Pertanika J. Sci. & Technol. 32 (4): 1481 - 1500 (2024)

PERTANIKA JOURNALS

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Effects of Different Throttle Opening and Air Intake Lengths on the Volumetric Efficiency of SI Engine Using 1D Simulation Method

Mohamad Firzan Ahmad Harazi*, Abdul Aziz Hairuddin, Azizan As'arry and Siti Ujila Masuri

Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia

ABSTRACT

Engine performance is influenced by volumetric efficiency, an engine's ability to put air into its cylinders. It is known for its intake length being tuned based on engine speed due to the air pressure wave behavior. However, the airflow into the intake system is controlled by the throttle opening, so there is a need to study the performance effect of intake length that is tuned based on it. Thus, this current study focuses on the impact of different throttle opening and intake lengths in relation to engine speed on the volumetric efficiency of the Proton CamPro 1.6L SI engine. The simulation runs on different ranges of engine speeds from 1000 rpm to 7000 rpm and different intake lengths with different throttle opening angles. The critical finding of this study revealed that tuning intake length based on throttle opening showed an improvement of 1.3% for volumetric efficiency at the low rpm range. It is by tuning the intake length to 400 mm at a throttle opening of 70° for 1000 rpm and 450 mm intake length with a throttle opening of 50° at 2000 rpm. However, it showed that 90° or wide-open throttle provides the best volumetric efficiency for mid and high-range rpm for all intake lengths. The highest efficiency achieved is 101% at 4000 rpm with a 500 mm length intake and wide-open throttle. The findings from this study contribute to a good understanding of engine performance through intake length tuned based on throttle opening.

Keywords: Engine speed, spark ignition engine, throttle opening, variable intake length, volumetric efficiency

ARTICLE INFO

Article history:
Received: 24 May 2023
Accepted: 18 December 2023
Published: 16 July 2024

DOI: https://doi.org/10.47836/pjst.32.4.03

E-mail addresses:
firzanharazi@gmail.com (Mohamad Firzan Ahmad Harazi)
ahziz@upm.edu.my (Abdul Aziz Hairuddin)
zizan@upm.edu.my (Azizan As'arry)
ujila@upm.edu.my (Siti Ujila Masuri)
* Corresponding author

ISSN: 0128-7680
e-ISSN: 2231-8526

INTRODUCTION

Two major types of internal combustion engines in the automotive industry include spark ignition (SI) engines and compression ignition (CI) engines. Both types of engines have been subject to study and advancement for their performance and emission improvement. These improvements include the advancements and tuning in injection systems (Channapattana et al., 2023), ignition timing control (Rimkus et al., 2022), intake system tuning (Shin et al., 2022), exhaust system tuning (Allawi et al., 2019) and nanoparticle's additive (Chatur et al., 2023).

One of the important parameters in assessing engine performance is volumetric efficiency (VE), which is used to measure the effectiveness of the engine induction process (Heywood, 2018). On average, SI engines have volumetric efficiency ranging from 80% to 100% across their engine speed range. Thus, various methods and tunings have been studied to maximize the engine's volumetric efficiency. Volumetric efficiency is important for improving engine power output, fuel efficiency, and reduction of emissions. Increasing the volumetric efficiency can lead to significant improvement in combustion efficiency. A study by Talati et al. (2022) showed that they improved volumetric efficiency by using variable intake length, which is tuned based on engine speed. The results showed that the VE could be improved by 6%, which also improves fuel consumption and thermal efficiency by 0.83% and 1.77%, respectively. According to Pahmi et al. (2019), implementing pressure waves during the intake valve opening process increased the volumetric efficiency. This improvement led to an enhanced brake mean effective pressure (BMEP) due to the higher amount of air in the cylinder, producing a greater pressure peak of the mean effective pressure inside the cylinder.

Another experiment was done by Sivashankar et al. (2018), in which they implemented Chrysler's ram theory and Helmholtz resonator theory to determine the optimum length for inertia air charging. The result showed an increase in volumetric efficiency by 6% and a decrease in brake-specific fuel consumption by 11% under full load conditions. Fuel economy and emission can also be improved by volumetric efficiency through downsizing of the engine because improved volumetric efficiency of a smaller engine can provide better or the same power output for the bigger engine but with less volumetric efficiency (Namar et al., 2021). Other than that, a study by Jemni et al. (2013) showed that different intake manifold designs significantly affected both engine performance and emission. It is supported by Raja and Selvam (2022), who researched maximizing the quantity of air in the cylinders by optimizing the intake manifold using CFD. From the result, they observed that flow harnessing in the intake could improve engine torque by 10%, along with an emission reduction.

Among the intake systems used to improve engine VE is variable intake manifold (VIM), which improves engine VE across different engine speeds (Ceviz, 2007). This technology improves a car's torque and power at different engine speeds through volumetric efficiency (Jagadishsingh et al., 2016). According to Malkhede and Khalane (2015), a constant intake length only provides the best volumetric efficiency at the limited range of engine speed while having an adverse impact on another engine speed. Thus, VIM improves this limitation by having an additional intake length, which provides the best volumetric efficiency at the concerned engine speed. As its name implies, the variable intake manifold has two or more specific stages of intake configuration that vary based on engine speeds (Wan, 2011).

The configuration can be divided into plenum volume and runner intake length (Hartman, 2013). Based on Hosaka & Hamazaki (1991), Honda NSX has implemented a Variable Volume Induction System (VVIS) with a resonance chamber for its intake manifold to increase the torque for a medium speed range. This system has an additional second plenum and is separated from the primary manifold by six butterfly valves that open between 4600 and 4900 rpm by manifold vacuum. It is an example of a variable in the plenum's volume. Another study by Potul et al. (2014) reported that despite its improvement, the intake manifold with a two-stage system requires a very large space as there is a need to accommodate two intake runners for every cylinder. Alves et al.(2018) showed that the intake manifold can divided into three stages. The first stage is the longer stage in which both valves are closed, forcing the air to travel for the longest way. The second stage is when the lower valve opens and forces the air flow through the intermediate path. The last stage is when the upper valve opens, causing the mixture to flow through the shortest length. However, Potul et al. (2014) argued that the problem with 3-stage VIM is that its entire length of runner is used only for a short range of rpm.

After years of variable intake manifold technology, the continuously variable intake manifold (CVIM) was introduced in 2002, as the BMW V8 became the first standard engine in the world equipped with this technology (Hirschfelder et al., 1990). According to Lenz (1990), it brings the advantage of ideal adaptation of the lengths of intake ports to the desired engine speed, especially at high speed. Through this, they achieved the goal of optimum resonance pipe supercharging across a wide range of engine speeds. Bari & Sawant (2019) found that continuously variable intake manifolds are able to boost volumetric efficiency by an average of 3.2% over the operating speeds of the engine, while a two-variable length intake manifold can boost an average of 1.4% over the operating range.

According to Sawant and Bari (2018), continuous intake tuning can boost the performance of an IC engine by over 4% improvement in volumetric efficiency. It occurs through induction pressure boost by tuning intake systems when the intake valve opens. However, it was found that minimum improvement of volumetric efficiency at high rpm such as 8500rpm. Malkhede and Khalane (2015)supported it, describing that engine with a wide speed range, an idle speed greater than 3000 rpm, and continuously variable intake runner length can improve volumetric efficiency compared to fixed intake runner length. However, much study is required to improve continuously variable intake manifold because the improved volumetric efficiency is relatively small compared to turbochargers and superchargers. Furthermore, Potul et al. (2014) argued that CVIM has a problem: the entire length of its runners is used only for a short range of rpm. The length cannot continuously decrease as the rpm increases. Thus, the continuously variable intake manifold design should be studied further for improvement.

In driving a car, the main control for its speed is the throttle opening through the throttle pedal. The throttle opening controls the area, allowing air to enter the intake system and the engine cylinder. Although throttle opening is directly proportional to volumetric efficiency (VE) and engine performance, wide-open throttle (WOT) does not exactly cause maximum volumetric efficiency and performance. According to a study by Kardan et al. (2018), the best engine performance was at 75% of the throttle position because a higher load than 75% would result in the choke phenomena at the intake valve. It was found that the engine performance achieves maximum torque, power and thermal efficiency, values which were 4.16Nm, 0.87kW and 18%, respectively. It is supported by a study by Tavakoli et al. (2020), which revealed that the engine was efficiently regulated with the throttle during lower steady-state loads. However, the throttle could not recover the engine characteristics during lower load; thus, its application in the fast transient state is worthless.

A simulation study on the influence of the throttle opening angle on the intake system by Xu and Cho (2017) concludes that the 60° angle of the throttle body had better air velocity distribution and pressure distribution than that of the wide-open throttle and other lower opening angles. In the study, different throttle opening positions of 0°, 30°, 45°, 60° and 90° were compared to find the optimum throttle angle for complete burning and reducing exhaust emission. Complete burning in the engine allows the combustion chamber to be free from unburned fuel, which improves the volumetric efficiency as a larger amount of air-fuel mixture can be drawn into the chamber. It can result in improved overall engine performance. Besides, a real experiment study by Hamada et al. (2023) highlighted that running the SI engine at wide-open throttle conditions resulted in better efficiency, reduced waste heat and reduced environment compared to part throttle conditions. This study evaluated the engine's performance based on thermodynamic analyses performed at different engine speeds from 1500 rpm to 4000 rpm. The improvement in wide-open throttle conditions was due to improved heat quality with combustion and its reduced entropy generation compared to part throttle conditions.

Meanwhile, another study by Talati et al. (2022) showed that an intake manifold with different combinations of opened throttle bodies could further improve volumetric efficiency. From the study, the result indicates that there is an improvement in volumetric efficiency, brake torque, brake specific fuel consumption, brake thermal efficiency and heat release rate of the engine compared to the stock intake manifold, which was 6.33%, 7.23%, 0.83%, 1.77% and 11.79%, respectively. There is also a study on the effect of unthrottled operation with early intake valve closure on engine performance. The results showed that the gross mechanical efficiency can be improved, but the gross indicated thermal efficiency decreases due to poor combustion. The poor combustion was due to weak turbulence and low gas temperature at the spark timing (Zhou et al., 2020). Another study investigates the differences between gasoline and natural gas for two throttle positions. The study found that gasoline has approximately equal brake power across 1000 to 6000 rpm for 50% throttle compared to 100%. However, brake mean effective pressure (BMEP) for gasoline was better at 50% throttle position compared to 100% throttle position (Aljamali et al., 2014).

The reason why throttle opening has various effects on volumetric efficiency is because intake components in between the throttle body and engine cylinder are also an influential factor. As an example, the intake manifold and intake valve also affect the volumetric efficiency of the engine because the improvement of volumetric efficiency by air intake length tuning is often based on the utilization of compression wave and suction wave effects (Jagadishsingh & Jadhav, 2016; Potul et al., 2014). Through these wave utilization, the volumetric efficiency can be improved by more than 100% (Bari & Sawant, 2019; Ghodke & Bari, 2018; Sawant & Bari, 2017). Therefore, the engine's torque and power can be increased and its curve can be broadened, too.

Based on Mauger (2004), in compression wave, the air flows through the intake manifold runner and past into the cylinder, then strikes the intake valve as it closes. Thus, a high-pressure wave is generated, and it travels back and forth along the closed intake runner length (McKee et al., 2006). When the intake valve opens, a negative pressure wave is produced due to the reduction in cylinder pressure. At the speed of sound, the pressure travels through the columns between the intake valve and the end of the runner. A pressure depression is created when a pressure wave pulse reaches the plenum chamber and decreases gas density at the runner entrance. Through this, the surrounding gas flows immediately into the depression. The incoming gas's inertia causes an effect with a reflected positive pressure wave (Heisler, 1995).

The suction wave is created when the intake valve opens, and the cylinder's vacuum is exposed to the intake manifold. This low-pressure wave travels upstream to airflow and gets reflected from the inlet boundary, which turns to high-pressure waves that travel downstream into the cylinder (Sawant & Bari, 2017). The tuning effect occurs when this wave properly arrives at a time; it increases the local density of intake flow, which helps increase the volumetric efficiency (Tabaczynski, 1982). This effect is termed natural supercharging or acoustic supercharging because if the arrival time is correct with the opening and closing of the intake valve, the region acts like a compressor on a turbocharger or supercharger, which rams air at a pressure above atmospheric (Hamilton et al., 2009).

It is supported by Wang et al. (2021), who studied the impacts of the continuous variable valve lift (CVVL) system and unthrottled load control on the performance of the spark ignition engine. The study found that the intake air mass flow at the intake ports became smoother, plus turbulence flow and its intensity were strengthened when using this method, which is beneficial to accelerating combustion rate and improving combustion efficiency. One of the reasons for the improvement was that the CVVL reduced the reversed mass flow rate by intake flow, which increased engine volumetric efficiency. Second, this unthrottled load control demonstrated the elimination of pressure waves during the intake stroke, increasing the volumetric efficiency. Another study by Bari and Sawant (2019) on the effect of intake runner length and valve timing showed that engine volumetric efficiency can be boosted to 7.78% when using both variations in runner length and valve timing. Meanwhile, the result also showed that the volumetric efficiency can boosted only to 3.2% when using variations only in runner length. Besides that, a study by Jemni et al. (2021) proved that changing intake length continuously with the rpm can improve an average of 39.7% volumetric efficiency compared to the original engine configuration at 1000 rpm. The study found that using optimal intake length at 500 rpm increases the in-cylinder velocity by about 60%, 58% and 48%. According to these studies, both throttle and intake length showed a relation in pressure wave by intake flow, which affects the volumetric efficiency and engine performance.

Optimal intake runner length can be calculated using either Chrysler Ram theory or Helmholtz Resonator Theory, which was proved by an experimental study by Adithya et al. (2021). Improvement in volumetric efficiency would greatly influence other engine performance characteristics such as brake torque, brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE). Thus, it effectively enhances the spark ignition engine performance under both part and full load conditions (Wasiu et al., 2021). According to these previous studies, both throttle and intake length showed a relation in pressure wave by intake flow, which affects the volumetric efficiency and engine performance.

Numerous engine performance studies have been conducted through experiments and simulations. Both methods have their advantages and disadvantages. As for simulation, the time and cost of developing an efficient engine can be significantly reduced by implementing 1D simulation. Diesel RK, AVL Boost, GT Power, and Lotus Engine Simulation (LES) are among the leading commercial engine simulation packages used in the automotive industry. Researchers used all these as they had the required functionality to predict engine behavior and performance.

Lotus Engine Simulation (LES), which was developed by Lotus Engineering, is also commonly used by researchers and recommended for engine performance improvement. Allawi et al. (2021), who used it for a variable valve timing simulation study, recommended using Lotus software by car manufacturers to improve the engine system performance. Their study reveals that an overlap case of 98° demonstrates an improvement in brake-specific fuel consumption by 3% and a 6.2% volumetric efficiency. Another study by Magdas et al. (2020) demonstrated how the LES is capable of predicting the interior predestination engine's behavior. Using this software, they approached the 1D simulation possibilities on the variable valve timing system. One of the important results includes adjusting the variable valve opening height up to 15mm to allow an increase in torque by 3Nm and power by 4kW. Based on this, they concluded that simulation using LES provides useful results for further investigation on engine optimization. It is also supported by a study by Nouhov and Chen (2002) that models and simulates the valve timing effect on the 4-stroke spark-ignition engine. They reported that intake valve opening could reduce the backflow during the overlapping periods through the inlet charging effect.

Based on the preceding summarized literature, many studies have been done on the air intake system to improve the spark ignition (SI) engine performance. For simulation software, previous researchers commonly used LES to study the inlet charging effect or the wave pressure phenomenon effect on engine performance which is, closely related to throttle opening and intake runner length as part of the intake system. However, no literature has used LES software to investigate the effects of different throttle openings and air intake lengths on volumetric efficiency in SI engines. Hence, this research aims to investigate the effect of different throttle opening and air intake lengths on the volumetric efficiency of SI engines using the 1D simulation method. This study would help researchers improve the method of tuning both throttle opening and intake length based on engine speed, contributing to better volumetric efficiency and engine performance.

MATERIALS AND METHODS

Engine Specifications

This study was done by using Lotus Engine Simulation. The simulation setup for this study is based on the CamPro 1.6 engine from Malaysia automobile manufacturer Proton. Thus, the simulation's engine specification is based on this engine. The intake throttle, intake port, intake plenum, intake port, intake valve, engine cylinder, exhaust valve, and exhaust port are the constant specifications required to execute this simulation. The details of each specification used in the simulation are in Table 1.

Table 1
Specifications of the engine

Components	Specification value
Intake throttle diameter	52 mm
Intake plenum volume	2.5 liters
Intake port throat diameter	28 mm
Intake valve opens	12°
Intake valve close	48°
Intake valve max lift	8.5 mm
Cylinder bore	76 mm
Cylinder stroke	88 mm
Cylinder con-rod length	180 mm
Cylinder compression ratio	10
Exhaust valve open	45°
Exhaust valve close	20°
Exhaust valve max lift	8 mm
Exhaust port throat diameter	25 mm

During the simulation, the engine runs through four-stroke cycles: intake, compression, power, and exhaust. There are seven different rpm simulated ranging from 1000 to 7000 rpm. The amount of air that fills the cylinder during each rpm cycle is determined via a fluid flow equation by the 1D simulation. Then, the volumetric efficiency can be determined. For this study, the simulation parameters in the Lotus Engine simulation are set up as shown in Table 2.

Table 2
Simulation parameters

Parameter	Range
Engine speed (rpm)	1000 rpm to 7000 rpm
Intake manifold length (mm)	200 mm to 500 mm
Combustion strategies	Stoichiometric mixture (lambda =1)
52 mm diameter throttle angle (°)	10° to 90°
Spark timing	MBT spark timing

Configuration of Simulation

The simulation's flow of operations begins with the crank angle in the engine cylinder rotating in the induction cycle, which sucks air from the inlet and moves it via the intake throttle, plenum, runner pipe, intake port, and intake valve before entering the engine cylinder. Next, the compression and power cycle take place based on the crank angle rotation position. The air was consequently forced out of the exhaust exit, followed by the plenum, exhaust port, and exhaustvalve. During each rpm cycle, the efficiency of air sucked into the cylinder is calculated based on this process. The flow of operation can be referred to as Figure 1.

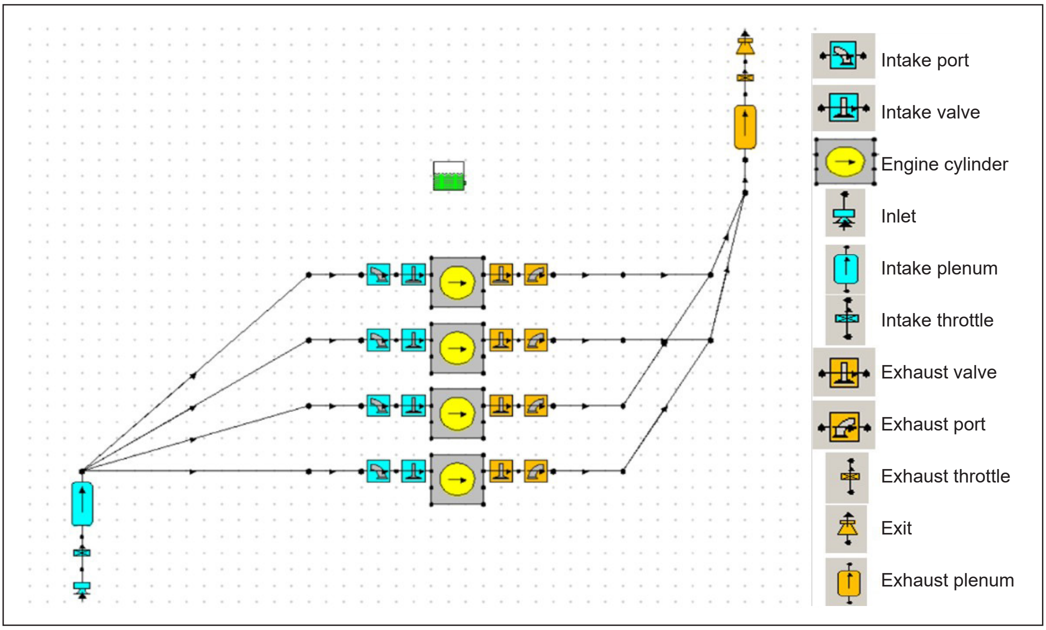

Figure 1. Configuration of simulation in Lotus Engine simulation

Equations

The wave phenomena inside the engine manifold strongly affect the volumetric efficiency of the engine. This pressure wave traveling inside the runner and plenum of the manifold is calculated by solving conservation equations for mass, momentum, and energy at each time step. The Lotus Engine Simulation Program and study by Winterbone and Yoshitomi (1990) are used for the equation's references.

Volumetric Equation

Based on the ratio of air trapped in a cylinder to the mass of air that might be trapped within the cylinder's swept volume, the 1D simulation solves volumetric efficiency, as shown in Equation 1. Meanwhile, the momentum, continuity and energy equation determine the mass flow rate trapped in the cylinder.

$$\eta = \frac{M_i}{\frac{N}{2} V_s \rho_i} \tag{1}$$

where η = volumetric efficiency; M_i = mass flow rate; ρ_i = inlet density; V_S = piston displacement; N = engine speed in rev/unit time

Momentum Equation

The momentum equation is also a form of the conservation law, in which the sum of the pressure and shear forces acting on the control volume equals the sum of the momentum change rate in the control volume and the net momentum flux out of it, as in Equation 2.

$$-\frac{\partial(\rho F)}{\partial x}dx + \rho\frac{dF}{dx}dx - \frac{1}{2}pu^2 f \pi D dx = \frac{\partial(upFdx)}{\partial t} + \frac{\partial(p\,Fu^2)}{\partial x}dx \tag{2}$$

where F= cross-sectional area; ρ = density; p = momentum; u = initial velocity; f = friction coefficient; D= diameter of duct; t= time

Continuity Equation

According to the continuity equation, the rate at which mass enters a system equals the rate at which mass leaves a system. The gradient of the mass flux, the length of the duct element, dx, and its cross-sectional area, F, can all be used to calculate the mass change rate within the control volume (Equation 3).

$$\frac{\partial(pF)}{\partial t} + \frac{\partial(puF)}{\partial x} = 0 \tag{3}$$

where F = cross-sectional area; p = momentum; t = time; u = initial velocity; ∂x = length of element

Energy Equation

By applying the first law of thermodynamics to a controlled volume, the energy equation can be derived as Equation 4. The equation had e_0 and h_0 represent the fluid's internal energy and enthalpy of fluid, respectively. This equation can include the radial heat transfer from the gas to the wall or vice versa.

$$\frac{\partial(\rho e_0 F)}{\partial t} + \frac{\partial(\rho u h_0 F)}{\partial x} - q\rho F = 0 \tag{4}$$

where F= cross-sectional area; ρ = density; e_0 = internal energy; h_0 = enthalpy; t = time; u = initial velocity

RESULTS AND DISCUSSION

This simulation was performed on a 4-cylinder engine with different throttle openings and intake runner lengths-the engine speeds used in the setup range from 1000 to 7000 rpm. The volumetric efficiency maps based on throttle opening and intake runner length are created from the simulation.

Validation of the Simulation

The outcome of this simulation was validated with a study conducted by Mohiuddin and Rahman (2008) that included both experiment and simulation results to ensure the accuracy of this simulation model. Their experimental study was conducted on the same engine type, Proton Campro 1.6, used for this simulation study. The specifications of the engine can be referred to in Table 1. Both experimental results by Mohiuddin and Rahman (2008) and the current simulation result of VE% on the same engine can be compared in Figure 2. It demonstrated a small difference between these VE%, notably between 3000 and 4000 rpm. Overall, the results were close, with an average error of less than 3%. Thus, it can be concluded that the results in Figure 2 prove the validity of this study simulation configuration and the VE% results.

Effect of Throttle Angle Opening on Volumetric Efficiency Across a Range of rpm

The Lotus Engine Simulation was run on a 4-cylinder engine at different intake manifold lengths and throttle angle opening. This setup was repeated at different engine speeds ranging from 1000 to 7000 rpm. The result of volumetric efficiency based on simulation is as in Figure 3. It shows that overall, as the engine rpm increases, the throttle opening angle needs to increase to maintain high volumetric efficiency. However, specifically at 10° to 30°, the volumetric efficiency decreases with the increase in rpm. The graph also showed that when the throttle opens at 40°, the volumetric efficiency increases with rpm until it peaks at 4000 rpm and starts to fall in efficiency for much higher rpm. Meanwhile, for the range from 50° and above, the volumetric efficiency increases with rpm until it peaks at 5000 rpm and starts to fall in efficiency for much higher rpm. The 3D mapping of volumetric efficiency based on throttle angle and rpm is shown in Figure 3.

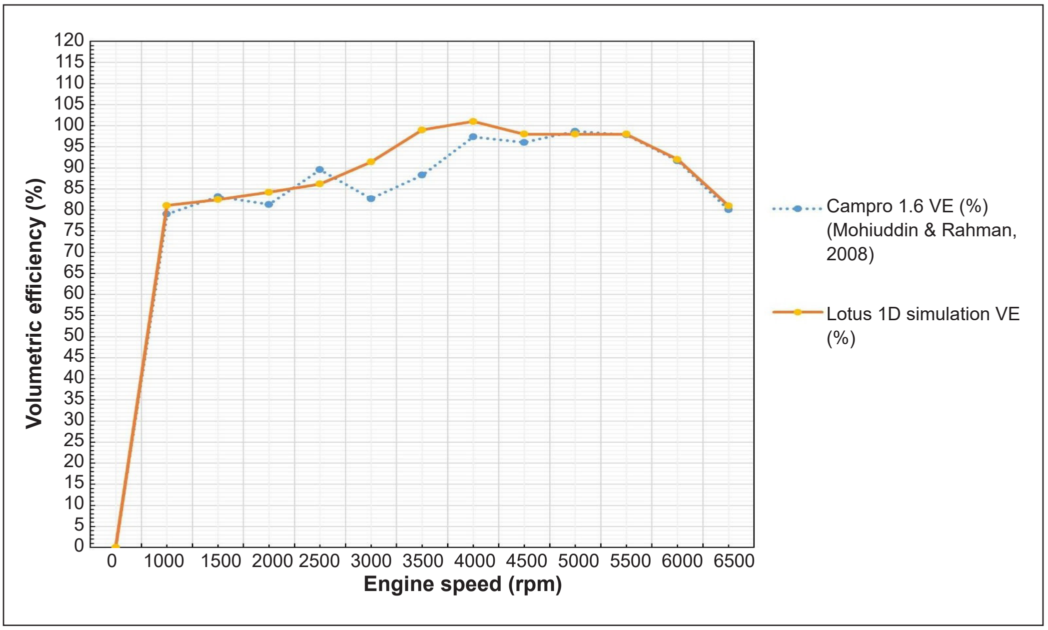

Figure 2. Volumetric efficiency comparison between experimental (Mohiuddin & Rahman, 2008) and Lotus 1D simulation across a range of rpm

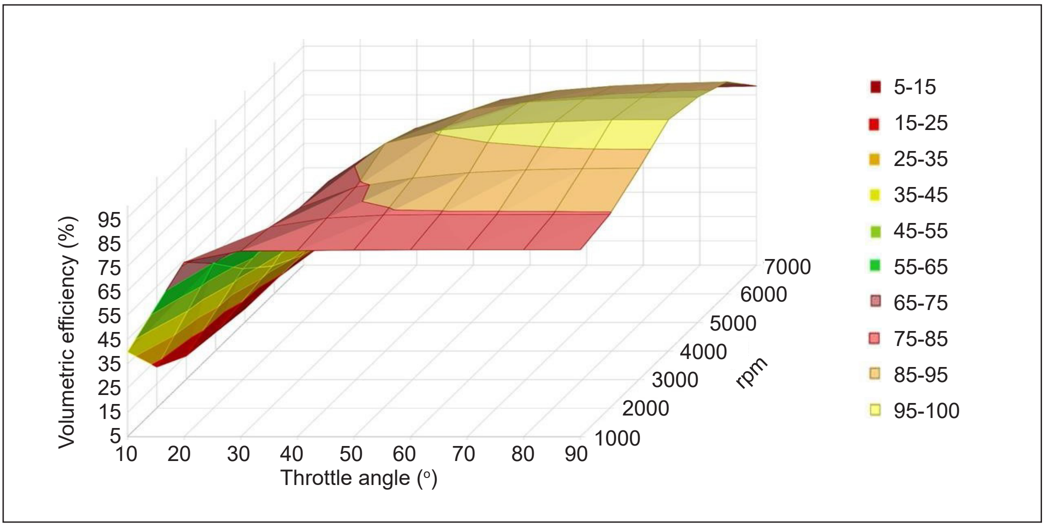

Figure 3. Volumetric efficiency mapping at different throttle angles across a range of rpm

Effect of Throttle Angle Opening and Variable Intake Runner Length on Volumetric EfficiencyAcross a Range of rpm

Based on Figure 4, the bigger the throttle opening, the better the volumetric efficiency of the cylinder. A longer intake runner showed better volumetric efficiency, but the differences in each intake runner's length had no major impact on volumetric efficiency. Based on the throttle angle at 30°, the runner length was lower than 350 mm and showed a drop below 80.95% of volumetric efficiency. For runner lengths over 350 mm, the maximum volumetric efficiency achieved is 81.85% at 70° of throttle opening, and the minimum efficiency is 80.95%. It is due to volumetric efficiency in the cylinder being interrelated with the pressure wave. The inlet pressure value during the short period before the intake valve closes almost entirely determined the volumetric efficiency on that rpm (Ohata & Ishida, 1982). The pressure wave at 1000 rpm is not significantly higher than the tuning of runner length and is unable to augment the trapped air mass in the engine cylinder. Mohiuddin and Rahman (2008) agree that the amplitude of the pressure wave nearest to the maximum valve opening is the main concern when tuning the runner length to control arrival time. Overall, a long runner length above 350 mm can achieve high volumetric efficiency earlier than a short runner length below 350 mm.

The preceding fluctuation of the pressure wave can be referred to in Figure 5 for low rpm. The open exhaust valve (EVO) and the closed exhaust valve (EVC) are indicated by yellow lines on both the left and right sides, respectively. Meanwhile, a blue line on both the left and right sides indicates the intake valve opening (IVO), and the intake valve closing (IVC) is indicated by a blueline on both the left and right sides. The inlet pressure value right before the intake valve closes can be determined from the crossing line between the red and blue lines of IVO.

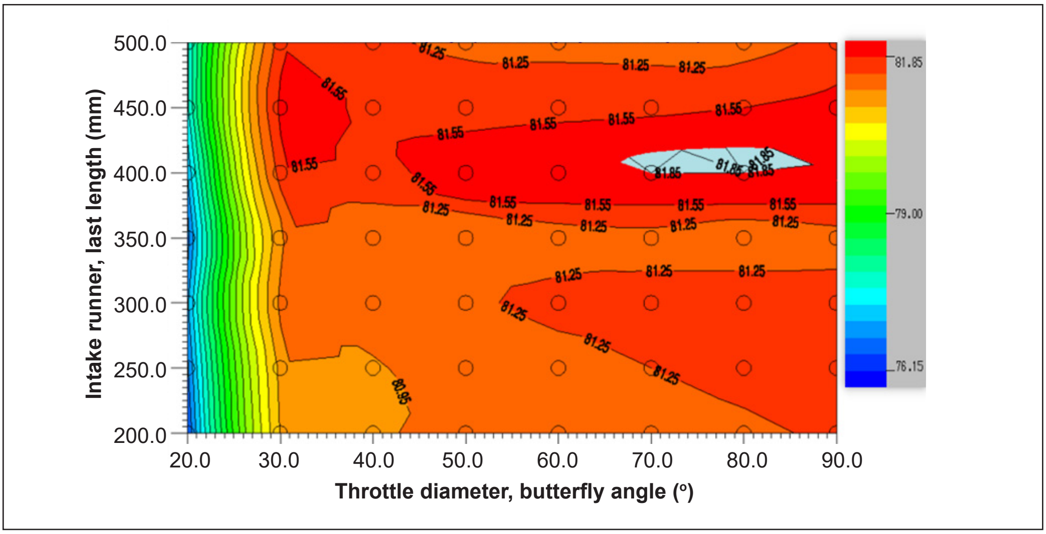

Figure 4. Volumetric efficiency at 1000 rpm

The difference in pressure amplitude for high rpm can be seen in Figure 6, which has 1.7 bar ofpressure for maximum amplitude, while Figure 5 shows only 1.06 bar of pressure. The volumetricefficiency can be improved by tuning the runner length so the maximum pressure occurs rightbefore the intake valve opening, as in Figure 6.

Therefore, referring to Figure 7, an intake length above 450 mm is the quickest in terms of achievinghigh volumetric efficiency of 84% at a 40° throttle opening, while an intake length shorter than 400 mmneeds at least 60° of throttle opening to achieve the same volumetric efficiency. The maximum volumetric efficiency is 85.1% at 450 mm of runner length and 50° of throttle opening.

As in Figure 8, an intake length of 500 mm is the quickest in terms of achieving high volumetric efficiency of 91.7% at a 60° throttle opening, while an intake length below 450 mm can only achieve upto 89.4% volumetric efficiency at the same throttle opening. The highest volumetric efficiency is 94% when the intake length is 500 mm and the throttle opening is 90°. This result agreed with a study by Pahmi et al. (2022) that revealed volumetric efficiency was highest at 103% for long-length runners while showing a reduction for shorter-length runners at 2000 rpm and 3000 rpm enginespeeds. However, the study

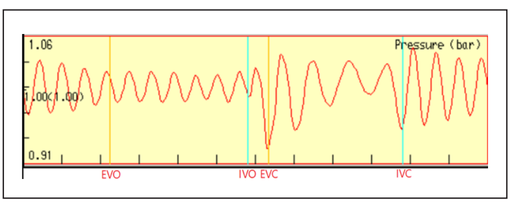

Figure 5. Pressure fluctuation at intake port for full engine cycle at 1000 rpm

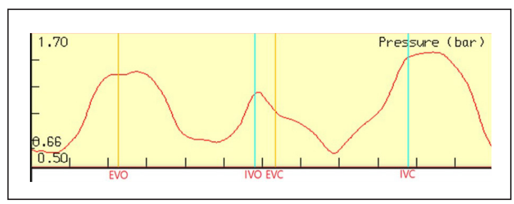

Figure 6. Pressure fluctuation at intake port for full engine cycle at 7000 rpm

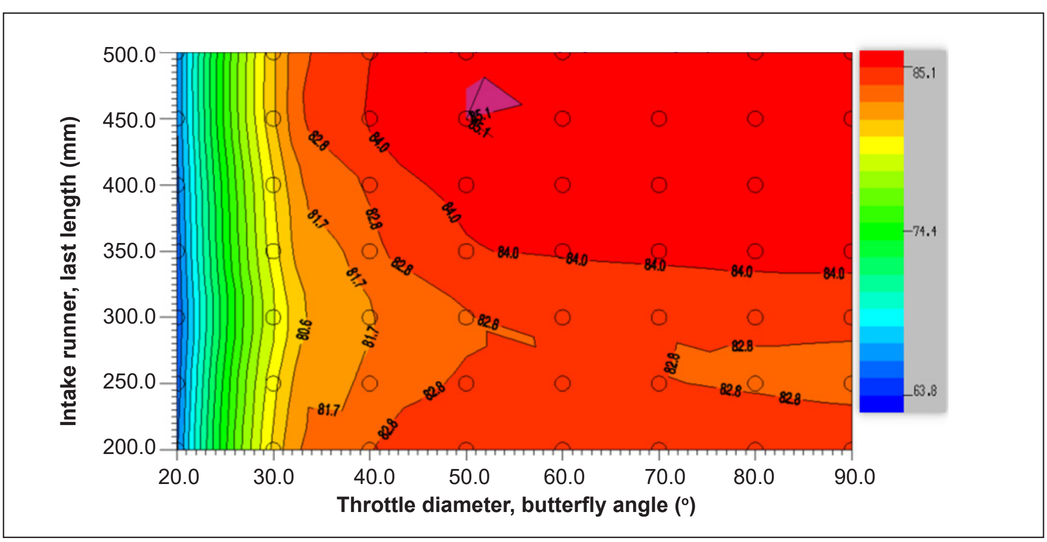

Figure 7. VE (%) of different intake runner lengths across a range of rpm

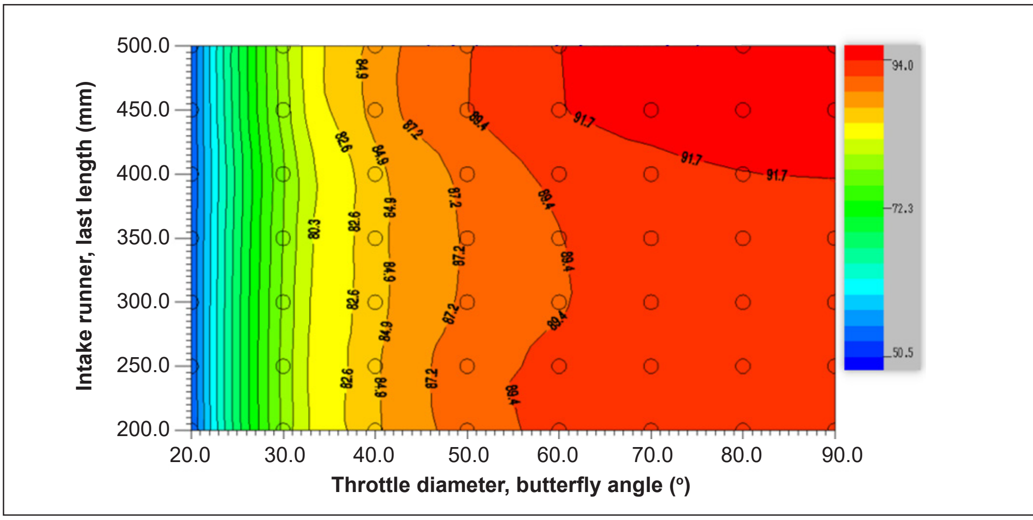

Figure 8. Volumetric efficiency at 3000 rpm

was done on a single-cylinder engine, so the longest length used was 229.7 mm, and the short length runner used was 153.2 mm. This difference in volumetric efficiency is due to the fact that a multiple-cylinder engine would have a reduced mass flow rate during intake stroke when a runner has air back flow that causes another runner to have reverse flow from the suction of the firstrunner in the same plenum (Ling & Tun, 2006).

As for the 4000 rpm graph in Figure 9, an intake length of 500 mm is the quickest in terms of achieving high volumetric efficiency of 97.8% at 60° throttle opening. In contrast, an intake length below 400 mm needs a bigger degree of throttle opening followed by a decreased intake length to achieve the same volumetric efficiency. The highest achieved volumetric efficiency is 101% at 500 mm of intake length and wide-open throttle.

As for the 5000 rpm graph in Figure 10, an intake length of 450 mm is the quickest in terms of achieving high volumetric efficiency of 94.7% at 60° throttle opening. In contrast, an intake length below 400 mm needs a bigger degree of throttle opening followed by a decrease in intake length to achieve the same high volumetric efficiency. The shortest runner length, 200 mm, needs at least 80° throttle opening to achieve the same volumetric efficiency. The highest volumetric efficiency can be achieved by 98.2% by tuning the intake length to 450 mm and the throttle opening at 90°.

As for the 6000 rpm graph in Figure 11, an intake length below 250 mm is the quickest in achieving a high volumetric efficiency of 90.8% at a 60° throttle opening. In contrast, an intake length above 250 mm needs a bigger degree of throttle opening followed by an increased intake length until 400 mm to achieve the same high volumetric efficiency. The maximum volumetric efficiency achieved for a runner length longer than 400 mm is 87.3%, while the highest volumetric efficiency achieved is 94.3%, and throttle opening is 90°.

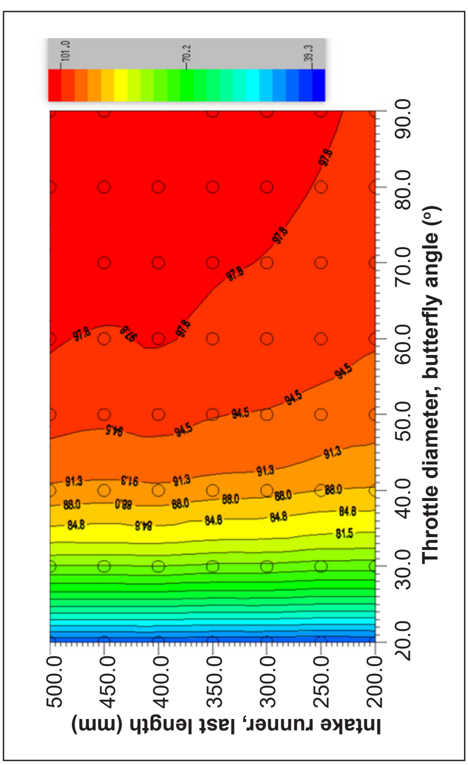

Figure 9. Volumetric efficiency at 4000 rpm

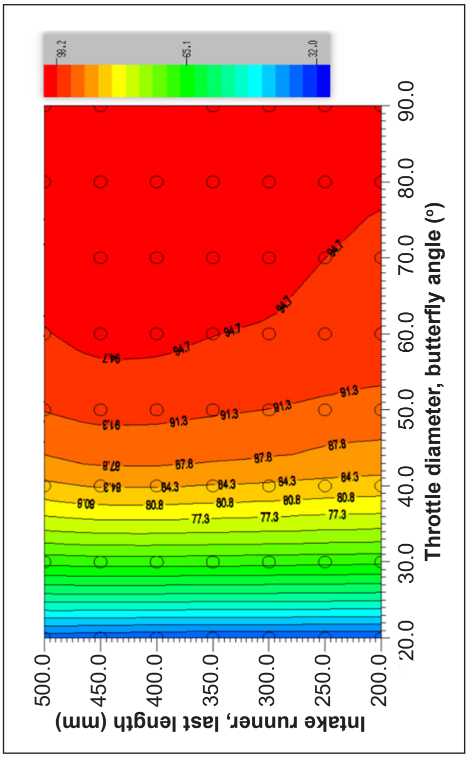

Figure 10. Volumetric efficiency at 5000 rpm

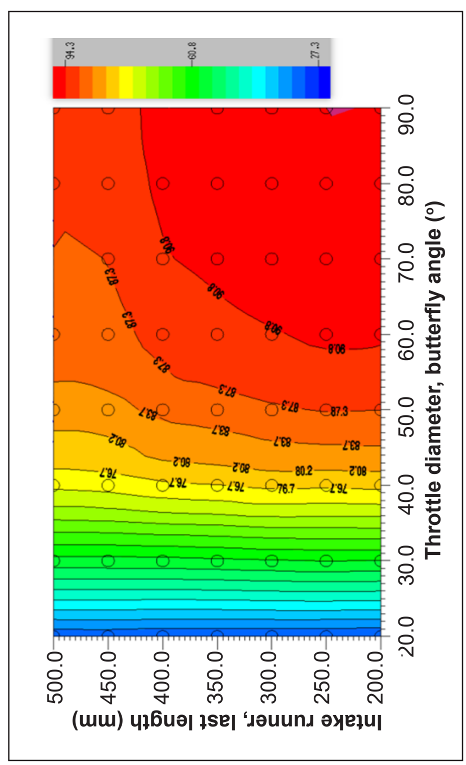

Figure 11. Volumetric efficiency at 6000 rpm

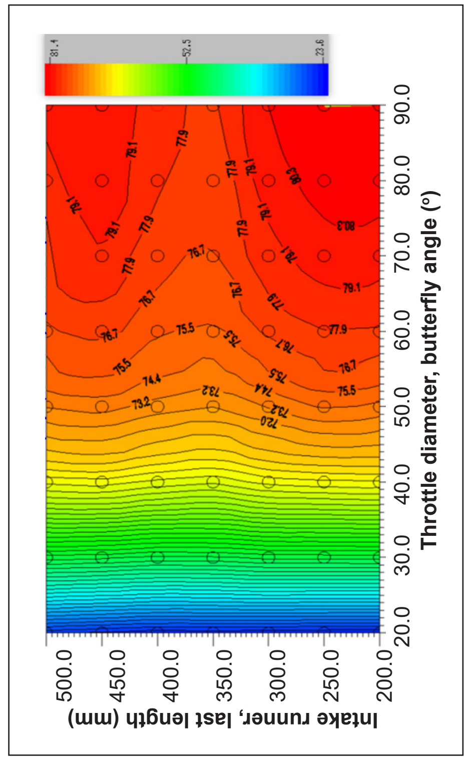

Figure 12. Volumetric efficiency at 7000 rpm

As for the 7000 rpm graph in Figure 12, an intake length of 200 mm is the quickest in achieving a high volumetric efficiency of 80.3% at 80° of throttle opening. A runner length over 300mm can only achieve volumetric efficiency of up to 79.1% compared to 80.3% for short runner length. The highest volumetric efficiency that can be achieved is 81.4% at 200 mm intake lengthand 90° of throttle opening.

CONCLUSION

This study conducted a simulation investigation on the effect of different intake runner lengths with different throttle openings on the engine performance characteristics of a 4-cylinder engine. This study was conducted using 1D simulation in Lotus Engine Simulation software. The major findings are presented below:

1. For a lower range of throttle opening (10–30°), the volumetric efficiency decreases with increased rpm.
2. At a 40° throttle opening, the volumetric efficiency increases with the increase of rpm up to 4000 rpm and then drops as rpm goes higher.
3. For a high range of throttle openings (50–90°), the volumetric efficiency increases with the increase of rpm up to 5000 rpm and then drops as rpm goes higher.
4. At 1000 rpm and 2000 rpm, the length of the intake runner does not have any major impact on volumetric efficiency performance, with an improvement of only around 1% due to low-pressure wave amplitude in low rpm engine speed. It was revealed that maximum VE% happens at 70° throttle opening with 400mm intake length and 50° throttle opening with 450mm intake length for these low rpm ranges.
5. At 3000 rpm, an intake length longer than 400mm does have a better effect on volumetric efficiency, around 4%, compared to an intake length shorter than 400mm. Overall, long-length runners need smaller throttle openings to achieve high volumetric efficiency compared to short-length runners.
6. From 4000 rpm until 5000 rpm, the longer length of the intake runner showed major improvement in volumetric efficiency compared to the short length. The highest volumetric efficiency achieved is 101% when the runner length is 500mm at WOT. A long intake length of 400mm and above helps the engine achieve volumetric efficiency of up to 97.8% with a smaller throttle opening of 60°.
7. From 6000 rpm to 7000 rpm, shorter length of intake runner showed major improvement in volumetric efficiency compared to long length runner. The highest volumetric efficiency achieved is 94.3% when runner length is 250mm at WOT. A short intake length of 300mm and below helps the engine achieve volumetric efficiency of up to 90.8% with a smaller throttle opening of 60°.
8. Overall, intake length tuning shows a significant improvement in volumetric efficiency at 60° of throttle opening. Long runner length is best for volumetric

efficiency at low and mid-range rpm (1000–5000 rpm), while short runner length is best for volumetric efficiency at high range rpm (6000–7000 rpm). The WOT of the throttle opening is the best for volumetric efficiency in all rpm ranges of engine speed except at 1000 and 2000 rpm. Both rpm results revealed minor improvement in volumetric efficiency at a low rpm range due to a low inlet pressure wave. Thus, further study is required to determine a possible method for improving the inlet pressure wave.

ACKNOWLEDGEMENTS

The authors thank Universiti Putra Malaysia for providing research facilities and grant. The study is supported by the GP-IPS research grant from UPM with project code GP-IPS/2021/9706000.

REFERENCES

Adithya, K., Ahmed, F., Padmanathan, P., Mohan, C. G., & Prakash, R. (2021). Design optimization of intake manifold of dual fuel engine. *Materials Today: Proceedings*, *45*, 646-651. https://doi.org/10.1016/j.matpr.2020.02.726

Aljamali, S., Mahmood, W., Abdullah, S., & Yusoff, A. (2014). Comparison of performance and emission of a gasoline engine fuelled by gasoline and CNG under various throttle positions. *Journal of Applied Sciences*, *14*(4), 386-390. https://doi.org/10.3923/jas.2014.386.390

Allawi, M. K., Oudah, M. H., & Mejbel, M. K. (2019). Analysis of exhaust manifold of spark-ignition engine by using computational fluid dynamics (CFD). *Journal of Mechanical Engineering Research and Developments*, *42*(5), 211-215.

Allawi, M., Mejbel, M., & Oudah, M. (2021). Variable Valve Timing (VVT) modelling by Lotus engine simulation software. *International Journal of Automotive and Mechanical Engineering*, *17*, 8397-8410.

Alves, L. O. F. T., dos Santos, M. G. D., Urquiza, A. B., Guerrero, J. H., de Lira, J. C., & Abramchuk, V. (2018). *Design of a new intake manifold of a single cylinder engine with three stages* [Technical Paper]. SAE International. https://doi.org/10.4271/2017-36-0172

Bari, S., & Sawant, P. (2019). Improvement of performance by 2-step variations of intake runner length and intake valve timing in the induction system of a SI engine. *Energy Procedia*, *160*, 108-115. http://dx.doi.org/10.1016/j.egypro.2019.02.125

Ceviz, M. A. (2007). Intake plenum volume and its influence on the engine performance, cyclic variability and emissions. *Energy Conversion and Management*, *48*(3), 961-966. https://doi.org/10.1016/j.enconman.2006.08.006

Channapattana, S. V, Campli, S., Madhusudhan, A., Notla, S., Arkerimath, R., & Tripathi, M. K. (2023). Energy analysis of DI-CI engine with nickel oxide nanoparticle added azadirachta indica biofuel at different static injection timing based on exergy. *Energy*, *267*, Article 126622. https://doi.org/10.1016/j.energy.2023.126622

Chatur, M. G., Maheshwari, A., & Campli, S. (2023). Investigation of waste cooking oil–diesel blend with copper oxide additives as fuel for diesel engine under variations in compression ratio. *International Journal of Energy and Environmental Engineering*, *14*, 791-802. https://doi.org/10.1007/s40095-022-00549-7

Ghodke, S., & Bari, S. (2018). *Effect of integrating variable intake runner diameter and variable intake valve timing on an SI engine's performance*. Transportation Research Board. https://doi.org/10.4271/2018-01-0380

Hamada, K. I., Ibrahim, T. K., Rahim, M. F., Rahman, M. M., & Bakar, R. A. (2023). Throttling effect on the availability and sustainability of a gasoline-fuelled spark ignited multi-cylinder engine. *Engineering Research Express*, *5*, Article 045057. https://doi.org/10.1088/2631-8695/ad0ad3

Hamilton, L. J., Cowart, J. S., & Rozich, J. J. (2009, April 20). *The effects of intake geometry on SI engine performance* [Technical Paper]. SAE International. https://doi.org/10.4271/2009-01-0302

Hartman, J. (2013). *How to tune and modify automotive engine management systems* (2nd ed.). Motorbooks International.

Heisler, H. (1995). *Advanced Engine Technology*. SAE Intl.

Heywood, J. B. (2018). *Internal combustion engine fundamentals* (2nd ed.). McGraw-Hill Education.

Hirschfelder, K., Völkl, W., Kühnel, H. U., Sinn, W., & Huck, A. (2002). The first continuously variable intake system in the new eight-cylinder engine from BMW. *MTZ Worldwide*, *63*, 2-6. https://doi.org/10.1007/BF03227525

Hosaka, T. & Hamazaki, M. (1991). *Development of the variable valve timing and lift (VTEC) engine for the Honda NSX* [Technical Paper]. SAE International. https://doi.org/10.4271/910008

Jagadishsingh, B., Wankar, A., & Jadhav, N. P. (2016). A review paper on effect of intake manifold geometry on performance of IC engine. *International Journal of Advance Research and Innovative Ideas in Education, 2*(2), 102-106.

Jagadishsingh, B., & Jadhav, N. (2016). Effect of variable length intake manifold on performance of IC engine. *International Journal of Current Engineering and Technology, 5*, 47-52. https://doi.org/10.14741/Ijcet/22774106/spl.5.6.2016.9

Jemni, M. A., Driss, Z., Kantchev, G., & Abid, M. S. (2013). Intake manifold shape influence on the unsteady in-cylinder flow: Application on LPG bi-fuel engine. In M. Haddar, L. Romdhane, J. Louati & A. B. Amara (Eds.), *Design and Modeling of Mechanical Systems* (pp. 331-338). Springer. https://doi.org/10.1007/978-3-642-37143-1_40

Jemni, M. A., HadjKacem, S., Ammar, M., Saaidia, R., Brayek, M., & Abid, M. S. (2021). Variable intake manifold geometry influence on volumetric efficiency enhancement at gaseous engine starting speeds. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, *235*(2), 548-559. https://doi.org/10.1177/0954408920973129

Kardan, R., Baharom, M. B., Mohammed, S. E., Aziz, A. R. A., Zainal, A. E. Z., & Firmansyah. (2018). The effect of engine throttle position on the performance characteristics of a crank-rocker engine fitted with a conventional cylinder head. In *6th International Conference on Production, Energy and Reliability 2018: World Engineering Science & Technology Congress (ESTCON)*, (Vol. 2035, No. 1). AIP Publishing. https://doi.org/10.1063/1.5075549

Lenz, H. P. (1992). Basic principles of mixture formation. In *Mixture Formation in Spark-Ignition Engines* (pp. 38-111). Springer. https://doi.org/10.1007/978-3-7091-6692-5_2

Ling, J. & Tun, L. T. Y. (2006). *CFD analysis of non-symmetrical intake manifold for formula SAE car* [Technical Paper]. SAE International. https://doi.org/10.4271/2006-01-1976

Magdas, V. B., Mastan, D. C., & Burnete, N. (2020). Simulation possibilities of the internal combustion engine management elements using Lotus Engine Simulation software. *IOP Conference Series: Materials Science and Engineering*, *997*(1), Article 012121. https://doi.org/10.1088/1757-899X/997/1/012121

Malkhede, D. N., & Khalane, H. (2015). *Maximizing volumetric efficiency of IC engine through intake manifold tuning* [Technical Paper]. SAE Intenational. https://doi.org/10.4271/2015-01-1738

Mauger, T. W. (2004). *Selection of an engine and design of the fuelling system for a Formula SAE car*. [Degree dissertation]. University of Southern Queensland. https://sear.unisq.edu.au/54/

McKee, R. H., McCullough, G., Cunningham, G., Taylor, J. O., McDowell, N., Taylor, J. T., & McCullough, R. (2006). *Experimental optimisation of manifold and camshaft geometries for a restricted 600cc four-cylinder four-stroke engine* [Technical Paper]. SAE International. https://doi.org/10.4271/2006-32-0070

Mohiuddin, A., & Rahman, A. (2008). Investigation and probable solution of low end torque dip problem of Campro 1.6 L engine. *International Journal of Mechanical and Materials Engineering*, *3*, 176-186.

Namar, M. M., Jahanian, O., Shafaghat, R., & Nikzadfar, K. (2021). Engine downsizing; Global approach to reduce emissions: A world-wide review. *HighTech and Innovation Journal*, *2*(4), 384-399. https://doi.org/10.28991/HIJ-2021-02-04-010

Nouhov, D. F., & Chen, R. (2002). A simulation study on the effect of inlet valve opening on performance of high speed engines. In *Proceedings of the 17th Internal Combustion Engine Symposium* (pp. 149-152). Society of Automotive Engineers of Japan.

Ohata, A. & Ishida, Y. (1982). Dynamic inlet pressure and volumetric efficiency of four cycle four cylinder engine [Technical Paper]. SAE International. https://doi.org/10.4271/820407

Pahmi, A., Basri, M. H., Mustaffa, M. E., Yaakob, Y., Sharudin, H., Ismail, N. I., & Talib, R. J. (2019). Intake pressure and brake mean effective pressure analysis on various intake manifold design. *Journal of Physics: Conference Series*, *1349*(1), Article 012080. https://doi.org/10.1088/1742-6596/1349/1/012080

Pahmi, A., Mustaffa, M. E., Basri, M. H., Ismail, N. I., Azmi, H., Sharudin, H., Othman, R., & Mat, S. C. (2022). Effect of intake length on the engine performance of single cylinder engine. *Proceedings of Mechanical Engineering Research Day, 2022*, 129-130.

Potul, S., Nachnolkar, R., & Bhave, S. (2014). Analysis of change in intake manifold length and development of variable intake system. *International Journal of Scientific & Technology Research, 3*(5), 223-228.

Raja, K., & Selvam, A. J. (2022). Experimental investigation of four stroke single cylinder SI engine by modified intake manifold by using computational fluid dynamics. *International Journal of Ambient Energy*, *43*(1), 229-236. https://doi.org/10.1080/01430750.2019.1630310

Rimkus, A., Vipartas, T., Kriaučiūnas, D., Matijošius, J., & Ragauskas, T. (2022). The effect of intake valve timing on spark-ignition engine performances fueled by natural gas at low power. *Energies*, *15*(2), Article 398. https://doi.org/10.3390/EN15020398

Sawant, P., & Bari, S. (2017). Combined effects of variable intake manifold length, variable valve timing and duration on the performance of an internal combustion engine. In *ASME 2017 International Mechanical Engineering Congress and Exposition, Volume 6: Energy* (pp. 1-10). American Society of Mechanical Engineers. https://doi.org/10.1115/IMECE2017-70470

Shin, J., Kim, D., Son, Y., & Park, S. (2022). Effect of intake manifold geometry on cylinder-to-cylinder variation and tumble enhancement in gasoline direct injection engine. *Scientific Reports*, *12*, Article 19862. https://doi.org/10.1038/s41598-022-24079-8

Sivashankar, M., Balaji, G., Barathraj, R. K., & Thanigaivelan, V. (2018). Phenomena of brake specific fuel consumption and volumetric efficiency in CI engine by modified intake runner length. *IOP Conference Series: Materials Science and Engineering*, *402*, Article 012086. https://doi.org/10.1088/1757-899X/402/1/012086

Tabaczynski, R. J. (1982). *Effects of inlet and exhaust system design on engine performance* [Technical Paper]. SAE International. https://doi.org/10.4271/821577

Talati, H., Aliakbari, K., Ebrahimi-Moghadam, A., Farokhad, H. K., & Nasrabad, A. E. (2022). Optimal design and analysis of a novel variable-length intake manifold on a four-cylinder gasoline engine. *Applied Thermal Engineering*, *200*, Article 117631. https://doi.org/10.1016/j.applthermaleng.2021.117631

Tavakoli, S., Schramm, J., & Pedersen, E. (2020, October 14-16). *The effect of air throttle on combustion process and emission formation in marine lean-burn gas engines.* [Paper presentation]. Proceedings of the 5th World Congress on Momentum, Heat and Mass Transfer, Lisbon, Portugal. https://doi.org/10.11159/CSP20.117

Wan, M. (2011). Intake and exhaust. *AutoZine*. https://www.autozine.org/technical_school/engine/Intake_exhaust.html

Wang, J., Duan, X., Wang, W., Guan, J., Li, Y., & Liu, J. (2021). Effects of the continuous variable valve lift system and Miller cycle strategy on the performance behavior of the lean-burn natural gas spark ignition engine. *Fuel*, *297*, Article 120762. https://doi.org/10.1016/j.fuel.2021.120762

Wasiu, S., Rosdee, A., Opatola, R. A., Al Haddabi, A., & Khan, A. S. A. (2021). Effects of variable length intake manifold on performance of gasoline engine using GT Power Software. *International Journal of Engineering Research & Technology*, *9*(12), 673-678.

Winterbone, D. E., & Yoshitomi, M. (1990). *The accuracy of calculating wave action in engine intake manifolds* [Technical Paper]. SAE International. https://doi.org/10.4271/900677

Xu, C., & Cho, H. (2017). The analysis of influence of throttle body on engine intake system. *International Journal of Engineering and Technology*, *9*(5), 3481-3486. https://doi.org/10.21817/ijet/2017/v9i5/170905048

Zhou, X., Chen, Z., Zou, P., Liu, J., Duan, X., Qin, T., Zhang, S., & Shen, D. (2020). Combustion and energy balance analysis of an unthrottled gasoline engine equipped with innovative variable valvetrain. *Applied Energy*, *268*, Article 115051. https://doi.org/10.1016/j.apenergy.2020.115051