

THE EFFECT OF TURBOCHARGER PRESSURE AND INTERCOOLER TEMPERATURE ON ENGINE PERFORMANCE

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المخلص

نظراً لتفاقم مشكلة تلوث الهواء الخطيرة الناتجة عن انبعاثات محركات الاحتراق، مثل أول أكسيد الكربون (CO) والوقود الهيدروكربوني (HC) الغير محترق وأكاسيد النيتروجين (NO_x) والجسيمات الصلبة الكربونية (Soot) C وبسبب ارتفاع أسعار النفط، لهذا يجب اتخاذ خطوات للحد من التلوث ومن الاستهلاك النوعي للوقود، خصوصاً في محركات الاحتراق. لتحسين كفاءة محرك الديزل وتخفيض الانبعاثات يمكن استرداد كمية الحرارة من غازات العادم والاستفادة منها. تم في هذه الورقة تطوير نمذجة حسابية بلغة FORTRAN لدراسة تأثير ضغط الشاحن التريبيني ودرجة حرارة المبرد البيئي على أداء المحرك وانبعاثاته. بُنيت النمذجة الحالية على أساس "الديناميكا الحرارية التطبيقية لمحركات الاحتراق الداخلي" للمؤلف C.R. FERGUSON. تظهر النتائج أنه هناك تأثير كبير لضغط الشاحن التريبيني ودرجة حرارة المبرد البيئي على القدرة المنتجة للمحرك والتي تزداد بشكل ملحوظ عند زيادة ضغط الشاحن التريبيني وفي درجات حرارة منخفضة للمبرد البيئي مع تحسين في استهلاك الوقود النوعي للمحرك. من خلال تطبيق برنامج المحاكاة على محرك الديزل (MAN) متوسط السرعة رباعي الاشواط يعمل بشاحن تريبيني، بينت النتائج أن الكفاءة الحرارية ارتفعت لأكثر من 47% والاستهلاك النوعي للوقود انخفض إلى 126 جرام/كيلوواط ساعة عند ضغط الشاحن التريبيني 0.25 ميجاباسكال ودرجة حرارة المبرد البيئي 325 كلفن، مقارنة مع النتائج بدون نظام الشاحن التريبيني التي كانت كفاءتها الحرارية 44% والاستهلاك النوعي للوقود 132 جرام/كيلوواط ساعة.

ABSTRACT

Due to serious air pollution problem caused by engine emissions such as carbon monoxide CO, un-burnt Hydrocarbon HC, Oxides of Nitrogen NO_x , and solid particulate matter C (Soot), and the increase of oil prices, steps must be taken to reduce pollution, and reduce fuel qualitative discharge, especially in combustion engines. To improve the efficiency and reduce the emissions of Diesel engines, some of the exhaust gases heat could be recovered and utilized to improve the efficiency of the engines. In this paper, a simulation has been developed to study the effect of the turbocharger pressure and the inter-cooler temperature on the engine performance. FORTRAN language was applied for this study based on "Internal Combustion Engine Applied Thermodynamics" by C.R. FERGUSON. Results show that, the engine performance is significantly affected by the turbocharger pressure and the inter-cooler temperature, by increasing the Turbocharger pressure and decreasing the inter-cooler temperature the engine power output is strongly improved and the specific fuel consumption of the engine is reduced. By applying the present code to a medium four-stroke MAN Diesel and Turbo-engine, the thermal efficiency is raised to over 47% and the specific fuel consumptions can be as low as 126 g/kWh at turbocharger pressure of 0.25 MPa and inter-cooler temperature of 325 K, compared to the results without turbocharger system where the thermal efficiency was 44% and the specific fuel consumption was 132 g/kWh.

KEYWORDS: Diesel Engine; Turbocharger; Inter-Cooler; Thermal Efficiency; Fuel Consumption.

INTRODUCTION

In forced induction engine, the air intake pressure is mainly forced by the compressor to maintain high air intake pressure through entire engine speed. The engine behavior in engine performance, fuel consumption and exhaust emissions aspects are influenced by the magnitude of air intake pressure, it needs to extract more energy from the combustion process. The large amount of air increases the potentiality of fuel chemical elements to be burned with oxygen. As a result, the engine performance and fuel economy are increased while the unburned exhaust emissions components are reduced. The maximum power of the engine depends on the amount of fuel it can burn and this in turn depends on the availability of air. Thus, more air is necessary to increase the engine power. One way to increase the air to the engine is to add a turbocharger with intercooler that simply raises the pressure of the air. [1]. Turbochargers were originally known as turbo-superchargers when all forced induction devices were classified as superchargers. Nowadays the term "supercharger" is usually applied to only mechanically driven forced induction devices. The key difference between a turbocharger and a conventional supercharger is that the latter is mechanically driven by the engine, often through a belt connected to the crankshaft, whereas a turbine driven by the engine's exhaust gas powers a turbocharger. Compared to a mechanically driven supercharger, turbochargers tend to be more efficient. Turbochargers are commonly used on marine diesel engines, truck, car, train, electric generators, and construction equipment engines [2].

For the last two decades, various attempts were made to improve the power output of an engine and to reduce its emissions by making some changes and installing some additional accessories like intercooler in the turbocharging technology. This will carry on in the future because in coming days there will be increase in the demand of fuel efficient engines with more power and minimum emissions and this is possible with some advancements in turbocharging technology [3].

A turbocharger consists of a compressor and a turbine linked by a shared axle so if the turbine rotates, the compressor also rotates. The turbine inlet receives exhaust gases from the engine causing it to rotate. This rotation in turn drives the compressor, which compresses the ambient air and delivers it to the intake manifold through an intercooler of an engine at higher pressure, and low temperature resulting in greater amount of air entering the cylinder [4].

A four-stroke engine can take in only so much air, and how much fuel it needs for proper combustion depends on how much air it takes in. Engineers calculate engine airflow requirements using three factors are engine displacement, engine revolutions per minute (RPM) and volumetric efficiency. Volumetric efficiency is a measure of how well an engine breathes. It is a comparison of the actual volume of air drawn into an engine to the theoretical maximum volume that could be drawn in. Volumetric efficiency is expressed as a percentage. [5]. One of the most important problems faced in turbo-charging systems is that air density is decreasing while compressing air. Compressing the air via turbochargers creates pressure and high temperature. The pressure creates more horsepower but the high temperature reduces the density of the charged air. The less dense the air that enters combustion chamber, less power will be generated. Various methods have been developed to cool down charge air, which is heated during turbo-charging

process. One of these methods is to use a compact heat exchangers called as intercoolers to cool charging air. As the air is cooled, it becomes denser, and denser air makes better combustion to produce more power [6].

An efficient way, which was used to reduce the fuel consumption, was based in reduction cylinder volume of internal combustion engine and power to be same or higher. Key component was turbocharged diesel internal combustion engine. Increased compressor outlet air pressure can result in an excessively hot intake charge, significantly reducing the performance gains of turbo charging due to decreased density. Passing charge through an intercooler reduced its temperature, allowing a greater volume of air to be admitted to an engine, intercoolers have a key role in controlling the cylinder combustion temperature in turbocharged engine. The author, through his worked out programmed code in MATLAB presented effect of intercooler (as a heat exchange device air-to-liquid with three different size and over – all heat transfer coefficient and one base) at multi-cylinder engine performance for operation at a constant speed of 1600 RPM. Author concluded that maximal temperature in engine cylinder was decreasing from 1665.6 K at $SU = 1000$ to 1659.2 K at SU (surface area x heat transfer coefficient) = 1600, sometimes engine power and volumetric efficiency was increased. In addition, intercooler performance was increased with increased the design parameter [7].

There are mainly three concerning problems present in automobile industry i.e. environmental effect, cost and comfort problems. Therefore, internal combustion engines were required to have not only a high specific power output but also to release less pollutant emissions. For these reasons, that time light and medium duty engines were being highly turbocharged because of having negative environmental effects of internal combustion engines. Due to mentioned facts, there were studies going onto improve internal combustion engine performance. Studies for turbo-charging systems were also included in this range. One of the most important problems faced in turbo-charging system that the air density was decreasing while compressing air. The inter-cooling concept was introduced and performance increase of diesel engine by adding inter-cooling process to a conventional supercharging system in diesel engine was analytically studied. Pressure drops, air density and engine revolution were used as input parameters to calculate the variation of engine power output. In addition, possible downsizing opportunities of the cylinder volume were presented. It was found that the engine power output can be increased 154% by ideal intercooler while single turbocharger without intercooler can only increase 65%. Also, a meaningful 50% downsizing of the cylinder volume possibility achieved by means of turbo charging and intercooling [6].

A theoretical FORTRAN language have been developed based on the book titled "Internal Combustion Engine Applied Thermodynamics" by C.R. FERGUSON for studying the effect of the turbocharger pressure and intercooler temperature on engine performance.

COMPUTATIONAL ENGINE MODELING

In the present model which is developed in FORTRAN language, the working space of combustion chambers of the analyzed model was built in accordance with the real engine geometry of a Four-Stroke MAN Diesel & Turbo engine [9]. Calculation starts in BDC at the beginning of compression stroke for starting conditions of pressure and temperature (P_i and T_i). At the beginning of compression there is air in combustion chambers, at θ_s [deg.] of crank angle (CA) before TDC; the fuel under high pressure is being injected in the cylinder. Research was carried out for lean equivalence ratio (ϕ).

After finishing the calculation, data files can be used to determine pressure and temperature of combustion process as functions of crank angle. Usefulness of numerical modeling of the processes as a tool, which assists during designing and developing combustion systems, in this paper the theoretical model is used to study the effect of the initial pressure and temperature on the Engine performance (Engine with inter-cooler turbo-charging system).

Compression ignition engine (Diesel Engine) combustion analysis is performed using a differential energy equation analysis to determine either the effective energy release or the effective fuel injection rate for a given cylinder pressure profile. The effective fuel injection rate \dot{m}_f is based on the assumptions that the chamber mixture is homogeneous and in thermodynamic equilibrium conditions during the injection and combustion process, and ideal gas behavior is also assumed. The code is based on the book "Internal Combustion Engine Applied thermodynamics" By C.R.FERGUSON, WILEY & SONS 1986 [8].

The open system first law for the combustion chamber, typical calculations for a direct injection (DI) engine use Equation (1) with the injected fuel explicitly included:

$$\frac{\dot{m}_{fi}}{\dot{m}_{ft}} = \frac{\omega}{\theta_d \Gamma(n)} \left(\frac{\theta - \theta_s}{\theta_d} \right)^{n-1} \exp \left[\frac{-(\theta - \theta_s)}{\theta_d} \right] \quad (1)$$

Where:

θ is the Crank angle.

θ_s is the start of fuel injection.

θ_d is a measure of the injection duration.

$\Gamma(n)$ is the Gamma Function = $\int_0^\infty t^{n-1} e^{-t} dt$ (Abramowitz, 1972).

\dot{m}_{fi} is the total injected fuel

ω Engine frequency, [1/sec].

n Shape parameter.

$1 \leq n \leq 2$ for direct injection (DI) chamber

$3 \leq n \leq 5$ for divided chamber

The rate of change of "Burned fuel" in the cylinder is given by equation (2):

$$\frac{d\dot{m}_f}{d\theta} = \frac{1}{\omega} \left(\dot{m}_{fi} - \frac{\dot{m}_t \phi F_s}{1 + \phi F_s} \right) \quad (2)$$

\dot{m}_t is the total mass of air and fuel

The rate of change of "Burned air" in the cylinder is given by equation (3)

$$\frac{dm_a}{d\theta} = \frac{-\dot{m}_t / \omega}{1 + \phi F_s} \quad (3)$$

And the equivalence ratio at any time is given by equation (4):

$$\phi = \frac{m_f}{F_s m_a} \quad (4)$$

The mass in the cylinder at any time is:

$$m = m_a + m_f \quad (5)$$

The energy equation applied to the cylinder contents is given by equation (6):

$$\frac{dU}{d\theta} = -\frac{\dot{Q}_l}{\omega} - P \frac{dV}{d\theta} - \frac{\dot{m}_l h_l}{\omega} + \frac{\dot{m}_f h_f}{\omega} \quad (6)$$

Where

f_s is the stoichiometric ratio

U is the Internal energy.

\dot{Q}_l is the Rate of heat loss.

P is the pressure in the cylinder.

V is the Volume.

h_l is the enthalpy of blow-by fluid.

h_f is the enthalpy of fuel.

By assuming that the system is a homogeneous.

$$U = mu = mu(T, P, \phi)$$

$$V = mv = mv(T, P, \phi)$$

$$h = mh = mh(T, P, \phi)$$

The functional relationships indicated are for equilibrium combustion products, a subroutine ECP is used.

The heat loss rate is given by equation (7);

$$\dot{Q}_l = H \left(\frac{\pi B^2}{2} + \frac{4V}{B} \right) (T - T_w) \quad (7)$$

Where:

B is the cylinder bore, [m].

H is heat transfer coefficient [$J/(m^2.K.sec)$].

T is the combustion temperature [K].

In this case; assuming that the cylindrical combustion chamber with walls temperature T_w [K]. The volume is calculated as a function known from the engine geometry and engine speed.

The principle behind the operation of a diesel engine is the compression-ignition cycle. Downward movement of the piston causes air to be drawn or air forced charged into the engine cylinder where it is compressed on the upward stroke of the piston. Fuel is injected as the piston approaches the end of the compression stroke, and ignites spontaneously. The increase in pressure generated by the fuel burning provides the power of the engine.

A Four-cylinder medium duty C.I. engine have been selected (MAN Diesel & Turbo) [9], engine specifications are:

Engine cycle	4-Stroke
Engine Speed [rpm]	750
Bore [m]	0.225
Stroke [m]	0.3
Inlet air temperature [°C]	52
Inlet air pressure [MPa]	0.2
Bmep [bar]	18.1
Brake Power [kW/cyl.]	135

The code input data are shown in Table (1), in this simulation work over various operational conditions of intercooler turbocharger in terms of T_i and P_i .

Table 1: Input Data for present model.

1	Compression Ratio.		r	13,5
2	Bore.		B [m]	0.225
3	Stroke.		S[m]	0.3
4	Half Stroke to Rod Ratio.		EPS	0.168
5	Engine Speed.		RPM [rev/min]	750
8	Equivalence Ratio		ϕ	0.8
10	Initial Pressure.		P_i [MPa]	0.2
11	Initial Temperature.		T_i [K]	325
12	Wall Temperature.		T_w [K]	650
13	Start of Injection.		θ_s [deg]	-18
14	Fuel Injection Pressure.		P_{inj} [MPa]	250
15	Crank Advance Angle.		θ_c [deg]	2
16	Fuel.		Diesel Fuel.	###

RESULT AND DISCUSSION

After finishing calculation, data files of this model can be used to determine pressure of combustion process as a function of cylinder volume and crank angle. Figures(1) and(2)show the P- θ diagrams of the selected engine (Four-Stroke MAN Diesel & Turbo), with specification given in table (1). Results in these figures, show the effect of the initial pressure and temperature during the compression and expansion process of the engine.

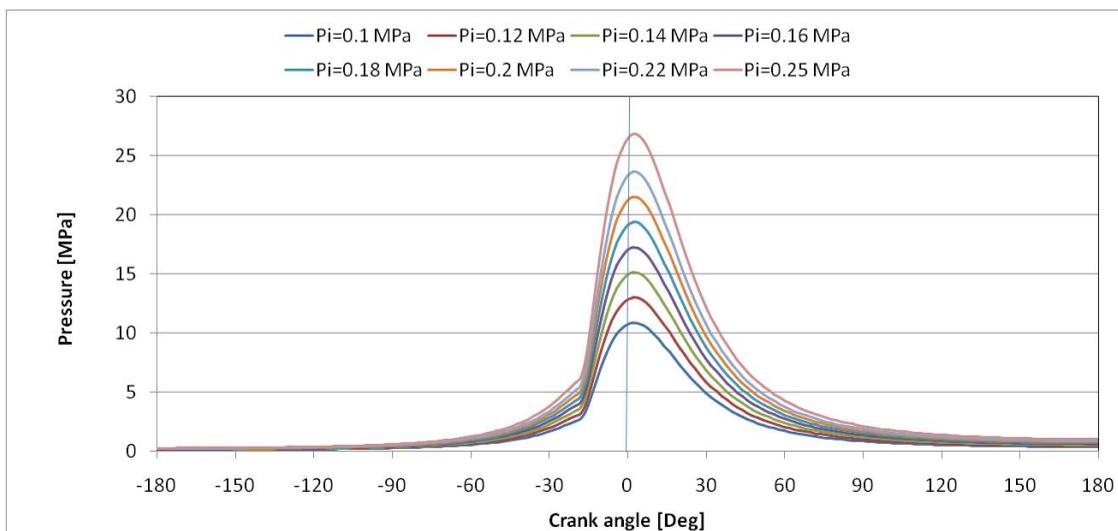


Figure 1: Effect of the turbocharger pressure on the pressure in the cylinder (P) versus crank angle (θ) at inter cooler temperature of 325 K.

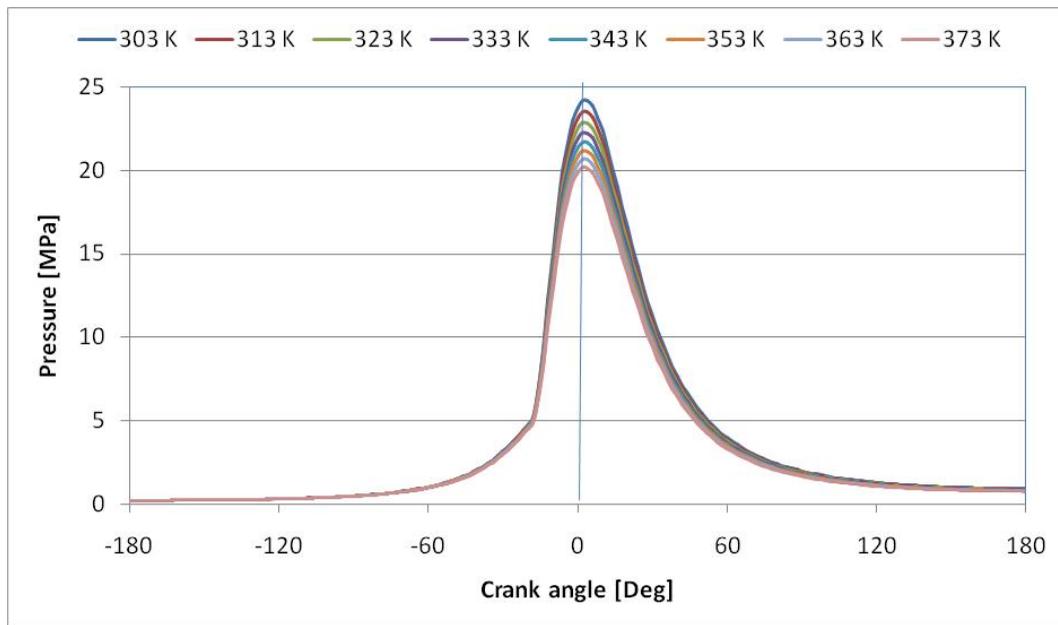


Figure 2: Effect of the Inter-cooler temperature on the pressure in the cylinder (P) versus crank angle (θ) at turbocharger pressure of 0.2 MPa

Figures (3) and (4) show the amount of air charged into the cylinder at the beginning of the compression stroke with the effect of turbocharger and inter-cooler. It is clear from the results that the amount of air is increased with the increasing the turbocharger pressure (Figure 3) and decreasing the inter-cooler temperature (Figure 4).

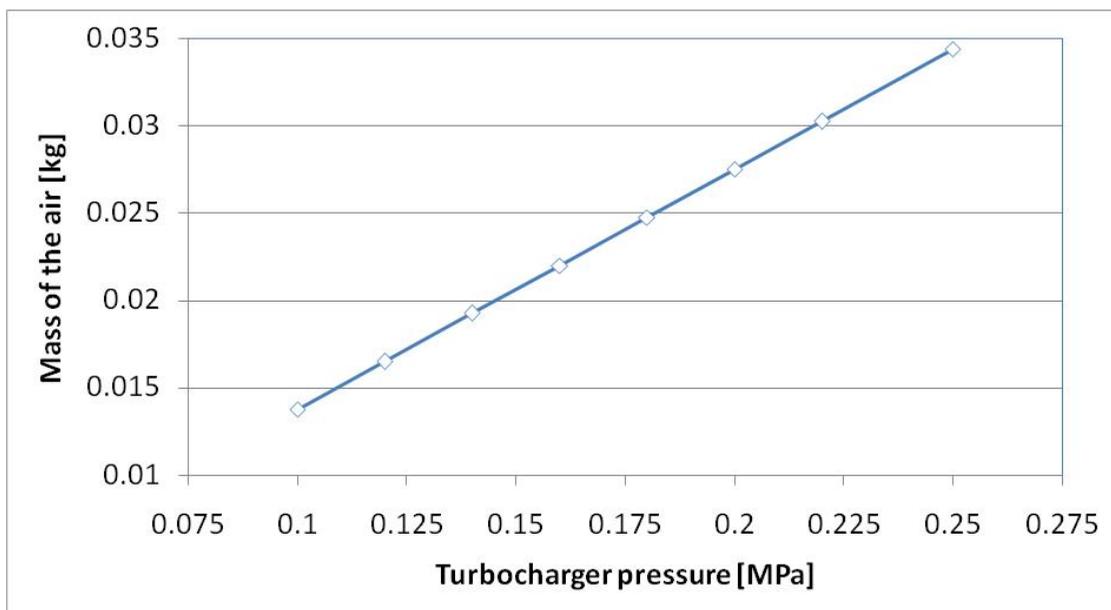


Figure 3: Effect of the turbocharger pressure on the amount of air at the beginning of compression stroke, at inter-cooler temperature of 325 K.

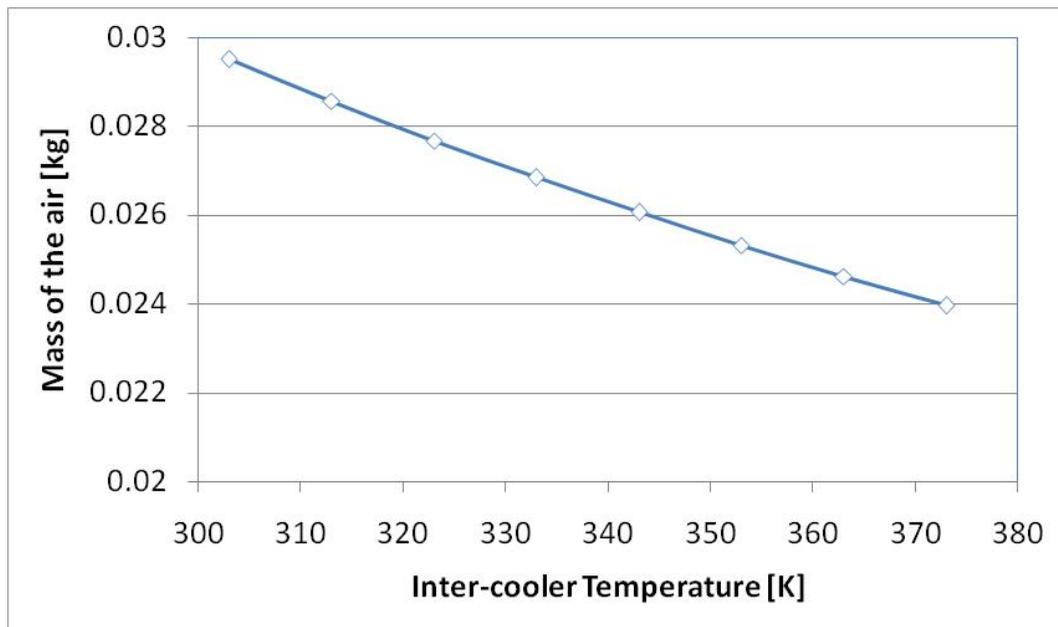


Figure 4: Effect of the inter-cooler temperature on the amount of air at the beginning of compression stroke, at turbocharger pressure of 0.2 MPa.

Figures (5) and (6) show the indicated mean effective pressure (IMEP) as a function of Turbo-charged pressure and the inter-cooler temperature. It can be seen from the figures that, the IMEP is significantly changed with turbo-charged pressure and inter-cooler temperature. High values of IMEP are achieved at high turbo-charged pressure and at low inter-cooler temperature.

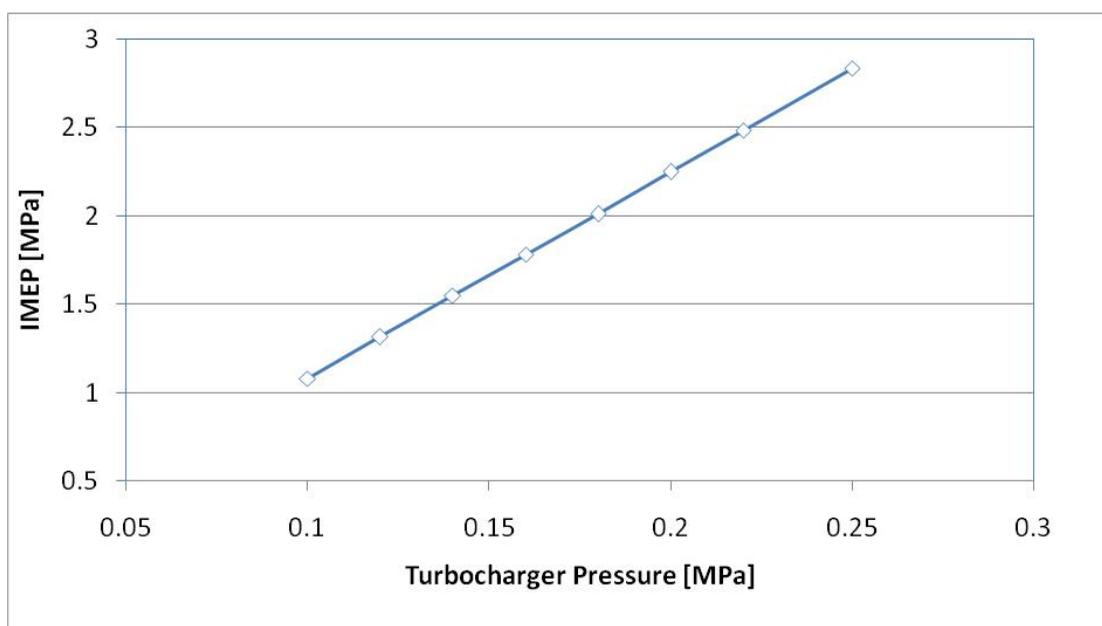


Figure 5: Effect of the turbocharger pressure on the Indicated Mean Effective Pressure (IMEP) at inter-cooler temperature of 325 K.

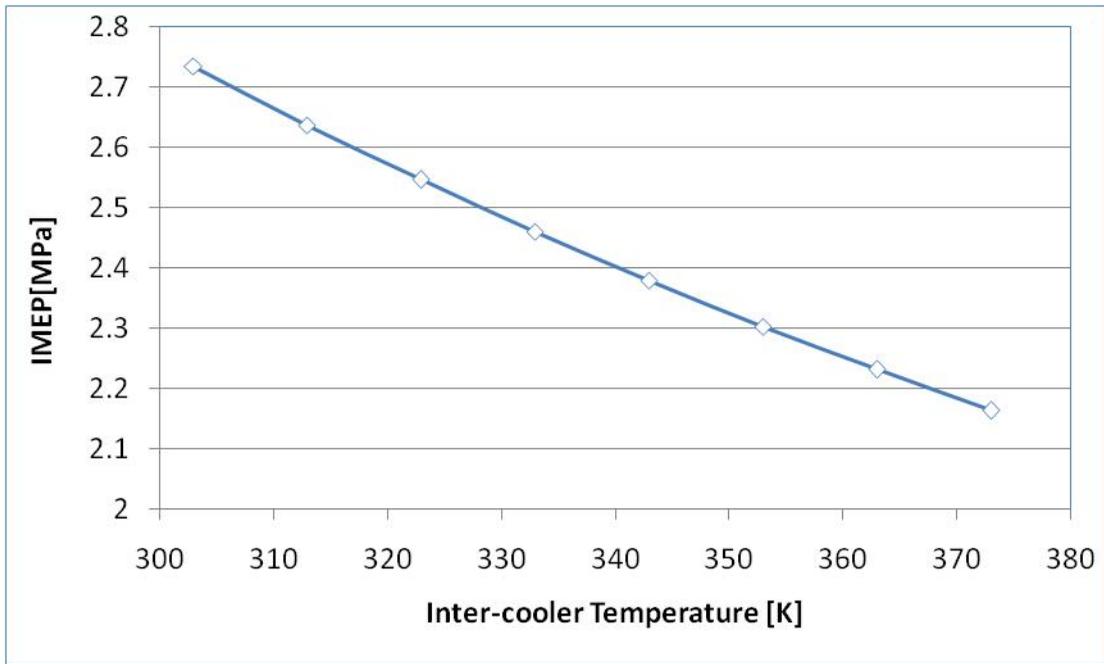


Figure 6: Effect of the inter-cooler temperature on the Indicated Mean Effective Pressure (IMEP) at turbocharger pressure of 0.2 MPa.

Figures (7) and (8) show the effect of the turbo-charged pressure and the inter-cooler temperature on the maximum pressure in the engine cylinder, results show that; the turbo-charged pressure and the inter-cooler temperature have a significant effect on the maximum pressure in the cylinder.

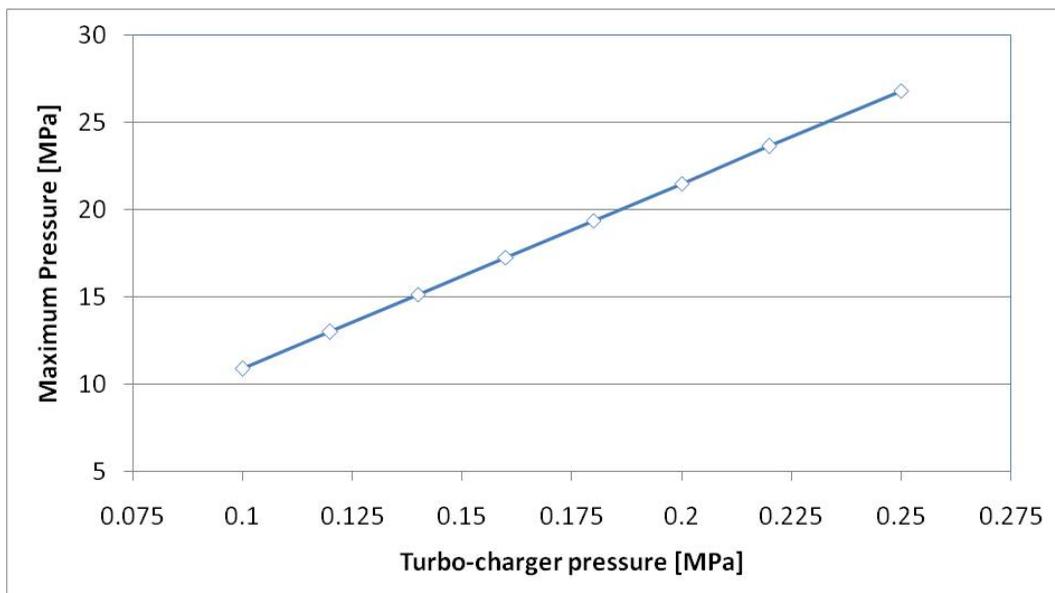


Figure 7: Effect of the turbocharger pressure on the maximum pressure in the cylinder at inter-cooler temperature of 325 K.

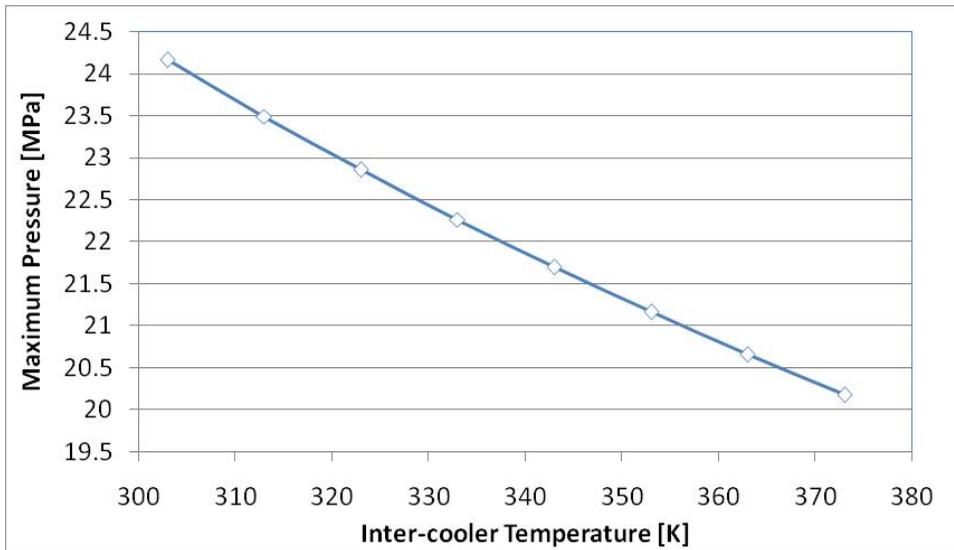


Figure 8: Effect of the inter-cooler temperature on the maximum pressure in cylinder at turbocharger pressure of 0.2 MPa.

Figures (9) and (10) show the indicated power (PI) as functions of Turbo-charged pressure and the inter-cooler temperature. It is evident from the figures that the indicated power is strongly related to the Turbo-charged pressure and the inter-cooler temperature, in this engine test, the indicated power at Turbo-charged pressure of 0.25 MPa increased more than 2.5 times when the engine without turbocharger.

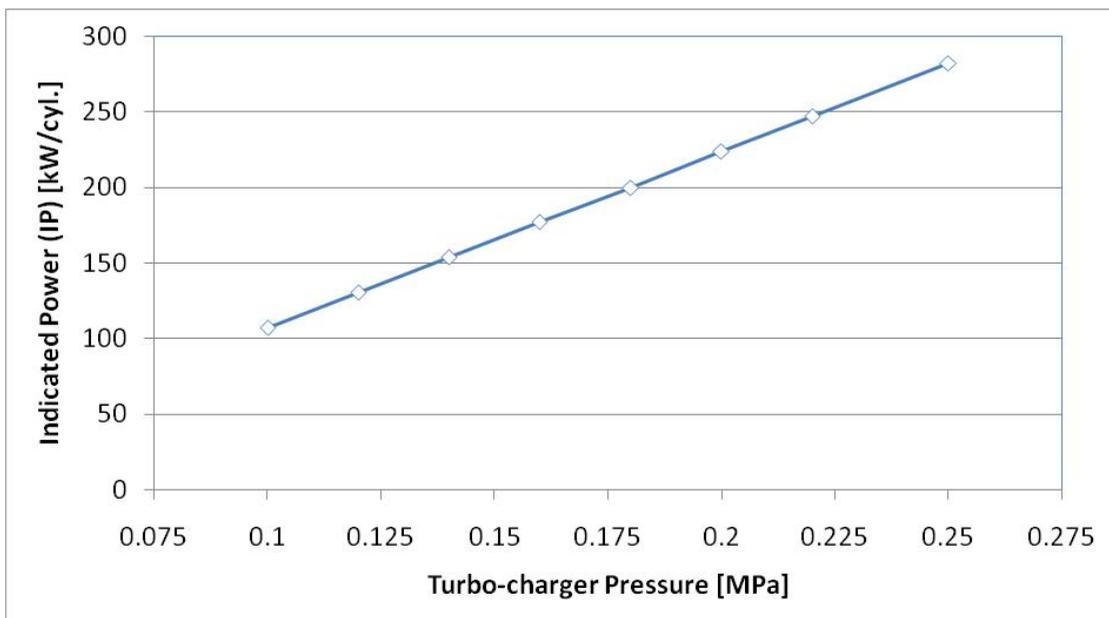


Figure 9: Effect of the turbocharger pressure on the Indicated Power (IP) at inter-cooler temperature of 325 K.

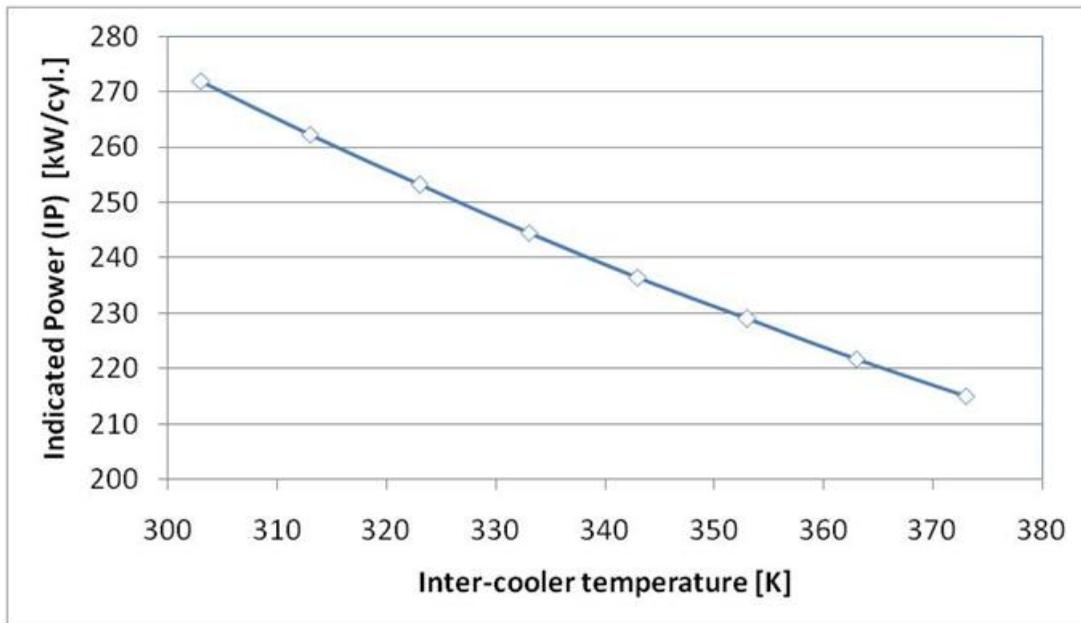


Figure 10: Effect of the inter-cooler temperature on the Indicated Power (IP) at turbocharger pressure of 0.2 MPa.

Figures (11) and (12) show the thermal efficiency as a function of turbo-charged pressure and inter-cooler temperature, it can be seen from the results that the thermal efficiency is increase significantly as the turbocharger pressure is increased. By decreasing the inter-cooler temperature inlet to the engine, the thermal efficiency also is strongly increases. The results demonstrate that the thermal efficiency is clearly related to the turbo-charged pressure with inter-cooler, the results show that the thermal efficiency increase is non-linear with turbo-charged pressure.

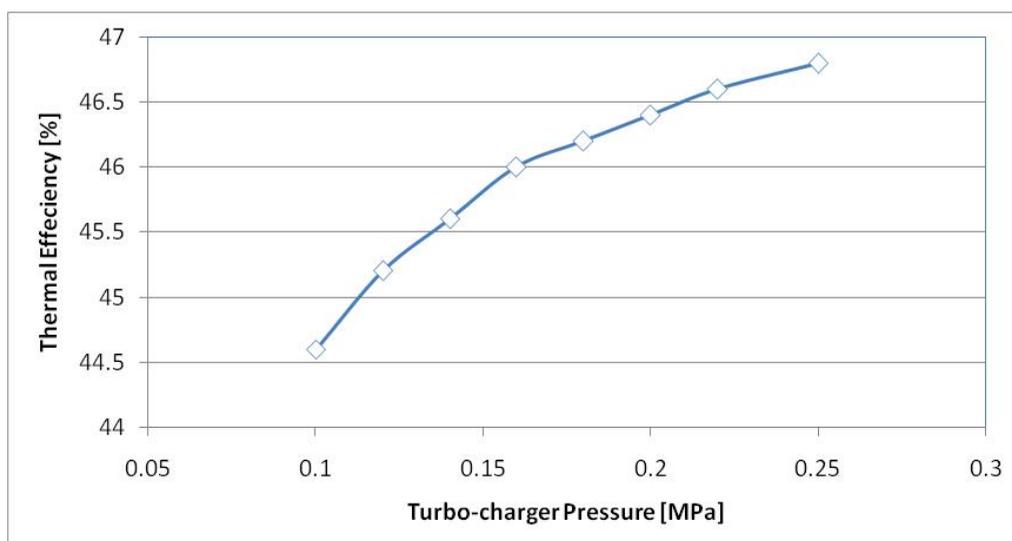


Figure 11: Effect of the turbocharger pressure on the thermal efficiency at inter-cooler temperature of 325 K.

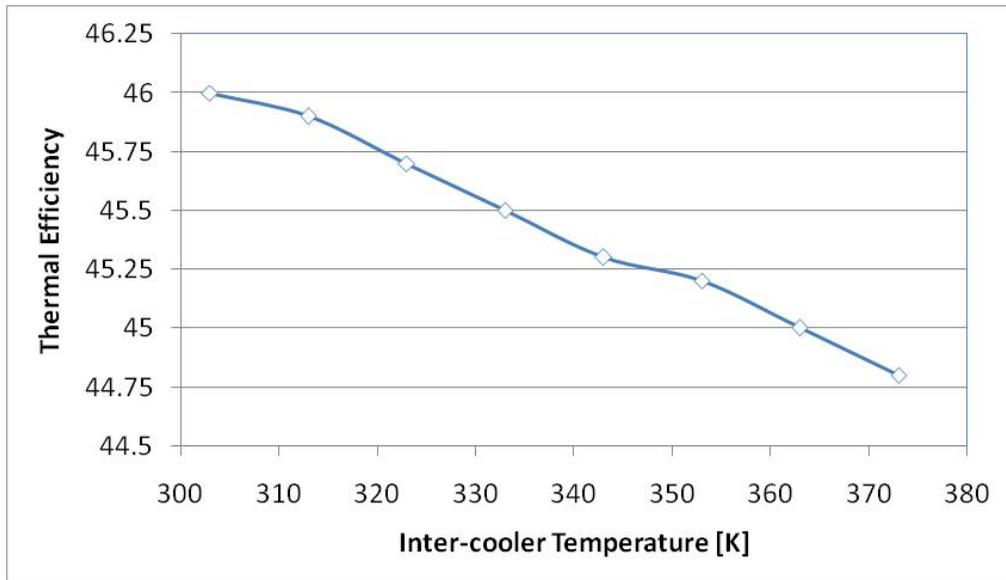


Figure 12: Effect of the intercooler temperature on the thermal efficiency at turbocharger pressure of 0.2 MPa.

Figures (13) and (14) show the specific fuel consumption as a function of turbo-charged pressure and the inter-cooler temperature. From the figures, it is clear that the specific fuel consumption strongly decreases when the turbo-charged pressure increased, and increases with decreasing of inter-cooler temperature.

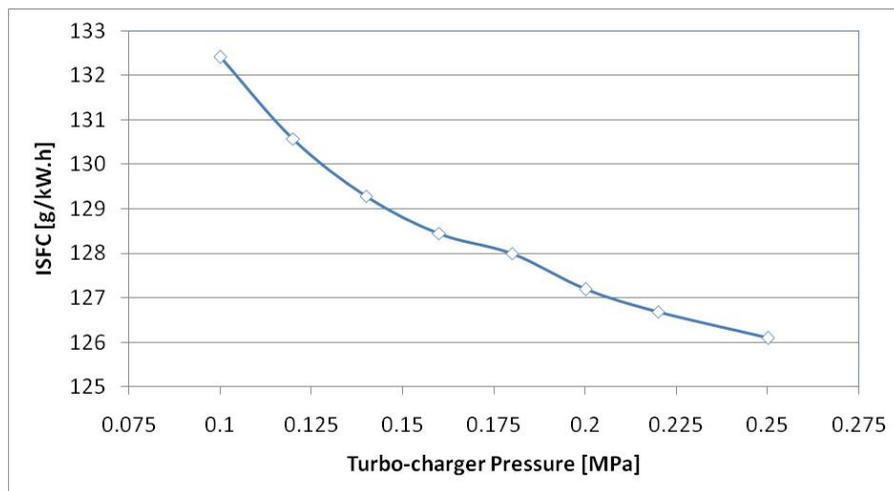


Figure 13: Effect of the turbocharger pressure on the Indicated Specific Fuel consumption (ISFC) at inter-cooler temperature of 325 K.

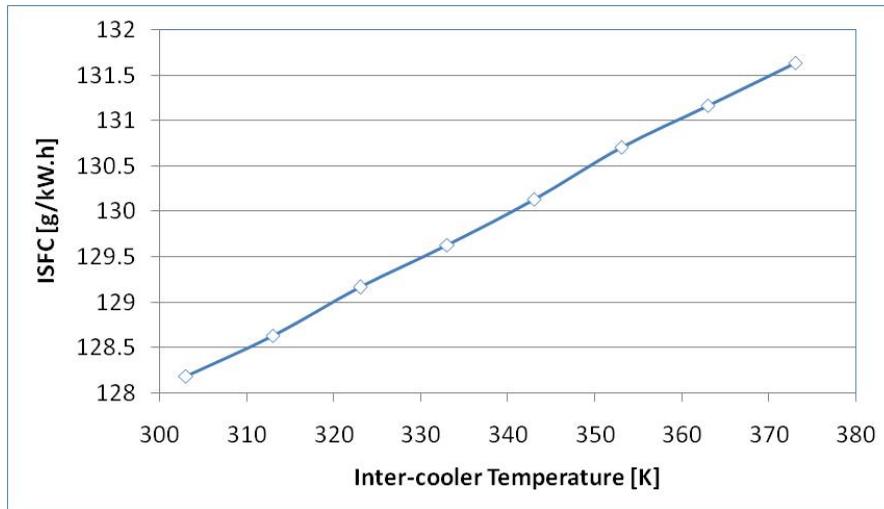


Figure 14: Effect of the inter-cooler temperature on the Indicated Specific Fuel Consumption (ISFC) at turbocharger pressure of 0.2 MPa.

CONCLUSIONS

Modern diesel engines always use a turbocharger system with inter-cooler to improve the engine performance. MAN B&W Diesel designed and successfully field-tested a package of suppressing the formation of soot in highly turbocharged engines. In this research, a four-stroke MAN Diesel & Turbo middle speed diesel engine was studied under the rating condition of 750 rpm and 135 kW/cyl. FORTRAN simulation was established to simulate the performance of the diesel engine under different operation conditions of turbo-charged pressure and inter-cooler temperature. Thermodynamic analysis of the turbocharged Diesel engine was based on the book "Internal Combustion Engine Applied Thermodynamics" By C.R. FERGUSON, [8]. The conclusions are; by keeping the equivalence ratio constant, the results show that the specific fuel consumption decreased with increasing the turbo-charged pressure, and by decreasing the inter-cooler temperature. The results also show that the indicated power was significantly increased with a turbocharging and intercooling, at turbocharger pressure of 0.25 MPa and with inter-cooler Temperature of 325K, the indicated power was increased more than 2.5 times, compared with the engine without turbo-charged (0.1 MPa).

Nomenclature

Abbreviation	Description
RPM	Revolution Per Minute
BDC	Bottom Dead Centre
CA	Crank Angle
TDC	Top Dead Centre
DI	Direct Injection
C I	Compression Ignition

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