wet conditions. The reduction is more noticeable at high engine speed in terms of absolute brake power difference, although the general trend is similar for both speed conditions. These findings confirm that cooler intake-air conditions are more favourable for maintaining higher brake power. Therefore, intake-air temperature remains a critical parameter affecting engine performance, even when the engine operates under highly humid atmospheric conditions.

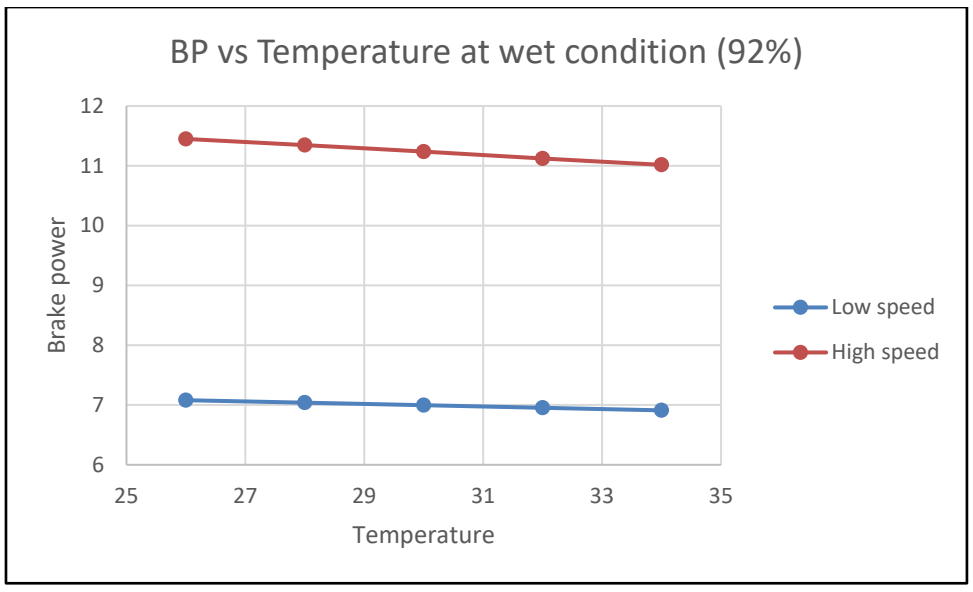


Figure 4.10 Brake Power Vs Temperature at Wet Condition (92%)

4.4.4 Effect of Intake-Air Temperature on BP at Dry Condition (68%)

Figure 4.11 presents the variation of brake power with intake-air temperature under dry atmospheric conditions, where the relative humidity was maintained at approximately 68%. A clear decreasing trend is observed for both low-speed and high-speed operating conditions as the intake-air temperature increases from 26 °C to 34 °C. This indicates that higher intake temperature reduces the ability of the engine to produce brake power, mainly due to the reduction in intake-air density and the corresponding decrease in oxygen mass available for combustion.

At low engine speed, brake power decreases gradually from approximately 6.65 kW at 26 °C to about 6.35 kW at 34 °C. Although the reduction is relatively moderate, the trend confirms that low-speed operation is affected by thermal degradation of the intake charge. At lower engine speed, the intake flow momentum is weaker, and the cylinder filling process depends more strongly on the static density of the incoming air. As the intake temperature increases, the air becomes less dense, resulting in a lower mass of air entering the cylinder during each intake stroke. Consequently, less oxygen is available to support combustion, which leads to a reduction in brake power.

At high engine speed, brake power is substantially higher than that at low speed, decreasing from approximately 10.45 kW at 26 °C to around 9.67 kW at 34 °C. The higher brake power at increased engine speed is expected because the engine completes more combustion cycles per unit time and generates greater intake flow momentum. However, the decreasing trend remains evident, showing that the beneficial effect of higher engine speed cannot fully overcome the negative influence of hot intake air. The reduction in air density at elevated temperature still limits the quantity of oxygen inducted into the combustion chamber, thereby reducing the combustion energy released and the useful brake power output.

Compared with the wet condition, the brake power under dry conditions is generally lower at the same intake temperature. This suggests that the lower humidity level provides less latent heat absorption and less cooling influence on the intake charge. Under wet conditions, the presence of more water vapour may slightly reduce the thermal effect of hot intake air through evaporative cooling. However, under dry

conditions, this cooling contribution is weaker, causing the intake charge to be more directly affected by the increase in temperature. As a result, the engine becomes more sensitive to intake-air heating, particularly at high-speed operation where the absolute reduction in brake power is more noticeable.

Thus, the brake power decreases progressively with increasing intake-air temperature under dry conditions. The reduction is caused mainly by lower air density, reduced oxygen availability, and less effective cylinder charging. The findings confirm that cooler intake-air conditions are more favourable for maintaining higher brake power. Therefore, proper intake-air temperature control is important, especially when the engine operates in relatively dry and hot atmospheric conditions.

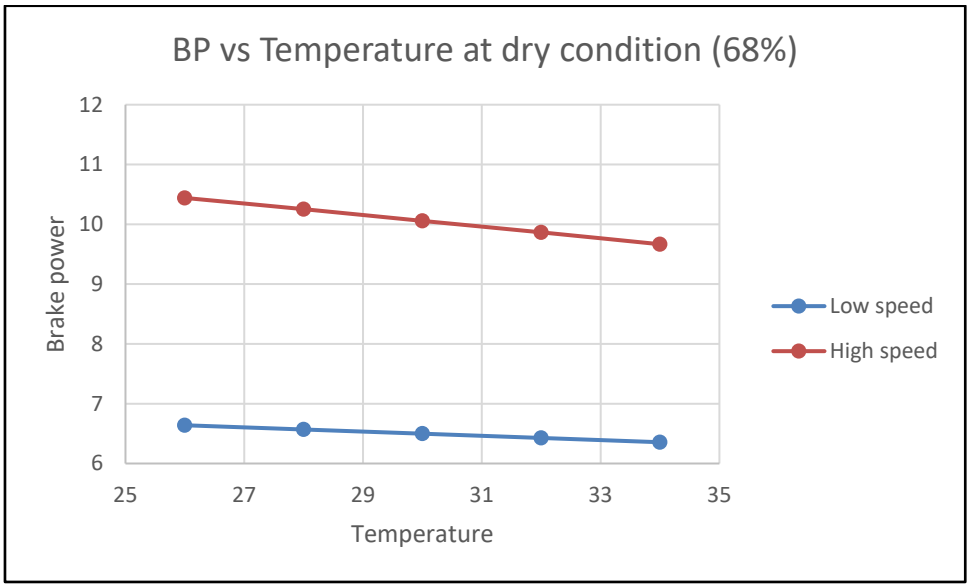


Figure 4.11 Brake Power Vs Temperature at Dry Condition (68%)

4.4.5 Effect of Relative Humidity on BP at Cold Condition (26°C)

The graph presented in Figure 4.12 illustrates the variation of brake power with respect to humidity under cold operating conditions for both low and high-speed scenarios. The observed trend indicates a consistent decrease in brake power with increasing humidity across both speed ranges. At low speed, brake power shows a gradual decline from approximately 7.1 units at 68% relative humidity to around 6.9 units at 9% humidity. This indicates a relatively modest sensitivity to humidity changes,

suggesting that at lower engine speeds, the effect of increased moisture in the intake air may slightly reduce combustion efficiency, but the impact remains limited. The combustion process under cold conditions is already constrained by lower temperatures, and additional humidity likely contributes to further reductions in thermal efficiency and air-fuel mixing quality.

In contrast, the high-speed scenario demonstrates a more pronounced reduction in brake power, dropping from approximately 11.4 units at 68% humidity to 11.0 units at 92% humidity. While the absolute values are higher than those at low speed, the relative decline is also more significant. At higher speeds, engines typically operate at higher loads, and any deviation in air properties (such as increased humidity) can more substantially affect combustion dynamics. High humidity reduces the oxygen concentration per unit volume of air due to the displacement by water vapor, which may lead to incomplete combustion and lower power output, especially under cold start or cold ambient conditions.

The overall negative correlation between humidity and brake power aligns with theoretical expectations. Increased humidity under cold conditions tends to reduce the intake air density and alter flame propagation characteristics during combustion. This effect appears more detrimental at high speeds, likely due to the higher dependency on optimal air-fuel ratios and combustion timing. The results suggest that humidity adversely affects engine brake power under cold conditions, with the effect being more prominent at higher speeds. These findings are important for understanding engine behavior in variable climatic conditions and can inform the design of intake air management systems, particularly in regions with high relative humidity and cold ambient temperatures.

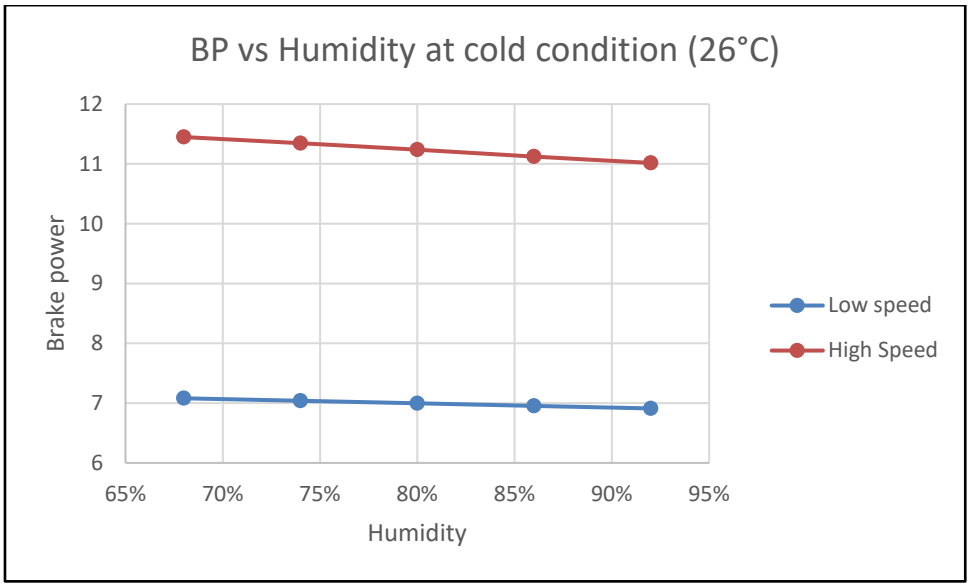


Figure 4.12 Brake Power Vs Humidity at Cold Condition (26°C)

4.4.6 Effect of Relative Humidity on BP at Hot Condition (34°C)

Figure 4.13 illustrates the variation of brake power with increasing humidity under hot ambient conditions for both low-speed and high-speed engine operations. The graph reveals a consistent downward trend in brake power as humidity increases from 70% to 90%, aligning with theoretical expectations related to the thermodynamic behavior of humid air. At low speeds, brake power decreases modestly from approximately 6.7 units at 68% humidity to around 6.3 units at 92% humidity. Although this decline is relatively small, it is still indicative of reduced combustion efficiency. In hot conditions, the intake air already possesses lower density due to higher temperatures. When humidity increases, water vapor content further displaces oxygen molecules in the intake charge, leading to a richer air-fuel mixture and reduced combustion quality. This compounded effect contributes to a steady but less severe drop in brake power at low speeds.

The impact of humidity is more pronounced at high engine speeds, where brake power decreases from 10.4 units at 68% humidity to 9.7 units at 92% humidity. This steeper decline reflects the higher sensitivity of high-speed engine operation to changes in intake air composition. At high speeds, the engine demands more air to maintain optimal combustion. However, in hot and humid conditions, the volumetric efficiency

decreases, and the higher presence of water vapor limits the availability of oxygen. As a result, incomplete combustion or reduced peak cylinder pressure can occur, leading to lower brake power output.

Comparing this trend with the results under cold conditions (as previously discussed), it becomes evident that hot environments exacerbate the adverse effect of humidity. While both thermal and moisture content contribute to lower air density, high ambient temperatures reduce the cooling effect of fuel vaporization and may lead to earlier knocking or poor charge mixing further impairing power generation.

These findings suggest that engine performance in hot and humid climates may suffer significantly, particularly during high-speed operation. From an engineering standpoint, this underscores the importance of intake air conditioning systems such as intercoolers or humid air compensation strategies to mitigate power losses. It also highlights the need to adapt engine calibration maps for varying climate zones to maintain optimal performance and fuel efficiency. Based on this, the experimental data confirms that increased humidity under hot conditions negatively affects brake power, with a more substantial impact observed at higher engine speeds. These results reinforce the necessity of climate-aware engine design and operation strategies.

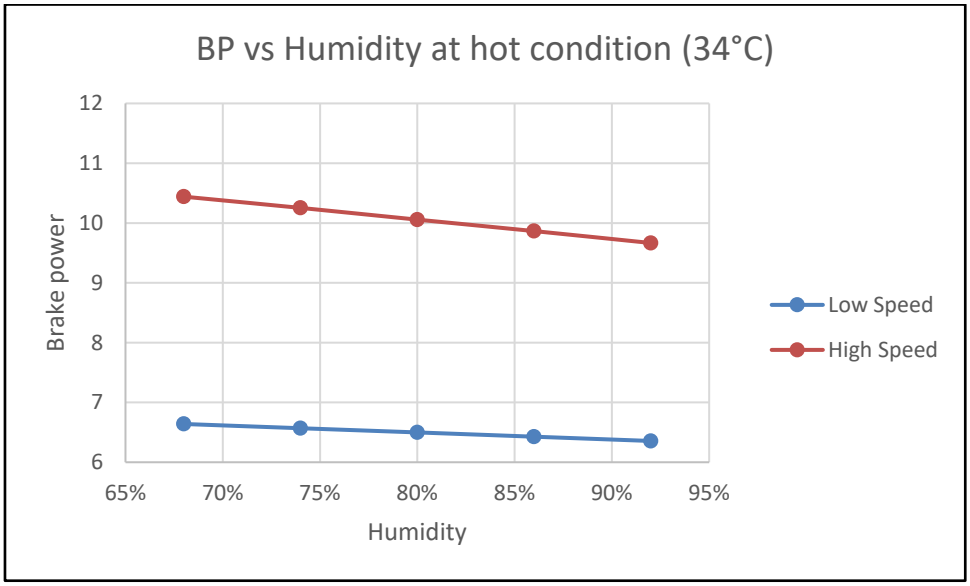


Figure 4.13 Brake Power Vs Humidity at Hot Condition (34°C)

The influence of humidity on engine brake power under varying thermal conditions has been investigated and analyzed through controlled testing at both low and high engine speeds. The results, as presented in Figure 4.12 and Figure 4.13, demonstrate a clear and consistent inverse relationship between humidity and brake power output across all tested scenarios.

Under cold ambient conditions, an increase in humidity resulted in a gradual decline in brake power. While both low-speed and high-speed operations were affected, the effect was more pronounced at higher speeds. This is attributed to the displacement of oxygen by water vapor in the intake air, which reduces combustion efficiency an effect amplified under cold conditions due to slower evaporation and reduced flame propagation.

In contrast, under hot ambient conditions, the reduction in brake power with increasing humidity was even more significant, particularly at high speeds. The combination of high temperature and high humidity leads to a substantial decrease in air density and oxygen availability, which severely affects the engine's volumetric efficiency and combustion quality. The data shows that brake power decreased more rapidly in hot conditions than in cold conditions for the same range of humidity, highlighting the compounding negative effects of temperature and moisture on engine performance.

Comparative analysis between cold and hot conditions reveals that hot and humid environments pose a greater challenge to engine performance. The reduction in brake power is more severe in hot climates, indicating that engines operating in such conditions may require enhanced intake air cooling or adaptive tuning to compensate for environmental effects.

The findings of this study confirm that ambient humidity, especially when combined with elevated temperatures, significantly impacts engine brake power, with greater sensitivity observed at higher engine speeds. These insights are critical for the design and calibration of internal combustion engines, particularly for vehicles expected to operate in diverse climatic regions. Future work should explore humidity mitigation strategies such as intake air dryers, intercooling, or real-time adaptive control systems to sustain engine efficiency under varying environmental conditions.

4.5 Performance Analysis of Brake Torque (BT)

4.5.1 DOE Analysis on Brake Torque (BT)

Based on the full factorial DOE design, a total of 75 simulation runs were executed, consisting of different combinations of engine speed, intake-air temperature, and relative humidity levels. The complete run matrix and corresponding brake torque responses are presented in Table 4.7. The brake torque trends are analysed across three engine speed levels (2500 rpm, 3500 rpm, and 4500 rpm), with intake-air temperature varied from 26°C to 34°C and relative humidity varied from 68% to 92%, representing realistic tropical operating conditions.

In the first set of simulations at 2500 rpm (Run 1 to Run 25), brake torque decreases consistently with increasing relative humidity at constant temperature. At 26°C, brake torque reduces from 27.04 N·m at 68% humidity (Run 1) to 26.40 N·m at 92% humidity (Run 5). A similar decreasing trend is observed at higher temperatures. For example, at 34°C, brake torque decreases from 25.36 N·m at 68% humidity (Run 21) to 24.28 N·m at 92% humidity (Run 25). These results indicate that humidity produces a measurable reduction in brake torque at low engine speed, likely due to reduced oxygen availability associated with increased water vapour content in the intake charge.

To evaluate the effect of intake-air temperature at the same engine speed, temperature was increased progressively from 26°C to 34°C while maintaining the same humidity range. At 2500 rpm and 68% humidity, brake torque decreases from 27.04 N·m at 26°C (Run 1) to 25.36 N·m at 34°C (Run 21). At 92% humidity, brake torque decreases from 26.40 N·m at 26°C (Run 5) to 24.28 N·m at 34°C (Run 25). This confirms that intake-air temperature contributes to brake torque reduction at low speed due to the reduction in intake charge density and inducted air mass.

In the second engine speed level at 3500 rpm (Run 26 to Run 50), brake torque values are generally lower than those at 2500 rpm but remain relatively stable across most combinations. At 26°C, brake torque decreases slightly from 25.74 N·m at 68% humidity (Run 26) to 25.18 N·m at 92% humidity (Run 30). At 34°C, brake torque

reduces from 25.55 N·m at 68% humidity (Run 46) to 24.54 N·m at 92% humidity (Run 50). These results show that the combined effect of higher temperature and humidity continues to reduce brake torque, although the magnitude of variation is moderate within this mid-speed operating condition.

In the final engine speed level at 4500 rpm (Run 51 to Run 75), the lowest brake torque values were recorded across the investigated range. At 26°C, brake torque decreases from 24.30 N·m at 68% humidity (Run 51) to 23.38 N·m at 92% humidity (Run 55). As temperature increases to 34°C, brake torque further decreases from 22.16 N·m at 68% humidity (Run 71) to 20.51 N·m at 92% humidity (Run 75). This demonstrates that brake torque decreases significantly at higher engine speed, which is consistent with the typical torque-speed characteristic of spark ignition engines where torque tends to reduce beyond the mid-speed region due to breathing limitations and reduced volumetric efficiency at high rpm. In addition, the negative influence of higher intake temperature and humidity becomes more pronounced at high speed, where the engine is more sensitive to reductions in inducted air mass and oxygen availability.

Overall, the DOE results demonstrate that engine speed has a strong influence on brake torque, where brake torque is highest at low speed and decreases as engine speed increases toward 4500 rpm. Intake-air temperature and relative humidity both contribute to brake torque reduction across the investigated range, with the lowest torque occurring under combined high temperature (34°C) and high humidity (92%) conditions. These findings provide a clear baseline understanding of brake torque behaviour, which will be further analysed using response surface modelling and interaction assessment in the subsequent section.

Table 4.7
Brake Torque Effect

Run	Engine Speed	Temperature	Relative Humidity	Brake Torque (N·m)
1	2500	26	68	27.04
2	2500	26	74	26.89
3	2500	26	80	26.73
4	2500	26	86	26.56
5	2500	26	92	26.40
6	2500	28	68	26.67

7	2500	28	74	26.49
8	2500	28	80	26.31
9	2500	28	86	26.12
10	2500	28	92	25.94
11	2500	30	68	26.27
12	2500	30	74	26.06
13	2500	30	80	25.85
14	2500	30	86	25.64
15	2500	30	92	25.43
16	2500	32	68	25.83
17	2500	32	74	23.05
18	2500	32	80	25.36
19	2500	32	86	25.12
20	2500	32	92	24.88
21	2500	34	68	25.36
22	2500	34	74	25.09
23	2500	34	80	24.82
24	2500	34	86	24.55
25	2500	34	92	24.28
26	3500	26	68	25.74
27	3500	26	74	25.60
28	3500	26	80	25.45
29	3500	26	86	25.32
30	3500	26	92	25.18
31	3500	28	68	25.75
32	3500	28	74	25.59
33	3500	28	80	25.43
34	3500	28	86	25.26
35	3500	28	92	25.10
36	3500	30	68	25.72
37	3500	30	74	25.53
38	3500	30	80	25.35
39	3500	30	86	25.17

40	3500	30	92	24.98
41	3500	32	68	25.65
42	3500	32	74	25.44
43	3500	32	80	25.24
44	3500	32	86	25.02
45	3500	32	92	24.80
46	3500	34	68	25.55
47	3500	34	74	25.31
48	3500	34	80	25.07
49	3500	34	86	24.80
50	3500	34	92	24.54
51	4500	26	68	24.30
52	4500	26	74	24.08
53	4500	26	80	23.85
54	4500	26	86	23.60
55	4500	26	92	23.38
56	4500	28	68	23.86
57	4500	28	74	23.59
58	4500	28	80	23.32
59	4500	28	86	23.05
60	4500	28	92	22.77
61	4500	30	68	23.36
62	4500	30	74	23.05
63	4500	30	80	22.73
64	4500	30	86	22.41
65	4500	30	92	22.09
66	4500	32	68	22.79
67	4500	32	74	22.44
68	4500	32	80	22.08
69	4500	32	86	21.72
70	4500	32	92	21.34
71	4500	34	68	22.16
72	4500	34	74	21.76

73	4500	34	80	21.34
74	4500	34	86	20.94
75	4500	34	92	20.51

The effects of engine speed, intake-air temperature, and relative humidity on brake torque were analysed to identify the dominant contributors to torque output within the investigated operating range. Figure 4.14 shows that engine speed exhibits a strong negative influence on brake torque, indicating that it is the most influential factor affecting torque response. As engine speed increases from 2500 rpm to 4500 rpm, brake torque decreases substantially from approximately 26.1 N·m to 23.0 N·m. This behaviour is consistent with the typical torque–speed characteristic of a naturally aspirated spark ignition engine, where torque tends to reduce at higher speeds due to reduced time available for cylinder filling and increased breathing and pumping losses.

In addition, intake-air temperature shows a moderate negative effect on brake torque. Increasing temperature leads to a reduction in brake torque from approximately 25.4 N·m to 23.8 N·m, which is attributed to the decrease in intake-air density at higher temperature and the corresponding reduction in inducted air mass and oxygen availability for combustion. Relative humidity also demonstrates a negative influence, although the magnitude of change is smaller compared with engine speed and temperature. Brake torque decreases slightly from approximately 25.0 N·m to 24.1 N·m as humidity increases, which can be associated with charge dilution effects caused by increased water vapour content in the intake air. Overall, the results confirm that engine speed is the dominant parameter governing brake torque reduction, while temperature and humidity contribute secondary decreases within the investigated range.

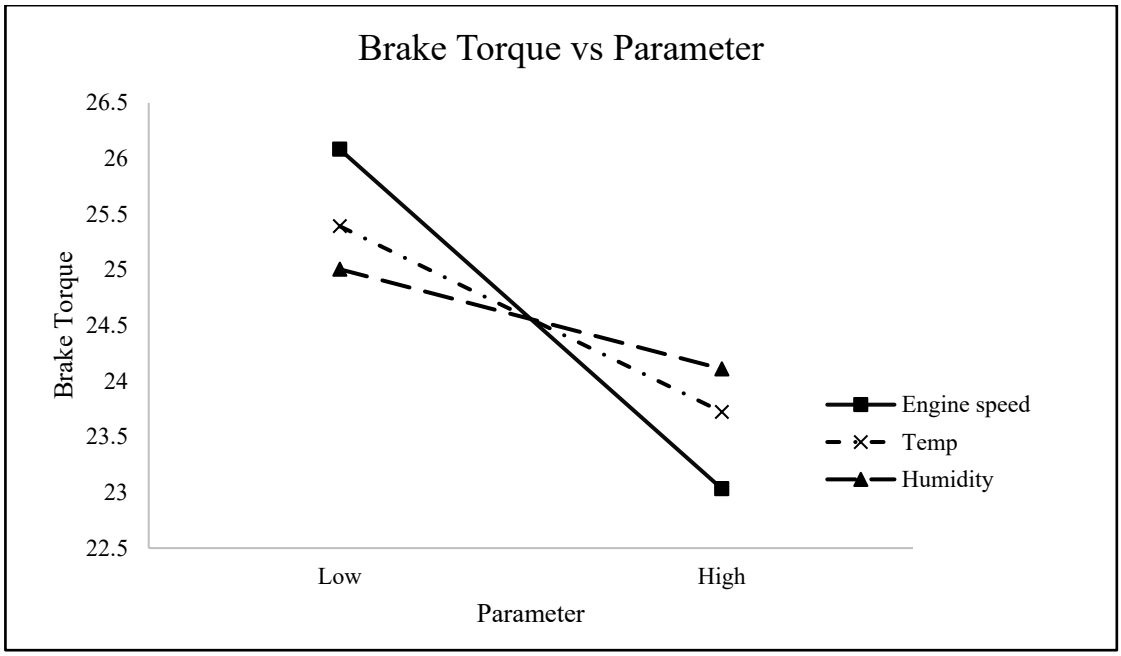


Figure 4.14 Linear Effect Analysis on Brake Torque

4.5.2 Response Surface Model (RSM) Analysis on Brake Torque (BT)

The approximation fitting comparisons for brake torque are summarised in Table 4.8, where the regression model adequacy is evaluated using the coefficient of determination, R-squared (R^2). The linear regression model produced an R^2 value of 0.79, indicating that a first-order approximation explains only 79% of the brake torque variability. This suggests that the brake torque response cannot be fully represented using purely linear relationships within the investigated operating range. To improve prediction accuracy, higher-order regression models were therefore examined.

The squared regression model achieved the highest R^2 value of 0.91, while the cubic regression model produced an R^2 value of 0.90, confirming that a second-order formulation provides a more accurate representation of the brake torque response compared with the linear model. The improvement in R^2 reflects the presence of non-linear behaviour associated with torque production, where brake torque is influenced by speed-dependent breathing characteristics and intake-air property variations that do not vary linearly across the selected parameter bounds.

Based on these results, the squared regression model was selected as the most suitable approximation model for brake torque because it provides the best overall agreement with the DOE dataset while maintaining a simpler mathematical form than

the cubic model. This selected model is subsequently used for response surface interpretation and optimisation analysis within the defined operating limits. The obtained R^2 value confirms that the developed approximation model is sufficiently reliable to support prediction and optimisation of brake torque for the investigated combinations of engine speed, intake-air temperature, and relative humidity.

Table 4.8
Approximation Fitting Comparisons Based on Regression Model

Regression Model	**Brake Torque**
	R-Squared (R^2)
Least Square Regression with Linear Model	0.79
Least Square Regression with Squared Model	0.91
Least Square Regression with Cubic Model	0.90

The ANOVA results for brake torque are summarised in Table 4.9, where statistical significance is evaluated at a 95% confidence level ($\alpha = 0.05$). Based on the p-values obtained, engine speed, intake-air temperature, and relative humidity all exhibit statistically significant effects on brake torque within the investigated operating range ($p < 0.05$). Engine speed is the most dominant factor, with an F-value of 318.95 and a p-value of 2.81×10^{-35}, confirming that brake torque varies significantly with engine speed. Intake-air temperature also shows a statistically significant influence ($F = 60.80$, $p = 7.23 \times 10^{-16}$), indicating that temperature variations contribute measurably to brake torque changes through their effect on intake charge density and combustion potential. In addition, relative humidity demonstrates a statistically significant effect ($F = 17.53$, $p = 7.27 \times 10^{-07}$). Although its contribution is smaller than engine speed and temperature, the statistical significance indicates that humidity variation within the selected range produces measurable changes in brake torque, consistent with charge dilution and reduced oxygen availability associated with increased water vapour content.

Following the significance evaluation, a regression model was developed to represent brake torque as a function of the investigated parameters. The resulting

regression equation is presented in equation (4.3) and provides a predictive relationship between brake torque and the input variables within the defined bounds. In this model, BT represents brake torque, RPM represents engine speed, Temp denotes intake-air temperature (°C), and Humidity denotes relative humidity (%). Overall, the ANOVA outcomes are consistent with the DOE trend observations and linear effect analysis, where brake torque decreases with increasing engine speed and is further reduced under higher intake-air temperature and humidity conditions. The ranking of influence based on the F-values confirms that engine speed is the dominant contributor, followed by temperature and humidity, thereby supporting the response behaviour observed across the full factorial dataset. Consequently, the developed regression model provides a statistically justified basis for response surface interpretation and subsequent optimisation of brake torque within the investigated operating range.

Table 4.9
Brake Torque Analyzed by ANOVA

Parameters	**Degree of Freedom (DOF)**	**Sum of Squares**	**Mean Squares**	**F-value**	**p-value**
Engine Speed, S	2	137.16102	68.580509	318.94659	2.81e-35
Temperature, T	2	26.145539	13.072769	60.797379	7.23e-16
Humiditty, H	2	7.5365200	3.7682600	17.525004	7.27e-07
Error	68	14.621491	0.2150219		
Total	74	185.46457			

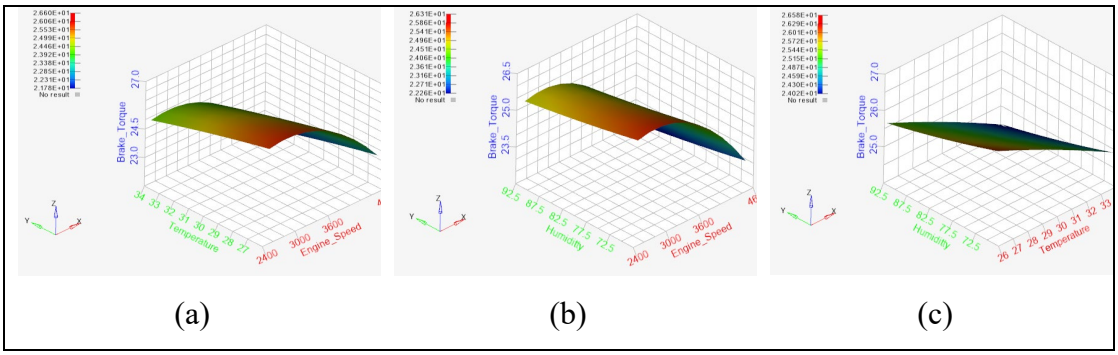
$$BT = 24.933 + (0.006)\,S + (-1.518e\text{-}04)\,T + (-0.084)\,H + (-1.119e\text{-}06)\,S^2 + (-0.003)\,T^2 + (2.939e\text{-}04)\,H^2 \quad (4.3)$$

Figure 4.15(a) illustrates the combined influence of engine speed and intake-air temperature on brake torque, with relative humidity fixed at 80%. The response surface shows that brake torque decreases as engine speed increases across the investigated range. This behaviour is consistent with the typical torque–speed characteristic of naturally aspirated spark ignition engines, where torque reduces at higher rotational speed due to reduced time available for cylinder filling and increasing flow and

frictional losses. In addition, brake torque shows a negative correlation with intake-air temperature, where increasing temperature from 26°C to 34°C produces a further reduction in torque. This reduction is primarily attributed to the decrease in intake-air density at higher temperature, which lowers the inducted air mass and limits the available oxygen for combustion, resulting in reduced indicated and brake torque. Overall, the surface confirms that engine speed is the dominant contributor, while intake-air temperature introduces a secondary reduction in brake torque.

Figure 4.15(b) presents the brake torque response surface as a function of engine speed and relative humidity, with temperature maintained at 30°C. The surface indicates that brake torque reduces noticeably with increasing engine speed, consistent with the dominant trend observed in the DOE results. A mild decreasing trend is also observed as relative humidity increases from 68% to 92%, particularly at higher engine speeds. This behaviour can be explained by the increased water vapour content in humid intake air, which reduces the effective oxygen concentration and contributes to charge dilution. Although humidity may provide limited evaporative cooling, its influence within the investigated range is insufficient to compensate for the reduction in oxygen availability and combustion potential. Therefore, the response surface suggests that higher brake torque is achieved under low engine speed and lower humidity conditions, while high humidity contributes to a measurable torque reduction.

Figure 4.15(c) illustrates the interaction between relative humidity and intake-air temperature on brake torque at a constant engine speed of 3500 rpm. The surface shows that brake torque decreases as both humidity and temperature increase, confirming the combined negative influence of hot and humid intake conditions on torque output. The reduction with temperature is associated with reduced intake charge density, whereas the reduction with humidity is linked to oxygen displacement and dilution effects due to increased water vapour fraction. Compared with the strong influence of engine speed, the humidity–temperature interaction produces a smaller but still measurable reduction in brake torque. Overall, the response surfaces confirm that brake torque is maximised under lower engine speed, lower intake-air temperature, and lower relative humidity, which is consistent with the DOE trends and the ANOVA ranking reported earlier.



(a) (b) (c)

Figure 4.15 Brake Torque Response Surface Versus (a) Temperature and Engine Speed, (b) Humidity and Engine Speed, and (c) Humidity and Temperature

4.5.3 Effect of Intake-Air Temperature on BT at Wet Condition (92%)

Figure 4.16 presents the variation of brake torque with intake-air temperature under wet atmospheric conditions, where the relative humidity was maintained at approximately 92%. A consistent decreasing trend is observed for both low-speed and high-speed operating conditions as the intake-air temperature increases from 26 °C to 34 °C. This indicates that higher intake-air temperature negatively affects the torque-producing capability of the engine, even under highly humid intake conditions.

At low engine speed, brake torque decreases gradually from approximately 27.05 Nm at 26 °C to about 26.40 Nm at 34 °C. Although the reduction is moderate, the trend clearly shows that increasing intake temperature reduces the effective cylinder filling process. As the intake air becomes hotter, its density decreases. This reduces the mass of air inducted into the cylinder during the intake stroke. Consequently, the oxygen available for combustion is reduced, leading to lower combustion pressure and reduced brake torque output.

At high engine speed, brake torque decreases from approximately 24.30 Nm at 26 °C to around 23.40 Nm at 34 °C. The torque value is lower than that obtained at low speed throughout the temperature range. This behaviour can be attributed to the shorter time available for air induction and combustion at higher engine speed. Although high-speed operation increases the number of power strokes per unit time, the cylinder filling process becomes more restricted due to reduced intake duration and higher flow losses.

Therefore, the brake torque produced at high speed remains lower than that at low speed.

From a thermodynamic perspective, the high humidity condition may provide a slight charge-cooling effect due to the presence of water vapour in the intake air. However, this cooling benefit is not sufficient to overcome the negative effect of increasing intake temperature. At elevated temperature, the reduction in air density becomes more dominant, resulting in a lower oxygen mass entering the combustion chamber. In addition, the presence of water vapour may also reduce the proportion of dry air available for combustion, which further limits the combustion intensity.

The brake torque decreases progressively with increasing intake-air temperature under wet conditions. The reduction is observed at both low and high engine speeds, confirming that intake-air temperature is a significant factor affecting engine torque performance. The results also show that low-speed operation produces higher brake torque than high-speed operation under the same humidity condition. Therefore, maintaining cooler intake-air conditions is important for sustaining higher torque output, especially when the engine operates in a highly humid environment.

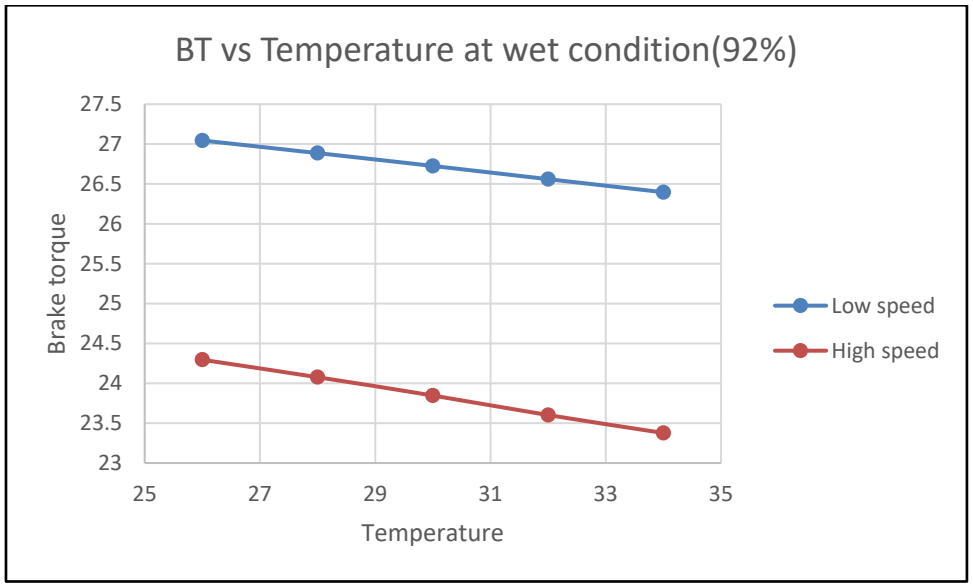


Figure 4.16 Brake Torque Vs Temperature at Wet Condition (92%)

4.5.4 Effect of Intake-Air Temperature on BT at Dry Condition (68%)

Figure 4.17 presents the variation of brake torque with intake-air temperature under dry atmospheric conditions, where the relative humidity was maintained at approximately 68%. A clear decreasing trend is observed for both low-speed and high-speed operating conditions as the intake-air temperature increases from 26 °C to 34 °C. This indicates that the increase in intake-air temperature reduces the torque-generating capability of the engine under dry intake conditions.

At low engine speed, brake torque decreases from approximately 25.4 Nm at 26 °C to about 24.3 Nm at 34 °C. This reduction can be attributed mainly to the decrease in air density as the intake temperature increases. When the intake air becomes hotter, the mass of air inducted into the cylinder during each intake stroke is reduced. As a result, the oxygen available for combustion decreases, leading to lower combustion pressure and reduced brake torque output.

At high engine speed, brake torque decreases more noticeably, from approximately 22.2 Nm at 26 °C to around 20.5 Nm at 34 °C. The lower torque value at high speed compared with low speed is expected because the time available for air induction, fuel–air mixing, and combustion becomes shorter at higher engine speed. Although the engine produces more power at high speed due to a greater number of combustion cycles per unit time, the torque produced per cycle is reduced because of greater intake restriction, higher flow losses, and less complete cylinder filling.

Compared with the wet condition shown previously, the brake torque under dry conditions is consistently lower at the same intake-air temperature. This suggests that the lower humidity level provides less charge-cooling contribution through latent heat absorption. Under dry conditions, the intake charge is more directly affected by temperature rise. Therefore, the reduction in air density becomes more dominant, causing a greater decrease in the effective air mass entering the combustion chamber.

Overall, brake torque decreases progressively with increasing intake-air temperature under dry conditions. The effect is observed at both low and high engine speeds, with the high-speed condition showing a larger absolute reduction. These

findings confirm that cooler intake-air conditions are more favourable for sustaining engine torque. Therefore, intake-air temperature control is important for maintaining torque performance, particularly when the engine operates in dry and hot atmospheric conditions.

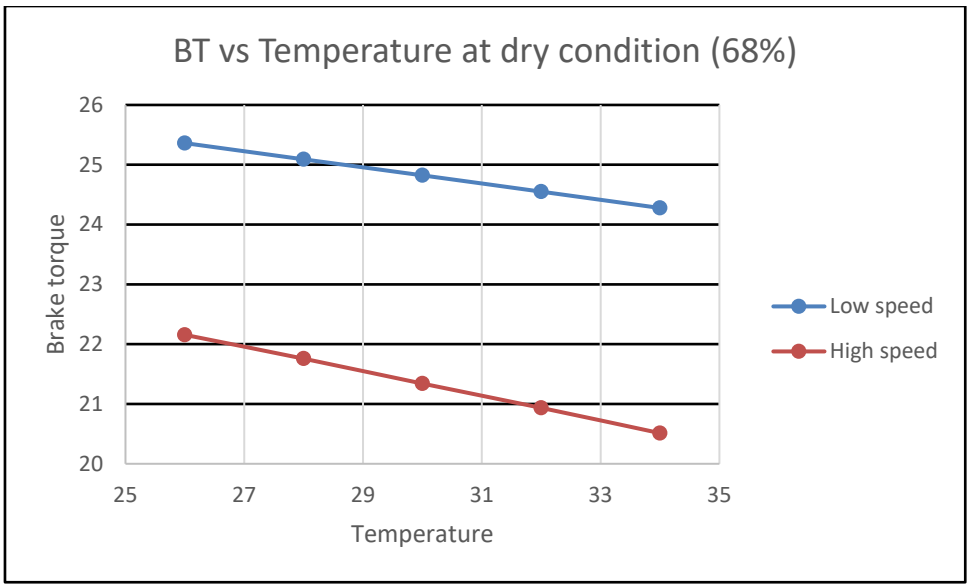


Figure 4.17 Brake Torque Vs Temperature at Dry Condition (68%)

4.5.5 Effect of Relative Humidity on BT at Cold Condition (26°C)

Figure 4.18 illustrates the effect of humidity on brake torque under cold environmental conditions, assessed at both low-speed and high-speed engine operation. The data show a consistent decline in brake torque as humidity increases from 70% to 92%, regardless of engine speed. This trend indicates that increasing moisture content in the intake air adversely affects engine torque output even when ambient temperatures are relatively low.

At low speed, the brake torque decreases from approximately 27.0 Nm at 70% humidity to 26.4 Nm at 92% humidity. Similarly, at high speed, torque drops from around 24.3 Nm to 23.4 Nm across the same humidity range. The reduction in brake torque with increasing humidity is primarily due to the reduction in oxygen concentration in the intake air, as water vapor displaces oxygen molecules. This results in lower air-fuel combustion efficiency, reducing the amount of energy released during the power stroke and hence the torque produced.

Moreover, the negative impact of humidity is observed to be more significant at high speeds, where the combustion process is more sensitive to variations in intake air quality due to reduced residence time for air-fuel mixing and ignition. At low speeds, although the torque is higher overall, the gradual decline indicates that humid air still disrupts optimal combustion, albeit to a lesser extent.

The consistent decline in torque under cold conditions suggests that even in thermally favorable environments (i.e., cooler temperatures with denser air), humidity remains a limiting factor for torque generation. This has practical implications for vehicle and engine performance in humid but cool climates, such as coastal or temperate regions.

The results reinforce the importance of humidity compensation strategies in engine control systems. These may include adjustments to fuel injection timing, air-fuel ratio, or the use of intake air dryers or intercoolers to maintain consistent performance under varying humidity levels.

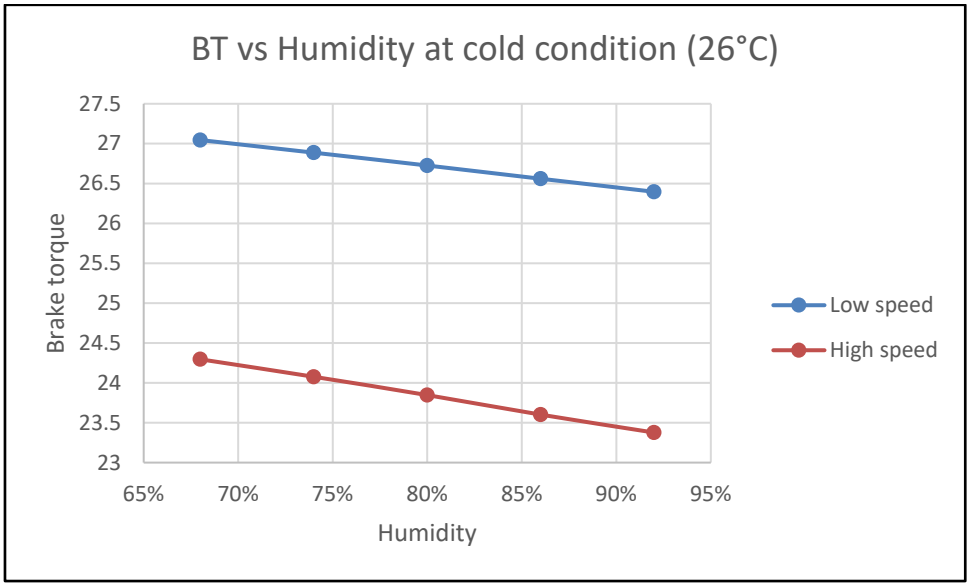


Figure 4.18 Brake Torque Vs Humidity at Cold Condition (26 °C)

4.5.6 Effect of Relative Humidity on BT at Hot Condition (34 °C)

Figure 4.19 presents the effect of humidity on brake torque under hot environmental conditions, for both low-speed and high-speed engine operations. The

results show a clear inverse relationship as humidity increases from 70% to 92%, brake torque consistently declines at both operating speeds. This trend aligns with established thermodynamic principles, where increased humidity reduces the oxygen density of the intake air, leading to less efficient combustion and reduced torque output.

At low speed, brake torque drops from approximately 25.3 Nm at 70% humidity to 24.3 Nm at 92% humidity, a reduction of around 1.0 Nm. At high speed, a more significant drop is observed, from 22.2 Nm to 20.5 Nm, corresponding to a torque loss of 1.7 Nm. These results indicate that high-speed operation is more adversely affected by increased humidity under hot conditions, likely due to the compounded effects of reduced oxygen content, elevated air temperatures, and shorter air-fuel mixing times at higher engine speeds.

The hot ambient temperature exacerbates the negative impact of humidity, as the air is already less dense due to heat, and the addition of moisture further displaces available oxygen. This combination results in a notable reduction in combustion efficiency, especially at high engine speeds, where air handling and cylinder filling dynamics become increasingly sensitive to variations in air quality.

Moreover, when compared to the corresponding cold condition data refer to Figure 4.18, it is evident that the overall brake torque values are lower in hot conditions across all humidity levels. This highlights the cumulative degradation effect of high temperature and high humidity, which jointly impair the engine's ability to generate torque.

These findings underscore the importance of adaptive engine management systems that can compensate for environmental variations in real time. Techniques such as dynamic air-fuel ratio control, advanced ignition timing, or intake air cooling via intercoolers can help mitigate the performance losses associated with high humidity, particularly in hot climates where the risk of power degradation is most pronounced.

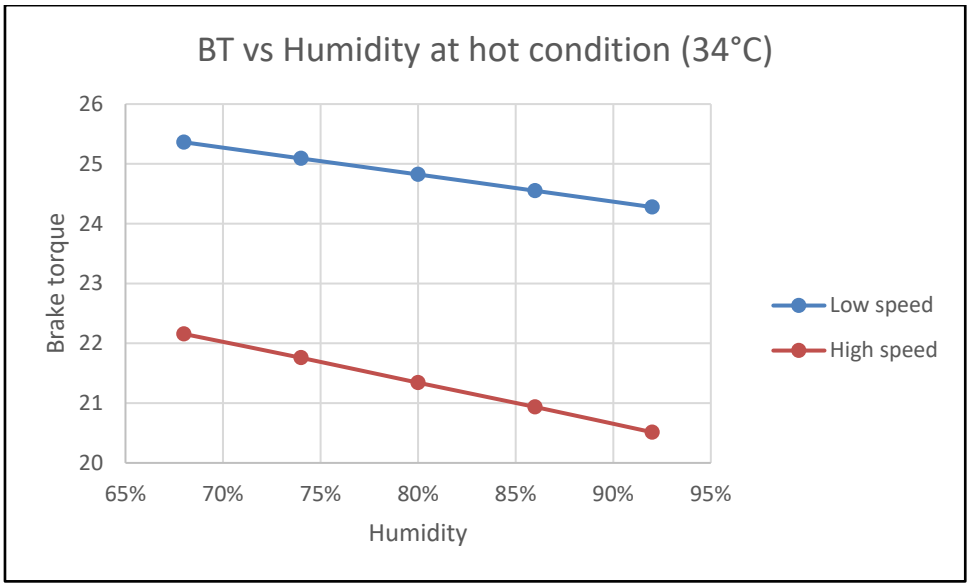


Figure 4.19 Brake Torque Vs Humidity at Hot Condition (34 °C)

4.6 RSM-Based Optimization of VE, BP, and BT

This section presents the RSM-based optimisation performed to identify the most favourable combination of engine speed (RPM), intake-air temperature (°C), and relative humidity (%) that maximises volumetric efficiency (VE), brake power (BP), and brake torque (BT). The optimisation was implemented in Altair HyperStudy using surrogate models developed from the DOE response matrix. The Global Response Search Method (GRSM) was applied to explore the design space, with 2000 evaluation points used to determine the best-performing solutions within the investigated operating range.

The optimisation results are summarised in Table 4.10. All optimum solutions occur at intake conditions close to 26°C and 68% RH. This outcome indicates that cooler and drier intake air provides the most favourable environment for engine performance. As engine speed increases from 2852 rpm to 4496 rpm, VE increases from 0.93 to 0.97. Brake power increases from 8.24 kW to 11.14 kW. This behaviour is expected because higher engine speed increases the frequency of combustion cycles and the rate of useful work output.

In contrast, brake torque decreases as engine speed increases. Brake torque reduces from 27.10 N·m at 2852 rpm to 24.00 N·m at 4496 rpm. This trend reflects the

typical trade-off between torque and power across the operating range. Torque is generally higher at low-to-mid engine speeds, whereas brake power continues to increase at higher speed. Overall, the optimisation confirms that maximum performance is achieved under low intake-air temperature, low relative humidity, and high engine speed, where VE and BP are maximised within the selected parameter limits.

Table 4.10
GRSM Optimisation Results for Maximum VE (%), BP (kW), and BT (N·m) Within The Investigated Operating Range

Engine Speed	Temperature	Relative Humidity	Volumetric Efficiency	Brake Power	Brake Torque
2852	26	68	0.93	8.24	27.10
3010	26	68	0.93	8.65	27.10
4002	26	68	0.96	10.59	25.52
4496	26	68	0.97	11.14	24.00

4.7 Chapter Summary

This chapter presents the results and discussion of the GT-Power simulation study on the effects of intake-air temperature (26–34°C), relative humidity (68–92%), and engine speed on the performance of a naturally aspirated spark-ignition engine. The responses analysed were volumetric efficiency (VE), brake power (BP), and brake torque (BT) using a structured DOE–RSM workflow. The findings confirm that engine speed is the dominant parameter, producing the strongest influence on VE and BP. Intake-air temperature introduces a measurable reduction in performance due to reduced intake charge density at elevated temperature. Relative humidity produces a smaller effect on VE but contributes measurable reductions in brake output under humid conditions due to charge dilution and reduced oxygen availability.

RSM-based optimisation using the Global Response Search Method (GRSM) with 2000 evaluation points indicates that the most favourable performance occurs near 26°C and 68% RH, where VE and BP are maximised within the investigated bounds. Across the investigated range, VE increases from 0.93 to 0.97 and BP increases from 8.24 kW to 11.14 kW as engine speed increases, while BT decreases from 27.10 N·m to 24.00 N·m, reflecting the expected torque–power trade-off. Overall, the results

demonstrate that cooler and drier intake conditions support more stable and improved engine performance, particularly at higher operating speed. Based on these findings, the next chapter presents the overall conclusions of the study and provides recommendations for future work to enhance modelling fidelity and extend the analysis to a wider range of operating conditions.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

This chapter presents the conclusion of the present work. This study successfully investigated the influence of intake-air temperature and relative humidity on the performance of a naturally aspirated single-cylinder spark ignition engine using GT-Power simulation under operating conditions representative of Malaysia's tropical climate. The performance evaluation was conducted using three key responses namely volumetric efficiency (VE), brake power (BP), and brake torque (BT). The simulation framework was established using a full factorial Design of Experiments (DOE) approach in Altair HyperStudy. The engine speed, intake-air temperature, and relative humidity were selected as the main design variables. The investigated engine speed range was 2500 rpm to 4500 rpm, while intake-air temperature was varied from 26°C to 34°C and relative humidity from 68% to 92%.

The results confirm that engine performance is sensitive to intake-air properties, particularly through their influence on intake charge density and combustion potential. Under favourable intake conditions near 26°C and 68% RH, volumetric efficiency increased from 0.93 at 2852 rpm to 0.97 at 4496 rpm. In term of brake power, it increased from 8.24 kW to 11.14 kW. In contrast, brake torque decreased from 27.10 N·m to 24.00 N·m as engine speed increased, which reflects the expected torque–speed characteristic of spark ignition engines. Overall, the findings demonstrate that cooler and drier intake conditions support improved breathing and higher brake output, while torque remains more favourable at lower-to-mid engine speed. Therefore, Objective 1 was achieved.

Building on the individual response evaluation, the interaction between intake-air conditions and engine speed was analysed to establish performance trends under tropical climate scenarios. The results confirm that engine speed is the dominant contributor affecting volumetric efficiency and brake power. Then intake-air

temperature and relative humidity introduce secondary reductions in performance. As engine speed increases, both VE and BP rise substantially due to enhanced intake inertia and a higher rate of useful work output reaching peak values of 0.97 and 11.14 kW, respectively. However, increasing intake-air temperature reduces performance due to lower air density and reduced inducted air mass. Meanwhile increasing humidity contributes additional reductions through oxygen displacement and charge dilution effects. These trends confirm that hot and humid intake conditions negatively affect performance across the investigated speed range and performance improvements are most pronounced when higher engine speed operation is combined with cooler intake air. This finding concluded the success achievement of second objective.

Following the trend and interaction analysis, a simulation-based optimisation was carried out to identify the most favourable intake-air configuration for maximum engine performance. The optimisation was implemented using response surface models developed from the DOE response matrix in Altair HyperStudy. The Global Response Surface Model (GRSM) with 2000 evaluation points was applied to explore the design space. The optimisation results consistently identified the best-performing solutions near the lowest intake bounds of 26°C and 68% RH, confirming that cooler and drier intake air provides the most favourable operating condition for performance enhancement. Under these intake conditions, volumetric efficiency reached up to 0.97 and brake power reached up to 11.14 kW, while brake torque remained highest at the lower-speed optimum with a maximum of 27.10 N·m. Therefore, the optimisation confirms that maximum engine performance under tropical conditions is achieved through low intake-air temperature, low relative humidity, and higher engine speed operation, while torque remains more favourable at lower-to-mid speed due to the inherent torque–power trade-off. Therefore, the third objective of the study was achieved.

5.2 Recommendation

To further strengthen the reliability and applicability of the present findings, several recommendations are proposed for future work. First, future studies should extend the operating range beyond the selected meteorological limits to evaluate engine

robustness under extreme or transient conditions. Although the present work focuses on Malaysia-representative conditions, intake-air temperature above 34°C and humidity beyond 92% RH may occur locally due to heat soak, urban microclimates, or enclosed engine bay effects. Extending the parameter range will provide improved insight into performance degradation boundaries and allow more comprehensive optimisation strategies for tropical climates.

Secondly, refinement of the GT-Power model is recommended by improving the representation of combustion, heat transfer, and friction sub-models. Future work may include a sensitivity study on key GT-Power parameters such as the heat transfer correlation selection, friction model constants, and combustion burn rate calibration. This will ensure the model remains physically consistent and avoids over-reliance on curve fitting, especially when the model is used for prediction outside the calibration range.

Thirdly, intake system improvement strategies should be explored to achieve the favourable intake conditions identified in this study. Since the optimum performance consistently occurs near 26°C and 68% RH, future work should evaluate the feasibility of intake-air conditioning techniques such as improved intake duct routing, thermal shielding, intercooling concepts for naturally aspirated engines, or humidity control through air drying concepts. These approaches may improve performance consistency under hot and humid environments.

Fourthly, future work should conduct primary experimental validation using an in-house engine dynamometer instead of relying only on secondary reference data. The experiment should control intake-air temperature and relative humidity within the selected DOE range and directly measure volumetric efficiency, brake power, and brake torque. Comparing these measured results with the GT-Power predictions will strengthen model reliability, quantify prediction errors more accurately, and improve the practical validity of the simulation findings.

Finally, future research should expand the response evaluation beyond VE, BP, and BT to include fuel consumption and emissions indicators. The inclusion of brake specific fuel consumption (BSFC), air–fuel ratio stability, combustion efficiency, and

emission formation trends (CO, HC, NOx) will provide a more complete assessment of engine performance under tropical intake conditions and support stronger recommendations for engine calibration and intake system design.

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His multidisciplinary educational background in electronic, electrical, and mechanical engineering, combined with extensive industrial experience, has strengthened his interest in engineering applications involving simulation, optimization, and performance analysis. His current research focuses on the investigation of the effects of air intake temperature and humidity on the volumetric efficiency of a single-cylinder spark ignition engine using GT-Power simulation and Design of Experiments (DOE) techniques.

LIST OF PUBLICATION

Som, A. H. M., Basri, M. H., Mat, S. C., Pahmi, A., Rabilah, R., & Azmi, H. (2024). The Volumetric Efficiency of a Single-Cylinder Spark-Ignition Engine as Affected By Air Intake Temperature And Humidity. Jurnal Mekanikal, 47(December), 92–100. https://doi.org/10.11113/jm.v47.552