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EFFECT OF ANTI-SURGE VALVE AND BYPASS FLOW CONTROL MECHANISM ON THE PERFORMANCE OF TURBOCHARGED SPARK IGNITION ENGINE AT ALTITUDE

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ABSTRACT

Today, CAD/CAM simulations as a strong tool to estimate performance of various systems, reduce costs and testing time is taken into consideration. In this study GT-POWER software have been used to model the performance of spark-ignition internal combustion engines. The result shows, engine power drops at high altitude. To solve this problem, the engine equipping by turbocharger is attended and with regard to surge and choke criteria in compressor appropriate turbocharger is selected. In accordance to avoid surge occurrence in turbocharging process, an anti-surge valve mechanism in compressor has been defined. At the last step, in order to control the amount of inlet fuel to engine, other control mechanism on anti-surge valve has been used to control the extra flow rate. In accordance to results, this mechanism increased the power of engine up to 40 percent and provides fuel consumption efficiency over performance at sea level.

KEYWORDS: Anti-Surge Valve, Gt-Software, Internal Combustion Engine, Turbocharging

Turbocharging history backs to invention of internal combustion engines. Alfred Buchi invented the first practical version of turbochargers for internal combustion engines which was moved by engine exhaust gases. Brown and Baveri Company started commercial producing of turbochargers in 1923 (Watson and Jonata, 1982).

Designers use turbochargers, to achieve an engine with smaller dimension and preserving power production and efficiency. The basis of this approach is to drive a compressor by using a turbine. Thereupon pressure and density of inlet air to engine increase and the inlet air flow rate will increased too. This approach provides more inlet fuel to engine and more power of engine as well (Watson and Jonata, 1982; Heywood, 1988; Garrett et al., 2001).

For reduction of fuel consumption and preserving low pollution in spark-ignition engines, the designers use some methods like; low displacement volume of engine, turbochargers, direct fuel injection and various performance of valves. This approach will increase the potential of higher engine efficiency up to 30 percent (Renberg, 2008). Silva et al. show the pollution of carbon dioxide decreases 15-49 percent, by reduction of engine dimension and using turbochargers and flowing tow low cost strategies of engine stop-start and fuel cut-off (Silva et al., 2009).

Many researches on effects of turbochargers on internal combustion engines have been done. In accordance with these studies, turbochargers increase the power of engines, ofcourse, if appropriate turbocharger is chosen (Watson and Jonata, 1982; Heywood, 1988; Garrett et al., 2001). Krakianitis and Sadoi presented a method for selecting an appropriate turbocharger for a special engine. However, they found a range of turbochargers for a special engine by using of theoric relations, but final selection only obtained by experimental tests.

Developments in manufacturing of turbocharger system components, have led to a series of studies on the impact of these changes. Kesgin investigated the effect of turbocharging system on the performance of a natural gas engine. He showed the efficiency of turbochargers has a direct effect on engine efficiency. Whatever back pressure of turbine and pressure drop of compressor be lower, the efficiency of engine will be further. He showed, however, if the turbine inlet and compressor outlet are connected to the center of the related manifold, engine efficiency is greater than the case of connection from one end, but due to the high costs of construction and maintenance, it is not commonly.

Some examples of high-tech turbocharger are bi-inlet and variant blades turbines. Westin, exhibited turbine with variable geometry improves turbocharger efficacy up to 60 percent, whereas, twin-entry turbines increases up to 24 percent (Westin, 2002). Utilizing a turbine with variable geometry decreases 18% diameter of turbine wheels, on the other hand it increases efficiency and outlet power. Adaptation of engine with unstable performance nature and turbine and compressor with stable performance nature requires to use accurate control mechanisms. Common case of these mechanisms is wastegate. Thomasson et al. have investigated pressure strengthen control mechanism by wastegate in steady state and transient flow [9]. As another control mechanism we can mention to anti-surge valve. In order to control compressor performance and avoid the occurrence of surge, the anti-surge valve has been employed usually. Dimitrios and George have inspected on the various mechanisms of anti-surge valves. They reduced the standard deviation of pressure fluctuations and provided safe operation of compressor away from surge area as well as by control algorithm of PID.

In this study we have investigated the effects of altitude on engine performance due to geometrical characteristic and

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performance condition. Then selection criterion of appropriate engine because of improvement of engine performance has been studied. In the next step, to avoid of surge occurrence, we have introduced suitable control mechanism and investigated its effects on safe performance of system. Finally, by using bypass flow rate mechanism we have controlled effects of turbocharger and avoided mechanical and thermal stresses..

TEST CASE

In this experiment we have used a LYCOMING engine model of HIO-360-D which is a four cylinder spark-ignition engine with air cooling system. Locating pattern of cylinders is horizontally opposed. More information of specific engine has been shown in table 1.

Table 1. Engine Specifications

HIO-360-D Engine	
No. of Cylinder	4
Bore	83(mm)
Stroke	81.4(mm)
Displacement	5.91(litre)
Compression Ratio	10:1
Rated Power	141 kW at 3200rpm

Note that the fuel is aviation 100LL gasoline with higher Octane number than regular one. This selection makes more resistance against knock phenomena.

In order to test the engine, we have used an eddy current dynamometer which is made by API company model of FR 400 BRL. The maximum amount of power absorption, torque and measurable rotation are 400 hp, 850 Nm and 12000 rpm respectively. In figure 1, test room and connecting posture of engine to dynamometer has been illustrated. The measurements have been done at rotation of 1800 to 3200 rpm. In each cycle the throttle valve has varied from lowest to maximum values (full load) and the results has been recorded. Power and fuel consumption graphs of engine are shown in figure 2, 3 correspondingly. It should be noted that these graphs have been obtained at full load mode to brief presentation.

Figure 1. A schematic view of test room

ENGINE PERFORMANCE SIMULATION

In this part we have simulated the engine by GT-POWER software and compared the results with experimental data.

SIMULATION AND VERIFICATION

Today, CAD/CAM simulations as a tool to estimate performance of various systems, reduce costs and testing time is taken into consideration. In this study specified engine and its components have been simulated by GT-POWER software carefully. Modeling of software is based on fluid mechanics laws, thermodynamic laws, mass conservation law, equilibrium reactions and chemical kinetics. In particular, combustion simulation of this software is based on one region and multi regions approaches. In accordance with unification of thermodynamic properties in each region, pressure unification developed in all volume of cylinder (Benson and Rowland, 1979). In this investigation we have used multi-regions approach. Border detection of regions is based on flame turbulent level. Flame propagation speed is different depend on fuel and thermodynamic properties of mixture in combustion chamber (Pourkhesalian et al., 2010). To obtain accurate results, it is necessary to calibrate empirical coefficients of the combustion model by test data (Berberan-Santos et al., 1997). Hence, we have paid special attention to calibrate the model coefficient by experimental data, in order to understand the behavior of engine different operation conditions.

Experimental data and numerical results of power and fuel consumption are compared in figures 2 and 3.

In according to figure 3, good agreement between experimental and numerical results about fuel consumption can be observed. The averaged error between numerical and experimental results is about 7% which shows verification of the selected model.

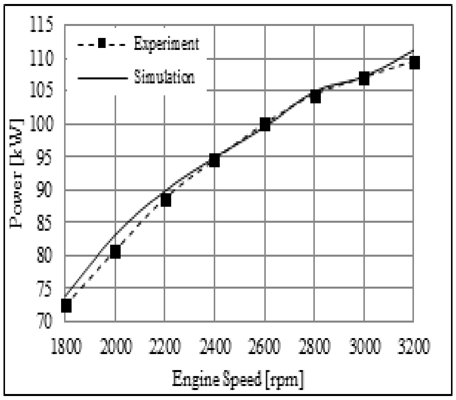

Figure 2. Brake power variations versus engine speed.

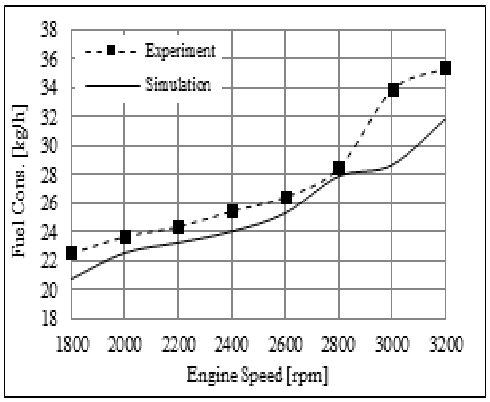

Figure 3. Fuel consumption variations versus engine speed.

PERFORMANCE SIMULATION IN ALTITUDE

According to our desire, the engine should work at high altitude. As altitude increases air pressure drops and this reduction has a destructive effect on engine performance. It is difficult to provide engine performance conditions at high altitude in a lab. So we have to use software to obtain influence of altitude on the engine.

The maximum operation altitude of mentioned engine is 4.5 km from sea level. Equation 1 shows the relation between temperature, altitude and pressure.

$$P = P_{S.L.} \exp\left(\frac{-gh}{RT}\right)$$

(1)

Where T is temperature at desired altitude.

By using equation 1 we have investigated engine performance condition at altitude of 2.7 km from sea level. A comparison between power at desired altitude and sea level is shown in figure 4.

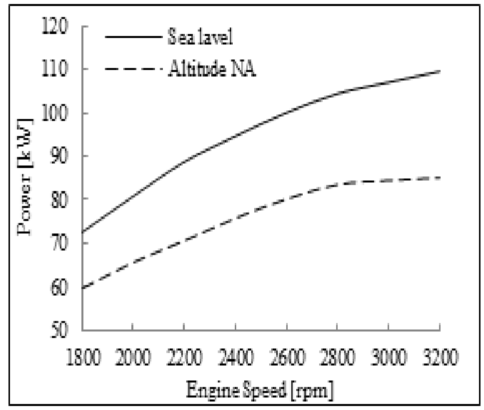

Figure 4. Variation of brake power versus engine speed.

According to figure 4, by increase of altitude the engine power drops dramatically. The approach of this study is to recoup the losses by using an appropriate turbocharger.

TURBOCHARGER

In this part, we introduce general description about turbocharger system and its performance. Generally turbo machines are not suit to work with a piston machines. Thus the composition of the gasoline engine and the turbocharger must be carefully designed. General purpose of this part is to find good agreement between engine and turbocharger for best performance.

INVESTIGATION OF COMPONENTS AND MATCH LOGIC

The amount of passing air based on geometrical characteristics, engine performance condition and amount of amplification in compressor specify by equation 2.

$$\dot{m}_a = \eta_v \frac{N}{2} \rho_{a,i} V_d$$

(2)

Compressor power needed to create the desired pressure ratio will be obtained from equation 3.

$$\dot{W}_C = \frac{1}{\eta_C}\left(\dot{m}_a + \dot{m}_B\right) h_{0i} \left[\left(\frac{P_e}{P_{0i}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

(3)

Where $\dot{m}_B$ is outlet mass flow rate from anti-surge valve to atmosphere.

Equation 4 by consideration of shaft efficiency which has connected compressor and turbine determines compressor power needed.

$$\dot{W}_C = \eta_{mech} \dot{W}_T$$

(4)

The amount of turbine power through passing fluid can be calculated by following equation:

$$\dot{W}_T = \eta_T \left(\dot{m}_a + \dot{m}_f - \dot{m}_W\right) h_{0i} \left[1 - \left(\frac{P_e}{P_{0i}}\right)^{\frac{\gamma-1}{\gamma}}\right]$$

(5)

In equation 3 and equation 5 we should note that the efficiency of turbine and compressor in turbochargers system is based on the stagnation to static logic. This is because of less usage of flow velocity and less waste in this system (Watson and Jonata, 1982). In equation 5 $\dot{m}_f$ is flow rate of injection fuel in manifold and will be computed according to $\dot{m}_f = \dot{m}_a[\mathrm{FAR}]$ and fuel to air ratio. $\dot{m}_W$ is passing flow rate of wasegate and will be calculated based on geometrical characteristic and movement mechanism of wasegate to achieve functional specifications and optimal performance at desired area. Mass flow rate through a valve is established upon by passing of a compressible flow through an obstacle. This relation is based on the analysis of one-dimensional compressible flow and considering effects of actual flow as a discharge factor. In accordance to choking or not choking in manifold, mass flow rate will be calculated from equation 6 or 7 respectively. The criteria of choking occurrence is a pressure ratio greater than $\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$ on each side of manifold (Kesgin, 2005).

$$\dot{m} = \frac{C_D A_R P_0}{\sqrt{RT_0}} \left(\frac{P}{P_0}\right)^{\frac{1}{\gamma}} \left\{\frac{2\gamma}{\gamma-1}\left[1 - \left(\frac{P}{P_0}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{\frac{1}{2}}$$

(6)

$$\dot{m} = \frac{C_D A_R P_0}{\sqrt{RT_0}} \sqrt{\gamma} \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

(7)

Where T_0 and P_0 in these equations are stagnation temperature and pressure of upstream and P is downstream pressure.

The amount of required air by the engine determines the initial size of turbocharger. Looking at catalogs which provided by the manufactures, the initial size of turbocharger can be selected. On the other hand, turbocharger's engine can operate in a wider range of mass flow than compressor. It shows the importance of drawn air flow on the compressor map than turbine map. According to full line of engine operation which is overlapped in all range of velocities and loads to compressor characterestics, the final selection of turbocharger will be done. Figure 5 shows this overlapping.

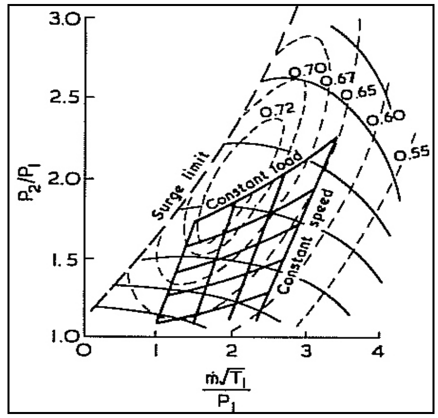

Figure 5. Overlapping curve of engine performance and compressor

By increasing of inlet density of compressor, mass flow rate rises gradually, if the engine operates at constant speed but the load grows gradually. Air flow of engine can overlaps on compressor characteristic curve (e. g. figure 5). The goal is to select a compressor which constant speed line of engine be at the middle level of higher efficiency part of compressor's map. If engine works at constant load, this situation is similar to fix Brake Mean Effective Pressure (BMEP) while, the engine speed increases. Volume ratio of air flow because of growth of engine speed will be increased also. Effective surface of turbocharger turbine flow is constant. So the inlet pressure of turbine enlarge. It is clear that increase in pressure leads to an increase in available energy for expansion through the turbine and increase amplification pressure in compressor also. Thus, the engine constant load line is not on compressor characteristic curve horizontally. It increases by growing of engine speed. It is obvious on constant load lines in figure 5.

General characteristics curve of engine should be between choke (right side of compressor curve in figure 5) and surge (left side of compressor curve in figure 5) lines at the upper level of compressor efficiency curve.

The margin between surge and nearest point of the engine performance should be enough large to stay away from surge area.

SELECTION OF AN APPROPRIATE TURBOCHARGER

In agreement with pervious parts, in order to achieve a proper adoption for engine, all performance points of engine which is equipped to turbocharger should be obtained. As mentioned above, performance points include constant speed lines and constant load which are overlapped on compressor curve. If engine performance condition be at safe region and upper level of compressor efficient curve, it ensures suitable adaptation of engine and compressor.

In this study we have used GT-POWER software to obtain performance conditions of an engine which equipped with a turbocharger. In spark-ignition engines, the throttle controls load at constant rotation. This process performs by changing the density of suction air and the consumption fuel of engine (Korakianitis and Sadoi, 2005).

Since the simulation mode requires control mechanisms that are abstract in vitro condition, we have used opening changes in throttle. Thus, the constant speed lines have been acquired by preserving of engine speed and changes in opening of throttle and constant load lines simulated by impounding of throttle position and changing in engine speed. So engine performance condition in conjunction with turbocharger may be obtained. The process repeated for several of turbochargers and engine curves adopted on compressor map. Compressor map includes compressor efficient contours in term of reduced mass flow through the engine and pressure ratio in two sides of compressor. In this experiment in order to adaptation of engine and turbocharger, different turbochargers of Garrett Company are used. Figures 6 to 8 show overlapping of engine performance condition on compressor performance maps in types of GT32, GT35 and GT37 (Hajilouy-Benisi et al., 2009). Hajilo et.al showed characteristic curve of twin-entry turbines-pulse turbocharger, according to flow rate through each duct will change. It shows pulse turbochargers needs to be more studied.

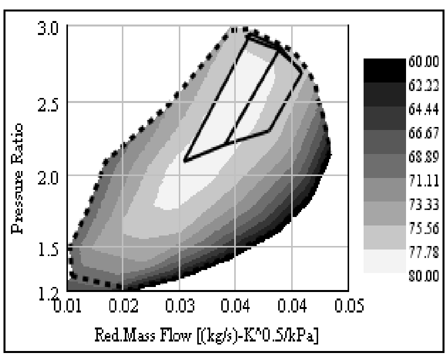

Figure 6. Adaptation of engine performance condition with turbocharger of GT32.

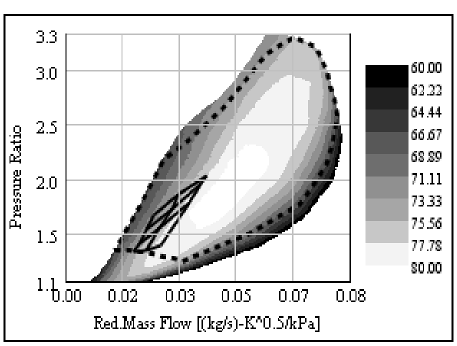

Figure 7. *Adaptation of engine performance condition with turbocharger of GT35.*

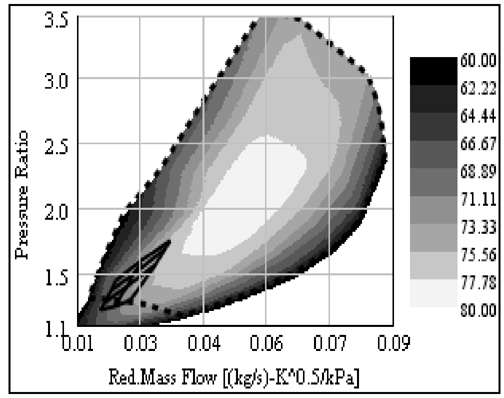

Figure 8. Adaptation of engine performance condition with turbocharger of GT37.

According to figure 6, engine performance condition is so close to choke region of compressor and as a result turbocharger of GT-32 is small for our desired engine. It should be noted that approaching of engine performance condition to choke region is because of software extrapolation features [13]. The engine performance condition actually choke off, but the compressor performance condition is not to define outside of choke region.

The adaptation of engine performance condition with turbocharger of GT37 has been illustrated in figure 8. According to this figure, performance condition of engine is close to surge region and is at the down level of compressor map.

But in accordance with figure 7, it is obvious that the conjunction of engine with turbocharger of GT35 is simulated better than two other turbochargers. Because engine performance condition is located at upper region of compressor efficient map and the closest performance point to surge region is about 20 percent of recommended mass flow rate (Watson and Jonata, 1982).

It should be noted that the choice of turbocharger has been carried out without considering anti-surge valve and wastegate.

ANTI-SURGE VALVE

Surge is an instability of flow through compressor which appears as a periodical sweep. This phenomena causes a lot of noise, a sudden increase in temperature, an increase in blades stress and mechanical damages. The phenomena is due to a decrease in flow rate at specific speed and as a result of inability of fluid to pass over from current pressure ratio. In this situation return flow is appeared also. It usually starts with period stall and with further reduction in flow rate which leads to surge. Necessary condition for occurrence of surge is to be at positive slope in constant speed lines. These points cannot self compensate probably disturbences. So surge character line at compressor character curve will be obtain by $\frac{dPR}{d\dot{m}} = 0$

In order to avoid surge occurrence in compressor, axial or radial one, anti-surge valve is used usually. Various mechanisms have been presented for these valves which all of them are based on reduction of compressor downstream pressure and according to surge control line (to avoid surge occurrence). We use this line to compensate uncertainly in the measurements and delay in valve performance. There are some descriptions for this parameter that one of them has been shown in equation 8.

$$SM = \frac{PR_S - PR_{SC}}{PR_{SC}}$$

(8)

Where PR_S is pressure ratio at surge line, PR_{SC} is pressure ratio at surge control line and SM is surge control limitation. Some amounts have been suggested for surge control line. Among them we have used 0.25 for axial multistage compressor of Komposty and 0.15 for radial compressor of Henderson [17]. We should note that high amount of this parameter causes compressor performance drop because of proximity of high efficiency lines and surge line. Figure 9 shows, compressor characteristic curve of turbocharger GT35 and surge control line.

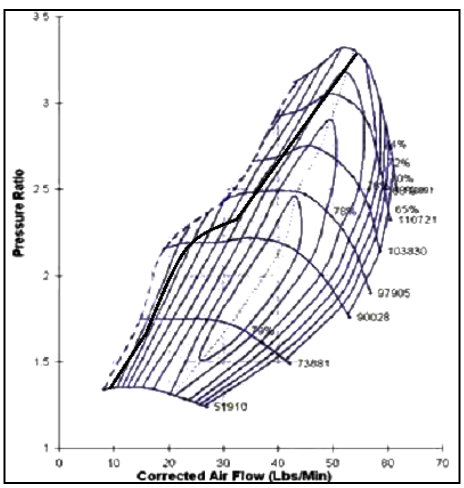

Figure 9. Compressor characteristic curve of turbocharger GT35 and surge control line

Figure 10 presents some anti-valves which have been used in this examination. This mechanism calculates the downstream pressure leads to surge by reading of mass flow rate and compressor upstream pressure and according to surge control line. In next stage, read upstream pressure has been compared with calculated upstream pressure. If the pressure exceeds the valve opening command is issued. In this study because of computer simulation we can remove delay of valve performance and consider lower amount for surge control limitation.

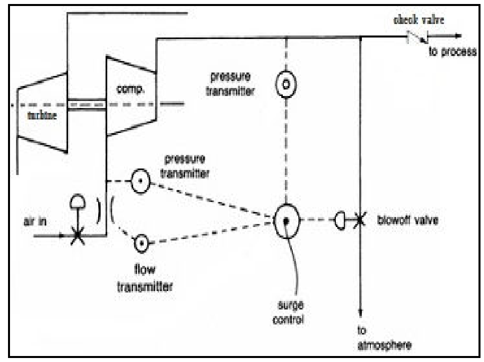

Figure 10. Anti-surge valve and its control mechanism

Outlet fluid of valve chooses one of the two selectable path according to performance condition. First path is entering to atmosphere and second is return to the inlet flow of compressor. In this study, outlet flow of valve is exhausted to atmosphere because of non-harmful of fluid and greater control of inlet flow to the compressor. We use check valve in main path of engine to prevent backflow to engine and instability of engine.

In this part we have investigated the effect of this mechanism on performance of system. For this purpose we compared pressure ratio versus modified flow rate curve of a compressor with compressor characteristic curve for totally open wasteage in 1800, 2200 and 3000 rpm. The comparisons have been illustrated in figures 11 and 12. According to figure 11, the performance of compressor in rotation of 3200 rpm is in safe region and faraway of surge and chokeing. But in rotation of 1800 and 2200 rpm, compressor performance curve is in the surge region. To avoid surge occurrence we have used an anti-surge valve. By using this valve, compressor performance curve will be modified to figure 12. This modification is happened by opening of the valve and reduction pressure ratio at low flow rate regions.

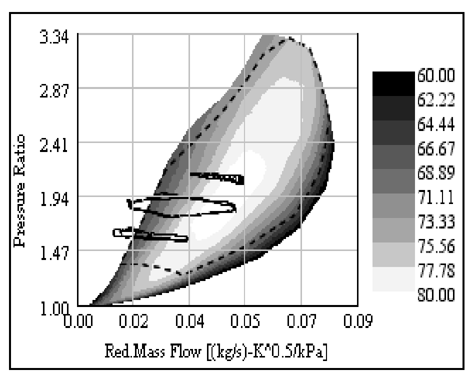

Figure 11. Comparison of compressor performance curve in an engine cycle

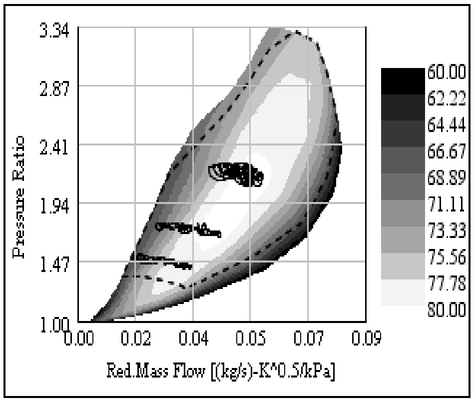

Figure 12. Comparison of compressor performance curve in an engine cycle equipped to an anti-surge valve.

Effects of turbochargers on engine performance in altitude

The goal of using turbochargers in this investigation is to solve engine performance problem at high altitude. We have introduced the bad effects of altitude on engine performance by using GT-software. Therefore, in this section we have tried to compensate power drop by using of turbocharger GT35 and more entrance air flow. Engine turbocharger circuit is equipped to anti-surge valve and there is no wastegate also.

Figure 13 shows, engine power at sea level and at high altitude without/with turbocharger for completely open throttle. In accordance with this figure, turbocharger could solve engine power drop even it works better than sea level. In figure 14, fuel consumption with and without turbocharger has been compared. As it clear, because of more entrance air flow to engine, the fuel consumption with turbocharger is more than without it. By a comparison between figures 13 and 14 it is obvious that fuel Specific consumption by using of turbocharger has improved.

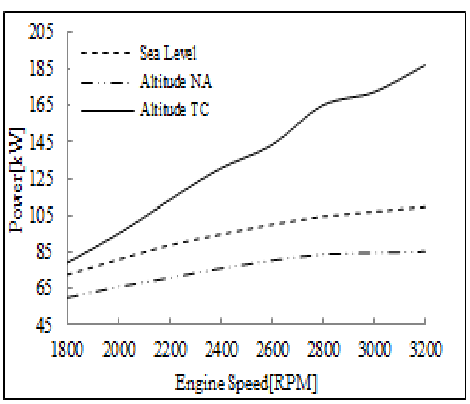

Figure 13. Break power variation versus engine speed.

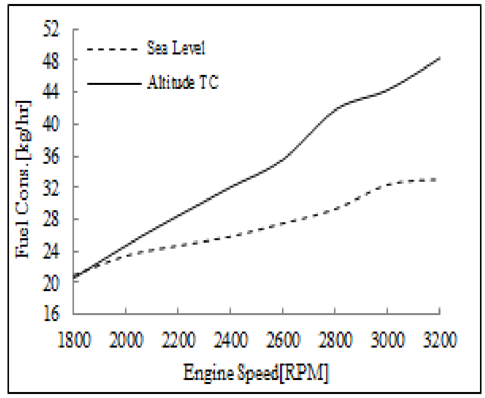

Figure 14. Variation of fuel consumption versus engine speed.

The analysis of anti-surge valve performance shows, the effects of this valve is up to rotation of 2600 rpm and after that it does not have significant effect on system performance. This deficiency is because of receding from surge region. Figure 15 illustrates effects of anti-surge valve regions at rotation of 1800 rpm. According to this figure, opening valve command has been sent at specific times because of growth of pressure after compressor. The opening of valve will be continued when the pressure after compressor drop under surge control pressure. According to results, about 18 percent of flow through compressor has been bypassed to prevent surge by anti-surge valve.

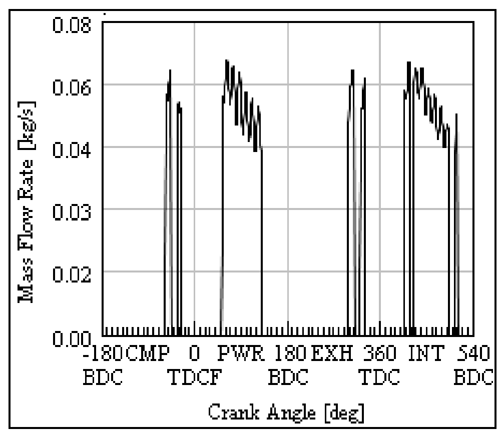

Figure 15. Mass flow rate variation of anti-surge valve versus crank angle in engine speed of 1800 rpm.

Pressure variation after compressor and before turbine as a cycle average has been shown in figure 16.

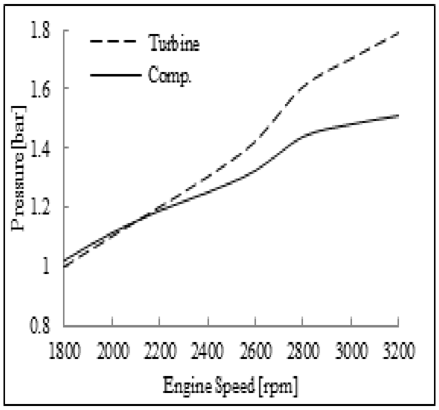

Figure 16. **Cycle average variation before turbine and after compressor versus engine speed.**

In pervious part, engine performance simulation based on constant performance equivalence ratio for different altitudes and rotations have been done. The result of this simulation is increase of production power and fuel consumption of engine, as it clears in figure 15. This growth is because of the lack of control mechanism on inlet flow rate. We use control mechanism like wastegate to control engine fuel consumption and production power to avoid thermal and mechanical stress. This study is an attempt to use developed surge control mechanism. It works by setting the effective surface and constant discharge coefficient for valve in different rotations. Thus, the occurrence of surge will be decreased. If surge phenomena happen, surge control mechanism works and increases valve effective surface by more opening and estranges system from surge range. Figure 17 shows engine production power with inlet flow control mechanism for completely open throttle. In this situation, flow control criteria is amount of inlet fuel to engine at sea level (test conditions) according to figure 18. For practical application, pressure amplitude by compressor can be criteria and acts as surge control mechanism.

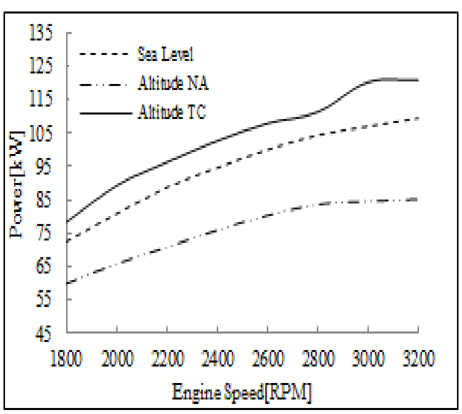

Figure 17. **Power variation versus engine speed.**

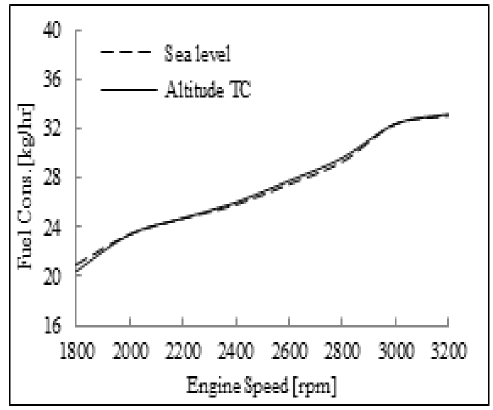

Figure 18. **Fuel consumption variation versus engine speed.**

Figure 19 shows, mass flow rate through the compressor, engine and anti-surge valve. By this graph we can investigate the influence and quality of valve performance in different rotations. According to this figure, at high speed rotation, about 25 % of flow rate through compressor is bypassed by valve. Flow rate through turbine and compressor are equal because we do not have wastegate in this system. Also we can investigate presented equation on session 4 by curves of figure 19.

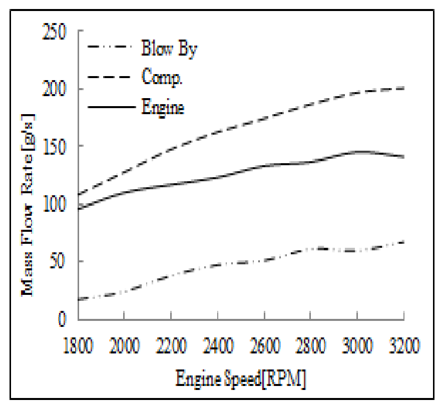

Figure 19. **Flow rate through system components in different engine speeds.**

The variation of pressure before turbine and after compressor has been exhibited in figure 20. By a comparison between figures 16 and 20, we find that valve control performance on flow rate, can also control production and consumption power of turbine and compressor respectively.

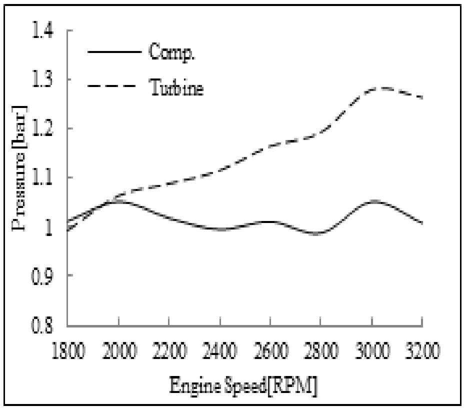

Figure 20. Variation of pressure before turbine and after compressor versus engine speed.

CONCLUSION

In this study GT-POWER software have been used to model the performance of spark-ignition internal combustion engines. In accordance with experimental and simulation results and average error of 2% and 7% for power and fuel consumption respectively, a validation of the study has obtained. Simulation results indicate engine power drop at altitude. To address this shortcoming, the engine has been equipped to a turbocharger selected by surge and choke criteria. To avoid surge occurrence in compressor, anti-surge valve have been used. In the final step, another control mechanism on the anti-surge valve to control amount of inlet fuel to engine have been utilized. This mechanism bypasses extra flow rate of compressor. The results show that by using turbocharge and the mentioned control mechanism even at altitude of 2700 m achievement of a higher power than that of sea level with the same amount of fuel consumption is possible.

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