Intake pressure and brake mean effective pressure analysis on various intake manifold design

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Abstract. The internal combustion engine has an intake system that preparing sufficient charges for the engine cylinder. This study is focused on the effect of different intake geometry on the intake pressure and brake mean effective pressure to correlate volumetric efficiency and brake power performance. Five types of intake geometry are simulated by a one-dimensional computational tool. Through the simulations, it can be found the maximum volumetric efficiency predicted by taper design at 1.15 bar of intake pressure and 12.50 bar of brake mean effective pressure when volumetric efficiency reached to 115% and brake power of 19.5 kW. The baseline intake and bellmouth intake showing intake pressure at 0.91 bar except for both single bend intake and s-bend intake indicated 0.92 bar intake pressure and 9.35 bar of brake mean effective pressure. The measurement of intake pressure and brake mean effective pressure over various intake geometry displayed a significant influence on the volumetric efficiency and brake power trend.

1. Introduction

The function of the intake system is to spread the combustion mixture evenly to an engine cylinder that strictly influenced the engine performances. The flows in the intake manifold represent the compression waves give significant impact to the engine performance which can be empirically estimated to produce the desired torque curve [1]. Intake tuning becomes a simple method to boost engine power that utilizes on the principle of increasing the amount of air-fuel mixture for combustion. By using the airflow harmonics at specific engine speeds, intake tuning forces more air into the engine cylinders that are resulting in higher torque and power [2]. The benefit of a tuning effect emerged when the compression wave arrives at the time of inlet valve closure [1].

Gas dynamics models had been in use for many years to study the entire processes in an internal combustion engine. These models are developed from mass, momentum and energy conservation equation to understand about phenomenon involved in the intake and exhaust system [3]. In the past, the method of characteristic was used to solve the gas dynamics equation. Finite different methods
were later introduced as tools for solving gas dynamic equations in intake and exhaust manifold that proving more efficient and flexible than the method of characteristic.

Induction tuning is now used on a wide range of spark ignition and diesel engine. The length of intake gave a significant effect on the mass flow rate and pressure drop through the ports in the single cylinder research direct injection diesel engine, motored at 1000-3000 rpm [4]. Besides intake length, cylinder pressure was an important parameter to the engine performance investigation [5].

The design of the tuned inlet system was typically worth in which various group of pipes and plenums were used to anticipate the desired torque curve [1]. During the movement of the piston downward in the intake stroke, a reduced pressure occurred at the inlet valve and this pressure influence the pressure at the open end of the pipe. At the approximate mid-stroke, the piston was near its maximum velocity and the maximum pressure drop occurs across the valve which resulted in the maximum negative pressure (rare fraction wave) at the inlet valve. The rarefaction wave traveled down the pipe to open end and was reflected as a compression wave. A tuning effect occurred when the compression wave arrived at the time of inlet valve closure [1].

The induction tuning that incorporated resonator volume systems can contribute to volumetric efficiency enhancement. A single-engine diesel combined with the variation of pipe length and volume of resonator gave impact to a volumetric efficiency of over 115% over 65% of the engine speed ranges [6]. Besides, the increased airflow gave benefit to the reduction of fuel consumption and smoke emissions. It was found that intake tuning had a more dominant influence in the breathing capabilities of the engine compared to exhaust tuning and both were independent of each other. A research on the effect of intake and exhaust system on engine performance had been conducted to test the engine with no intake and exhaust system. Intake lengths demonstrated a known relationship where maximum volumetric efficiency was obtained at lower speeds for longer intake lengths and vice versa and it helped the breathing performance beyond what the engine with no pipes was able to produce [7].

Positive volumetric efficiency required shorter intake lengths as engine speed increased. Besides, the time for wave travels in the intake system much shorter at high engine speeds to preserve positive pressure at the end of the intake stroke, requiring shorter distances to be travelled. The discussion was what time the wave must travel along the length of the pipe and be reflected for maximum pressure.

The intake design of the internal combustion engine has a significant effect on improving intake pressure and brake mean effective pressure. In this study, five different intake configurations proposed by Mariucci [8] were modeled and simulated using Gt-Power software. The intake design is designated as baseline, taper, bellmouth, single bend and s-bend. At first, the baseline model is simulated and calibrated with the experimental data taken by Mariucci [8]. The taper, bellmouth, single bend and s-bend used the same baseline setup to predict the intake pressure and brake mean effective pressure for the maximum volumetric efficiency and brake power performance.

Gt-Power is a one-dimensional computational tool to investigate the flow and heat transfer in the piping and other components of an engine system. The flow model involves the simultaneous solution of the continuity, momentum and energy equations. These equations are solved in only one dimension, which means that all quantities are averages across the flow direction. The engine specifications such as bore, connecting rod length, compression ratio, maximum lift for both intake and exhaust valve, and period of valve opening are required to simulate engine model in Gt-Power.
2. Methodology

In this study, the engine and five types of intake geometry are simulated using Gt-Power software. The intake system is a combination of intake piece (Components that depend on the intake design), barrel throttle, adapter section, fuel rail block and intake port. Also, the injection system creates in InjAF-RatioConn template places the injector at the midpoint (input 0.5 in injector location attribute) of fuel rail block. The type of fuel uses in InjAF-RatioConn is indolene-combustion, which is set at 300 K with vaporized fuel fraction 0.3. An engine is constructed using EngCylinder and EngCrankTrain objects. In these objects, data on engine geometry such as bore, connecting rod length, clearance height, number of cylinders required to be input that can be referred to table 1.

Table 1. Single cylinder engine specification [8]

| Engine type                  | Single cylinder spark ignition |
|------------------------------|--------------------------------|
| Bore x stroke (cm)           | 8.9 x 7.95                     |
| Rod Length (cm)              | 13.81                          |
| Compression Ratio            | 10.5:1                         |
| Clearance Volume (cm³)       | 47.10                          |
| Maximum Valve Lift           |                                 |
| Intake (cm)                  | 0.914                          |
| Exhaust (cm)                 | 0.937                          |
| Valve Timing                 |                                 |
| Intake open (CAD)            | 308.0                          |
| Intake duration (CAD)        | 286.0                          |
| Exhaust open (CAD)           | 86.5                           |
| Exhaust duration (CAD)       | 326.0                          |

A few assumptions are made due to lack of technical detail of the engine geometry such as the wrist pin to crank offset, where engine lubrication and cooling is assumed negligible. A ValveCamConn object represents valves characteristics for intake and exhaust. The engine detail, valve data in Gt-Power requires lots of input such as valve diameter, discharge coefficient, valve lift profile, valve opening, valve duration and valve lash. Diameter for intake valve is 35 mm and exhaust valve of 30 mm. Discharge coefficient is depending on valve diameter while the valve lift profile is relied on the maximum lift, valve opening and valve duration. Figure 1 shows the engine model and intake system that simulated in the Gt-Power environment and intake geometry is summarized in figure 2.

The volumetric efficiency is calculated from the ratio of actual air mass flow rate over theoretical air mass flow rate drawn to engine cylinder during induction process that occurs at 308 degrees of crankshaft intake valve opening and 594 degrees of crankshaft intake valve closing. The interval during the intake process in this simulation was limited to 286 degrees of the crankshaft.
Figure 1. Intake system and engine setup in Gt-Power environment

| Intake Type       | Dimensions and Configurations                                                                 |
|-------------------|------------------------------------------------------------------------------------------------|
| Baseline intake   | Total length = 26.45 cm                                                                       |
| Taper intake      | \( L_t = 26.45 \text{ cm}; \quad D_t = 5.94 \text{ cm}; \quad \text{Taper area ratio} = 2.0 \) |
| Bellmouth intake  | \( R_i = 0.21 \text{ cm}; \quad R_i/D = 0.05; \quad \text{Overall length} = 25.21 \text{ cm} \) |
| Single bend intake| \( R_c = 8.4 \text{ cm}; \quad R_c/D = 2.0 \)                                                   |
| S-bend intake     | \( R_c = 8.4 \text{ cm}; \quad R_c/D = 2.0 \)                                                 |

Figure 2. Intake dimensions and configurations. [8]
3. Results and discussion

The baseline intake is simulated and the numerical results are compared with the experimental data from Mariucci [8]. The model validation for baseline as shown in table 2 showed below 5% of the difference with the Mariucci’s experimental baseline geometry. This small difference is important for the accuracy of the model simulated in Gt-Power.

Table 2. Validation result for baseline intake.

| Engine Speed, rpm | Volumetric efficiency, % (Experiment) [8] | Volumetric efficiency, % (Simulation) | Difference, % |
|-------------------|-----------------------------------------|--------------------------------------|--------------|
| 1000              | 87.0                                    | 86.4                                 | 0.7          |
| 2000              | 85.0                                    | 84.0                                 | 1.2          |
| 3000              | 103.5                                   | 103.5                                | 0.0          |
| 4000              | 100.0                                   | 100.0                                | 0.0          |
| 5000              | 95.0                                    | 96.7                                 | 1.8          |
| 5500              | 81.0                                    | 81.6                                 | 0.7          |

The internal combustion engine exhibit nearly constant volumetric efficiency for all speed although the engine performance trends such as power and torque have low magnitude at low speed and continue to increase as the high engine speed. The longer the interval, causes more air to be drawn to engine cylinder but compensates compression ratio that significant indicator for engine brake output performances.

Intake configurations will affect engine performances, especially volumetric efficiency and brake power. Five differences intake configuration from Mariucci [8] be simulated using Gt-Power. As shown in table 3, the highest of volumetric efficiency is indicated by taper intake as much as 115% at 4250 rpm. The bellmouth intake predicted the lowest maximum volumetric efficiency of 109.5% at speed lower of 3750 rpm. The baseline intake, single bend intake, and s-bend intake presented the maximum volumetric efficiency at the same engine speed of 3750 rpm that peak at 112.0%, 110.0% and 111.0% subsequently.

Although the taper intake recorded the highest volumetric efficiency, the maximum brake power of 19.5 kW for the taper intake occurred at the engine speed 4250 rpm was lower as compared to bellmouth intake which peak as much as 20.0 kW at 4750 rpm. This condition is happening due to constant fuel injection timing for all intake configurations. Additionally, the maximum brake power was seemed to shift to the lower engine speed when the maximum volumetric efficiency exists at the higher engine speed. The constant air-fuel ratio for all type intake configurations limits the maximum brake power. The shifting peaks of volumetric efficiency to higher engine speed rely on the air pressure inside the intake system [2]. The maximum brake power for the baseline intake was 19.0 kW at 4750 rpm and increase to 19.5 kW for the single bend intake and s-bend intake at 4750 rpm engine speed.

Table 3. Maximum volumetric efficiency and brake power for various intake configuration.

| Intake Configuration | Maximum Volumetric Efficiency, % | Engine Speed, RPM | Maximum Brake Power, kW | Engine Speed, RPM |
|----------------------|----------------------------------|-------------------|-------------------------|-------------------|
| Baseline             | 112.0                            | 3750              | 19.0                    | 4750              |
| Taper                | 115.0                            | 4250              | 19.5                    | 4250              |
| Bellmouth            | 109.5                            | 3750              | 20.0                    | 4750              |
| Single bend          | 110.0                            | 3750              | 19.5                    | 4750              |
| S-bend               | 111.0                            | 3750              | 19.5                    | 4750              |
Air pressure in the intake system was counted to permit the maximum air entering the engine cylinder during the intake process. The intake process started as the intake valve open and the piston traveled to the downward position, creating vacuum pressure due to expanding volume. The air pressure in the intake system was at ambient pressure, and the pressure difference caused the air flow to the engine cylinder through the intake port. In figure 3, the amplitude of air pressure behind the intake valve was dropped to the range of 1.05 bar and 0.80 bar during the intake valve opening at 308 degrees of the crankshaft. The pressures that behaved sinusoidal indicated the peak of pressure 1.15 bar at 360 degrees of crank angle and 4250 rpm engine speed for taper intake caused the highest maximum volumetric efficiency compared to other intake configurations. At the 360 degrees of crank angle, the baseline intake and bellmouth intake showed the pressure of 0.91 bar and 0.94 bar while both single bend intake and s-bend intake predicted pressure of 0.92 bar. The positive reflective waves during the intake valve opening were significant to enhance more amount of air entering the engine cylinder during the intake process.

![Figure 3. Intake pressures for intake configurations at 4250 rpm engine speed.](image1)

Brake mean effective pressure (BMEP) is the average pressures in the engine cylinder. As indicated in figure 4, taper intake produced the highest magnitude of BMEP as much as 12.50 bar at 4250 rpm engine speed. The bellmouth intake produced 10.21 bar BMEP at 4250 rpm engine speed. Different intake configurations exhibited BMEP of 9.35 bar at 4250 rpm for baseline intake, single bend intake and s-bend intake. The taper intake showed the highest BMEP peaks at 4250 RPM because during that time, intake pressures in the intake system recorded the highest amplitude compare to other intake configurations.
Figure 4. Brake mean effective pressure (BMEP) for intake configurations.

BMEP in the cylinder directly related to the brake power measurement. The highest value of BMEP will result in the best brake power magnitude at the given engine speed. In a simple approach, measurement of intake pressures can use to analyze volumetric efficiency trends while BMEP is essential for brake power predictions.

4. Conclusions
Intake geometries become dominant to affect intake pressure magnitudes that are mainly contributed to the volumetric efficiency performance. Taper intake showed the highest intake pressure of 1.15 bar at an engine speed of 4250 rpm caused the volumetric efficiency raised to 115%. As the highest intake pressure gained at 4250 rpm, consequently, the maximum BMEP of 1.50 bar appeared at the same engine speed. Additionally, the brake power for taper intake reached to maximum 19.5 kW at an engine speed of 4250 rpm that 500 rpm faster than the others intake configuration. During the engine speed at 4250 rpm, the baseline intake, bellmouth intake, single bend intake and s-bend intake showed lower intake pressures as compared to taper intake that predicted at 0.91 bar, 0.94 bar respectively and 0.92 bar for both single bend intake and s-bend intake. The intake pressure relation to BMEP caused others intake configurations to have much lower BMEP of 10.21 bar for bellmouth intake and 9.35 bar for baseline intake, single bend intake and s-bend intake. In conclusion, intake pressure affects the volumetric efficiency and BMEP of internal combustion engine performances significantly.

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