International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161

Available at http://inpressco.com/category/ijcet

Research Article

Upgrading the performance of a six-cylinder CNG Engine with the induction of Turbocharger for HCV application

Sumit A. Kadam[1*], Debjyoti Bandyopadhyay[2], Nishant S. Kulkarni[3], Sandeep D. Rairikar[4] and S. S. Thipse[5]

[1,3] Mechanical-Design Engineering Department, Savitribai Phule Pune University, Vishwakarma Institute of Technology, Pune, India
[2,4,5] Automotive Research Association of India (ARAI), Pune, India

Received 05 July 2021, Accepted 01 Aug 2021, Available online 04 Aug 2021, **Vol.11, No.4 (July/Aug 2021)**

Abstract

The world is having catastrophe of environmental pollution and fossil fuel depletion. Adaptation of alternative fuels is a healthy solution in reducing exhaust emissions in the automobile sector. Compressed Natural Gas (CNG) as a fleet fuel has played a vital role in the HCV sector. Many developmental and optimization work has been taken place for the CNG engines in the recent times. Due to the recent upsurge in diesel prices, the HCV sector is moving towards the CNG fuel vehicle. The HCV sector requires a heavy performance engine for its day-to-day application. In this research paper a baseline six-cylinder, naturally aspirated CNG engine used for bus application is selected to upgrade its power and torque performance. Based on the baseline CNG engine data, an appropriate turbocharger for the engine is selected with the help of M/s Garrett turbocharger manual. A 2-D simulation of the turbine is also carried out to understand the pressure and temperature distribution profile inside the turbine. The experimental results showing the increase in power, torque, volumetric efficiency, BMEP and thermal efficiency is illustrated in the research work below.

Keywords: *CNG, Turbocharger, Compressor map, Power, Torque.*

1. Introduction

With emerging stringent pollution legislations and limited availability of liquid fossil fuels, demand for improving fuel efficiency is raising and deduction of harmful emissions has become the most important job for the present engine researchers. Diesel engine has higher thermal efficiency; however, the emission of NO_x and PM stays as a major concern with increasing number of HCV and LCV vehicles and decreasing of crude oil resources, it seems that the use of alternative fuels is inevitable in the upcoming future. However, CNG has some benefits compared to gasoline and diesel from an environmental perspective. It is a cleaner fuel as compared to gasoline or diesel as far as emissions are concerned. Compressed natural gas is an environmentally clean alternative to non-renewable fuels. The main constituent of CNG fuel is the methane composed of one carbon atom and four H_2 atoms. CNG is a colorless and odorless fluid in the gaseous state composed of methane (88%), ethane (6%) propane (1.51%), butane (0.47%), iso-butane (0.41%), iso-pentane (0.19%), pentane (0.13%), hexane (0.27%), and impurities like carbon (0.59%), (hydrogen sulphide-trace, water-trace, oxygen-trace), nitrogen (0.3%).

*Corresponding author's ORCID ID: 0000-0003-0203-2703
DOI: https://doi.org/10.14741/ijcet/v.11.4.4

The use of CNG as an alternative fuel results in significant reduction in emission level of vehicles pollution like CO, HC, NO_x and PM.

The objective of this research work is to upsurge the power and torque for 5.6 liters, six-cylinder naturally aspirated CNG engine having a maximum power of 94 kW by upgrading it with suitable turbocharger. It has been seen that the introduction of turbocharger has increased the volumetric efficiency of the engine by 10-15% compared to the naturally aspirated engine (Shahin, 2017). The turbocharger not only increase the power of the engine but also improve the combustion within the cylinder by significant improving the air-fuel mixture in a SI engine (Emara et al., 2016). Due to good combustion of the fuel, BSFC will always gradually decrease with increase in speed, which gives good economic system.

In a study by Y. Takada (Kato et al., 2018) shows that the turbocharger Selection for an engine with the help of Garrett high performance compressor map is used. And the boost was varied from 100 kPa to 300 kPa. Due to increase in boost pressure, there is an increase in air flow rate to the cylinder.

2. Turbocharger Selection

In the baseline specifications of CNG engine, the compression ratio is 10.2:1 which is appropriate for

CNG Engine. The reduction in compression ratio improves the proper mixing of CNG fuel in engine. The standard CR for CNG engine is around 10:1 to 13:1. As the engine selected for the research work is an under square engine so, the CR is kept low to avoid knocking.

Table 1 Engine Specifications

Specifications	Baseline CNG Engine	Targeted CNG Engine
No. of cylinders	6	6
Engine Type	Natural Aspiration	Turbocharged Intercooled
Bore*Stroke	102mm*116mm	102mm*116mm
Capacity	5782 cc	5782cc
Maximum Power	95 kW @ 2400 rpm	160kW @2400 rpm
Maximum Torque	425 Nm @ 1500 rpm	690 Nm @ 1500 rpm
Compressor Ratio	10.2 : 1	11.2 : 1
BSFC	280 g/KWh	260 g/kWh

So, the Parameters need to be Studied and Calculated for selection of turbocharger for CNG engine are mentioned below –

Mass Air Flow rate required to generate targeted power is given in equation below.

$$\dot{m}\left(\frac{g}{s}\right) = p_{engine}(kW) * \frac{A}{F} * BSFC\left(\frac{g}{kWh}\right)/3600 \quad (1)$$

Now, Manifold Intake Absolute Pressure is evaluated in the equation below.

$$MAP(kPa) = \dot{m} * \left(\frac{R * T_{int}}{\eta_v}\right) * \left(\frac{2*60}{RPM * disp(L)*1000}\right) \quad (2)$$

Pressure drop is developed in between compressor outlet and engine manifold, to find compressor outlet pressure(Pawar & Bhosale, 2011)(Hollingsworth & Maywald, 2019) P_{2c}

$$P_{2c} = MAP + \Delta P_{loss} \quad (3)$$

Pressure Loss between the Compressor and the Manifold (kPa). Some restrictions offered by air filter, to find compressor inlet pressure P_{1c}

$$P_{1c} = P_{amb} - \Delta P_{filter} \quad (4)$$

Pressure Ratio is defined as the Absolute outlet pressure divided by the Absolute inlet pressure (Ravindra D. Kapse & Dr. R. R. Arakerimath, 2017).

$$r = \frac{P_{2c}}{P_{1c}} \quad (5)$$

Compressor Outlet Temperature

$$T_2 = \left[\frac{(((T_1+273)*PR^{\gamma})-273-T_1)}{\eta_c}\right] + T_1 \quad (6)$$

Intercooler Outlet Temperature

$$T_{2'} = (1 - \eta_{int})(T_2 - T_1) + T_1 \quad (7)$$

Using mathematical modeling, the result of air mass flow rate and pressure ratio at different engine speed obtained and plotted on various compressor maps available for the turbocharger selection. The compressor map with the operating characteristics of turbocharger in graphical form that describes the boost pressure, compressor efficiency, turbo speed lines and mass flow rate. So, the plotting of points on appropriate compressor map is done as shown in figure 1 below.

The figure 1 shows the maximum plotted points lies in area of high efficiency island at around 75% peak efficiency zone of compressor map without exceeding surge line i.e., left hand boundary and choke line which is right hand boundary. So, the appropriate turbocharger is selected that is Garrett® GT2252 170 HP - 250 HP waste gate. The inducer diameter and exducer diameter of the compressor is 40mm and 52mm respectively. In compressor map the six engine operating points at various rpm are plotted(Garrett Advancing Motion, 2020).

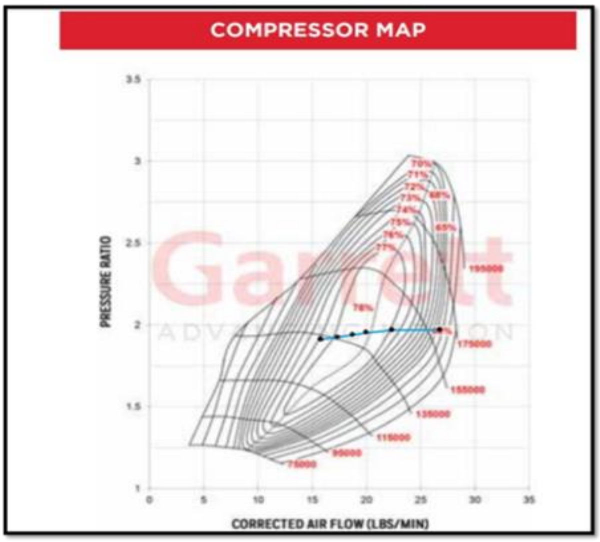

Fig.1 Compressor mapping for the selected turbocharger

3. 2-D Simulation Approach

The designed made by accurate dimensions of the turbocharger turbine wheel, and turbine housing in SolidWorks software. This is an important stage where the performance of the proposed design was studied via 2-D simulation tool; the performance of the turbocharger is needed to be investigated. Through flow simulation tool it is possible to carry out more in-depth investigations and go into more detail regarding the study of the flow, as well as the possibility of obtaining a greater number of results and outcomes.

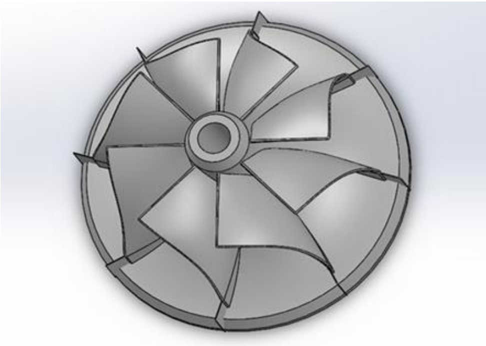

Fig.2 Turbine wheel design

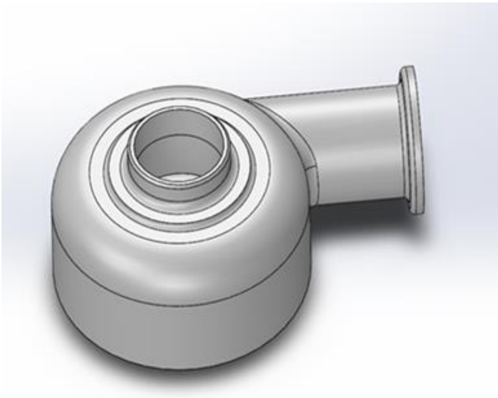

Fig.3 Turbine housing design

Table 2 Input data considered for designing of turbine

Description	Data
Inducer diameter	50 mm
Exducer diameter	43 mm
Number of blades	8
Fan material	Aluminium alloy
Housing material	Aluminium alloy
Housing Inlet Diameter	36 mm
Housing Outlet Diameter	32 mm

3.1 Case 1: Static Flow Analysis at 2400 rpm

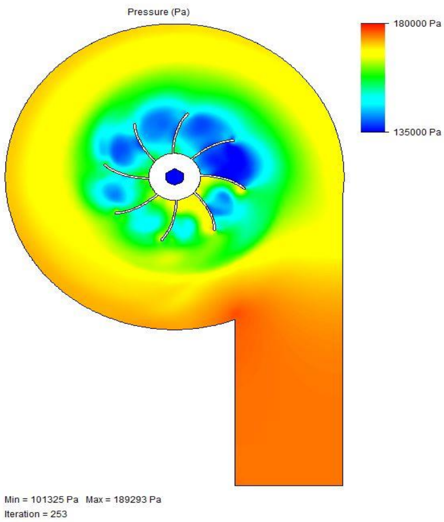

Fig.4 Pressure Flow Analysis from inlet to outlet

Fig.4 shows the air suction pressure obtained at inlet vane was about 189.2 kPa which is the red orange bright region while the fluid pressure discharge to the turbine wheel from outlet vane was about 135 kPa.

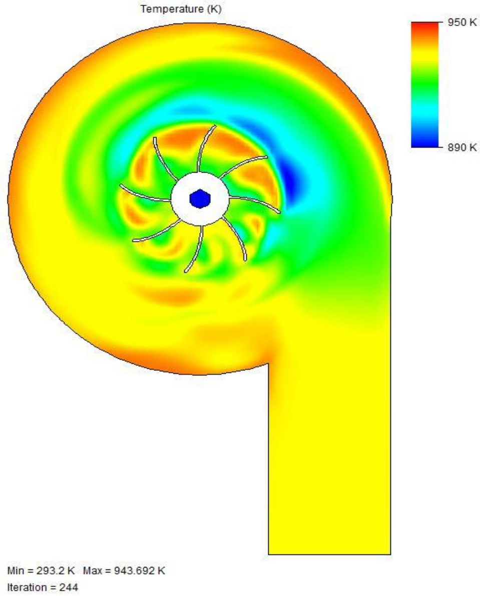

Fig.5 Temperature Flow Analysis from inlet to outlet

The Fig.5 shows temperature at the inlet vane temperature was about 943 K while the temperature after the fluid discharge from the turbine wheel was 890 K. This temperature profile proves that the temperature profile is within the turbocharger blade factor of safety limits.

3.2 Case 2: Static Flow Analysis at 1800 rpm

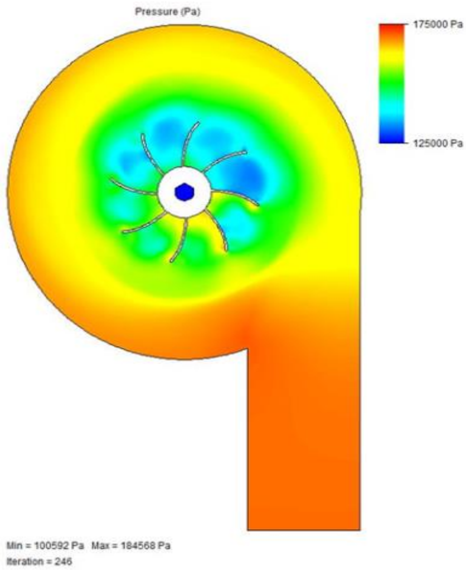

Fig.6 Pressure Flow Analysis from inlet to outlet

The Fig.6 fluid pressure obtained at inlet vane was about 184.5 kPa which is the while the fluid pressure discharge from the inlet vane to turbine wheel was about 125 kPa which is the blue green region.

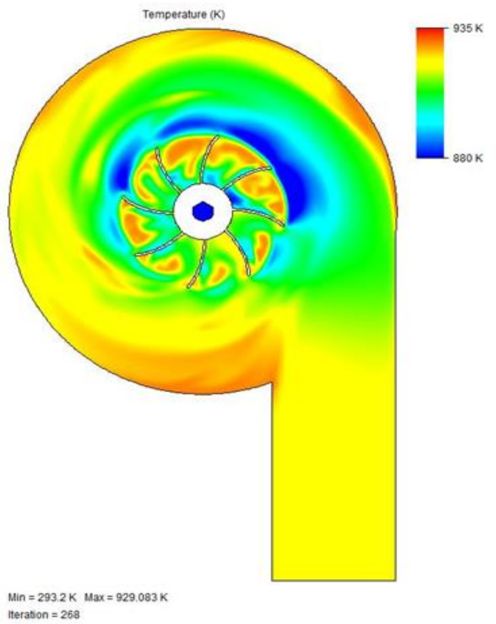

Fig.7 Temperature Flow Analysis from inlet to outlet

The above Fig.7 temperature at the turbine wheel was around 880 K while the temperature after the fluid discharge from the inlet vane was around 929 K.

3.3 Case 3: Static Flow Analysis at 1500 rpm

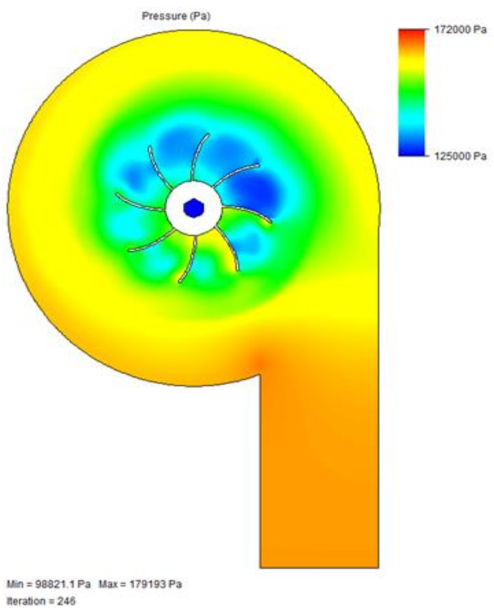

Fig.8 Pressure Flow Analysis from inlet to outlet

The Fig.8 shows fluid pressure obtained at fan was about 122 kPa which is the bright green blue colour while the fluid pressure discharge at the inlet vane was about 179.1 kPa.

The Fig.9 shows temperature at the turbine wheel was just slightly lower than the temperature of air after discharge from the inlet vane. The temperature at the turbine wheel was around 860 K while the temperature after the fluid discharge from the inlet vane was around 908 K.

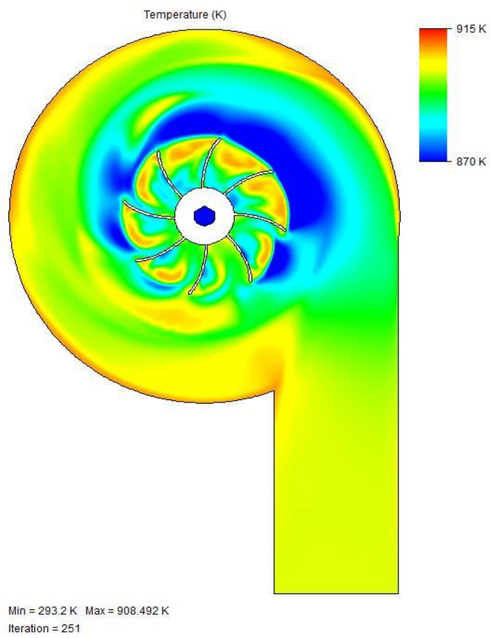

Fig.9 Temperature Flow Analysis from inlet to outlet

3.4 Simulation Outcome and Conclusion

- This study is about the 2 D simulation of the designed turbocharger. In this study, the outcome is that the performance is determined based on the two important parameters which are pressure and temperature inside the turbocharger turbine region.
- Simulation has been carried out in SOLIDWORK software at flow simulation where static flow analysis was conducted on the turbocharger designed in order to analyze the effect of various pressure and temperature at various areas from inlet conditions to outlet conditions the behavior of materials.
- Good performance of turbocharger should have high pressure, high velocity and low temperature inside the turbocharger turbine. For the existing design, the SOLIDWORKS software have been used. The material used was aluminium alloy which having density of 2680 kg/m^3.
- The results for the simulation were maximum around 189 kPa for pressure and 943 K for temperature inside the turbocharger turbine when the fluid discharges from inlet vane. The results show different value at the turbine wheel due to high pressure flow at initial stage which is around 179.1 kPa for pressure, and 908.1 K for temperature. The Factor of Safety (FOS) at which the turbine can withstand or sustain at maximum temperature about 1073 K beyond which material failure may occur. And while conducting 2 D simulation it was found that the Maximum temperature is around 943.2 K.
- This shows that the air pressure and temperature behavior at designed turbocharger gives satisfied results.

4. Experimental Setup

The above experimental work of project is carried out in Engine Development Laboratory Department of the Automotive Association of India (ARAI) Pune. The

Fig.**10** shows the schematic diagram of turbocharged CNG Engine. The cool air enters the engine's air intake with the help of conditioned air system which maintain the air condition according to STP and heads toward the compressor. The test was performed under ambient conditions at 298 K temperature and 101.25 kPa pressure. The CNG tank in which CNG fuel is stored is passed and controlled by CNG regulator valve. The compressor blade and housing of the turbocharger helps to draw the ambient air inside. The compressor compresses the intake air and heats up the intake air flowing and blows it out again. Hot compressed air from the compressor passes through the intercooler, which cools it down to 45°C. Intercooled compressed air enters the cylinder's air intake manifold with the means of throttle body. The extra oxygen helps to burn fuel in the cylinder at a rapid rate. As the engine cylinder burns more fuel, it produces energy more quickly and sends more power output to the flywheels via the piston and crankshaft. Waste gas from the cylinder exits through the exhaust manifold to the turbine blade. The hot exhaust gases blowing from the turbine fan make it rotate at higher speed. The spinning wheel turbine is mounted on the same shaft as the compressor. So, as the turbine wheel spins, the compressor wheel spins continuously. The exhaust gas leaves the tailpipe via an after treatment system, wasting less energy.

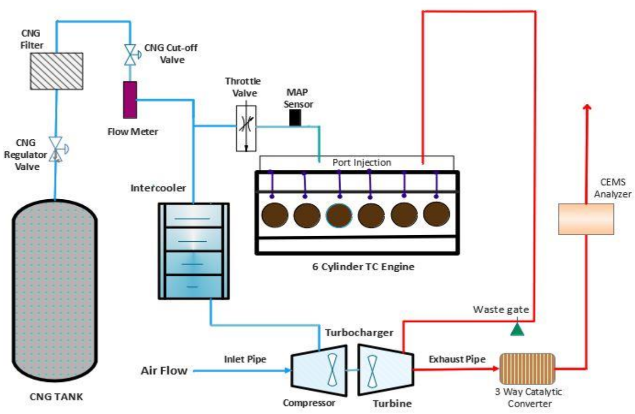

Fig.10 Schematic layout of experimental setup of Turbocharged CNG Engine

5. Results and Discussion

The performance of the engine was experimentally tested with and without turbocharger where the effect of various parameters on engines with respect to Torque, Brake Power, Brake Mean Effective Pressure (BMEP), Brake Specific Fuel Consumption (BSFC), Volumetric Efficiency and exhaust emissions were investigated between Turbocharged (TC) CNG Engine and Naturally Aspirated (NA) Engine. As it is evident that the minimum and the maximum deviation percentages from the experimental data are around 2.7% and 4.2%, respectively. The following parameters were measured using transient dynamometer in test laboratory and test were carried out under standard conditions shown in **Error! Reference source not found.** and various sensors for measuring inlet and outlet conditions.

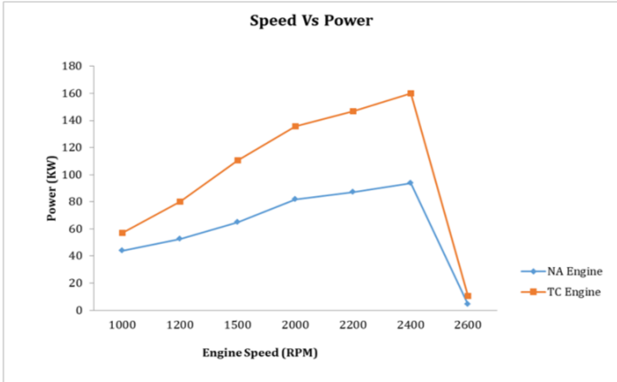

Fig.11 NA Engine and TC Engine Power results comparison

Fig.11 and Fig.12 present the results of brake power and brake torque at WOT for both NA and turbocharger CNG engine. On average, the increment of 45 - 50% in power output can be seen throughout the speed range for TC engine. The maximum brake power obtained by NA and turbocharged engine were 94 kW and 159.8 KW respectively at rated 2400 rpm.

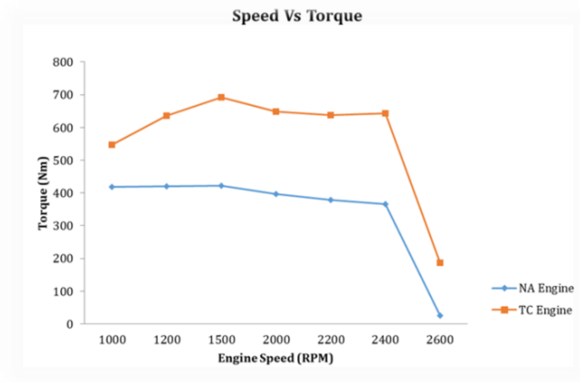

Fig.12 NA Engine and TC Engine Torque results comparison

Fig.12 in the case of torque, maximum torque obtained by NA Engine and Turbocharged Engine were 423 Nm and 692.1 Nm respectively both at 1500 rpm. A flat torque has been observed over the lower speed conditions. There is almost 60% of additional torque output generated with the TC engine.

Fig.13 shows Turbocharged Engine results which produced remarkably 2.5 - 15% BSFC lower compared to NA Engine. The minimum BSFC of NA Engine and turbocharged engine are 215 g/kWh and 196 g/kWh respectively both at 1500 rpm. Because of lower BSFC, turbocharged CNG engine achieves higher Fuel Consumption Economy compare to NA Engine.

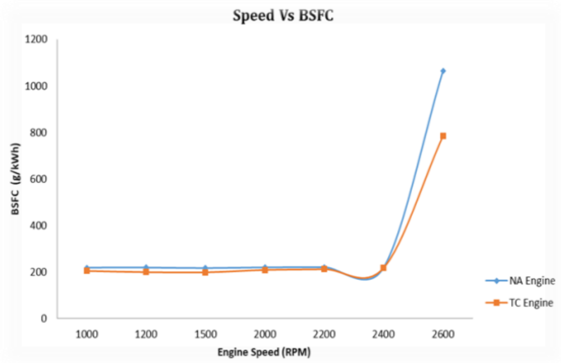

Fig.13 NA Engine and TC Engine BSFC results Comparison

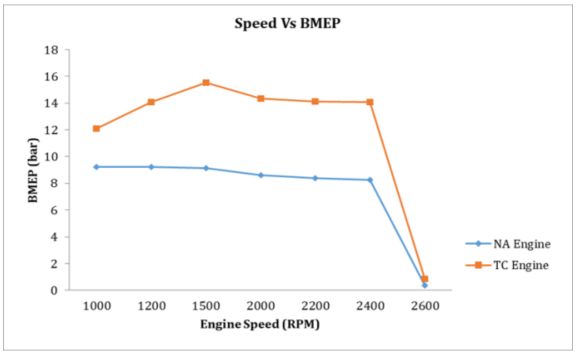

Fig.14 NA Engine and TC Engine BMEP results comparison

As shown in Fig.14 the BMEP of turbocharged CNG Engine is 12– 24 % higher than NA CNG engine. This is because higher intake pressure created by turbocharger increased peak pressure during expansion stroke after TDC. The displacement of air by NA Engine in the cylinder reduces the volumetric efficiency and consequently causes the BMEP loss.

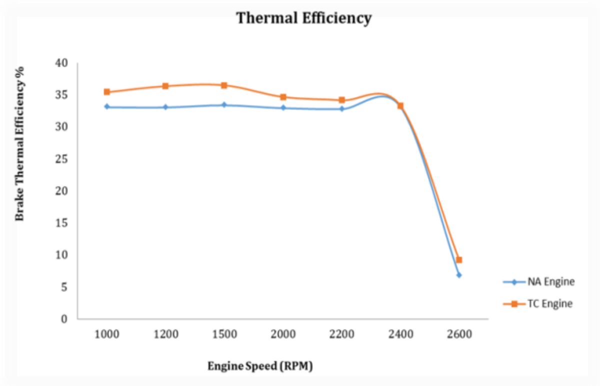

Fig.15 NA Engine and TC Engine Thermal Efficiency results comparison

The Fig.15 shows the thermal efficiency is around 5% throughout the various speed ranges higher in TC engine compared to NA engine.

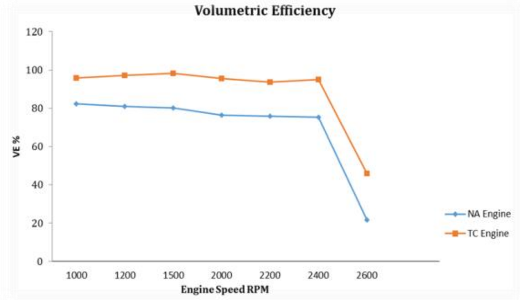

Fig.16 NA Engine and TC Engine Volumetric Efficiency results comparison

The

Fig.**16** shows the Volumetric efficiency measured the maximum amount or air into the engine and higher volumetric efficiency increase the power output. There is 12 - 24% volumetric efficiency rise with turbocharged operation compared to NA engine.

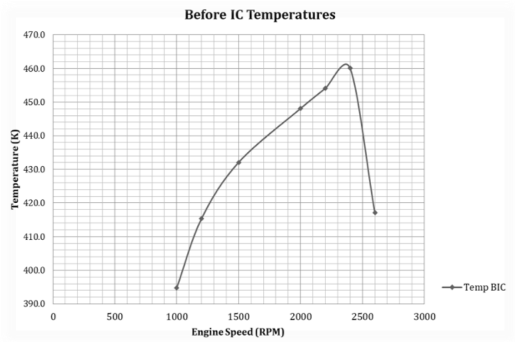

Fig.17 Before IC Temperatures for TC engine

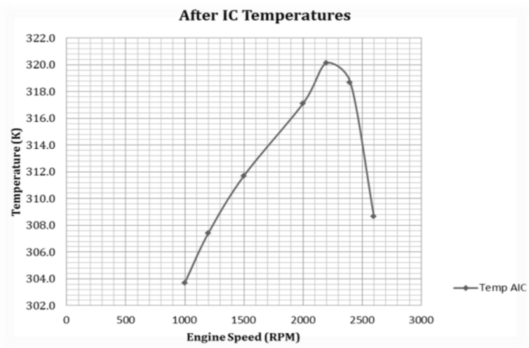

Fig.18 After IC Temperatures for TC engine

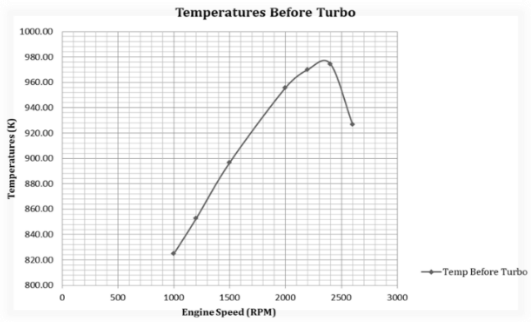

Fig.19 Temperatures before Turbo for TC engine

6. BS VI emission results with TC engine

The engine after fitment with turbocharger and intercooler were tested for BS VI emission norms considering the needful engine ECU calibration. The outcome of the WHTC BS VI emission test is shown in Fig.20 and Fig.21.

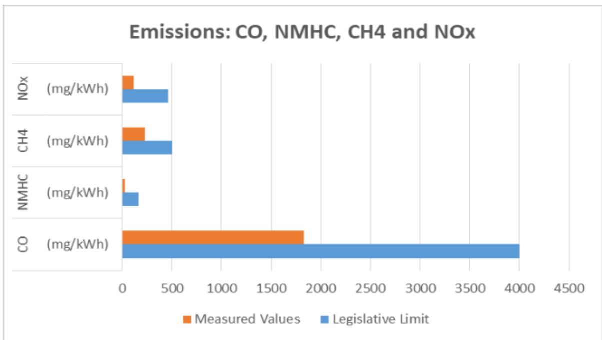

Fig.20 BS VI CO, NMHC, CH_4 and NO_X emissions graph

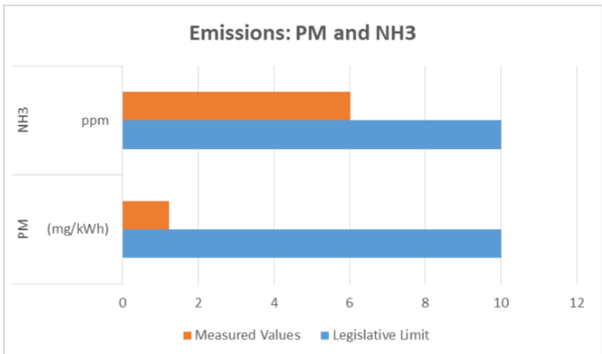

Fig.21 BS VI PM and NH_3 emissions graph

The BS VI emissions are well within legislative limit for the TC engine for CO, NMHC, CH_4, NO_X, PM and NH_3 emissions.

Conclusion

In this research study the turbocharging of 5.6 liter, 6-cylinder CNG fueled NA Engine is carried out to achieve targeted power was investigated experimentally under standard conditions. This study demonstrates that stratified charge CNG with turbocharger has a potential for higher engine power output and improves superior fuel economy. From the results following conclusions are listed below.

1) Turbocharged CNG Engine results 30% higher increment in brake power and 45% increment in brake torque.
2) Turbocharged CNG Engine produced minimum BSFC compared to NA engine.
3) Turbocharger improves the volumetric efficiency of CNG engine by 12– 24%.
4) Emission of pollutant gaseous from CNG engine due to turbocharger has significantly reduced by 3 – 15% reduction of unburned HC and CO, this engine produces less greenhouse gases per unit power, and therefore, it is more efficient in this aspect. The cause of reduction in emission is due to the stoichiometric mixture of air and fuel for TC engine.
5) Turbocharging uses exhaust gas energy which leads to increase in engine performance efficiency. The future demand for turbocharger in automobile industry has been increasing and this demand is expected to be raised for CNG engine.
6) The 2 D Simulation carried out, the results outcome shows that it was found that the maximum pressure 189.2 kPa and maximum temperature is around 943 K temperature, at initial stage it was around 179 kPa for pressure, and 908 K for temperature. The FOS at which the turbine wheel can be withstand at maximum temperature about 1073 K, so the designed turbocharger gives satisfied results.
7) With the help of compressor maps the appropriate turbocharger can be selected for targeted power output for particular engine. Improved rated power and torque are observed in turbocharged CNG Engine as compared to baseline NA engine.
8) The air compressed by turbocharger increases to higher temperature, the use of Air-to-Water Intercooler reduces the increased air temperature which results in improvement in volumetric efficiency as compared to NA Engine.

Abbreviations

A/F Air Fuel Ratio
BMEP Brake Mean Effective Pressure
BS Bharat Stage
BSFC Brake Specific Fuel Consumption
CNG Compressed Natural Gas
FOS Factor of Safety
IC Intercooler
N Engine speed in rpm
NA Naturally Aspirated
P pressure in kPa
p Power in kW
P_{2c} Compressor Outlet Pressure
P_{1c} Compressor Inlet Pressure
P_{amb} Ambient Air pressure
ΔP_{loss} Pressure Loss

r Pressure Ratio
T Temperature in K
T_e Effective Torque in Nm
T_{int} Temperature at Manifold Intake
$T_{2'}$ Intercooler Outlet Temperature
T_2 Compressor Outlet Temperature
T_1 Atmospheric Temperature
TC Turbocharger
V_d Engine Displacement in m^3
WHTC World Harmonized Transient Cycle
η_υ Volumetric Efficiency
η_c Compressor Efficiency
η_{int} Intercooler Efficiency
γ Heat Capacity Ratio (1.4)

References

Emara, K., Emara, A., & Razek, E. S. A. (2016). Turbocharger Selection and Matching Criteria in a Heavy Duty Diesel Engine. *International Journal of Scientific & Engineering Research*, *7*(12), 609–615. https:// doi.org/ 10.14299/ijser.2016.12.009

Garrett Advancing Motion. (2020). Performance Catalog Vol 8. *Garret Motion*, *8*, 28.

Hollingsworth, J., & Maywald, F. (2019). *Compression Efficiency*.

Kato, H., Ito, H., & Shima, J. (2018). *SA E TECHNICAL Development of Hologram Head-Up Display a and. 41 2*.

Pawar, P. S., & Bhosale, S. Y. (2011). Selection and experimental validation of turbocharger for five cylinder CNG engine. *International Journal of Current Engineering and Technology*, *5*(5), 146–150. https://doi.org/10.14741/ ijcet/22774106/spl.5.6.2016.28

Ravindra D. Kapse, & Dr. R. R. Arakerimath. (2017). Study and Comparison of Charge Air Cooling Techniques their Effects on Efficiency of Automobile Engine. *International Journal of Engineering Research And*, *V6*(07), 196–201. https://doi.org/10.17577/ijertv6is070152

Shahin, M. (2017). *College of Engineering Department of Mechanical Engineering Senior Design Project Report Design of Turbocharge System for an Existing Gas Engine In partial fulfillment of the requirements for the*.