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Parametric Consideration of Marine Diesel Engine Output for Maximum Operation

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ABSTRACT

Diesel engines simulation has contributed immensely towards the aim of new evaluation and development. This present work contributes to a better simulation of the transient operation of improving the existing relation. It deals with the parametric consideration of Marine Diesel Engine (MDE) output for maximum operation. A four stroke caterpillar 3516B series MDE with 16 – VTS was used to actualize the work. A well-known model was adopted using temperature approach to obtain efficiencies of the engine. A computer program code named MDEPAC written in visual-basic programming language was developed. The result obtained affirmed that the value of 42.952KW to 1647.84KW of power output and 239.01kN/m^2 to 1791.13kN/m^2 for mean effective pressure should be maintained to avoid any breakdown of the engine.

Keywords: *Parametric consideration, marine diesel engine, output and maximum operation*

NOMENCLATURE

N = Revolution of the engine, rpm
K = Constant
L = Stroke of engine, m
A = Area of the cylinder, m^2
γ_v = Compression ratio
V_s = Swept volume, m^3
P_m = Mean effective pressure, kN/m^2
W = Power output of the engine, KW
T_2 = Compression temperature at stage 2, ^oC
T_1 = Initial compression temperature at stage 1, ^oC
P_2 = Compression pressure at stage 2, kN/m^2
P_1 = Compression pressure at stage 1, kN/m^2
γ_c = Cut off ratio
T_3 = Temperature at stage 3, ^oC
T_4 = Temperature at stage 4, ^oC
T_5 = Temperature at stage 5, ^oC
C_v = Constant volume compression
m = Mass flow rate, Kg/s
C_p = Specific heat capacity, KJ/kg
η_i = Indicated thermal efficiency, %
P_E = Effective power, KW
P_b = Brake power, KW
η_b = Brake thermal efficiency, %
γ_p = Isentropic compression ratio
BDC= Bottom Dead Center
TDC=Top Dead Center

I. INTRODUCTION

Compression Ignition Engines (CIEs) of diesel engines (DEs) as they are commonly known after their inventor Dr. Rudolph Diesel, convert chemical energy stored in fuel into mechanical work at the crank shaft revolution. Whilst these engines come in variety of different forms and vastly different sizes they are rely on the principle that fuel is ignited by heat generated during compression in the cylinder [1]. However, their operation is generally based upon either the two or four-stroke engine cycles, which refer to the number of piston strokes occurring during one cycle of event [2, 3].

The marine diesel engine (MDE) is a very complicated and rugged mechanical system due to the existence of the turbo charger and all the other sub-systems. These engines offer various advantages among which are high efficiency, high power concentration and long operational life time [4]. On the other hand, their large size can cause great difficulties in the diagnoses of improper operation. The parameters usually measured are various temperatures, vibration level, shaft speed, power output, flow rate and various pressure. Even after these data are in hand, it is extremely difficult in many cases, to identify the causes of the faults, since most of these parameters may have similar effects [5].

As a typical DE, there are however, fundamental mechanical and thermodynamic differences between them and other cycles which make compression less valuable than might be expected. In the theoretical cycle, there is no chemical change in the working fluid which is assumed to be air, and the exchanges in the cycle are made externally to the working fluid. In the practical cycle, the heat supply as obtained from the combustion products must be exhausted from the cylinder before a fresh charge air can be induced for the next cycle [6, 7]. The practical cycle also consists of the exhaust and induction processes together with the compression and expansion process as in the theoretical cycle [8].

Other Approaches

Ishiodu and Ogbonnaya [5] drafted a work on optimizing the performance of a MDE towards proactive condition monitoring. In the work, a computer program named MDEPEA written in V-Basic Programming Language was used to actualize their work.
Furthermore, Rahim [9], produced a work on performance of an irreversible Diesel cycle under variable stroke length and compression ratio. In that work, the relations between the power output and the thermal efficiency are derived in detail. Subsequently, the maximum power output and the corresponding efficiency limits of the cycle with considerations of heat transfer and friction like term losses are also found with clear detailed numerical examples.

Rao, [10] carried out experimental investigations on the influence of biodiesel on performance, combustion and emission characteristics of a Direct injection and CIE. In the work, the experiments were performed at different engine operating regimes with the injection timing prescribed by the engine manufacturers for diesel fuel. The engine characteristics with Jatropha biodiesel were compared against those obtained using diesel fuel.

A research on numerical simulation for parametric study of a two stroke compression ignition direct injection linear engine was executed by Ehab [11]. In that work, the simulating program adopted used a series of dynamic and thermodynamic equations that were solved simultaneously to predict the performance and analyzed the different factors affecting the operation of the two-stroke CIE coupled with liner alternator.

Approach used in this present work

The present work contributes to a better simulation of the transient operation by improving on the existing relations. It deals with parametric consideration of M D E output for maximum operation. This was brought to fruition using a software named MDEPAC writing in visual basic (V-Basic) programming language. MDEPAC stands for Marine Diesel Engine Parametric Analysis and Consideration. This was carried out with a case study of a caterpillar 16 VTS engine series 3516B, with 170mm bore/190mm stroke of approximately 1492KW power output.

2. MATERIALS AND METHODS

Strictly speaking, parametric analysis involves the determination of range of variations in a physical properties or thermodynamic properties of a given system whose behaviour has been studied only experimentally.
Caterpillar 3616B MDE is a high speed engine with trunk configuration. The engine operates on four stroke cycle and has a compression ratio of 134 to 1. It has a 170mm bore/190mm stroke with a maximum speed of 1600 rpm. Other features includes V16-cylinder arrangements and the higher B-ratings, can offer output up to around 2200KW by its counter clockwise rotation facing the fly wheel [4].

The theoretical analysis for the evaluation of a 4-stroke caterpillar 3516B series MDE parametric performance was carried out using the air standard dual cycle as shown in figure (1). Figure 1 shows a p-v diagram, which is a theoretical analysis of dual combustion cycle.

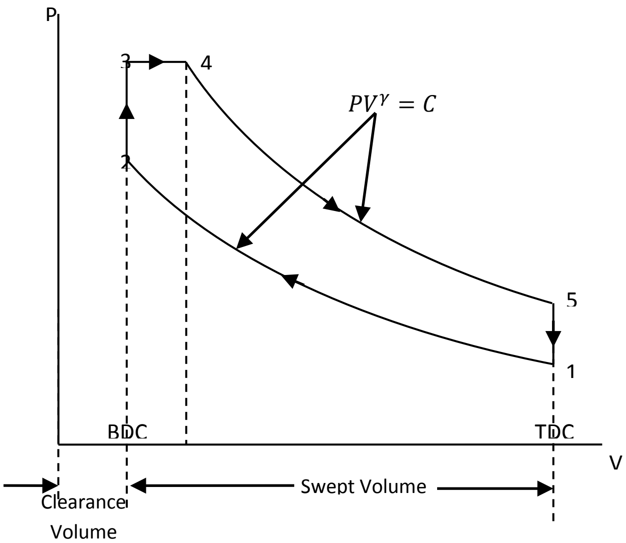

Fig 1: Dual Cycle P.V diagram for full load operation of model engine [6, 7]

In this cycle, the heat addition occurs during the constant volume process 2 – 3, Hence

$$Q_1 = M_{cv}\left(T_3 - T_2\right) + M_{cp}\left(T_4 - T_3\right) \qquad 1$$

The heat rejection takes place during the constant volume process 5 – 1 so that;

$$Q_2 = M_{cv}\left(T_5 - T_1\right) \qquad 2$$

The work output is therefore $\left(Q_1 - Q_2\right)$ with the result that the thermal efficiency of the cycle may be expressed as;

$$\eta_m = \frac{Q_1 - P_2}{Q_1} =$$

$$\frac{M_{cv}\left(T_3 - T_2\right)M_{cp}\left(T_4 - T_3\right) - M_{cv}\left(T_5 - T_1\right)}{M_{cv}\left(T_3 - T_2\right) + M_{cp}\left(T_4 - T_3\right)} \qquad 3$$

$$= 1 - \frac{\left(T_5 - T_1\right)}{\left(T_3 - T_2\right) + \gamma\left(T_4 - T_3\right)} \qquad 4$$

In order to express the above equation in terms of engine parameters, we shall express all temperatures in terms of T_1, therefore

Four process 1 – 2 in figure 1 and b.

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{r-1}, \; but \; \frac{p_2}{p_1} = r$$

$$\therefore\; T_2 = T_1\, r^{\,r-1} \qquad 5$$

From process 2 – 3, $\frac{p_2 v_2}{T_2} = \frac{p_3 v_3}{T_3}$ 6

So that

$$T_3 = T_2 \frac{p_3}{p_2}, \quad since\, V_2 = V_3$$

A new engine parameter, the pressure ratio is defined as

$r_p = \frac{p_3}{p_2}$ such that

$$T_3 = T_2\, \gamma_p = T_1\, \gamma_p\, \gamma^{r-1} \qquad 7$$

For process 3 – 4,

$\frac{P_3\, v_3}{T_3} = \frac{P_4\, v_4}{T_4}$ so

$$T_4 = T_3 \frac{P_4}{P_3} \frac{v_4}{v_3} \qquad 8$$

$$P_4 = P_3 \; and\; so\; T_4 = T_3 \frac{v_4}{v_3}$$

but

$$= T_3\, v_c = T_1\, \gamma_c\, \gamma_p\, \gamma^{v-1} \qquad 9$$

For process 4-5,

$\frac{P_4 v_4}{T_4} = \frac{P_5 v_5}{T_5}$ so that

$$T_5 = T_4 \frac{P_5}{P_4} \frac{v_5}{v_4} \qquad 10$$

Since $\frac{P_5}{P_4} = \left(\frac{v_5}{v_4}\right)^{r}$ the process being isentropic, then

$$T_5 = T_4 \left(\frac{v_4}{v_5}\right)^r \left(\frac{v_5}{v_4}\right) = T_4 \left(\frac{v_5}{v_4}\right)^{1-r} \quad 11$$

$$= T_4 \left(\frac{v_5}{v_3}\ \frac{v_3}{v_4}\right)^{1-r}$$

$$= T_4 \left(\frac{v_4}{v_5}\right)^{1-r} = T_1\, \gamma_c\, \gamma_p\, \gamma^{r-1}\, \gamma^{1-r}\, \gamma_c^{\ r-1}$$

$$= T_1\ \gamma_p\, \gamma_c^{\ r} \quad 12$$

Substituting all temperature values into the equation for the thermal efficiency of the dual cycle yields

$$\eta_m = \frac{1 - T_1\left(\gamma_c^{\ r}\ \gamma_p - 1\right)}{T_1\left(\gamma_p\,\gamma^{r-1} - \gamma^{r-1}\right) + \gamma T_1\left(\gamma_c \gamma_p \gamma^{r-1} - \gamma_p\,\gamma^{r-1}\right)} \quad 13$$

$$= 1 - \frac{\left(\gamma_c^{\ r}\ \gamma_p - 1\right)}{\gamma^{r-1}\left[\left(\gamma_p - 1\right) + \gamma\, r_p\left(\gamma_c - 1\right)\right]}$$

$$= 1 - \frac{1}{\gamma^{r-1}} \frac{\left(\gamma_c^{\ r}\ \gamma_p - 1\right)}{\left[\left(\gamma_p - 1\right) + \gamma\, r_p\left(\gamma_c - 1\right)\right]} \quad 14$$

Equation 13 is the expression for the thermal efficiency of the mixed or dual cycle. It is obtained using parametric analysis. Other engine performance parameters are;

For compression ratio $\gamma_v = {}^{v_1}\!/_{v_2}$ 15

Swept volume $v_s = v_1 - v_2$ 16

Net power output $W = p_m \, x \, v_s$

where p_m = mean effective pressure

v_s = swept volume

As earlier stated in Ishiodu and Ogbonnaya 2011, the power output can be determine as

$$W = p_m\ L\ AN\ ks \quad 17$$

So that

$$Vs = \frac{L\ ANks}{60}$$

where

L = *stroke of the engine*

A = Area of the bore

N = Revolution of the engine (rpm)

k = constant 1 for 2 stroke engine and ½ for four stroke engine

Then swept volume, Vs *becomes*

$$Vs = \frac{L\ ANks}{60} = k\ A\, ks\ x\, \frac{N}{60}$$

Brake thermal efficiency $\mu_b = \frac{P_b}{P_E}$ 18

where

P_b = *Brake power*

P_E = *Effective power*

Figure 2 is the flow chart for MDEPAC. The flow chart was used to write a double loop iterative v-Basic computer program. The program helped to calculate the parametric aspects of the referenced engine which includes all the thermodynamic properties of an engine, such as work output and MEP at various operating speed of the engine.

3. RESULTS AND DISCUSSION

The theoretical result obtained at various thermodynamic properties of the referenced engine is presented in table (1). The thermodynamic property of interests are temperature pressure and volume at strategic point shown in figure 1 (a) and (b). Other engine performance parameter which includes compression ratio, swept volume and power at various speeds is also shown in the table 1.

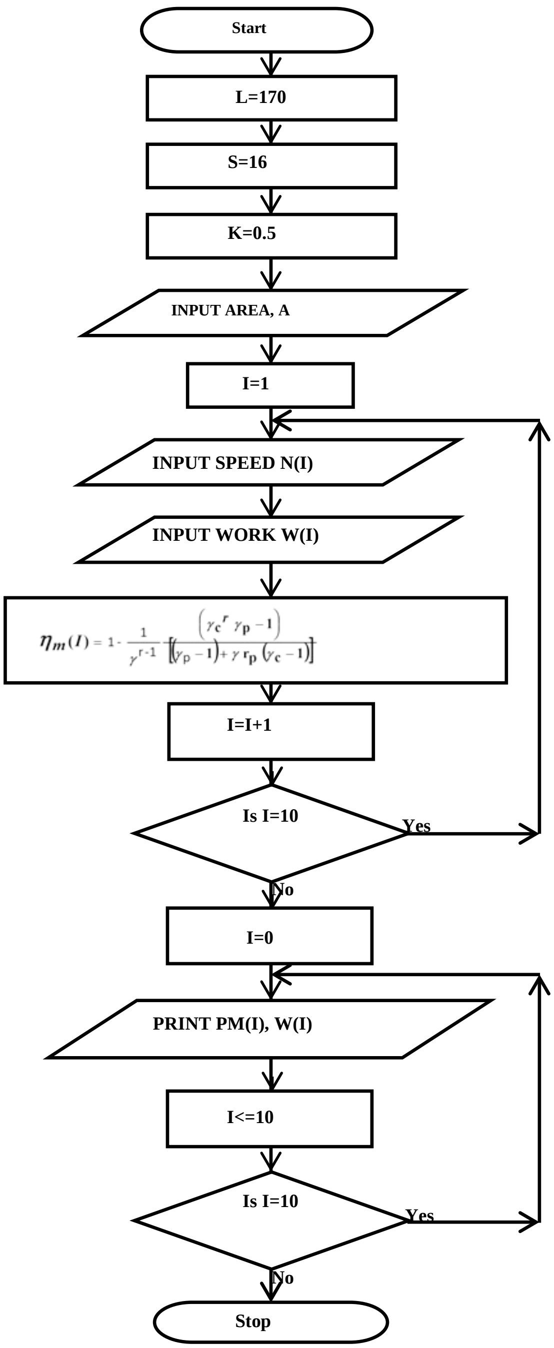

Fig. 2: Flow chart for MDEPAC

These results in tabular forms were used to show the values at different point of the air standard dual (mixed) cycle used for the evaluation of the combustion process of the engine.

Figure 3 shows the variation in the higher temperature at the constant volume located at point T_3. In the figure, it is found that T_3 increases with the increase of compression ratio.

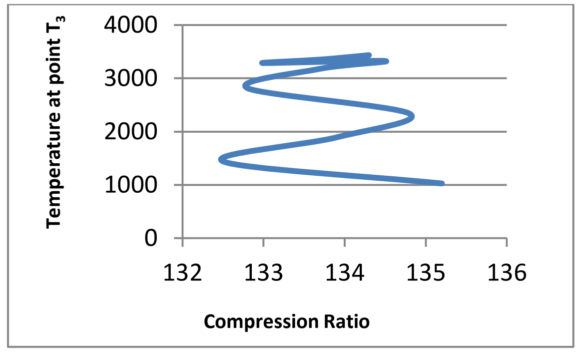

Fig 3: Plot of temperature against compression ratio

Figure 4 shows the plot of compression ratio against power output. From the graph, it can be seen that the power output versus compression ratio is approximately parabolic like curves. In other word, the power output increases with a resultant increase in compression ratio.

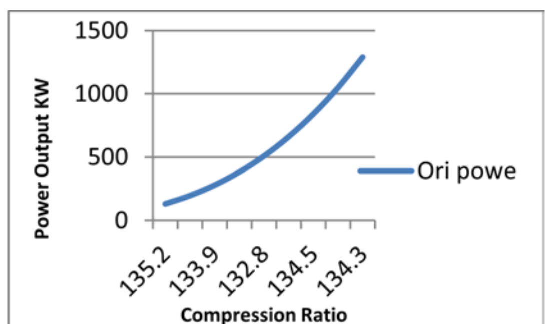

Fig 4: Power output against compression ratio

Figures 5 and 6 shows the relation between power output against mechanical and Brake thermal efficiency respectively. In the plots the dramatic increase in efficiency per unit increase in power output is demonstrated.

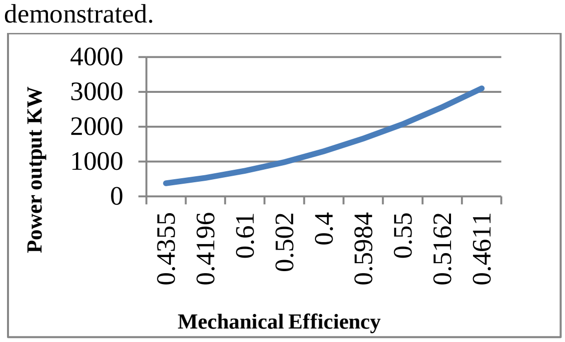

Fig. 5: Power output against mechanical efficiency

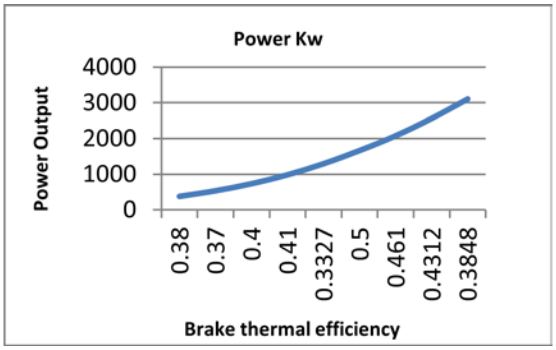

Fig. 6: Power output against efficiency

Figure 7 shows the graph of power output against speed for all the operational conditions of the engine under investigation ranging from 700 rpm to 1600 rpm. Original trial values of power with relation to speed from the manufacturer were drawn on the same graph in order to compare it with the calculated values obtained during the engine evaluation and analysis.

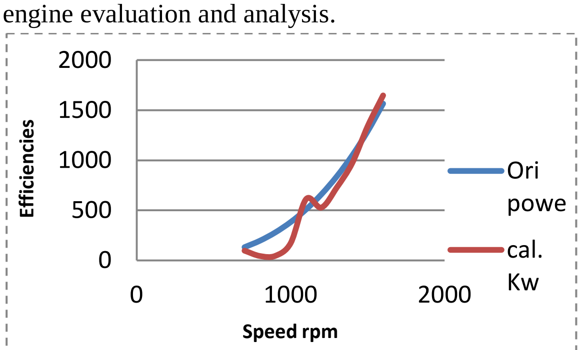

Fig. 7: Efficiency against speed

The relation between the different efficiencies at various speed of the engine under investigation is clearly shown in figure 8.

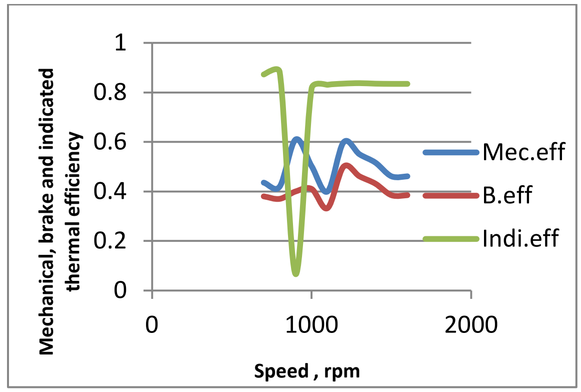

Fig. 8: Graph of mechanical, brake and Indicated thermal efficiencies against speed

From the graphs, it is evident that the division of brake power by the indicated power would give the mechanical efficiency which is a clear indication that the best performance of the engine occur at the designed speed of 1600 rpm.

Figure 9 shows the variation of speed of the engine under investigation at a given interval. From the graph, it is shown that the engine tends to increase as the operational time of the engine increases.

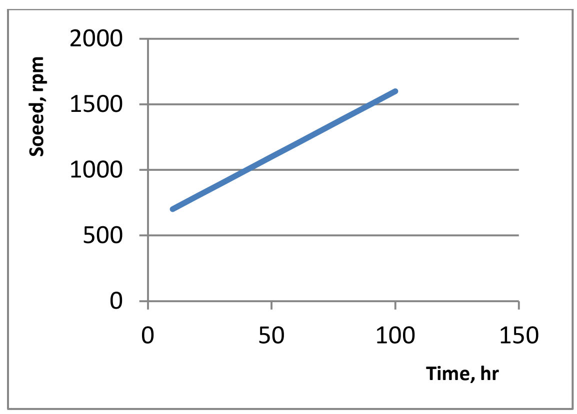

Fig. 9: Graph of speed against time

4. CONCLUSION

A work has been carried out on parametric consideration of MDE output for maximum operation. It is observed that the compression ratio plays a major role in the calculation of pressure, temperature and volume of the engine in conjunction with the initial intake values of the temperature and boost pressure gauge readings.

To determine the dramatic increase of engine performance, a well-known mathematical model was adopted using a temperature approach to derive the mechanical efficiency of the engine. A caterpillar 16VTS engine series 3516B engine with 170mm bore/190mm stroke of approximately 1492KW power output was used as the test engine. Simulation was also carried out using a software name MDEPAC writing in V-Basic programming language.

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Table 1: Different Values obtained for the air standard dual (mixed) cycle for the engine at all operating conditions

Pressure (bar)	P_1	1.01	1.04	1.086	1.155	1.274	1.452	1.685	2.142	2.558	2.921
	P_2	960	988.5	1032.23	1097.814	1210.92	1380.109	1601.57	2035	2431.35	2776.376
	P_3	459.1	663.629	909.111	1215.812	2151.003	2042.03	2478.237	3113.78	3792.73	4437.4
	P_4	459.1	663.629	909.111	1215.812	2151.003	2042.03	2478.237	3113.78	3792.73	4437.4
	P_5	0.616	0.916	1.246	1.652	2.915	2.756	3.333	4.26	5.26	6.01
Volume (m^3/s)	V_1	0.4056	0.4636	0.5215	0.5795	0.6374	0.6954	0.7533	0.8113	0.8692	0.9269
	V_2	0.003	0.0035	0.0039	0.0043	0.0048	0.0052	0.0056	0.0061	0.0065	0.0069
	V_3	0.003	0.0035	0.0039	0.0043	0.0048	0.0052	0.0056	0.0061	0.0065	0.0069
	V_4	0.0036	0.0042	0.0047	0.0052	0.0048	0.0062	0.0067	0.0073	0.0079	0.00828
	V_5	0.4056	0.4636	0.5215	0.5795	0.6374	0.6954	0.7533	0.8113	0.8692	0.9269
Temperature (K)	T_1	303	303	303	303	303	303	303	303	303	303
	T_2	2149.24	2149.24	2149.24	2149.24	2149.24	2149.24	2149.24	2149.24	2149.24	2149.24
	T_3	1027.83	1442.88	1892.89	2338.25	2817.77	3180.05	3325.69	3287.05	3352.66	3435.07
	T_4	1233.4	1731.456	2271.468	2856.3	3381.324	3816.06	3990.828	3944.46	4023.192	4122.084
	T_5	186.374	263.787	345.338	433.49	512.474	577.67	603.54	599.3	613.72	624.476
Compression Ratio (r_v)		135.2	132.5	133.9	134.8	132.8	133.7	134.5	133.0	133.7	134.3
Swept Volume (m^3/s)		0.4026	0.4601	0.5177	0.5752	0.6327	0.6902	0.7477	0.8052	0.8627	0.92
Power Input KW		378.24	535.31	734.44	984.47	1296.18	1665.71	2078.55	2563.89	3106.17	3720.184
Speed (rpm)		700	800	900	1000	1100	1200	1300	1400	1500	1600
Original power kw		131.1	195.7	278.7	382.3	508.9	660.7	840	104901	1290.3	1566
Calculated power kw		96.226	42.952	44.458	172.448	611.784	527.838	729.104	973.192	1341.107	1647.84
Engine efficiencies	Mechanical efficiency	0.4355	0.4196	0.61	0.502	0.4	0.5984	0.55	0.5162	0.4611	0.4611
	Indicated thermal efficiency	0.8725	0.8817	0.06569	0.8061	0.8308	0.8355	0.8374	0.8353	0.8345	0.8345
	Brake thermal efficiency	0.3855	0.37	0.4	0.41	0.3327	0.5	0.461	0.4312	0.3848	0.3848

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