INTERCOOLER EFFECT ON CONVENTIONAL SUPERCHARGING SYSTEMS

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Abstract

There are three certain problems in automotive applications that cause environmental effect, cost and comfort problems. Therefore, internal combustion engines are required to have not only a high specific power output but also to release less pollutant emissions. For these reasons, current light and medium duty engines are being highly turbocharged because of having negative environmental effects of internal combustion engines. Due to mentioned facts, there are studies going on to improve internal combustion engine performance. Studies for supercharging systems are also included in this range. One of the most important problems faced in supercharging systems is that air density is decreasing while compressing air. Also air with high temperature causes pre-ignition and detonation at spark ignited engines. Various methods have been developed to cool down charge air which is heated during supercharging process. One of these methods is to use a compact heat exchangers called as intercoolers to cool charging air. The purpose of an intercooler is to cool the charge air after it has been heated during turbocharging. As the air is cooled, it becomes denser, and denser air makes for better combustion to produce more power. Additionally, the denser air helps reduce the chances of knock. In this study, the intercooling concept was introduced and performance increase of a vehicle by adding intercooling process to a conventional supercharging system in diesel or petrol engine was analytically studied. Pressure drops, air density and engine revolution were used as input parameters to calculate the variation of engine power output. Also, possible downsizing opportunities of the cylinder volume were presented. It is found that the engine power output can be increased 154% by ideal intercooler while single turbocharger without intercooler can only increase 65%. Also a meaningful 50% downsizing of the cylinder volume possibility achieved by means of turbocharging and intercooling. Finally, future study needs about cycle characteristics of internal combustion engines with intercooling process and intercoolers were discussed.

Keywords: effectiveness, heat exchanger, heat transfer, intercooler, internal combustion engine, supercharging

NOMENCLATURE

Symbols
k – rate of specific heats
m – mass [kg]
$\dot{m}$ - mass flow rate [kg/s]
N – engine revolution [rev/min]
p – pressure [kPa]
P – power [kW]
R – specific gas constant [kJ/kgK]
T – temperature [K]
V – volume [m^3]
W – work [kJ]
η - efficiency

Subscripts
C – corrected
e – effective
Air – specification which belong to air
i – induced
K – compressor
M – engine
T – turbine
TB – turbocharger
Std – standard specifications at sea level
0 – initiation of compression in compressor
1 – compression initiation in cylinder
2 – compression end in cylinder
3 – expansion initiation in cylinder
4 – expansion end in cylinder
5 – expansion initiation in turbine
6 – expansion end in turbine
7 – entrance to compressor
8 – entrance to turbine
9 – scavenging start
10 – air suction end to cylinder

Superscripts
‘ – entrance to intercooler
* – cycle without turbocharge

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INTRODUCTION

Internal combustion engines (ICE) play a major role in our life. With respect to the various predictions, conventional internal combustion engines can be used around 10-30 years. This period is one of fourth of internal combustion engine's age. It means that their total environmental effects will have been multiplied approximately with 1.25 in this period. Also hybrid vehicles which will be alternatively used after conventional vehicles would be down, will use instead of lonely used internal combustion engines. These facts show that internal combustion engines should be optimized to lower its environmental effects. Today, as known, 70 % of carbon monoxide, 50 % of nitrogen oxide and 42 % of volatile organic compounds (hydro carbons) are originating from internal combustion engines [1]. Solution opportunities to decrease the aforementioned issues are preferred unless they increase cost, lower power output and comfort features. Supercharging is one of the preferred solutions to provide all them. By downsizing the engine cylinder volume and providing more oxygen, supercharged vehicles have released less exhaust emission into air, better exhaust emission proportion, sufficient power output and low specific fuel consumption [2]. Beside these advantages, supercharging systems can be further improved. Especially, charge air cooling methods take place in this improvement process. Heat exchangers are utilized in one of the charge air cooling methods which is called intercooling. Lee (2009) stated that according to EPA, human activities have increased the concentration of CO_2, one of the direct greenhouse gases known to increase the average temperature of the atmosphere by trapping the heat radiated from the surface of the Earth, by 36% globally since the Industrial Revolution, principally due to the combustion of fossil fuels. In 2006, CO_2 contributed 84.8% of total greenhouse gases in the United States. The total CO_2 emission has increased by 18% from 1990 to 2006. The sources of CO_2 vary by region, but most researchers cite transportation for about 33%. Electric power generation in the US produces about another third, while heating our homes, manufacturing, agriculture and clearing forests account for the rest [3].

In this study, intercooling effect on power output of ICE was studied. A diesel engine was considered and it was evaluated whether it was equipped with either a turbocharger or both a turbocharger and a super intercooler. Using thermodynamics laws and expressions, the power output of the engine was analytically examined by changing intercooling features such as pressure drop values and engine revolution at full load. Results were presented and interpreted as power (kW) and downsizing of the engine volume values (m^3).

LITERATURE REVIEW

There are different approaches to intercooling process in ICE. However some of these approaches also include supercharging which contain intercooling process in it as it is the main reason for charge air cooling. At 70s, various research and experimental applications of intercooling were carried out. An air-to-air intercooler was integrated to 163 HP tractor engine and it was observed that engine power output was increased without any side effects to material duration [4]. When 80s considered, it could be seen that automobiles were investigated for intercooling usage [5]. Also Thompson et al. (1987) reported that more than 20,000 BHP power output and 30 % fuel consumption decrement were attained by intercooler and regenerator usage in marine engines [6]. Those studies massively focused on diesel engines. In 90s, there are a lot of experimental and theoretical studies on supercharging effects to diesel engine performance characteristics [7,8,9] and some for spark ignition engine performance characteristics [10,11]. These studies commonly report that supercharging increases power output while decreasing specific fuel consumption and positively regulates exhaust emissions. At the end of 90s, there are more specific studies about intercooling effect on engine performance characteristics and most of these studies are experimental ones. Uzun [12] reported that specific fuel consumption of a diesel engine was decreased between 3% to 12% by utilizing intercooler. Bilen (1998) developed a software to predict performance of an intercooler with specific dimensions and to dimension intercooler for specific

performance values by using effectiveness transfer unit method [13]. Opacity of exhaust gases, specific fuel consumption and power output were measured as 15.78% improved, 9.5% decreased and 3% increased, respectively [14]. Exhaust emission proportion changes by intercooling utilization was investigated by Ozulku (2002) with European Steady State Test Cycle Mod 13 (ESC Test). While similar results were obtained for specific fuel consumption and power output, particle emissions found to be decreased around 20 to 50 %, NO_x emission as 4 to 24 %, hydrocarbon emissions as 20 to 24 % [15].

Recently, studies about intercooling and supercharging process have concentrated on mathematical modeling efforts. Especially, accurate charge air flow prediction is tried to be obtained by means of improved mathematical models [16]. Also, irreversibility values of the mentioned systems were investigated by analytical models which were developed from first and second law of thermodynamics [17]. To increase supercharging in spark ignited gasoline engines, various intercooling methods (staged intercoolers and compressors, turbine expansion cooling) were investigated by theoretically and experimentally [18,19, 20, 21]. Finally, there are various case studies about supercharging and intercooling configurations in newly developed internal combustion engines such as Homogenous Charge Compression Ignition Engines, Lean Burn Engines and Hydrogen Fueled Engines. 50 % specific fuel consumption decrease and 147 kW effective power output were obtained from a supercharged intercooled Lean Burn Spark Ignition Engine while the exhaust gas emission values obtained proper to Euro 6 emission regulations [22].

Various new or improved vehicle engine technologies are being exploited to reduce C02 emission by improving vehicle fuel economy. Among many technical innovations and improvements in these vehicles, engine downsizing (reduction in displacement volume and/or the number of cylinders) is one of the most effective methods to reduce fuel consumption, i.e. CO_2 emission [3]. Engine downsizing, the use of a smaller capacity engine operating at higher specific engine loads, is achieved by running with high levels of pressure boosting at full load using a supercharger or turbocharger. Lee [3] pointed out that most technical advances in automotive engineering can be viewed as means to allow engine downsizing as they improve the specific output of the engine. For example, in the past, one of the main limitations to maximum power for small Diesel engines was the ability to provide enough fuel in a limited injection period. Modern high pressure injection systems, such as common rail, have solved this problem significantly, allowing further downsizing of the engine.

In this study, effects of the intercooling process to supercharged conventional internal combustion engines were investigated in types of effective power output (kW) and downsizing cylinder volume value (m^3). Specifications of a diesel engine were selected to be used in the calculations. Then proper turbocharger system selection and matching were analytically performed. To observe the intercooling effect, a super intercooler that can cool charge air to ambient air temperature was taken into consideration. After calculating power output and downsizing cylinder volume with the intercooler, pressure drop effects in the intercooler were examined. At the end of this study, the calculated results are discussed and possible future study opportunities are presented.

THEORETICAL ANALYSIS

Diesel cycle was used in the approach as it was modified for turbocharger and intercooler. Diesel and modified Diesel Cycle for turbocharger and intercooler systems P-v diyagram are shown in Figure 1.

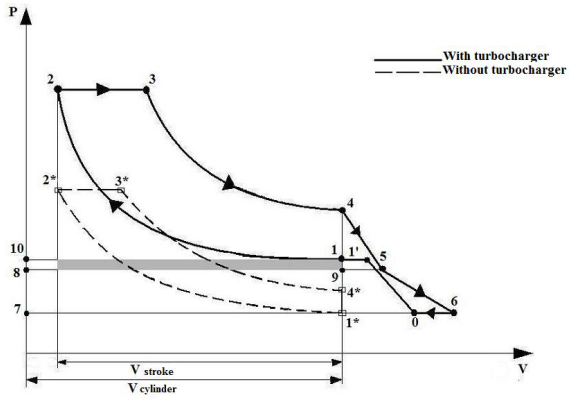

Fig. 1. *Modified Diesel Cycle for turbocharger and intercooler*

The main difference between the two cycles in Fig. 1 is the charge air system. Conventional diesel cycle does not have turbocharging system. Other than this component, power producing processes are the same. The process between 1-2 is an isentropic compression by the piston. As the piston goes upward, charge air gets hotter. At top dead point of the cylinder, fuel is started to spray into the hot air and expansion at constant pressure is initiated by combustion. 3-4 process is an isentropic expansion and 4-1 is constant volume heat rejection. However air continues its cycle in turbocharged engine while the cycle restarted in conventional diesel engine. In 4-5 process, hot exhaust air expands through turbine inlet. At 5-6 hot air expands to atmospheric pressure (isentropic) and its heat energy is converted to kinetic energy transferred to compressor wheel. Compressor sucks air from environment and compresses it at 0-6 process. Then compressed and heated air enters to intercooler and passes through the cylinder at 1'-1 process. The gray area in Fig 1 is "pumping mean effective work" which can be positive or negative due to rate of compression ratio to expansion ratio of compressor and turbine respectively. This work occurs at scavenging process of the piston. If it was positive which means that piston requires more power for scavenging due to back pressure, than the brake thermal efficiency would be lower and if it was negative, brake thermal efficiency would be higher than normal operation conditions [21].

To calculate power output of the engine with intercooler and turbocharger, assumptions are as follows:

- Charge air is an ideal gas,
- All compressions and expansions are isentropic,
- Specific heat values are taken at the ambient air temperature,
- The cycle does not involve any friction or mechanical losses,
- All expansion and compression processes take place in a quasie-quilibrium manner,
- The pipes connecting the various components of a system are well insulated, and heat transfer through them is negligible,
- Neglecting the changes in kinetic and potential energies of the working fluid.

During power calculations, thermodynamic laws were used and internal energy change of the air was calculated.

To match intercooler and turbocharger to the engine and integrate it, following calculations are implemented;

$$m_{Air} = \frac{p_1 V_1}{R T_1} \tag{1}$$

Induced and effective power outputs from engine are calculated with the following two equations;

$$P_i = \frac{N W_{net}}{30} \tag{2}$$

$$P_e = P_i \eta_M \tag{3}$$

To read compressor and turbine maps of the selected turbocharger, the following calculations should be made;

$$\dot{m}_{AirC} = \dot{m}_{Air} \frac{\sqrt{\frac{T_0}{T_{std}}}}{\frac{p_0}{p_{std}}} \tag{4}$$

$$\dot{m}_{AirCT} = \dot{m}_{AirT} \frac{\sqrt{\frac{T_5}{T_{std}}}}{\frac{p_5}{p_{std}}} \tag{5}$$

After all these equations, the following equation was iterated by changing turbine expansion ratio which was read from turbine map, and compression ratio P_1/P_0 of the turbocharger was obtained from $(T_1'-T_0)$ value owing to known values of ambient temperature and intercooling degree. During this procedure, air mass flow and turbocharger efficiency were changing, so iteration continues till these differences become small enough to be neglected and compression ratio corresponds to expansion ratio in energy balance.

$$\frac{T_4}{\left(\frac{p_4}{p_5}\right)^{\frac{(k-1)}{k}}}\left(1-\frac{1}{\left(\frac{p_5}{p_6}\right)^{\frac{(k-1)}{k}}}\right)=\frac{\dot{m}_{Air}\,(T_1-T_0)}{\dot{m}_{AirT}\;\eta_T\eta_{TB}\eta_K} \qquad (6)$$

During iterations, compressor map and turbine map of selected turbocharger were used. To measure effects of intercooler, charge air temperature and pressure were modified according to the super intercooler specifications. This super intercooler was considered as it can cool charge air to ambient air temperature and without no pressure drop, 3 % pressure drop and 10 % pressure drop, respectively.

RESULTS AND DISCUSSION

Analysis results are plotted in three different figures 2-4 which are power output values, power increase percentages and possible engine cylinder volume downsizing respectively. In this approach, power increase percentages give a better aspect comparing with power output values which may differ with real operation.

Engine power output values calculated with aforementioned analytical model are given in Fig. 2.

When power output values are considered, it can be seen that the intercooling process starts to affect after a certain revolution value of the engine. This delay effect occurs because of low temperature of charge air and low temperature difference between ambient air and compressed charge air. In another words, if supercharging system cannot make a significant difference between charge air and ambient air temperatures, adding an intercooler to the supercharging system would decrease performance because of its pressure drop effect. One more important clue comes from the figure is that increasing charge air mass flow rate too much with an intercooler at high rpm may cause a low working efficiency of the compressor. That is, it can be said that if an intercooler would be used, supercharging system elements should be selected according to it. It can also be observed from the figure that ideal intercooler massively affect power output whether with pressure drop or not.

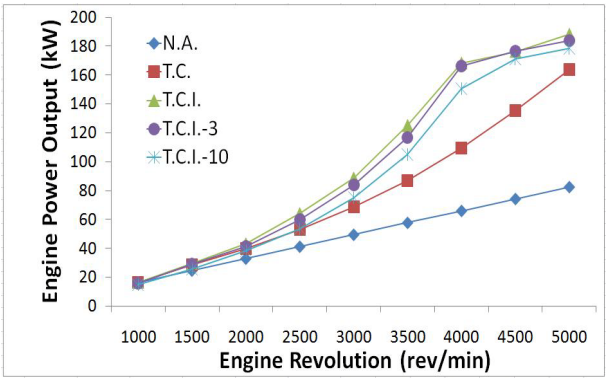

Fig. 2. *Power output values of the engine due to supercharging, N.A. - Naturally aspirated engine, T.C. - Engine with turbocharger and without intercooler, T.C.I. - Engine with turbocharger and intercooler, T.C.I.-3 - Engine with turbocharger and intercooler and 3 percent pressure drop, T.C.I.-10 - Engine with turbocharger and intercooler and 10 percent pressure drop*

Power increase percentages of the engine are provided in Figure 3. As seen in Fig. 3, power output can be increased 154% by ideal intercooler while single turbocharger without intercooler can only increase 65% engine power output. These numbers emphasize the importance of charge with cooled air. As percentages are further evaluated, pressure drop value of 3% slightly affects power output for a narrow revolution interval while there are no significant power differences in upper revolution values. It should be stated that 3% power drop value was selected due to the experimental data results given in the literature [13]. There can be a question that why ideal intercooler effect and ideal intercooler effect with 3 % pressure drop are approximately equal at high rpm. The answer is that the efficiency of compressor decreases sharply after a mass flow rate threshold, it cannot provide sufficient air to increase power further. Another interesting point is the effect of ideal intercooler with 10% pressure drop. It can easily be expressed that high pressure drop causes an important power loss. It indicates that intercoolers should be controlled in proper periods to eliminate negative effects of contamination. As seen in Fig. 3, pressure drop value of 10% for the engine with turbocharger and intercooler results in lower power increase compared with turbocharger without intercooler at lower rpm.

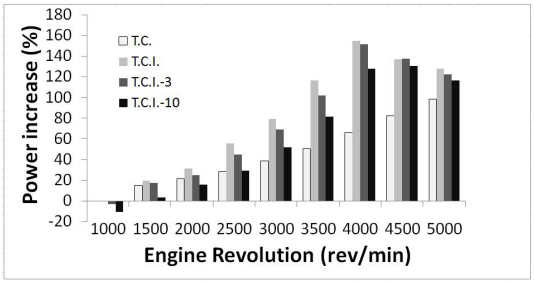

Fig. 3. *Power increase percentage of the engine due to supercharging system, T.C. - Engine with turbocharger and without intercooler, T.C.I. - Engine with turbocharger and intercooler, T.C.I.-3 - Engine with turbocharger and intercooler and 3 percent pressure drop, T.C.I.-10 - Engine with turbocharger and intercooler and 10 percent pressure drop*

Engine downsizing opportunities according to the supercharging system and engine revolutions are given in Fig. 4.

The downsizing of the cylinder volume is a popular topic in internal combustion engines because of specific fuel consumption decrease, lower noise and exhaust gas emissions and sufficient power that it offers. Beside these advantages, manufacturing costs and taxes decrease because of lower volume capacity in some countries. As it can be seen from Fig. 4, turbocharging and intercooling offer 30% to 60% downsizing which changes due to driving interval. High downsizing opportunity occurs at high rpm due to increased boost rate of turbocharger. Considering this fact, downsizing decision should be made according to concentrated drive interval of vehicles. For instance, downsizing a heavy duty diesel engine considering its high revolution values would be a mistake as it would operate intensively at lower rpm.

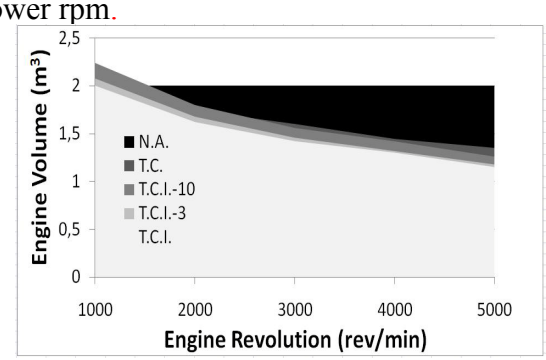

Fig. 4. *Engine volume variation for same power output in same revolution value, N.A. - Naturally aspirated engine, T.C. - Engine with turbocharger and without intercooler, T.C.I. - Engine with turbocharger and intercooler, T.C.I.-3 - Engine with turbocharger and intercooler and 3 percent pressure drop, T.C.I.-10 - Engine with turbocharger and intercooler and 10 percent pressure drop*

CONCLUSION

In this study, general charge air cooling effects to engine performance and supercharger system are analyzed. An analytical approach was performed by using compressor and turbine maps of a real turbocharger. Adding an ideal super intercooler to this system, power output values and possible downsizing values of a selected engine cylinder were examined.

There is a high potential of charge air cooling. This analysis reveals that supercharging system can double its effect by utilizing cooled air charge. However this positive effect is limited to a part of engine revolution range. Because charge air temperature is low during initiation revolutions, intercooling effect cannot be observed especially in turbocharged engines. This originates from turbo lag which is occurred because of the fact that insufficient exhaust gas flow rate cannot provide enough power for compressor. In superchargers that use mechanical compressors driven by engine, intercooler usage has more advantage comparing with turbochargers at lower rpm.

Pressure drop percentage is another important point in intercooling. Heat exchanger fins, contamination and air velocity determine pressure drop. If air velocity and fins are put aside, contamination attracts the interest. To avoid contamination and its negative effects, proper protective system equipments should be used and intercoolers should be controlled in proper periods. Also, there is an optimization problem stands. In order to increase heat transfer rate, various structural improvements can be added to intercoolers such as fins and wavy tubes. However, these structural changes also increase pressure drop. In this optimization problem, cost analysis should also be taken into consideration, because heat transfer enhancement structures lead to create high manufacturing costs. Intercoolers also affect compressor selection because of increasing mass flow rate so that supercharging systems should be selected due to this fact.

This study, in the other hand, reveals some research needs. To understand the efficiency of theoretical optimization methods of intercoolers, sufficient experimental data are needed. After that, a successful mathematical model is required in designing supercharging and intercooling systems, their heat exchangers and researching

their effects to internal combustion engines. Later on, some experimental work can be carried out to evaluate developed mathematical models.

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