Experimental investigation on soot reduction in city driving Diesel vehicles in comparison with EuroII standard

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Abstract
Effectiveness of the particles issued from diesel engines that are mainly soot, on human healthiness by international agency of cancer made in 1988 has shown that, the Particulate Material (PM) will increase the probability of suffering to cancer.
In this work first of all the naturally aspirated diesel engine of type OM314 from city driving motorbus and truck vehicles (Khavar) has been introduced. Then it is converted to limited pressure turbocharged OM314 Diesel engine. At the final stage the injectors pressure have been elevated from 200 bars to 240 bars with the purpose of decreasing the soot emission. In each stage in order to investigate the soot contents, the engine has been tested under ECE-R49, 13 mode standard test. Results show that the naturally aspirated engine does not cover the standard Euro I. The turbocharged OM314 engine catches the Euro I standard with specific soot emission 35% less then the naturally aspirated engine maybe due to reduction in ignition delay and better soot burnout process. The elevating of the injection pressure makes a better mixing of fuel to air and results an amount of specific soot 21% less than Euro I, but it does not cover the Euro II standard.

Keyword: Soot emission, Turbocharged Diesel engine, Nuzzle pressure.

Introduction

Particles are generated from a variety of sources, emissions from the internal combustion engines are one of the major global sources of particulate matter (PM). PM is known to contribute to climate change, reduce visibility, and affect human health [1].

Diesel engines are extensively used in automotive systems due to their better fuel economy compared to conventional gasoline engines as a result of their higher thermal efficiency. Despite these advantages diesel engines suffer from environmental drawbacks such as high levels of exhaust No_x (oxide of nitrogen) and particulate matter [2].

With increasing concern on the effect of air pollution on environment, animal and plant life, particularly in the field of road transport, vehicle exhaust emissions have in recent years, been subjected to increasingly stringent regulations. It is a matter of importance that diesel engines are an important source of particulate emissions and smoke. The particulate emission from diesel engines amounts to about 5% of the total emissions, which consists primarily of soot with some additional absorbed hydrocarbon materials [3].

Nomenclature			
T	engine torque (N.m)	ρ_f	fuel density (kg/m^3)
m°_{soot}	brake soot flow rate (g/h)	t_f	time of 50 cc fuel consumption (s)
S_{soot}	specific soot emission (g/kWh)	Q°_e	volumetric flow rate of exhaust(m^3/s)
P_{bm}	measured engine brake power (kW)	ρ_e	exhaust density (kg/m^3)
P_{bs}	standard engine brake power	P_e	exhaust pressure (kPa)
W_f	weighting factor	T_e	exhaust temperature (K)
V_{air}	air velocity (m/s)	PM	particulate matter
ΔP	orifice pressure drop (kPa)	N	engine speed (rpm)
ρ_{air}	air density (kg/m^3)	bsfc	brake specific fuel consumption (g/kWh)
m°_{air}	mass flow rate of air (kg/s)	$P_{s,d}$	standard dry-air absolute pressure (kPa)
A_o	orifice inlet area (m^2)	P_m	measured ambient-air absolute pressure (kPa)
C_D	discharge coefficient	$P_{v,m}$	measured ambient-water vapor partial pressure (kPa)
ρ_l	liquid density of the manometer (kg/m^3)	T_m	measured ambient temperature (K)
g	gravitational acceleration (m/s^2)	T_s	Standard ambient temperature (K)
ΔH	height difference of manometer liquid(m)	C_f	power correction factor
m°_f	mass flow rate of fuel(kg/s)	LIMP	limited inlet manifold pressure

Reducing PM emissions to the levels required by stringent new regulations poses a significant challenge for engine manufacturers. In addition to the emissions challenge, soot formation in diesel engines can also influence engine performance and have feedback effects on in-cylinder combustion and emission formation processes [4].

Smoke, or particulate emissions, occurs when there is insufficient air to completely burn the fuel. One of the factors which the designers vary to provide low emission levels with high performance and good fuel economy is to use the turbocharger which is driven by exhaust gas from the engine cylinder [5]. Increasing the intake pressure increases cylinder pressure, the amount of the charge air entrained into the jet relative to the fuel flow at the lift off length and leads to a reduction in both in-cylinder soot and exhaust particulate [6].

This study, will investigate the soot emission level of the naturally aspirated OM314 type diesel engine from city driving motorbus and truck vehicles (Khavar) and attempts to decrease it by using a turbocharger and elevating the injection pressure. In this research work soot emission is also compared with Euro II standard emission.

Turbocharger

The sole purpose, of which a turbocharger is used, is to improve the overall performance of the engine [7].

In Fig.1 the turbocharger system of an engine is shown. The rated brake power output is obtained through an adjustment of the turbocharger waste gate.

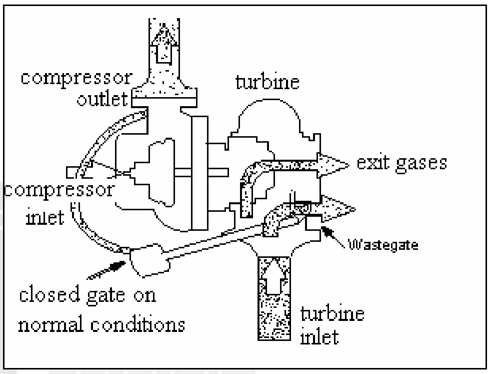

Fig.1: Schematic of turbocharger with waste-gate

Injection pressure

In diesel engines, combustion and emission characteristics are greatly influenced by quality of atomization and by the fuel-air mixture present in the combustion chamber [8]. Pressure is one of the most important parameters acting on the pulverization [8]. In present diesel engines fuel injection systems are designed to obtain higher injection pressure. So it is aimed to decrease the exhaust emissions by increasing efficiency, when injection pressure is increased fuel particle diameters will become small. Since formation of mixing of fuel to air becomes better during ignition period, smoke level and CO emission will be less [9].

Experimental apparatus and test conditions

- Experimental facilities

In this work as Fig.2 shows a four-cylinder, four-stroke, direct injection,naturally aspirated diesel engine with a peak power of 63kW and peak torque of 235 N-m at 1830 rpm was used. This was a 2006 production engine Daimler OM314 with a compression ratio of 17 to 1, bore and stroke 97mm and 128mm and displacement volume of 3.784 L. the engine was installed and operated on a 112kW DXF Heenan & Froude hydraulic dynamometer. An AVL 415 smart sampler was used to measure soot emission levels in the exhaust gas. An electrical speed meter was mounted on the engine flywheel to measure the engine speed. The temperatures of inlet and exhaust gases were recorded on PC utilizing K-type thermocouples attached to the engine while the pressure of the exhaust and the air inlet manifold was measured using Bourdon pressure gauge. Relative humidity and atmospheric pressure are read for each mode of test. In table 1 the instrumental resolution of the apparatus are indicated.

Table 1: Instrumental resolution of the test bed apparatus

Facility	Instrumental resolution
Smoke meter	0.1 mgr/kWh
Speed meter	1 rpm
Torque meter	1 N-m
Pressure gauge	0.1 mmHg
Thermocouple	0.1^{oC}

Experimental procedure

- Engine performance test

Internal combustion engines have upper and lower limits of torque and power published by manufacturers.

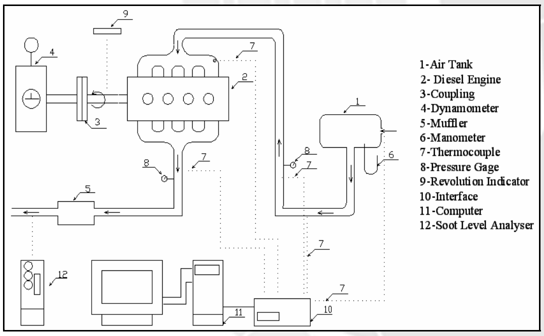

Fig.2: schematic of the engine test bed

Before the engine was provided for the tests, its performance was investigated to be in the permitted limitations.

The maximum power of the engine was measured for different speeds. Fig.3 and 4 represent the actual engine performance in comparison with the limits.

- The standard ECE-R49, 13 mode test.

In this study soot emissions of the heavy duty diesel engine under the ECE R49 13 mode test cycle were analyzed. OM314 diesel engine was tested under ECE-R49 13 mode sample method. PM at the exhaust at every test mode was separately sampled. According to the equations coming in the following, the brake specific soot emission for 13 modes, five modes of speed 1830rpm (speed at maximum torque), five modes of Speed 2800 rpm (rated power speed) and three modes of speed 700 rpm (idle speed), were calculated. This cycle is not representative of the engine real use on road, but allows repeatable conditions, useful for comparative tests [10]. This test should be under steady state operational conditions and for heavy duty diesel engines at every mode the torque is varied from 10% to 100% of the engine maximum torque at the specified speed, according to the regulation [11]. The soot emissions are measured in g/kWh. After the test, for each mode, a value is defined which stands for weighting coefficient.

Data processing

- Brake specific soot and bsfc calculations

The final brake specific soot level is obtained by Equation (1) [11]:

$$S_{soot} = \sum_{1}^{13} \frac{\dot{m}_{soot}}{P_{bs}} * W_f \qquad (1)$$

Where, P_{bs} stands for standard atmospheric brake power and W_f indicates the weighting factor. The pressure, humidity, and temperature of the ambient air inducted into an engine, at a given engine speed; affect the air mass flow rate and the power output. Correction factors are used to adjust measured power output values to standard atmospheric power output. The torque exerted on the engine by the dynamometer gives the measured power output by the Equation (2).

$$P_{bm} = 2\pi NT \qquad (2)$$

Relationship between measured power output and standard atmospheric power output can be expressed by Equation (3)

$$P_{bs} = C_f P_{bm} \qquad (3)$$

Where correction factor is given by Equation (4) [12]:

$$C_f = \frac{P_{s,d}}{P_m - P_{m,v}} * \left(\frac{T_m}{T_s}\right)^{1/2} \qquad (4)$$

Where, $P_{s,d}$, T_m, T_s, P_m and $P_{m,v}$ represent standard dry-air absolute pressure, ambient temperature, standard temperature, measured ambient absolute pressure and the measured partial water vapor pressure.

Air mass flow rate was measured by Bernoulli's method in this study. The air velocity equation can be expressed as Equation (5).

$$V_{air} = \sqrt{\frac{2\Delta P}{\rho_{air}}} \qquad (5)$$

Where, ΔP and ρ_{air} represent air pressure difference inside and outside of the surge tank and air density, respectively. The air mass flow rate can be expressed by the Equation (6)

$$\dot{m}_{air} = \rho_{air} V_{air} A_o C_D \tag{6}$$

Where, C_D and A_0 represent the coefficient of discharge, verified by 0.6, and the area of the orifice. By summarizing the above equations,

$$\dot{m}_{air} = C_D A_o \sqrt{2\Delta P \rho_{air}} \tag{7}$$

In this work the pressure drop is investigated by use of a manometer mounted on the surge tank orifice,

$$\Delta P = \rho_L g \Delta H \tag{8}$$

Where, ρ_L, g and ΔH represent density of monometer liquid, the gravitational acceleration and the height difference of liquid surfaces of the manometer. From Equations (7) and (8) the air mass flow rate is given by

$$\dot{m}_{air} = C_D A_o \sqrt{2 g \rho_L \Delta H \rho_{air}} \tag{9}$$

A calibrated burette and a stopwatch were used to measure the mass flow rate of fuel consumption. This measuring system is based on the time needed for consumption of specific volume of fuel. The equation can be expressed as

$$\dot{m}_f = \left[\rho_f / t_f \right] * 50 * 10^{-6} \tag{10}$$

Where ρ_f and t_f represent the density of diesel fuel, 0.83, and the time of 50^{cc} fuel consumption.
In the Equation (1) in order to measure the specific soot pollution, m°_{soot} is obtained from Equation(11)

$$\dot{m}_{soot} = \rho_{soot} * 10^{-3} * \dot{Q}_e * 3600 \tag{11}$$

Where, ρ_{soot} and Q^{o}_{e} represent the soot density, which is obtained from the smoke meter, and the volume flow rate of the exhaust. The following equations complete the correlations,

$$\dot{Q}_e = \frac{\dot{m}_f + \dot{m}_a}{\rho_e} \tag{12}$$

$$\rho_e = \frac{P_e}{0.287\, T_e} \tag{13}$$

Brake specific fuel consumption is calculated by Equation (14)

$$bsfc = \left[\dot{m}_f / (C_f * P_{bm}) \right] * 36 * 10^{+5} \tag{14}$$

Results and discussion

- Naturally Aspirated OM314 Diesel Engine

Engine factories publish graphs which mention the upper and lower limits of the maximum engine operation conditions. In this work the maximum torque and brake power of the engine was obtained for every operating point. Torque and brake power output versus engine speed graphs with upper and lower limits and test engine are given in Fig.3.
Brake specific fuel consumption versus engine speed with upper and lower limits, recommended by the factory, and the engine under test are given in Fig.4.
Fig.3 and Fig.4 show, the actual performance (operating characteristics) of OM314 diesel engine results. These results indicate that the natural aspirated engine is in an acceptable operating condition.
The steady state 13 mode cycle, ECE-R49 test was performed on the engine. The tests were conducted three times in order to examine the sensitivity of the test, and the averages of these 3 consecutive test results represents as the actual test result.
Fig. 5 shows the three brake specific soot results of the tests on the naturally aspirated OM314 diesel engine. The comparison of the engine soot emission and the standards Euro I and Euro II are given in Fig. 6.
This result indicates that the naturally aspirated OM314 diesel engine does not cover the Euro 0 standard level, as Pirouzpanah et al mentioned in ref. [13].

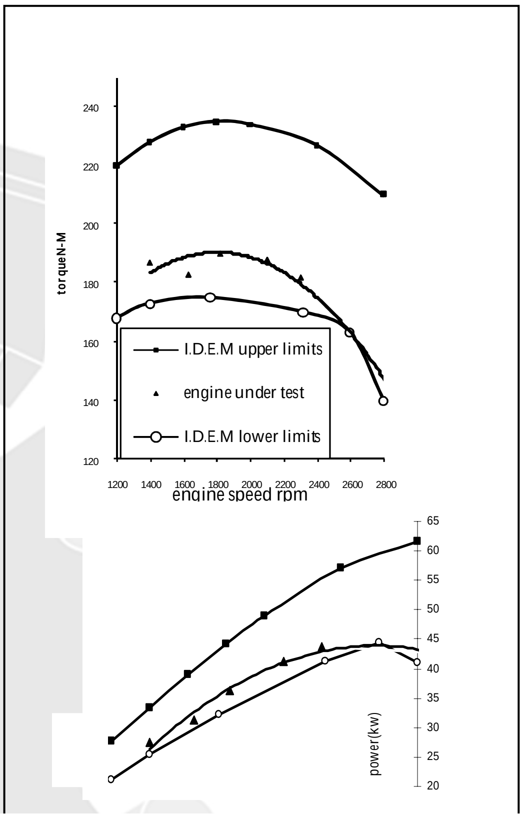

Fig.3: torque and brake power output vs. engine speed

- Effect of turbocharger

The engine is turbocharged without any change in compression ratio, fuel injection and valves overlap, aiming to a decrease in specific soot emission levels; it is called the limited inlet manifold pressure turbocharged engine (LIMP turbocharged engine).

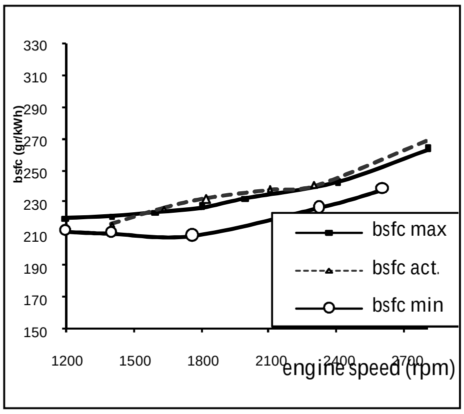

Fig.4: Engine bsfc vs. Engine speed

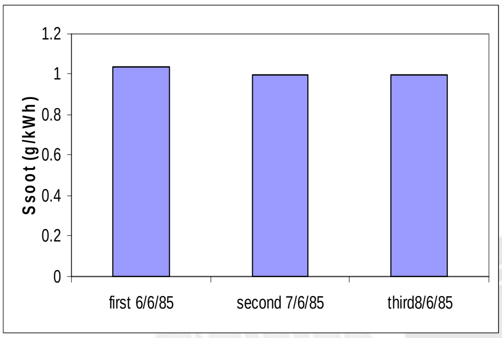

Fig.5: Brake specific soot emission at three ECE-R49 test results for natural aspirated OM314 diesel engine

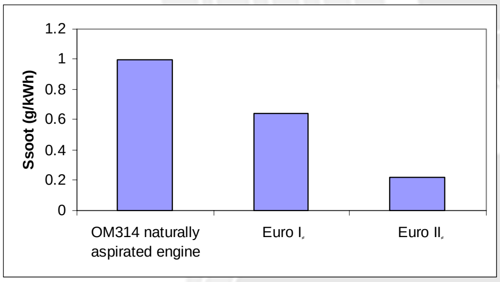

Fig.6: A comparison between soot levels of the naturally aspirated engine with Euro standards

In cooperation with Ferdowsi University of Mashhad, the Borg Warner turbo charger producing company in Germany proposed the suitable turbocharger, according to the data provided by the Ferdowsi University [14].

In the LIMP turbo-charging method although higher efficiency is obtained, as the fuel consumption is the same as naturally aspirated, there is no significant change in the engine power and torque. Thus ECE-R49 13 modes test, under steady-state cycle do not vary. It should also be mentioned

that due to exhaust back-pressure proposed by the turbocharger, the temperature of the cylinder will increase and thereby, the exhaust valve and upper ring of the piston would be exposed to more deterioration than before turbo-charging.
With regards to the sensitivity of the test, at this stage, the test is also repeated for three times as shown in Fig. 7.
The comparison of the soot levels are shown in Fig. 8 for naturally aspirated, turbocharged engine and Euro standard levels.
The results show that the soot emission decreases with increasing the inlet manifold pressure. This reduction may be due to increasing the intake-air temperature which results in reduction of ignition delay that prolongs the late combustion phase. This improves the soot burnout process.

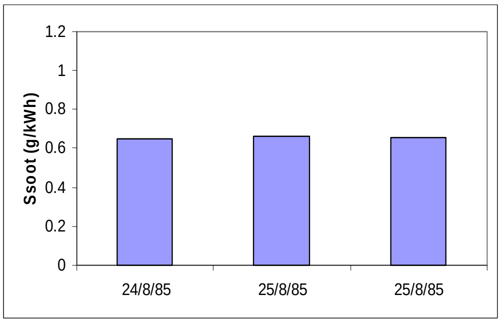

Fig.7: Brake specific soot emission at three ECE-R49 test results for turbocharged OM314 diesel engine

- Effect of pressurizing The Fuel Injection in Turbocharged Engine

In order to investigate the effect of fuel injection pressure on brake specific soot emission level, the injector pressure is adjusted for optimum value of 240 bars [15]. Washer(s) has been used for the adjustment of the injector, that according to the experiments each of them makes a 10 bars increase in pressure, and then tested by the test apparatus.

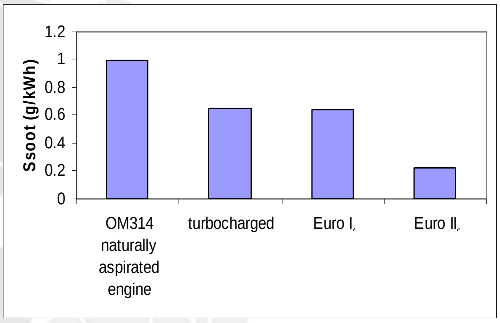

Fig.8: A comparison between soot levels of the turbocharged engine with Euro standards

After pressurizing, due to loss in fuel flow, because of the pressure drop, the injection pump is readjusted according to Bocsh standard table.
As the engine maximum power and torque do not vary, the 13 modes of the test do not alter and the test is performed just like previous stages. Fig. 9 and 10 show the three results of the test and the comparison between the results of three stages of the study, respectively.

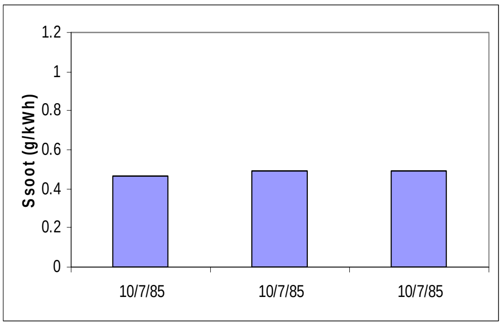

Fig.9: Brake specific soot emission at three ECE-R49 test results for turbocharged diesel engine with pressurized injection

The result indicates that higher injection pressure makes the fuel particle diameters to be smaller. Since formation of mixing of fuel to air becomes better during ignition period, Smoke level will be less.

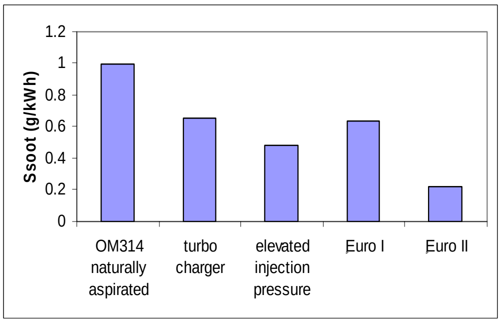

Fig.10: A comparison between soot level of the turbocharged engine with elevated injection pressure with Euro standards

Conclusions

In the present study, special investigation has been conducted on the soot emission level on an OM314 DI diesel engine. During the tests the engine was operated at three different conditions, naturally aspirated, LIMP turbocharged and elevated injection pressure.
It was observed that the naturally aspirated engine had acceptable performance characteristics but needed urgent attention in view of the soot emission levels.
LIMP turbocharged engine had reduced the soot emission level to the extent of 35% because of the higher pressure and temperature of intake-air and reduction of ignition delay which improves the soot burnout process, due to a prolong in the late combustion phase.
When the injection pressure was elevated, it was observed that the specific soot pollution decreased about 26% less than the turbocharged engine, and that was because smaller fuel particles diameter and better formation of mixing fuel to air. Also it is observed that the soot emission level of the engine was 21% less than the Euro I standard level but it does not match with the Euro II standard level.

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References

[1]. Jonathan P.R. Symonds, Diesel soot mass calculation in real-time with a different mobility spectrometer, aerosol science 38(2007) 52-68

[2]. Sam George, Samantha Balla, Effect of diesel soot on lubricant oil viscosity Tribology international 40(2007) 809-818

[3]. N.K. Miller Jothi, Experimental studies on homogeneous charge CI engine fueled with LPG using DEE as an ignition enhancer, Renewable Energy, Volume 32, Issue 9, pages 1581-1593, July 2007.

[4]. Lyle M. Pickett, Soot in diesel fuel jets: effects of ambient temperature, ambient density, and injection pressure, Combustion and Flame 138 (2004), 114-135.

[5]. Steve Arnold, Kelvin Sulpski, Mark Groskreutz, Gary Vrbas, Rob candle, S.M. Shahed, Advanced turbo-charging technologies for heavy-duty diesel engines, SAE paper 2001-01-3260

[6]. Dale R. Tree, Soot processes in compression ignition engines, progress in energy and combustion science 33 (2007)

[7]. K.S. Peat, A.J. Torregrosa, An investigation into the passive acoustic effect of the turbine in an automotive turbocharger, journal of sound and vibration 295 (2006)

[8]. E. Delacourt, Characterization of very high pressure diesel sprays using digital impinging techniques, Fuel 84 (2005) 859-867.

[9]. Ismet Celikten, An experimental investigation of the effect of the injection pressure on engine performance and exhaust emission in direct injection diesel engines, Applied Thermal Engineering 23 (2003) 2051-2060.

[10]. Luigi Turrio-Baldassarri, Emission comparison of urban bus engine fueled with diesel oil and bio-diesel blend, Science of the Total Environment 327 (2004) 147-169.

[11]. dieselnet.com/standards/eu/hd.htm

[12]. John.B.Heywood, Internal Com- bustion Engine Fundamentals, Mc Graw-Hill Book company 1988.

[13]. V. Piroupanah, M. Mirsalim, M. Afghahi and Y. Jeihouni, Converting OM-314 Diesel engine to Dual-Fuel (Diesel+Gas) Engine,Journal of engine research, Techno-Engineering Quarterly Vol, No.6,Summer 2005.

[14]. Ali Sabazadeh , Effect of supercharging and variation of manifold pressure on soot formation and OM314 engine parameters, thesis of master of science, mechanical engineering, supervised by M. Ghazikhani, Ferdowsi University of mashad, 2003.

[15] M. Ghazikhani, A. Darbandi, Effect of engine parameters on turbocharger second law efficiency in turbocharged diesel engines, ISME2007-1333.