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Hybrid turbocharged SI engine with cooled exhaust gas recirculation for improved performance

Jinsha Rajeevan[a,]*, Hans M H[b], Antonio Joseph[b], Kiran T S[c], Gireesh Kumaran Thampi[d]

[a]*P G Scholar, Department of Electronics and Communication, College of Engineering, Thalassery 670107, IndiabAssistant Professor,*
[b]*Department of Mechanical Engineering, Albertian Institute of Science and Technology, Kochi 682022, India*
[c]*Assistant Professor, Department of Electronics and Communication, College of Engineering, Thalassery 670107, India*
[d]*Associate Professor, Department of Mechanical Engineering, Cochin University of Science and Technology, Kochi 682022, India*

Abstract

Turbocharging with its most advanced forms is left with enough room for the improvement while operating in the lower engine speeds. The impacts of the same have been more visible with petrol engines due to low mass flow rate of exhaust gases. Mathematical model of the SI engine is generated using MATLAB, making use of two-zone combustion model and the thermodynamic relations developed using unsteady flow energy equation. The performance of engine when naturally aspirated, turbocharged and hybrid turbocharged is analysed using the model developed. Enough care is taken to address the occurrence of knock, which determines the extent of turbocharging; using wavelet analysis of the acoustic emissions from the engine. The possibility of technologies such as supercapacitor batteries for hybrid turbocharging, cooled EGR for controlling knocking and dissociation have also been considered in the proposed system. The results exhibit remarkable improvement of 40% in low end torques which pave the way for further downsizing of petrol engines.

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Keywords: Hybrid turbocharging; Supercapacitor; Cooled EGR; Knocking; Misfire; SI engine.

1. Introduction

Automotive researches have always been focused on developing high performance engines; enhancing the dynamic response irrespective of the manoeuvring conditions. Turbochargers with its sufficient boost pressure have

* Corresponding author. Tel.: +91-903-742-3084, +91 903-742-3082.
E-mail address: jee.jinsha@gmail.com

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remarkably improved the engine performance, fuel economy and lowered emission values, which led to the downsized IC engines. For the better utilisation of combustion chamber volume, turbocharging is done in both the petrol and diesel engines, however is not effective in all ranges of engine speed. At lower engine speeds, the power produced by turbine is very less due to the reduced flow rate of exhaust gas and hence the turbine speed, which in-turn force the compressor to stall. Turbolag is more severe in petrol engines than in diesel engines due to its light weight, smaller flywheel and wider mass flow range. A constant boost is intrusive over its full operating range for maintaining high performance at low engine speeds [1].

Nomenclature

T	Instantaneous temperature (k)
P	Instantaneous pressure (Pa)
ρ	Density of gas mixture (kg/m^3)
m	Mass of gas mixture (kg)
$\dot{m}$	Rate of change of mass (kg/s)
C_v	Specific heat at constant volume (kJ/kg K)
$\dot{Q}$	Heat transfer rate (kJ/s)
h	Specific enthalpy of gas mixture (kJ/kg)
V	Instantaneous cylinder volume (m^3)
R	Characteristics gas constant (kJ/kg K)
$\bar{S}_P$	Mean piston speed
k	Adjustable parameter that fixes the shape of the combustion progress curve
x_b	Mass fraction burned
α_{wall}	Fraction of mixture that burns in the duration of combustion
a	Adjustable constant that determines the duration of combustion
θ	Crank angle (degree)
θ_o	Crank angle at the start of combustion (degree)
k_{wall}	Ratio of slow burn duration to standard burn duration
$\Delta\theta$	Combustion duration (degree)

Suffixes

u	Unburnt
b	Burnt
in	Inlet
ex	Exit

Variable geometry turbocharging (VGT) uses pivoted nozzles to adjust according to varying exhaust flow rate there by reducing the turbolag to an extend and hence lowering NO_x emissions [2]. In VGTs, even though all the parts are exposed to extreme temperatures making them wear quickly, the very complex design and its sophisticated control systems enhanced the research for much simpler designs.

Chadwell and Walls [3] suggested a new technology called Super-Turbo, in which a turbocharger is coupled to continuously variable transmission through the engine crankshaft allowing it to act as a supercharger during lower engine speeds [4]. Later on, lot of advances had occurred in this field leading to the introduction of hybrid turbo. Honeywells e-Turbo has an electric motor and generator mounted on the same shaft of the turbocharger in which the extra torque is met by the electric motor at lower engine speeds. While at higher engine speeds, the excess energy is used to generate electricity and is stored in batteries [5]. Mitsubishis “hybrid turbo”, is a conventional turbo charger with a high-speed motor generator built in. The motor generator incorporated into this type of turbocharger assists the turbo when the exhaust gas energy is insufficient, thereby improving the transient response delay [6]. Similarly, Ford Motors Turbocharger Power Assist System (TPAS) is capable of supplying torque to the turbocharger shaft in the motoring mode and absorbing power from the turbocharger shaft and storing it in the battery in the generator mode [7]. The charge and discharge process in battery is a slow process and can degrade the chemical compounds inside the battery over time. As a result, power density of the batteries gets reduced and lose their ability to retain energy throughout their lifetime [8]. Since constant charging and discharging is necessary for the working of hybrid turbocharger, the usage of ordinary battery is not viable. Hence, in our work supercapacitor which has very quick discharge and charge acceptance and longer life than that of the ordinary battery is used. The quicker charging and discharging ability of the supercapacitor makes the hybrid turbocharging to respond quickly to the load fluctuations in the turbine, which again reduces the turbo lag.

Knocking is the major cause of turbocharging that affects the performance of the SI engines, hence a real-time analysis to reduce the occurrence of knocking become inevitable with the introduction of many advanced technologies in turbocharging. Many models have been developed based on engine operating parameters and fuel properties to predict the occurrence of knocking [9]. But these models cannot be used for all ranges of engine operation due to its lack of accuracy and complexities, hence cannot be used effectively for real-time analysis. Later on the parameters that are affected by knocking were used to find out the presence of knocking on the real-time basis. Pressure fluctuations inside the cylinder during the combustion process were used initially for determining the occurrence of knocking. In another work, Ollivier et al. [11] provide grooves in the cylinder liner facing the coolant flow for amplifying the transient temperature change that occurs in the presence of knocking for the analysis. Later on, there were several works based on acoustic emissions from the engine for obtaining information regarding the occurrence of knocking. In all those works the acoustic sensors were mounted on the engine and is processed using a data acquisition system for the further analysis.

In the present study, real-time analysis of knocking is done from the acoustic emissions produced by the engine using a condenser mic placed nearby the exhaust manifold. The work mainly focuses on the cost effective and easy method that could be adopted in automobiles to achieve greater performance. Further details of the effect of cooled EGR and hybrid turbocharging assisted by supercapacitor on the SI engine performance and the methodologies adopted is discussed in the following sections.

2. Thermodynamic Modelling

Assumptions taken for developing the thermodynamic evolution equation for developing the thermodynamic model is as follows:

- The gases in the cylinder are fully mixed and isotropic during intake, compression, expansion, and exhaust processes.
- All gases are considered to be ideal gases during the entire thermodynamic cycle. Gas properties are assumed to be the function of temperature only.
- During the intake and exhaust stroke, the thermodynamic system is considered as an open system and during compression and expansion it is a closed system.
- For the combustion process, two zones (burned and the unburned) separated by an infinitesimally thin flame is used and the heat transfer between the two zones is neglected.
- The cylinder wall temperature is assumed to be uniform and constant (400 K) [12].

A mathematical model is created based on the thermodynamic relations developed and other performance and geometric parameters for the analysis of the performance enhancement that could be achieved by turbocharging and cooled EGR. The details of the mathematical model created for the analysis is explained as follows:

2.1. Engine thermodynamics

The control volume considered for the analysis is limited to the combustion chamber and various energy interactions and mass flows occurring across the system is as shown in the Fig. 1. Thermodynamic relations for all the processes occurring inside the combustion chamber are developed based on unsteady flow energy equation. During the intake and exhaust stroke, the system is considered to be open and during compression, combustion and expansion process, the system is considered to be closed. Thermodynamic evolution equations to find temperature and pressure for all the strokes except for combustion stroke is obtained as follows:

$$\frac{dT}{dt} = \frac{1}{(m_u C_{v,u} + m_b C_{v,b})}\left[\dot{Q}_u + \dot{Q}_b + \dot{m}_{in}h_{in} - \dot{m}_{ex}h_{ex} - \dot{m}_u h_u + \dot{m}_b h_b - P\frac{dV}{dt}\right] \tag{1}$$

$$\frac{dP}{dt} = \left[P\left(\frac{\dot{m}_u}{\rho_u} + \frac{\dot{m}_b}{\rho_b} - \frac{dV}{dt}\right) + \frac{R_u}{C_{v,u}}\left(\dot{Q}_u + \dot{m}_{in}h_{in} - \dot{m}_u h_u - P\frac{dV}{dt}\right) + \frac{R_b}{C_{v,b}}\left(\dot{Q}_b + \dot{m}_{ex}h_{ex} - \dot{m}_b h_b - P\frac{dV}{dt}\right)\right]\frac{1}{V} \tag{2}$$

The value of each terms in (1) and (2) depends upon the type of process that the engine is undergoing. During the compression and expansion process $\dot{m}_{in}, \dot{m}_{ex}, \dot{m}_u$ and $\dot{m}_b$ will be zero. While during the suction and exhaust process $\dot{m}_{in} = \dot{m}_u, \dot{m}_{ex} = \dot{m}_b = 0$ and $\dot{m}_{ex} = \dot{m}_b, \dot{m}_{in} = \dot{m}_u = 0$ respectively.

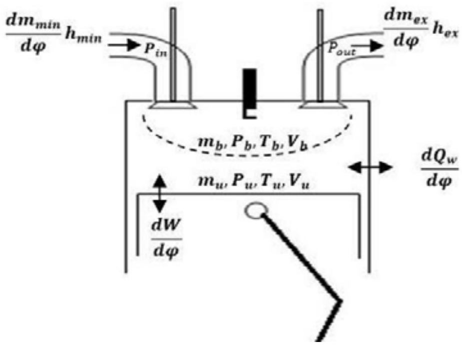


Fig. 1. Control volume of the engine considered with various energy and mass transfers during various thermodynamic processes.

During the combustion stroke the thermodynamic equations giving time evolution for both the unburned and burned zone is obtained as,

$$\frac{dT_u}{dt} = \frac{1}{m_u C_{v,u}}\left[\dot{Q}_u - P_u\frac{dV_u}{dt}\right] \tag{3}$$

$$\frac{dP_u}{dt} = \left[P_u\left(\frac{\dot{m}_u}{\rho_u} - \frac{dV_u}{dt}\right) + \frac{R_u}{C_{v,u}}\left(\dot{Q}_u - P_u\frac{dV_u}{dt}\right)\right]\frac{1}{V_u} \tag{4}$$

$$\frac{dT_b}{dt} = \frac{1}{m_b C_{v,b}}\left[\dot{Q}_b + \dot{m}_b(h_u - h_b) - P_b\frac{dV_b}{dt}\right] \tag{5}$$

$$\frac{dP_b}{dt} = \left[P_b\left(\frac{\dot{m}_b}{\rho_b} - \frac{dV_b}{dt}\right) + \left(\dot{Q}_b + \dot{m}_b\,(h_u - h_b) - P_b\frac{dV_b}{dt}\right)\frac{R_b}{c_{v,b}}\right]\frac{1}{V_b} \tag{6}$$

Initial values for T_u, P_u and P_b is taken as the temperature and pressure at the end of the compression process, while the initial value for T_b is taken as the adiabatic flame temperature.

2.2. Heat transfer

The heat transfer coefficient varies with the complex gas flow rates, piston position and time [13]. The correction for heat transfer coefficients developed by Hohenberg is simpler and accurate. Hence, it is used for modelling the heat transfer [14]. The correlation of heat transfer coefficient (h_g) is obtained as,

$$h_g = 130\,V^{-0.06}P^{0.8}T^{-0.4}\left(1.4 + \overline{S_p}\right)^{0.8} \tag{7}$$

2.3. Mass fraction burned

Double Wiebe function used to find the mass fraction burned (x_b) during the combustion process, accounting the slower burning rate of the charge at walls of the combustion chamber is [15],

$$x_b = (1-\alpha_{wall})\left\{1 - exp\left(-a\left(\frac{\theta-\theta_0}{\Delta\theta}\right)^{k+1}\right)\right\} + \alpha_{wall}\left\{1 - exp\left(-a\left(\frac{\theta-\theta_0}{k_{wall}\,\Delta\theta}\right)^{k+1}\right)\right\} \tag{8}$$

In addition to these, the volume of combustion chamber determined as a function of crank angle (θ) [12], mass flow rate of gas through poppet valve [12], gas properties as a function of temperature [13], valve and port geometry [13] etc. were used to create the mathematical model.

3. Acoustic analysis

The acoustic emission from the engine is recorded by means of a condenser microphone, which is then analysed using the MATLAB environment. Major problem associated with the recorded sound signal is the presence of noise that is to be eliminated before processing the recorded sound. For de-noising, the sound wave is first decomposed and de-noised using 1-D wavelet packet at level 4 using 9th order Daubechies wavelet. The level 4 is obtained as the best level after analyzing the wave using the wavelet toolbox GUI; hence used for the decomposition. The de-noised signal is analysed using the continuous wavelet transform 1-D tool box to plot its spectrogram.

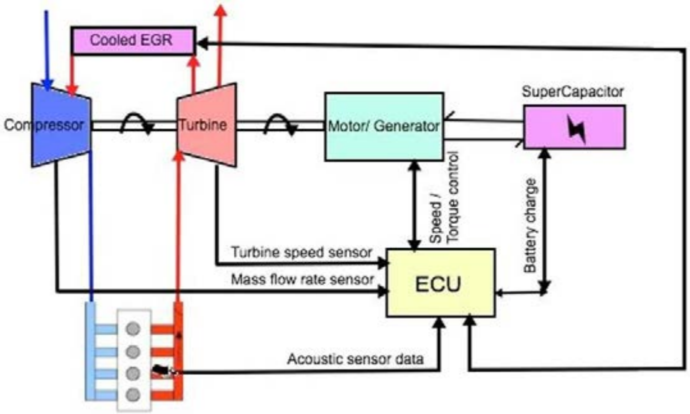


Fig. 2. Schematic diagram of the proposed system.

4. Proposed system

Figure 2. shows the schematic diagram of the hybrid turbo charger. Improving the low end torque for the proposed GDI petrol engine is achieved using a hybrid turbocharger. In addition to the normal turbocharger a high speed electric motor/generator is coupled on the same shaft. During compressor stall the motor torque generated will be coupled with turbo, thereby providing sufficient boost at low engine speed. At high turbine speeds it acts as a generator preventing turbine surge and eliminating the need for waste gate valve, providing enough power to the storage cell. Supercapacitor battery is capable of supplying the high current demands for motor operation and also capable of tapping the smallest leakage current available for storage. The cooled EGR loop prevents the engine from knock when boosted. A portion of the exhaust gas leaving the turbine is passed through the inter-cooler and is fed to the engine through the compressor, whenever necessary. This lowers the temperature to an optimum range and provides an effective check on knocking. Acoustic sensors are used to acquire the data's from the acoustic emissions produced by the engine to the ECU, where it is processed to detect the presence of knock. If the knocking is detected, the valve of the cooled EGR system is opened so that the cooled exhaust gas is recirculated into the engine for preventing the further occurrence of knock. The amount of cooled EGR will be in the proportion of the intensity of knocking. In hybrid turbocharging, the boost pressure is high so that the power produced will be more in the entire range of engine operation. The thermal efficiency is seen to be higher for lean

mixtures than in rich mixtures while the power produced will be higher for rich mixtures. Hence, in our work, we are focusing only on the lean mixtures for taking the advantage of it to have high thermal efficiency. Thus higher power generation with minimum fuel consumption could be possible by hybrid turbocharging the engine running on lean mixture.

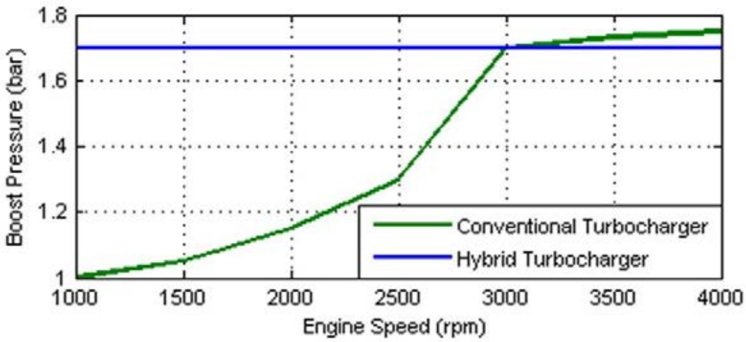


Fig. 3. Variation of boost pressure with the engine speed for both the conventional and hybrid turbocharger.

5. Results and Discussion

Mathematical model of the engine generated is analysed using MATLAB to study the effects of conventional and hybrid turbocharging on the engine performance. For the analysis of the effects of conventional turbocharging on the engine performance, the values of boost pressure is taken from the work done by Hans Mezger [10] which is seen to vary from 1 bar to 1.75 bar with the engine speed from 1000 rpm to 4000 rpm (Fig. 3). For the analysis of the effects of hybrid turbocharging, boost pressure is taken as 1.7 bar irrespective of the changes in engine speed. Details of the engine geometric and performance parameters considered for the analysis is shown in the table 1.

Table 1. Engine specifications considered for the analysis.

Bore	0.07 m
Stroke length	0.09 m
Connecting rod length	0.1973 m
Compression ratio	1:8.5
Ambient pressure	1 bar
Ambient temperature	303 K
Inlet valve opening time	10^o CA BTDC
Inlet valve closing time	50^o CA ABDC
Exhaust valve opening time	40^o CA BBDC
Exhaust valve closing time	10^o CA ATDC
Ignition timing	10^o CA BTDC

The results show that the brake thermal efficiency of the naturally aspirated engine increases initially and then starts decreasing with the further increase in the engine speed (Fig. 4). The brake thermal efficiency changes with the performance parameters like volumetric efficiency, in-cylinder temperature, equivalence ratio and engine speed. Lower volumetric efficiency of the naturally aspirated engine at lower engine speeds is due to the effect of back flow generated. But it shows an increasing trend with the engine speed, while at higher engine speeds it again gets reduced due to the lack of time available for the air to enter into the engine cylinder. At lower volumetric efficiency the fuel available for combustion will be low, however the frictional power that is to overcome will remain almost same, hence the brake thermal efficiency will also shows the same trend as volumetric efficiency. The in-cylinder temperature increases with the boost pressure which in-turn results in the dissociation of the gases like CO_2, H_2O, NO_x. At higher engine speeds, the time available for dissociated gases to get back to its initial form as the in cylinder temperature gets reduced during the expansion process will be much lesser than that at the lower engine speeds. In the hybrid turbocharged engine, the volumetric efficiency will be higher than that of the naturally aspirated and the conventional turbocharged engine, hence higher the brake thermal efficiency as shown in the fig.4. As the speed increases the reduction in the volumetric efficiency and the effect of dissociation makes the brake thermal efficiency of the conventional and hybrid turbocharged engine to reduce further than that of the naturally aspirated engine.

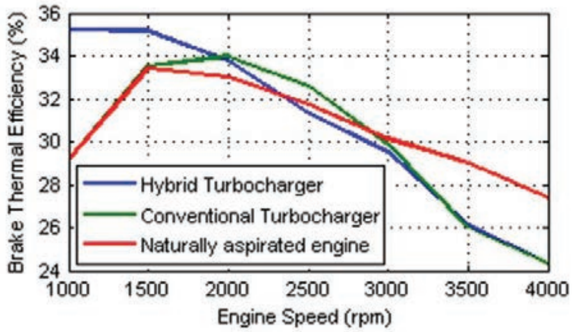


Fig. 4. Variation of brake thermal efficiency with the engine speed for naturally aspirated and turbocharged engines at equivalence ratio 0.9.

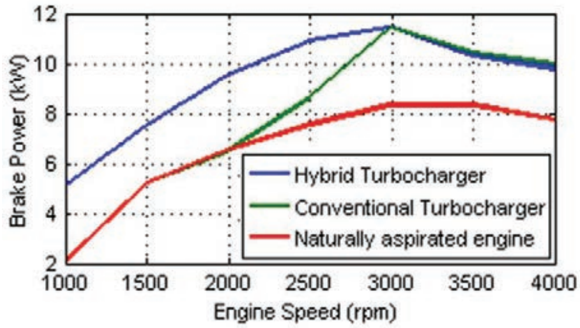
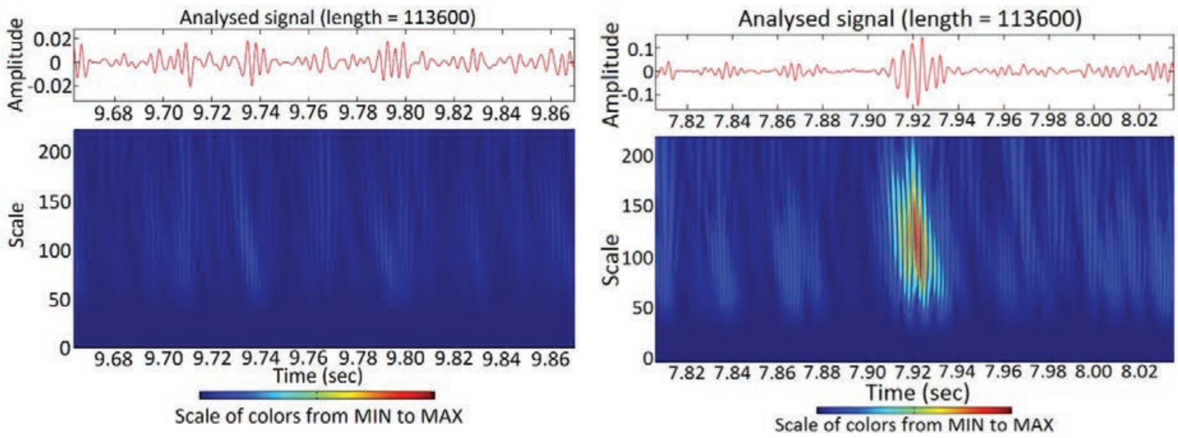


Fig. 5. Variation of brake power with the engine speed for naturally aspirated and turbocharged engines at equivalence ratio 0.9.



(a) (b)

Fig. 6. Time domain and spectrogram of the de-noised signal produced by 4 stroke 4 cylinder engine (a) during normal working condition (b) knocking condition.

However, the brake power produced by the turbocharged engine is higher than that of the naturally aspirated engine at all ranges of operation, due to its improved effective compression ratio and volumetric efficiency as shown in the fig. 5. Hybrid turbocharger is assisted by an electric motor at lower engine speeds to provide constant boost pressure, thereby improving the power produced by the engine at lower engine speeds when compared to that of the conventional turbocharger (Fig. 5). From the Fig 4 and Fig 5, it is seen that the brake thermal efficiency of the hybrid turbocharger is less than that of the conventional turbocharger in the engine speeds ranging from 2000 rpm to 3000 rpm while the power is more for the hybrid turbocharged engine than in the conventional turbocharger. Since the pressure increases with the in-cylinder temperature and the molecular density, the in-cylinder pressure will be high for hybrid turbocharged engine than the conventional turbocharger due to its increased volumetric efficiency. The temperature and pressure also gets increased further with the amount of supercharging. At high temperatures, the dissociation of the gases occurs by absorbing the thermal energy released during the combustion, thus reducing the thermal efficiency and power produced by the engine. But at higher boost pressures, the effect of dissociation on power will overcome by the effect of boost pressure. Thus the power produced by the hybrid turbocharger will be more than that of the conventional turbocharger even though the thermal efficiency is lesser. Power produced by the turbocharged engine should increase with the engine speed.

However, at higher speeds, reduced volumetric efficiency and the effects of dissociation reduces the power developed by the turbocharged engine than the conventional engines.

For acoustic analysis, sound produced by four stroke four cylinder ambassador engine (petrol) is recorded. The time domain and spectrogram of the de-noised signal obtained using the MATLAB (wavelet toolbox GUI) is shown in fig. 6(a) and 6(b). The sound file of 12 sec duration which is recorded during the time of engine knocking is taken for the analysis and the enlarged portion of two small time interval is shown in the fig. 6(a) and (b). From the results, it is seen that the amplitude of the acoustic waves is changing abruptly with the occurrence of knocking in both the lower and higher frequency ranges, denoted by the colour changes from blue to red in the spectrogram as shown in the fig. 6(b). The colour changes in the spectrogram from blue to red shows the variation of amplitude from minimum to maximum, while the scales in the spectrogram is corresponding to the frequency of the acoustic wave. During normal running condition of the engine, the acoustic wave produced shows closely a periodic behavior with lower changes in the amplitude as denoted by the fig. 6(a).

6. Conclusion

Thermodynamic analysis shows that brake power is improved by 50-100 % during the lower speed range, which is mainly due to the improvement in boost provided by hybrid turbocharging using supercapacitor, which provides high current discharge. The brake thermal efficiency of the hybrid turbocharged engine is found to be high at the lower engine speeds while it is much lower than that of the naturally aspirated engine at higher engine speed. The effect of dissociation of gases in the reduction of brake thermal efficiency of the hybrid turbocharged engine could be minimized by the cooled EGR. This reduces the in-cylinder temperature due to its higher specific heat capacity than the air, hence reducing the rate of dissociation of the gases. Turbocharging causes the in-cylinder temperature to increase further which results in the engine knocking. In our work, acoustic emission of the engine is used to analyse the engine knocking and the results show that during the occurrence of knocking the acoustic emissions produced by the engine falls in all ranges of frequencies, which could be detected by the ECU and the cooled EGR is send to the compressor and finally into the engine to control the occurrence of knocking.

Thus by providing a constant boost in all operating ranges and the control of knocking and dissociation using cooled EGR, SI engines could be operated at par with diesel engines.

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