EFFECT OF MECHANICAL SUPERCHARGER AND TURBOCHARGER ON THE PERFORMANCE OF INTERNAL COMBUSTION ENGINE: A REVIEW

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ABSTRACT

It has been always the aim of an engine designer to achieve twin goals of improved power output and minimum exhaust emissions. At present, all countries in the world are facing increasingly severe issues of energy crisis and environmental pollution. In an industrial country, more than 1/3 of the total energy consumption is caused by transportation. 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. 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 of them. There are many inventions aimed at increasing the performance of an IC engines. So, most engines nowadays are employed with either supercharger or turbocharger or combination of both with or without any accessories. The emphasis today is to provide a feasible engineering solution to manufacture economical and greener road vehicles. Due to these reasons, superchargers and turbochargers are becoming more popular nowadays. As a result, automobile becomes an important object for energy conservation and emissions reduction. As the main power source for automobiles, IC engine has attracted more and more attention from both scientists and engineers on its thermal efficiency. As it is well known, boosting pressure is an effectively approach to improve the IC engine power and performances, but the power required by gas compressor becomes a key issue. Usually, the gas compressor can be driven by various power sources, e.g., IC engine crankshaft, exhaust turbine, electric motor. According to the drive mode of gas compressor, the supercharging ways can be classified into mechanical supercharging, exhaust turbocharging, electric aided turbocharging, etc. It is widely accepted that exhaust turbocharging is a mature technology for IC engine. With the use of supercharger or turbocharger, not only power output, efficiency and emission characteristics improve but also engine downsizing is observed. The aim of this paper is to provide a review study on the techniques used to increase power output, reduce exhaust emissions and downsizing of an engine.

KEYWORDS: Downsizing, IC Engine, Supercharger, Turbocharger.

Supercharging is the method of increasing air density at inlet of the engine before entering into the engine cylinder and the device which performs this operation is known as supercharger. Supercharging of intake air can improve the engine power and combustion characteristics by boosting the intake pressure above atmospheric pressure. The experimental investigation shows that the output and by boosting the intake pressure above atmospheric pressure. The experimental investigation shows that output and torque performance of a supercharged engine are improved in comparison with the naturally aspirated engine. In the engine system with a supercharger, owing to supercharging of intake air into the cylinder, the combustion pressure, the rate of heat release, and the burning rate of fuel –air mixture has been found to be higher than those of the naturally aspirated engine [Lee et. al., 1996].

Superchargers are compressors which increase the suction pressure of air and thus increase density. Superchargers are also known as pressure boosting device .Theoretically, any device which increases pressure can be used as superchargers but based on application, types of superchargers are used. Turbochargers were initially known as turbochargers when all forced induction devices were classified as superchargers. Nowadays, supercharger is commonly applied to only mechanical driven system which takes power form engine crank shaft and turbochargers are used for those devices which are driven by gas turbine uses exhaust energy of the engine [Muqueem et. al., 2015]. With the use of above devices the power output of an engine increases, exhaust emissions are reduced and at the same time the downsizing of engine is observed. Apart from the mechanical superchargers and turbochargers, electric supercharger has been also developed. In electric supercharger the compressor is directly connected to an ultra-high speed motor, and the compressor boost pressure is controlled by the motor speed, independent of the exhaust turbine.

New concepts for the optimization of supercharging systems have been analyzed to improve fuel consumption, emissions and transient diesel engine response. In addition to the conventional VTG (Variable Turbine Geometry) where the variability takes place upstream of the turbine impeller, a new innovative variable turbine geometry called VOT (Variable Outlet Turbine) is investigated [Chebli et. al., 2011]. Another device which is the combination of supercharger and turbocharger, called super turbocharger has been used in some cases. The power output of an engine can be further

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increased with the use of intercooler or after cooler in combination with superchargers or turbochargers. Though there are three methods to increase the air consumption of an engine consequently power output yet supercharging is preferred over others.

The methods are as follows:

A. Increase the Piston Displacement

This increases the size and weight of the engine and also introduce additional cooling problem.

B. Running the Engine at Higher Speeds

This results in increased mechanical friction losses and improves greater inertia stresses on engine parts.

C. Increase the Density of the Charge

This allows a greater mass of the charge to be inducted into the same volume. This is the most preferred method to increase the power output of the engine because it increases the mean effective pressure of the engine consequently power output is increased, engine exhaust emission is reduced and engine downsizing is observed.

SUPERCHARGING IN SI ENGINE

Supercharging in SI engine is employed only in aircraft and racing cars engines. Apart from increasing the volumetric efficiency of the engine, Supercharging also increases the intake temperature of engine which reduces the ignition delay. And increment in the flame speed results knock or pre-ignite. For this reason, the supercharged petrol engine employ lower compression ratio but it can be avoided if supercharging is equipped with intercooler.

SUPERCHARGING IN CI ENGINE

In CI engine supercharging does not have any adverse effect on combustion but rather it improves combustion. Due to supercharging the pressure and temperature of inducted air increases which reduces ignition delay and hence better, quitter and smoother operation.

SUPERCHARGER V/s TURBOCHARGER

When power requirement to drive the compressor is obtained by means of belt, pulley, gear or chain through crankshaft is known as mechanical supercharger. But if the compressor is driven by gas turbine which runs by utilizing the exhaust gas energy then supercharger is known as turbocharger. From the thermodynamic point of view, the turbocharger system is attractive because it makes use of the exhaust energy. Supercharger reduces the power output since it takes power from crankshaft whereas turbocharger does not reduce power since it is operated by exhaust gasses which are going waste from the engine exhaust. But supercharger has high boost and high response and there is no turbo lag whereas in case of turbocharger turbo lag is there and high maintenance is required. Also it increases the weight of system. Normally supercharging pressure varies from 1.1 to 1.5 atmospheres and in some cases up to 2.5 atmospheres depending upon the type of supercharger used and on the engine capacity to withstand the supercharged condition [Korakianitis and Sadoi, 2005].

However, turbocharger performance is influenced by the mass flow rate of inlet air and engine speed. At a low speed range of small size engine, it is difficult to obtain sufficiently high boost pressure because of the insufficient energy of the exhaust gas. In addition, this system has a defect which is called a turbo lag. This is improved by reducing the rotating inertia of the turbocharger, or in some cases by using two or more smaller turbochargers in parallel rather than one larger one. Occasionally two turbochargers, sometimes with intercooling between them, are used in series to further increase intake pressure, particularly in some marine diesel engines.

In order to optimize a supercharged engine system, it is important to select the adequate compressor type. Since the engine speed and supercharger speed are in a fixed ratio to each other, boost pressure change with engine speed much more rapidly than in case of a turbocharged engine. Therefore, a supercharged engine has no time lag needed to raise the boost pressure. But this system has a defect that there is a mechanical loss to drive the supercharger [Lee et. al., 1996]. For the different mass-flow rates and operating speeds of piston, the combination of any piston engine with a turbocharger must be carefully planned. The turbocharger geometry must be carefully chosen so that the range of speeds and mass flows of exhaust gasses coincide with those of the piston engine while it is operating with the compressor-outlet and turbine-inlet conditions, with intake and exhaust manifolds. The basic size of the turbocharger is determined by the air required by the engine. The appropriate turbocharger can be chosen from compressor characteristic maps obtained from steady-flow tests provided by turbocharger manufacturers, and comparing that with the fuel map of the engine. The turbocharger compressor maps are used to identify minimum airflow, limit for continuous operation and minimum compressor efficiency. Theoretical turbocharger matching is useful to approach a range of turbocharger frames, but final testing is essential to investigate the effect of different turbochargers on the overall design-point and off-design-point piston-engine cycle performance. Different turbochargers are advantageous to an engine for different types of operation. The performance of a turbocharger is determined by the combination of compressor and turbine specification, and the turbine is not as sensitive to engine matching as the compressor.

Power input for mechanical driven supercharger:

$$P = \frac{\dot{m}_a C_p T_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1 \right]}{\eta_c \times 60} \text{ kW}$$

Where,

P = power input to supercharger in kW

$\dot{m}_a$ – mass of air supplied by supercharger in kg/min

C_p = specific heat of air in kJ/kg K

T_1 = initial temperature in K

p_1 = initial pressure

p_2 = delivery pressure

η_c – isentropic efficiency

TWO STAGE SUPERCHARGERS

A single stage supercharger becomes prohibitive in size and weight for high altitude application. Two stage superchargers are therefore used at high altitude. Two superchargers are used in tandem and the charged is compressed in two stages such an arrangement produces the necessary compression without excessive size or speed of impeller that would be required in case of single stage supercharger of same capacity.

TURBO SUPERCHARGER

A turbo supercharger is thus a variable speed supercharger whose capacity is increased by increasing the flow of the exhaust gasses through the turbine by reducing the blast gate opening when at low altitude auxiliary system is not used and exhaust gasses exit to atmosphere [http://www.iitg.ernet.in].

PERFORMANCE OF IC ENGINE WITH THE USE OF SUPERCHARGER AND TURBOCHARGER

An increase in brake mean effective pressure of 30 to 45 % is easily obtainable in any supercharged engine compare to naturally aspirated engine. Due to supercharging, engine torque increases in the range between 2000-3500 rpm. At the low speed range less than 1500 rpm, the engine torque is decreased due to friction loss and mechanical drive loss of the supercharger. In the case of high pressure range more than 4000 rpm, the engine torque also decreases with compression ratio decreasing. The engine output is increased with the supercharger at the medium speed range. Therefore, if the operation of a supercharger is suspended by the electromagnetic clutch under low speed and high speed range except the above effective range speed; the engine performance will be promoted by the charge of pressurized air into the engine cylinder [Lee et. al., 1996]. The power to weight ratio of the supercharged engine is much better than that of naturally aspirated engine. Due to physical limitations of the system, no guarantee of maximum performance of supercharger can be observed. Reliability of engine decreases due to increase in maximum pressure in the cylinder. Turbocharged engines have better thermal efficiency and better fuel economy. It is eco-friendly. But in turbocharged engine, engine weight increases, engine cost increases and there is problem of turbo lag [Pakale and Patel, 2015]. The most dramatic benefit of the supercharger is the much more rapid response of the compressor to load change achieving torque levels in less than one quarter the time of the stock turbo [VanDyne and Riley, 2007].Choice of different supercharging architecture can influence engine performance. Among the different architectures, architectures coupling one turbocharger with a mechanical compressor or two turbochargers are found to be the most performing in terms of engine output power and efficiency. In case of high altitude operation of an aircraft 2-stroke diesel engine, the engine target power can be reached by two turbochargers architecture. The performance of two turbochargers architecture can be further improved connecting electrically and not mechanically the low pressure compressor and turbine [Carlucci et. al., 2015].

With the use of VOT (Variable Outlet Turbine), the efficiency is increased by 6% and engine fuel consumption is reduced as compared to use of waste gate system [Chebli et. al., 2011]. The combination of all partial loading control methods decisively reduced the driving power demand compared with the power demand obtained without any partial load control. Compare to the case without partial load control, the engine torque increases by 7% to 15% in the area where the outlet pressure (po < 60 kpa) at different speeds. This corresponds to the region where the engine idles or operates at low speeds, and may be defined as the threshold for supercharger operation during partial load. The adoption of partial load control does not provide any benefits to the engine in the mid and high partial load areas (po > 60 Kpa), when the power decreases due to an insufficient supply of air into the cylinder [Bae and Bae, 2005]**.** As the boost pressure is increased, the adiabatic efficiency of the supercharger decreases due to the high outlet temperature of the compressor. The increase of inlet air temperature results in a decrease in engine output performance due to knock limited spark advance [Lee et.al., 1996].

Figure1. Shows the comparison of the power obtained in case of NA engine with SC engine at different speeds. From the analysis it can be seen that in spite of the decreased compression ratio, the cylinder pressure of a supercharged engine is higher than that of the naturally aspirated engine at low engine speed (1500 rpm). A similar trend has been applied to the cylinder pressure at the medium engine speed (3000 rpm). However, at the high speed (4000rpm), this trend does not occur and the cylinder pressure of a supercharged engine find to be lower than that of the naturally aspirated engine. From this, it can be concluded that supercharging of a gasoline engine with the lower compression ratio of 8.3 improves the combustion characteristics such as cylinder pressure at the range of low and medium speed.

These results indicate that the supercharged engine performance is mainly dependent on the mechanical loss to drive the supercharger at low speed. In addition, at high speed, the supercharged engine performance is more influenced by the compression ratio than mechanical loss.

Pakale and Patel, 2015 Most of the turbochargers used on HSDI Diesel engines are of waste-gated type. Recently, the Variable Geometry Turbocharger (VGT) with adjustable nozzle vanes is increasingly used, especially for a passenger car in European market. The full load performance result with VGT has been compared with the case of a mechanically controlled waste-gated turbocharger, so that the potential for a higher Brake Mean Effective Pressure (BMEP) could be confirmed. Within the same limitation of a maximum cylinder pressure and exhaust smoke level, the low speed torque could be enhanced by about 44% at maximum. At low speed, over 40 % of additional torque increase has been observed within the same exhaust smoke, the cylinder pressure, and the exhaust gas temperature limit, by adjusting the boost pressure and fuel delivery with the VGT.

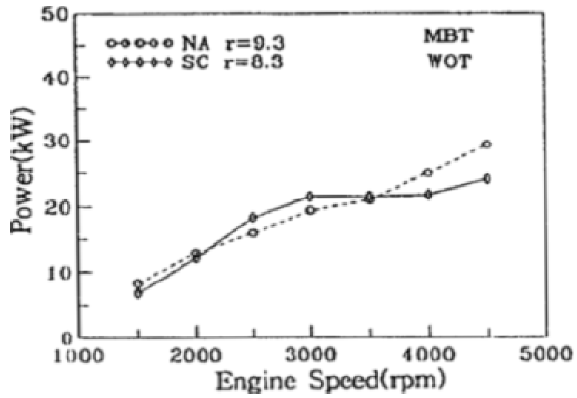

Figure 1: Comparison of NA and SC engine power

In the medium engine speed range, there is a marginal gain in the fuel consumption for the VGT, with the same fuel delivery. When the boost pressure and fuel delivery are increased, more torque could be achieved with the expense of the deterioration in fuel consumption. This is because the injection timing should be retarded not to exceed the maximum cylinder pressure limit. At high engine speed, with the same fuel delivery, the rated power can be enhanced by 3.5 %, mainly caused by the reduction of pumping loss. However, within the same boundary conditions, the power increase for the VGT could reach about 7.9 %. It is concluded that the application of VGT could provide HSDI Diesel engines with a great potential for full load performance, especially at low engine speed [Muqueem et. al., 2015].

Engine Downsizing

One means of fulfilling CO2 emission legislation is to downsize engines by boosting their power using turbochargers or mechanical superchargers. This reduces fuel consumption by decreasing the engine displacement. Engines are downsized when they possess high power levels, such as a high power density and/or high full load mean pressure. There are two possible ways to increase the power density, P_e/V_h: increase in engine speed n or the engine effective mean pressure p_{me} via the equation. $P_e/V_h = i \times n \times p_{me} = 2 \times n \times T/V_h$.

Where,

P_e = Effective power output in Kw

V_h = Piston displacement

i = number of cycles per crankshaft rotation

T = torque in Nm

However the main objective of downsizing is to obtain a significant reduction in the fuel consumption. A 1.3 liter boosted engine can have the same power output (85 kW) as a 1.8 liter standard engine, contributing to economical driving without sacrificing engine power. However, when idling, decelerating, or driving slowly, which do not require full charging, the high charging pressure of the supercharger equivalent to the high inlet air quantity causes poor fuel economy in gasoline engine. In these engines, the fuel consumption and emissions are controlled by electronic fuel injection, which regulates the supply of fuel in proportion to the inlet air quantity to obtain perfect combustion. Therefore, the excessive fuel demand encountered when no charging is required can be improved by decreasing the charging pressure and driving power of Compressor [VanDyne and Riley, 2007], [Bae and Bae, 2005].

Also a meaningful 50 % downsizing of the cylinder volume possibility can be achieved by means of turbocharging and intercooling. As it is observed that 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 [Canli et.al., 2010].

Intercooler Effect

One of the most important problems faced in supercharging systems is that air density is decreasing while compressing air. When air charge is compressed, it becomes hot. During supercharging, the temperature of air increases from 60 to 95 °C. When air gets heated, it expands and the density reduces. Because of this, the mass of air entering to the cylinder becomes lesser. This reduces oxygen availability in the cylinder for combustion. Further, supply of hot air to the engine may increase engine operating temperature [V. Ganesan]. When the air gets heated, it leads to preignition in SI engine. To avoid this 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 supercharging. As the air is cooled, it becomes denser, and denser air makes better combustion to produce more power. Additionally, the denser air helps to reduce the chances of knock. But after coolers are not needed in case of supercharger used in CI engine because there is no concern about engine knock. An effectiveness of 0.6 to 0.8 usually keeps cooler and size within reasonable limits of heat exchanger. Pressure drop percentage is another important point in intercooling. Use of coolers inevitable involves a pressure loss of 2-3 % of the entry absolute pressure. 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. The temperature drop through an after cooler is usually expressed in terms of effectiveness which is given as

$$C_c = \frac{T_1 - T_2}{T_1 - T_w}$$

Where,

C_c – cooler effectiveness

T_1 = entrance stagnation temperature

T_2 = exit stagnation temperature

T_w = coolant entrance temperature

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 initial revolutions, intercooling effect cannot be observed especially in turbocharged engine. In superchargers that use mechanical compressors driven by engine, intercooler usage has more advantage comparing with turbochargers at lower rpm [Canli et.al., 2010]. Using thermodynamics laws and expressions, the power output of the engine is analytically examined by changing intercooling features such as pressure drop values and engine revolution at full load. In this study it has been observed that engine power can be increased to 154% by ideal intercooler while single turbocharger without intercooler can only increase 65% engine power output [Muqueem et.al., 2015], [Canli et.al., 2010]. But 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. Further increasing charge air mass flow rate too much with an intercooler at high rpm may cause a low working efficiency of the compressor. Therefore, it can be said that if an intercooler would be used, supercharging system elements should be selected according to it. 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. 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.

Intercoolers also affect compressor selection because of increasing mass flow rate so that supercharging systems should be selected due to this fact [Canli et.al., 2010].

Exhaust Emissions

With the use of CX, comprex supercharger (pressure wave supercharger) , NO_x emission is reduced for all engine speeds via CX supercharging, but smoke emission is deterioted at low and medium engine speeds. CO and , SO_x emissions are both higher than those of naturally aspirated engine. CX supercharging may be an alternative way of reducing , NO_x emission, but the EGR ratio must be controlled precisely [Lee et.al., 1996], [Icingur et.al., 2002].

On diesel engines, the Miller Cycle and high pressure turbocharging in particular two-stage turbocharging enable substantial reductions in emissions of oxides of nitrogen (NOx) while improving fuel efficiency and power density [Pakale and Patel, 2015]. With the use of the VGT, it is possible to increase the charge air mass by about 10 ~ 20 % at a low speed range. As a result of this, the exhaust smoke is reduced and the fuel consumption is improved with the same fuel delivery and start timing of injection [Muqueem et.al., 2015].

Turbochargers provide an efficient method of utilizing exhaust energy to boost intake air pressure for improved engine performance and efficiency. However transient operation requires increased air delivery (via quicker compressor response) to allow more rapid fueling for acceleration in both diesel and natural gas engines. In diesel engines rapid boosting will avoid increased particulates caused by excessive fueling during acceleration. Another approached being researched heavily is the use of HCCI combustion to improve fuel economy and reduce emissions. HCCI combustion may be enhanced by utilizing a super turbocharger [VanDyne and Riley, 2007].

For naturally aspirated (NA) operation, the charge pressure decreases as the engine speed increases. Normally, for all pressure ratios the charge pressure increases with engine speed when supercharging is applied. From figure 2. It can be seen that in NA operation, the CO emission is lower for all engine speeds but the CO emission increases with supercharging. This may be caused by the external EGR. The inert exhaust gases dilute the charge, so the combustion process is deteriorated. The SOx emission is low for all engine speeds in NA operation. As for CX operation, the SOx emission is high, particularly at low engine speeds. The levels of SOx emissions depend on the sulphur content of the fuel and lubricating oil and the operating condition of the engine. As the combustion process deteriorated at low engine speed, the SOx emissions increased. By improving the combustion process, the SOx emissions would decrease.

The NOx emission is higher for all engine speeds in natural aspirated operation. When supercharging is applied, it is seen that the NOx reduction is proportional with the EGR ratio. This means that more EGR results in lower NOx emissions. Since the recirculated exhaust gases dilute the mixture, some of the oxygen is replaced with CO2. This will reduce the peak gas temperature and, therefore, NOx formation rates. Also, the heat capacity of the exhaust gases is higher than that of air. The exhaust gases would absorb a portion of the heat that is released during combustion. At low engine speeds, smoke emission is low in NA operation, but at high engine speeds, smoke emission is low with CX operation. This is probably caused by the volumetric efficiency and temperature drop by EGR. At low speeds, the pressure losses are low in NA operation, so the volumetric efficiency would be better.

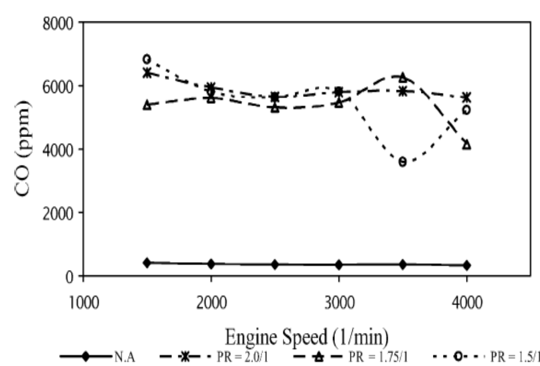

Figure 2: variation of CO emission at different engine speeds and pulley ratios

This increases the local oxygen concentration in the cylinder.So, the smoke emission will be better in NA operation. The reduction of in-cylinder peak temperature by EGR prevents complete oxidation of the fuel, so the smoke emission would deteriorate for CX operation. At high engine speeds, supercharging would eliminate these effects, NOx emission is reduced for all engine speeds via CX supercharging, but smoke emission is deteriorated at low and medium engine speeds. Actually, exhaust turbocharging is a kind of approach for IC engine exhaust gas energy recovery, since it uses exhaust gas to drive the turbine. Although the intake gas pressure is promoted through exhaust turbocharging, IC engine has to undergo a higher exhaust gas pressure due to the throttling effect in turbine. In other words, the boosting pressure of intake gas is at the cost of the increase of exhaust gas pressure. As a result, IC engine should consume some effective work during the exhaust process and thus the improvement of IC engine thermal efficiency is limited. Furthermore, the increased exhaust gas pressure results in a higher residual gas fraction (RGF) in cylinder, which has negative effects on the working process of IC engine [Icingur et.al., 2002].

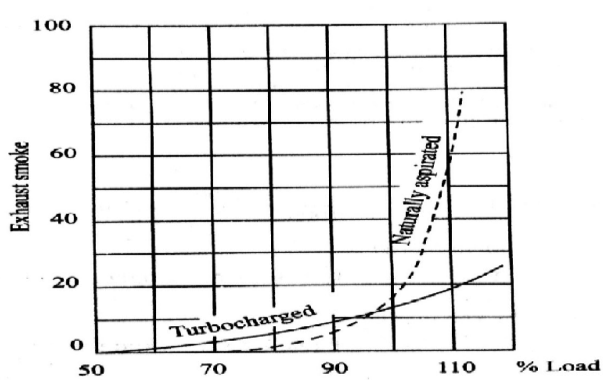

Figure 3: Comparison of exhaust smoke with load for NA and turbocharged engine

CONCLUSION

The literature review study presented in this paper provides general outline of the technologies used in the field of IC engine to increase the performance of an engine and reduce exhaust emissions. From the above study, it can be concluded that in recent few years, new advancements has been done to improve performance of engine like increased power output, reduce exhaust emissions and engine downsizing by adding some accessories like inter cooler in supercharging system. It is expected that in coming year, more new technologies will be developed and modification in existing technology will be done to improve the performance of an engine. The following conclusions can be drawn from the above literature review:

1. An increase in brake mean effective pressure of 30 to 45 % is easily obtainable in any supercharged engine compare to naturally aspirated engine at the range between 2000-3500 rpm.
2. The power to weight ratio of the supercharged engine is much better than that of naturally aspirated engine.
3. Due to physical limitations of the system, no guarantee of maximum performance of supercharger. Reliability of engine decreases due to increase in maximum pressure in the cylinder.
4. Also a meaningful 50 % downsizing of the cylinder volume possibility can be achieved by means of turbocharging and intercooling.
5. Supercharging system can double its effect by utilizing cooled air charge with the help of inter cooler.

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