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COMPUTATIONAL ANALYSIS OF AIR INTAKE SYSTEM FOR INTERNAL COMBUSTION ENGINE IN PRESENCE OF ACOUSTIC RESONATOR

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ABSTRACT

Volumetric efficiency is one of the important parameters which affect the performance of four-stroke engines. This study examines the effect of resonators on the volumetric efficiency over a wide range of engine speed. An intake system with and without resonator are simulated by using GT-POWER software. Intake systems with three configurations of resonators with various resonator volumes are represented in terms of volumetric efficiency. The three intake system configurations are in-series, side-branch and double resonator. The results obtained are compared with an intake system without resonator. An intake system with resonator gives a significant improvement of volumetric efficiency at medium and high speed compared to the intake system without resonator. Volumetric efficiency showed an increment when the volume of the resonator increased. Overall, simulations indicate that the presence of the resonator in the intake system affects the volumetric efficiency of the engine especially for single cylinder engines.

Keywords: volumetric efficiency, resonators, GT-POWER four-stroke engines, intake systems.

INTRODUCTION

Volumetric efficiency is the most important factors which affect the performance of the engine. The volumetric efficiency is influenced by many factors such as flow friction in the intake and exhaust system, induction system heat transfer, valve timing, valve flow friction, chocking in the inlet valve and port, in-cylinder heat transfer and wave phenomena. Volumetric efficiency can be increased by modification of the intake and exhaust system to increase the mass flow rate, reduce flow friction, reduce heat transfer to the fresh charge, adjust valve timing and install some parts to manipulate wave phenomena. The resonator can be used to improve the volumetric efficiency of the engine. This is possible due to the characteristics of resonator and it designs. It works on the theory of harmony and wave phenomena. As the air is being sucked into the cylinder through the intake system, it tries to ram into the resonator through its neck as a result increasing pressure inside the cavity. As the pressure increases, the air bounces out due to inertia causes a partial vacuum near the neck of the resonator, thus the air is again sucked into the cylinder. As a result, the resonator behaves like a shock absorber for the pressure waves. This research was focused on a study related to the effect of the acoustic resonators when it is installed in the intake system. Acoustic resonator is used to manipulate the wave inside the intake system and enhance volumetric efficiency of the engine. The effect of changing resonator configurations and volume on volumetric efficiency over a wide range of engine speed was investigated.

The used of acoustic resonator for Internal Combustion Engine (ICE) was investigated in many publications [1-7]. Some researchers used the resonator theory to predict engine tuning for specific use such as racing car engine. Another group used the resonator to improve the volumetric efficiency of the engine. The wave phenomena and gas dynamic effect have been studied by means of experimental and numerical methods to explore the capabilities of the resonators to improve volumetric efficiency [8]. There is a need to investigate the effect of resonator geometries on air flow; therefore it can be used to optimize the performance of the ICE. The effect of the resonator can be studied by varying the geometries of the resonator. Numerical method can be used to study the effect of resonator geometries and arrangements on volumetric efficiency. Such model is the objective of this paper. The details of the complete analysis of the resonator are described in this paper.

INTAKE SYSTEM AND RESONATOR MODEL

This analysis has been done for single cylinder and multicylinder engine by means of numerical methods. GT-Power software was used to simulate the air flow inside the intake system. Thus, the volumetric efficiency of the engine is obtained and analyzed.

Single cylinder engine

In this work, we consider a 500cc single cylinder engine with 82 cm bore, 0.005411 m^2 piston areas and 92 cm stroke. The engine has under square cylinder where the bore is smaller than its stroke. It produces peak torque at low engine speed. The details of engine specifications are shown in Table-1.

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Table-1. Engine specification.

Bore	83 mm
Stroke	92 mm
Rod Length	135 mm
Compression Ratio	9:1
Clearance Volume	62.5 cm^3
Maximum valve lift	
Intake	1.02 cm
Exhaust	1.02 cm
Valve timing	
Intake Open	166.0 CAD
Intake Duration	156.0 CAD
Exhaust Open	53.0 CAD
Exhaust Duration	156.0 CAD

Four model intake systems with and without resonators are considered in this analysis. The first model was set in the standard intake system. The standard intake system is used as a baseline model to figure the effect of the intake system equipped with a resonator compared to baseline mode. Figure-1 shows a schematic diagram of baseline model where V_1 is cylinder volume, A is the cross section area of the intake pipe and L is the length of the intake pipe. The length of the baseline model is 0.9 m, which is a suitable length for intake system when equipped with resonators.

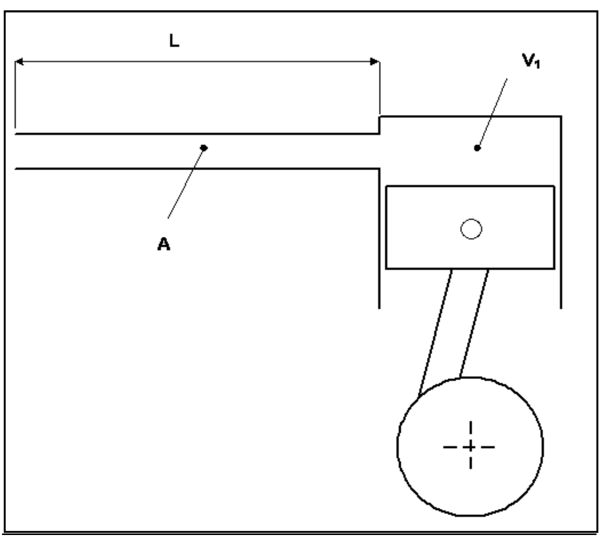

Figure-1. Baseline model.

The second model is in-series resonator as shown in Figure-2 where V_1 is cylinder volume, V_2 is resonator volume, A_1 and A_2 are a cross section in the intake pipe and L_1 and L_2 are the length of the intake pipe. Total length of the intake system with in-series resonator is the same as the baseline model (0.9 m). The resonator is placed close to the cylinder volume where it has a significant effect on volumetric efficiency as concluded from literature. The volume of the resonator is varied through three different volume ratios (V_2/V_1) which are 1, 3 and 10.

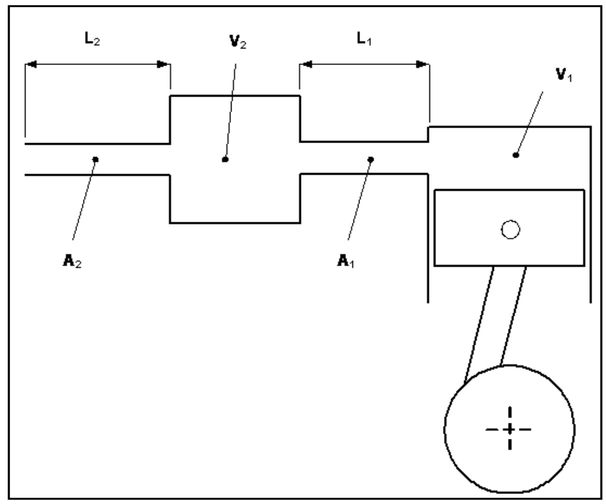

Figure-2. Intake system model with in-series resonator.

The next model is an intake system with side-branch resonator. The arrangement of side-branch resonator is shown in Figure-3 where V_1 is cylinder volume, V_3 is resonator volume, A_1 and A_2 are a cross section area of the intake pipe, A_3 is the cross section area of resonator neck, L_1 and L_2 are the length of the intake pipe, and L_3 is resonator neck length. The volume (V_3) of the resonator is set as variable. The other parameters such total length, location of pipe neck of side-branch resonator, cross-section area and diameter of intake pipe are considered constant.

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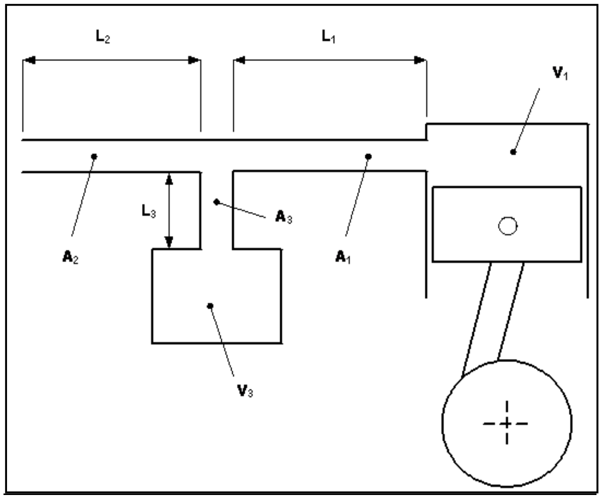

Figure-3. Intake system model with side-branch resonator.

The arrangement of the intake system equipped with a double resonator is shown in Figure-4 where V_1 is cylinder volume, V_2 and V_3 are resonator volume, A_1 and A_2 are a cross section area of the intake pipe, A_3 is the cross section area of the resonator neck, L_1 and L_2 are the length of the intake pipe, and L_3 is the length of the resonator neck. This intake system consists of a combination of two resonators, in-series and side-branch resonator. This intake system is similar to the intake system in the actual engine, where in-series resonator can be simulated as air filter box equipped with side-branch resonator at the side of the box. For the simulation, V_2 and V_3 are varied. This simulation shows the effect of resonator volume on volumetric efficiency, therefore the volume ratio for both resonators is such that $V_3/V_2 = 1$.

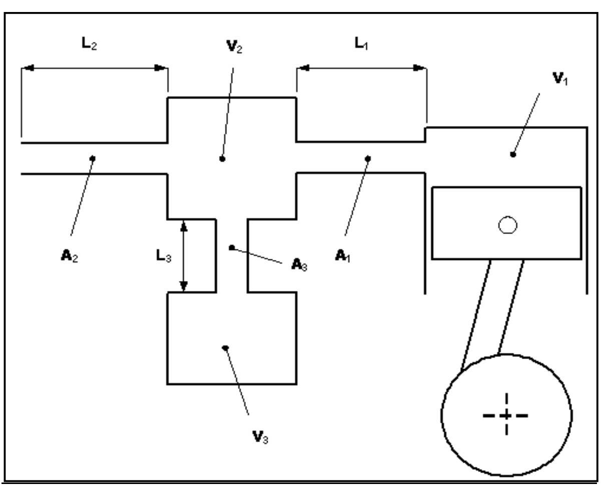

Figure-4. Intake system model with double resonator.

Multicylinder engine

The analysis is extended to model engines of two and three cylinders in-line. The engine has specifications similar to the one cylinder engine, except for the number of cylinders, firing order and firing interval. Two cylinders engine has firing order 1-2 and firing phase 360^o of crank angle, while three cylinders engine has firing order 1-3-2 and firing phase 240^o of crank angle. The intake system for multi-cylinder is considered similar to one-cylinder intake system for length, diameter, components and arrangement. However, the number of intake runners and intake port depends on the number of cylinders. Figure-5 and Figure-6showthe model of the intake system with a resonator for two and three cylinder engine respectively, where P_0 is the intake pipe, P1, $P_2$and $P_3$are an intake pipe runner, and P_R is a resonator pipe while the L_1 is intake runner length.

The side-branch resonator is investigated for multi-cylinder engine. It is due to the side-branch resonator is the most suitable resonator to analyze the effect of the resonator on volumetric efficiency with varying the resonator length, volume and neck area. Other resonators are not considered because the in-series resonator is considered as intake plenum and air box, while the double resonator is not suitable in the real engine because it consumes large space. The side-branch resonator is installed at the branch position between intake runner and the intake pipe as shown in Figure-5 and Figure-6. The location of the resonator is closer to the intake valve, to have a higher effect on the volumetric efficiency.

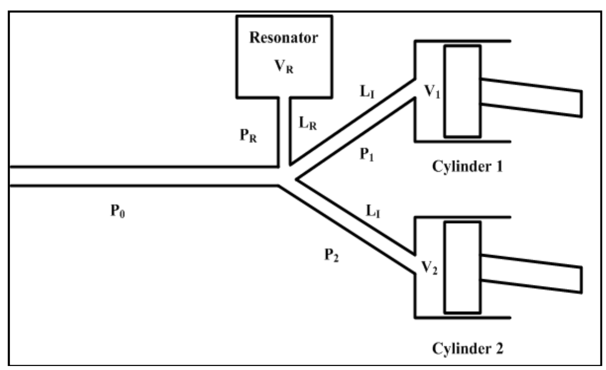

Figure-5. Two cylinder engine.

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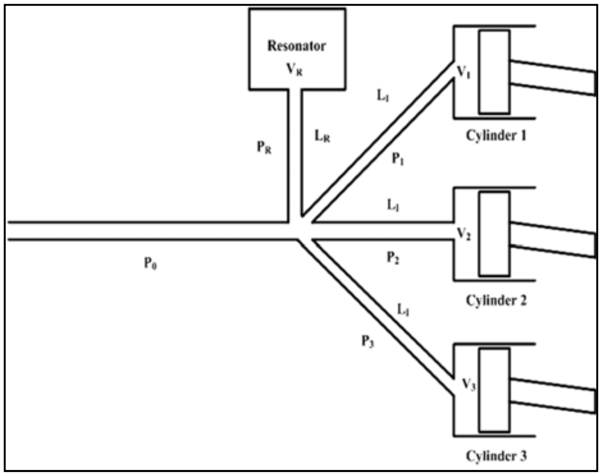

Figure-6. Three cylinder engine.

RESULTS AND DISCUSSION

Baseline model is used as a reference model. The results obtained from the baseline model are compared with other models for speed range from 1000 RPM to 15000 RPM.

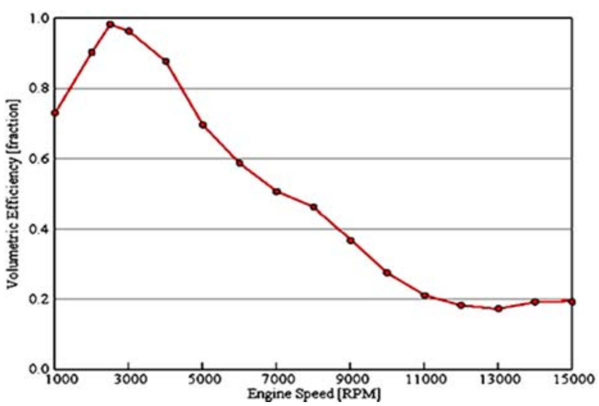

Figure-7. Volumetric efficiency for baseline model.

Figure-7 shows the volumetric efficiency of the baseline model versus the engine speed (RPM). The volumetric efficiency shows a maximum peak of 0.98 at about 2500 RPM or 41.7 Hz of engine frequency. By using a lumped element method calculation [2], the calculated natural frequency of the intake system is 66 Hz which is about 1.6 times engine frequency where the maximum peak of volumetric efficiency occurs. This is the agreement from the literature that the maximum peak occurs when natural frequency is 1.5 to 2.0 times the engine frequency. However, this is a rough comparison where the lumped element method considers the intake system geometries and cylinder volume, while the simulation takes the choking effect on the intake port into consideration.

From the observation, the volumetric efficiency gradually decreases with the increase of engine speed. The volumetric efficiency shows a decrease from 3000 RPM to 10000 RPM. When the engine speed increases the effectiveness of the engine to suck the fresh air is dropped, thus volumetric efficiency decreases. The volumetric efficiency becomes constant at 11000 RPM to 15000 RPM due to the maximum flow rate of air into the cylinder.

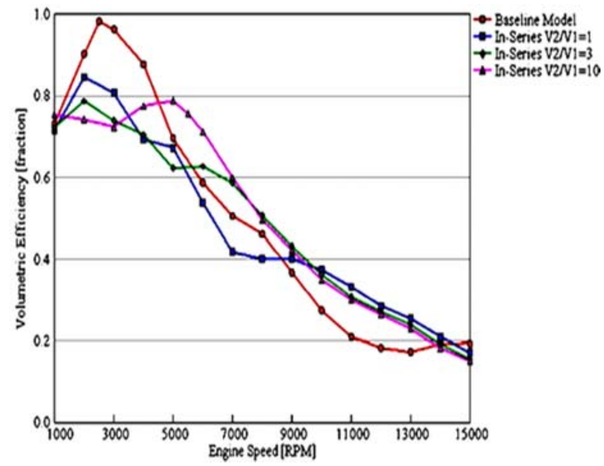

Figure-8. Volumetric efficiency for in-series resonator.

Figure-8 shows the volumetric efficiency for baseline and in-series resonator model. The arrangement of resonator in this model is in-line with the engine cylinder. The resonator volumes are varied where the volume ratio, V_2/V_1 are 1, 3 and 10 (i.e. the volumes of resonators are 500cc, 1500cc and 5000cc respectively). Three configurations, which differ in the volume ratio are analyzed. These ratios are calculated based on the volume of an engine cylinder.

From the graph, the results that obtained can be discussed according to speed range where speed from 1000 RPM to 4000 RPM can be considered as low speed range, 5000 RPM to 10000 RPM as medium speed and above 11000 RPM is high speed range. When the in-series resonator is introduced, the volumetric efficiency shows two peaks. The first peak is in the range of low speed and is lower than the peak of the baseline model. The second peak is in the range of medium speed, it becomes higher when the resonator volume increases. When the in-series resonator introduced, the system has two natural frequencies. By mean of simple element method, the maximum peak occurs when the natural frequency is about double of engine frequency. Table-2 shows the comparison between the numerical method (GT-Power) and analytical method (Simple Lumped Method) for volumetric efficiency peaks. There is a fair agreement between simulation and analytical peaks. Table-2 indicates that the intake systems have the natural frequencies about 1.4 to 2.5 times engine frequency for all resonator cases.

As mentioned in the literature [2], the optimum peaks of volumetric efficiency occur when the natural frequency between 1.5 to 2 times engine frequency.

Table-2. Calibration data using simple lumped method.

Vol Ratio V_2/V_1	Natural Frequency, f_n (Hz) (Analytical)		Engine Frequency, f_{eng} (Hz) (Numerical)		f_n/f_{eng} (Peak 1)	f_n/f_{eng} (Peak 2)
	Peak 1	Peak 2	Peak 1	Peak 2		
1	53	289	33	133	1.6	2.2
3	38	232	25	100	1.5	2.3
10	23	210	17	83	1.4	2.5

There is no significant effect of resonator volume on volumetric efficiency at high engine speed, but the volumetric efficiency slightly increases compared to the baseline model. The intake system with resonator behaves like the intake system with a short intake pipe that have the advantage of higher volumetric efficiency at higher engine speed. For the resonator with the volume ratio V_2/V_1 where the volume of the resonator equal to the volume of an engine cylinder, the first volumetric efficiency peak of 0.84 occurs at 2000 RPM, second peak of 0.68 occurs at 5000 RPM. Volumetric efficiency of this resonator is lower than the baseline model for low and medium speed of the engine, and it becomes higher than the baseline model after 9000 RPM.

For in-series resonator with V_2/V_1 = 3, the volumetric efficiency has its first peak of 0.79 at 2000 RPM. But, it is lower than baseline model and in-series resonator with V_2/V_1 = 1. A second peak of 0.62 occurs at 6000 RPM and it is higher than the case with V_2/V_1 = 1. For the largest in-series resonator volume(V_2/V_1 = 10), the first peak occurs at lower engine speed of 1000 RPM with volumetric efficiency of 0.73 and the second peak occurs at medium speed 5000 RPM with the volumetric efficiency of 0.79. The volumetric efficiency of this resonator is higher compared to the other resonator volumes at medium range of engine speed.

Overall, the volumetric efficiency of the engine in the presence of in-series resonators can be classified into three-speed range such as lower speed, medium speed and high speed as shown in Figure-8. The volumetric efficiency becomes lower at the lower speed engine as compared to the intake system without resonator. At medium speed range, the volumetric efficiencies for a volume ratio of 3 and 10 are higher than their values for the baseline model. However, for volume ratio 1, the volumetric efficiency is lower than the baseline model. The increasing volume ratio would increase the volumetric efficiency at medium range speed. At the high speed range, the volumetric efficiency increases when in-series resonator is installed. It can be observed that the maximum peak for the baseline model, in-series resonator with volume ratio 1 and 3 occur at the same speed 2000 RPM, while for in-series resonator with volume ratio 10 occurs at a speed of 5000 RPM.

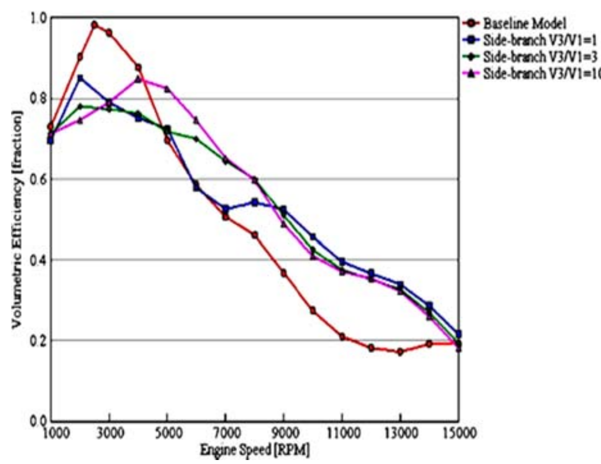

Figure-9. Volumetric efficiency for side branch resonator.

Side-branch resonator model is composed by a baseline intake system with a Helmholtz resonator in a side-branch. Figure-9 shows the volumetric efficiency of the intake system without resonator (baseline model) and intake system with side-branch resonator. Three side-branch resonator volumes ratio 1, 3 and 10 are considered. The effect of changing the resonator volume is studied.

For a side-branch resonator with the volume ratio V_3/V_1=1, the volumetric efficiency has a maximum value of 0.85 at 2000 RPM. However, it has lower efficiency at low engine speed. The efficiency is almost the same as its value for the baseline model at medium speed range from 5000 RPM to 7000 RPM. For higher speeds, the efficiency is higher than the baseline model. An intake system with side-branch resonator with the volume ratio V_3/V_1 =3 has a maximum peak of 0.79 at 2000 RPM, but it is lower than the peak value for baseline model and side-branch resonator with volume ratio 1. Volumetric efficiency increases for speed range of 5000 RPM to 15000 RPM. It is higher than the baseline model and side-branch resonator with the volume ratio $V_3/V_1 = 1$.

Volumetric efficiency for side-branch resonator with volume ratio 10 has a maximum peak of 0.85 at 4000 RPM. It is higher than its value for the others two volume ratios. However, the efficiency is lowest at low engine speed (1000 to 3000 RPM).

In conclusion, it can be observed that the maximum peak for the baseline model, side-branch resonator with volume ratios 1 and 3 occur at engine speed between 2000 RPM and 3000 RPM, while for side-branch resonator with volume ratio 10 occurs at higher RPM. The intake system with side-branch resonator has a lower volumetric efficiency than an intake system without side-branch resonator at low engine speed. The higher the volume of the resonator, the lower is the volumetric efficiency. This behavior change when the engine speeds over 4000 RPM and at medium engine speed, where volumetric efficiency increases as the volume of side-branch resonator increases. At high engine speeds, change in side-branch resonator volume gives slightly different volumetric efficiency. But, it can be seen that side-branch resonator with lower volume has higher volumetric efficiency in this speed range.

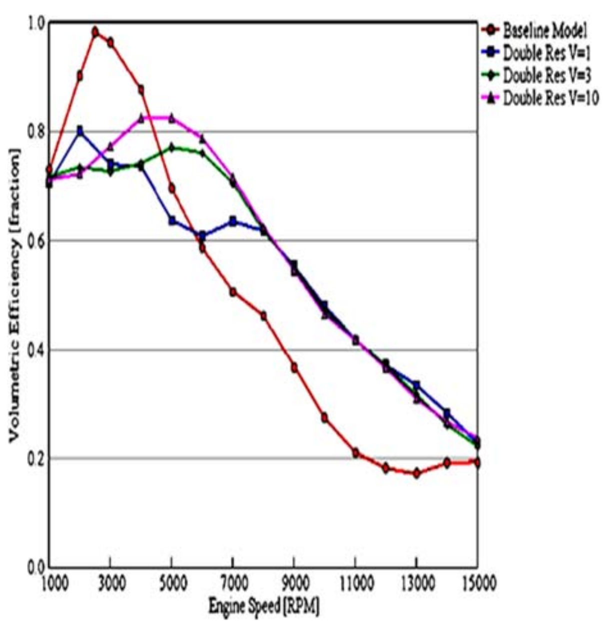

Figure-10. Volumetric efficiency for double resonator.

Figure-10 shows the volumetric efficiency against engine speed for intake system in the presence of double resonator. Double resonator is a combination of in-series and side-branch resonators. The variable of this resonator is the ratio of resonators volume to the engine cylinder volume. The two resonators have the same volume ($V_2 = V_3$).

Volumetric efficiency for the double resonator with volume ratio of 1 shows two peaks at about 2000 RPM and 7000 RPM, where the values are 0.8 and 0.65 respectively. However, maximum peak occurs at 2000 RPM. This volumetric efficiency is lower compared to volumetric for the baseline model at speed between 1000 RPM to 6000 RPM, and it becomes higher than the efficiency of the baseline model after 6000 RPM.

Volumetric efficiency of the double resonator with volume ratio of 3 shows two peaks at 2000 RPM and 5000 RPM. The first peak is 0.72 and occurs at 2000 RPM, while the second peak is 0.78. At lower speed, this volumetric efficiency is lower compared to the baseline model and the double resonator with volume ratio of 1. However, it starts to increase to become higher than the double resonator at engine speed 4000 RPM. It is higher than the baseline model at 5000 RPM. At medium speed, the volumetric efficiency always higher than the baseline model. But, it is between volumetric efficiencies of the double resonator with volume ratios 1 and 10.

For an intake system with the double resonator with volume ratio of 10, the volumetric efficiency is the lowest (0.72) at low engine speed from 1000 RPM to 2500 RPM. However, it starts to increase at 3000 RPM and its value 0.82 is higher than the double resonator cases. This double resonator has a maximum peak of volumetric efficiency at 4000 RPM, and its value is the highest. However, the efficiency is the lowest at low engine speed and the highest at medium engine speed.

In conclusion, volumetric efficiency of the intake system equipped with the double resonator have a significant effect to increase volumetric efficiency at medium and high engine speed as compared to the intake system without resonators. The effects of the resonator volume on volumetric efficiency can be seen at lower and medium engine speed. While at high engine speed, the effect is insignificant. At low engine speeds, the larger the volume of the double resonator the lower the volumetric efficiency. The effect of volume at medium engine speed is opposite with the effect at low engine speed where the larger the volume, the higher the volumetric efficiency.

Finally, among these three configurations of the resonator, the best results obtained are compared to the best volumetric efficiency over a wide range engine speed. In addition, the effect of different resonator volumes that influences the wave phenomena inside intake system is analyzed.

From the results obtained previously, the installation of resonators in the intake system would affect the volumetric efficiency over a wide range of engine speeds. At lower speed, the volumetric efficiency is decreased. While at the medium and high engine speeds, the volumetric efficiency increased compared to the baseline model. Also, the effect of resonator volume on volumetric efficiency is observed and can be concluded that at low engine speed, the increase in resonator volume would decrease the volumetric efficiency. At medium speeds, higher resonator volume would result in a higher volumetric efficiency. At high engine speeds, there is no significant change in volumetric efficiency for different resonator volume.

The volumetric efficiencies of all configurations of resonators are compared in Figure-11. At low engine speed, the intake system without resonator gives highest volumetric efficiency. While for intake system equipped with resonators, in-series resonator gives higher volumetric efficiency among these resonators. At medium and high engine speeds, intake system with the double resonator gives highest volumetric efficiency compared to the baseline model, in-series resonator and side-branch resonator.

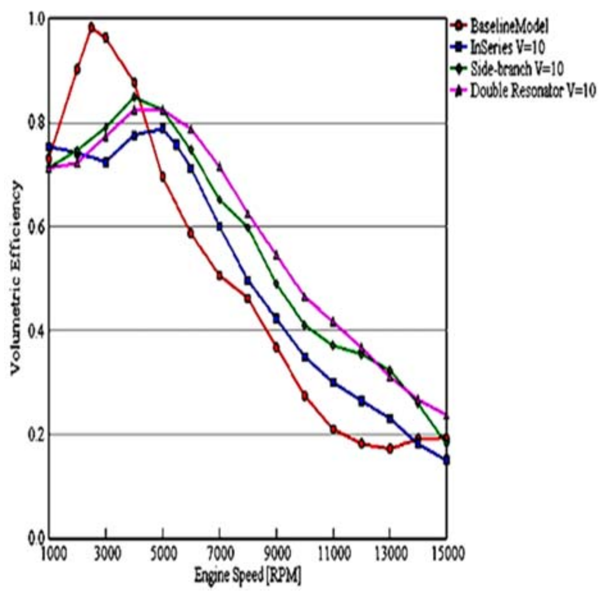

Figure-11. Volumetric efficiency for different arrangement of resonators.

The baseline model is the best configuration which provides the highest volumetric efficiency at low engine speed. Double resonator is the best configuration which provides highest volumetric efficiency at medium engine speed and high engine speed. Increasing the resonator volume of resonator, which result in increasing the volumetric efficiency? It is due toa large volume of the resonator gives effect on volumetric efficiency similar to the intake system with short intake pipe, where the resonator volume acts as an atmospheric container. Hence, the best way to obtain higher volumetric efficiency over a wide range engine speed is by installing the intake system with 'ON/OFF' resonator. At lower speed, the resonator is off and it is open at medium speed and high speed by ON/OFF switch.

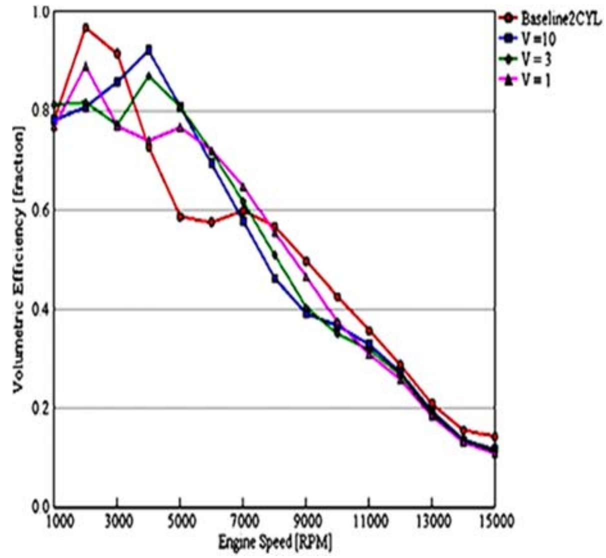

Figure-12. Volumetric efficiency for two cylinders engine.

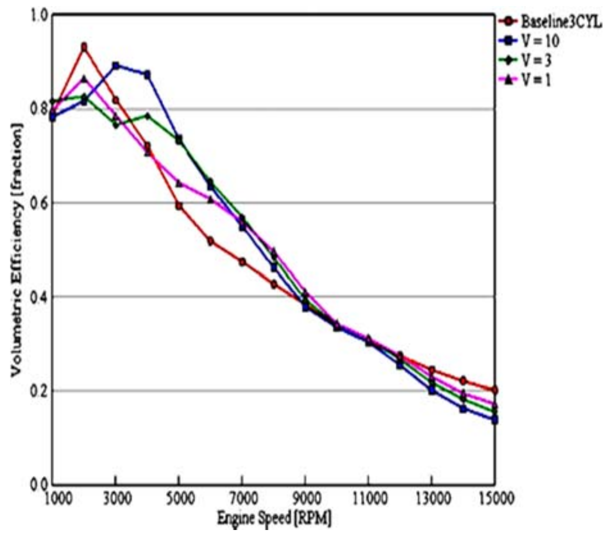

Figure-13. Volumetric efficiency of three cylinders engine.

Figure-12 and Figure-13 showed the effect of resonator volume on volumetric efficiency for two and three cylinder engines respectively. The volume of the resonator is varied based on the engine cylinder volume. Three resonators volume are considered in this case which are V=1, V=3 and V=10, where V is the ratio of resonator volume and engine cylinder volume. As shown in Figure-12, the effect of the intake system on volumetric efficiency for two cylinders engine can be seen over a wide range engine speed. The volumetric efficiency decreases at low and high engine speeds. However, at medium engine speed, the volumetric efficiency increases. This effect of

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resonator volume can be seen as engine speed about 4000 RPM to 7000 RPM. For V=10, the maximum volumetric efficiency has a peak closer to the baseline model and the peak occurs at higher engine speed as compared to the baseline model. This resonator volume has higher volumetric efficiency at low and medium engine speed in comparison with the baseline model and the other two resonator volumes.

Similar with two cylinders engine, the resonator volume influences the volumetric efficiency for three cylinders engine at low and medium engine speed. While at high engine speed, the effect is insignificant as shown in Figure-13. Increase in resonator volume would result in an increase in volumetric efficiency. The effect can be clearly seen at engine speed about 3000 RPM to 9000 RPM. At this range, the volumetric efficiency increases when the resonator is introduced. The larger the volume of the resonator result in the higher the volumetric efficiency. However, the volumetric efficiency decreases at low engine speed compared to the baseline model and the effect is insignificant at high engine speed. For V=10, it is suitable to increase the volumetric efficiency over a wide range of engine speed.

In conclusion, the effect of the resonator on volumetric efficiency for two and three cylinders engine is fairly small in comparison with that for a single cylinder engine. The improvement of the volumetric efficiency can be seen at medium engine speed only, while at low engine speed, it worsens the volumetric efficiency. At high speed, a small change in volumetric efficiency is achieved.

CONCLUSIONS

Resonators are proven as a device that can improve volumetric efficiency of a single cylinder engine. The effectiveness of resonators depends on the geometries of the resonator such as volume, length of neck and neck area. The proper design of the resonators will give significant effect on improving volumetric efficiency, especially at medium and high speed of the engine. In addition, the design of resonator must consider space available in the engine compartment. Thus, the optimum design of the resonator can be made where it improves the volumetric efficiency at all speed range of the engine. The effect of the resonator also exists for multi-cylinder engine. However, the effect is lower compared to single cylinder engine.

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