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RESEARCH ARTICLE

Mechanical Design and Theoretical Performance Analysis of a Modified Engine to Improve Fuel Efficiency

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Abstract

Background: It is a product-oriented breakthrough in technological research carried out for the following reasons: Each year, India imports more than Five lakh crore rupees (INR) worth of fuel, with commercial vehicles roughly using 4 lakh crore rupees worth of diesel. The engines of these vehicles are water-cooled, which keeps the temperature of the engine materials below 100°C. The temperature of the material must remain below 100°C for the reasons listed below. If the temperature in the cylinder surpasses 100°C, the water in the radiator will boil. When the temperature rises over 140°C, the liquid lubricant becomes charred and sticky and seizes the engine. Hence, if liquid oil is used, a radiator has to be utilised, and in that case, heat loss to the surroundings through the radiator is between 30 and 40% of the diesel equivalent. **Objectives**: To draw performance curves for the proposed modified single cylinder and to do thermal and design calculations. An engine of the single-cylinder category and diesel run by diesel in the design stage of conversion to drastically improve efficiency. **Methods:** In a stainless steel cylinder, a stainless steel piston is installed over a conventional piston, and the firing is transferred to the stainless steel piston, which lacks piston rings. Only a close gap is maintained between the stainless steel cylinder and the stainless steel piston, as no liquid lubricant is used, and the radiator can be eliminated. Fabrication drawings for the proposed modification of the single-cylinder diesel engine are made using AutoCAD to improve efficiency by adding two attachments. Thermal calculations are performed using fundamental equations, and performance curves are then generated and analysed. 3D modelling is carried out for the piston and cylinder independently using Autodesk Inventor. ANSYS software is used to get temperatures in selected regions and calculate heat loss from the hot piston bottom. A rigorous theoretical analysis was conducted on the proposed modification planned for optimum performance. **Findings:** The thermal performance calculations were made for various load conditions, viz., 0%, 20%, 40%, 60%, 80%, 100%, 120%, 130%, 140%, and 150% of rated load, and the thermal performance outputs are tabulated and displayed in the form of graphs. The theoretical analysis and discussions are detailed in this paper. **Novelty:** There will be a chance to improve overall efficiency by around 59% at the rated load.

Keywords: IC Engine; Diesel Engine; Fuel Saving; Thermal Efficiency; Performance

1 Introduction

The use of fossil fuels to generate energy for the transport, agriculture, construction, and power generation sectors is increasing daily. These fuels are refined from non-renewable energy sources, and their reserves are quickly depleted [1]. The modern engines, SI, CI, or gas turbines, now in use, are sophisticated units. Nevertheless, the ongoing pressure on fuel resources, the need to implement alternative fuel strategies in the future, the increasing population, energy consumption, and the resulting environmental problems mean that a high pace of development will continue for a considerable time [2]. With the current state of the art and its prospects, it may be better to consider engine development for higher efficiency and the development of alternative fuels. Engineers continuously strive to achieve great heights in thermal efficiency and energy conservation in internal combustion engines. Every engine converts energy into work, according to the energy conservation law. From this point of view, the diesel engine converts thirty per cent of the energy into work, and the remaining energy goes to the coolant, the exhaust, and is unaccounted for. The basic theoretical step through which the practical development of engines has occurred. With such a theoretical analysis, the level of power output and efficiency could have been reached, and internal combustion engines would have remained clumsy devices more of a curiosity than of practical value. Practically, in diesel engines, we can conclude from the observation that a higher temperature in the exhaust gas than that of the surroundings indicates more heat carried over by the exhaust gas. A certain amount of heat is also transferred to the coolant. The need for coolant has decreased over time, and it is now being attempted in this research work to almost eliminate it to maximise efficiency.

The fundamental engine design was altered by adding two attachments between the standard cylinder and cylinder head. The modified diesel engine's top cylinder and top piston are intended to be separated by a small distance. The internal diameter of the complete cylinder is chosen to be almost equal to the diameter of the current cylinder. Figure 1 's overall assembly drawing serves as an example of the Kirloskar engine conversion process. The top piston and the piston of the traditional engine are linked by a piston rod and move in unison. A typical engine has three temperature zones: a hot zone, an intermediate temperature zone, and a cold zone. The traditional component of the engine has not changed [3]. The firing is now being done in the hot spot. The normal engine and stainless steel piston are connected by a stainless steel piston rod guided by six bearings, enabling the two pistons to reciprocate as a single unit [4]. The conventional cylinder and piston guide the piston assembly. Removing the cooling fan will reduce heat loss by 30 to 40%, saving fuel. The engine efficiency can run between 50 and 58% at the rated load when a stainless steel cylinder and piston are used, and a stainless steel cylinder and piston can attain a material temperature of 650^{o}C.

Mechanical design for converting a conventional diesel engine and the fabrication drawing of the sectional views of the assemblies, sub-assemblies, and various parts. The constructional and functional details are also explained. The sketches are called engineering drawings when drawn accurately according to the standard accepted practice to convey all the necessary information to enable the workers to fabricate and make the assembly product. The art and technique of producing drawings are called drafting. Thus, drawing is an essential means of communication through which the design engineer's ideas are transformed into reality through new or improved valuable products. Computer-aided drafting gradually replaces manual drafting using (CAD). Even though computer-aided drafting will be the only drafting method that will be ideal, all the drawings were made using AutoCAD 2021 software. An overall assembly drawing demonstrates a product's comprehensive design, illustrating the product's parts.

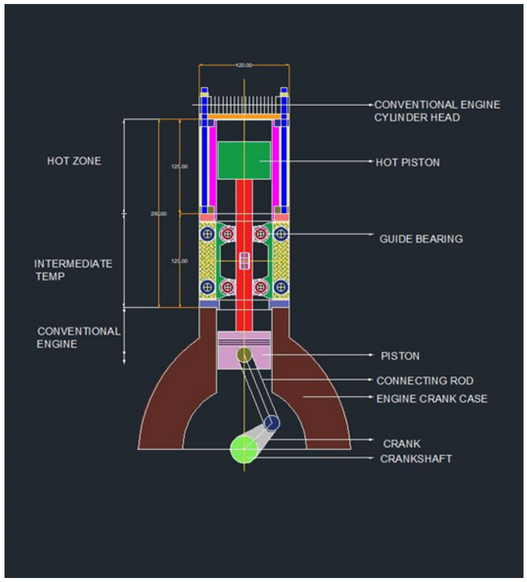

Fig 1. Kirloskar engine conversion work (overall assembly)

2 Methodology

The heat potential of a fuel that an engine cannot use. 60% of the fuel's heat energy must be wasted as rejected heat if a CI engine's thermal efficiency is only 40% at its best. Usually, the engine cooling system holds half of the rejected heat in the exhaust gas and transfers the other half to the engine hardware to release it into the atmosphere. The Low Heat Rejection Engine's basic design is based on isolating combustion chamber components. The higher cycle temperature and insulation improve performance and efficiency because of the coolant's capacity to store heat energy. Engines without thermal transfer are potentially superior to conventional engines since they perfectly follow the first law of thermodynamics. This energy concept sparked studies and paved the way for developing engines with limited cooling.

A stainless steel piston moves inside a stainless steel cylinder with low clearance and no oil usage attributable to the zero heat rejection principle. A second stainless steel engine cylinder will be added above the current engine cylinder. A stainless steel piston rod connected by bearings to a regular engine piston allows the two pistons to move as a single unit. The typical cylinder and piston are no longer employed for anything other than the guidance of the piston assembly and bearings; instead, the firing has been forced to occur on top of the stainless steel cylinder. As a result of the traditional cylinder not burning, the radiator is turned off, saving 35 to 40% of the diesel that would have been lost to heat loss through the radiator. The engine will run more efficiently due to the reduced heat flow.

The cost-effectiveness of a specific design and material, or the amount it can do without a particular feature to cut costs, can be used to evaluate its quality. Due to their much-increased strength, replacing steel with enhanced-strength steel is of tremendous interest. As a result, more high-strength steel products are on the market today. Many of them currently need to be cost-competitive with steel, and there are numerous technical and financial challenges with some of them. Especially for large parts, Stainless steel and super alloys are frequently used in high-temperature service applications because they are particularly resistant to creep. Because stainless steel's density and modulus are similar's to steel in stiffness-critical applications, switching directly from steel to stainless steel has a weight-saving effect. For the following reasons, stainless steel can be lighter than steel in applications where strength is essential.

Stainless steel 304 was chosen as the best material out of all those available to meet the needs and objectives of the product. When nickel and chromium are added to austenitic stainless steels, the austenite-phase field is extended, enabling austenite to be stable at room temperature. There are 18% Cr and 8% Ni in the well-known SAE/AISI 304 austenitic stainless steel. Austenite is stable at room temperature. Nickel and manganese are referred to as "austenite stabilisers" as a result. Other substances, such as chromium, silicon, and molybdenum, act as ferrite stabilisers. The austenite-phase field is constrained within what is known as a "gamma loop", and the ferrite-phase field is expanded by a ferrite-stabilising element (gamma, is the symbol for austenite).

2.1 Piston assembly

A piston assembly comprises an existing piston, a top piston, a piston rod assembly, and a junction between those three components. The Piston assembly drawing is shown in Figure 2. This top piston is welded to the current aluminium piston by a connecting piston rod. The top piston has approximately the same size as the conventional engine piston, and the two pistons and piston rods are fabricated to have a precision alignment [5].

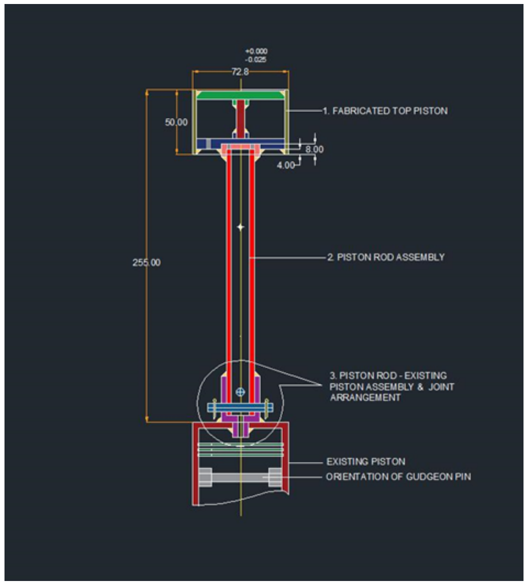

Fig 2. Piston assembly

Rather than its load-bearing compressive strength, a material's elastic stiffness determines a column's susceptibility to buckling. Because the failure due to buckling could occur before the tensions in the column satisfy the yield condition, the buckling load necessitates a design consideration from the stresses [6]. The structure fails due to instability brought on by the buckling. The aspect ratio of the column can be determined using the slenderness ratio S.

The radius of gyration for hollow circular section,

$K = \sqrt{I/A}$

$I = \pi/64 \text{ x } (2^4 - 1.3^4)$

$= \pi/64 \text{ x } (8 - 2.85)$

$I = 0.645 \text{ cm}^4$

Where

OD = 20 mm = 2 cm (approximately)

ID = 13 mm = 1.3 cm (approximately)

Area of cross-section,

$A = \pi/4 \text{ x } (2^2 - 1.3^2)$

$= \pi/4 \text{ x } (4 - 1.69)$

$A = 1.813 \text{ cm}^2$

Therefore,

$K = \sqrt{I/A}$

$= \sqrt{0.645/1.813}$

$K = 0.596 \text{ cm}$

Slenderness ratio

$= l/K$

$= 21/0.596$

$\lambda = 35.23$

If l/K< 40, it is a short column.

Hence as l/ K = 35.23<<40, the piston rod is a short column, and the piston rod will not buckle, as it has fixed ends.

90% of columns braced against sidesway and 40% of unbraced columns could be designed as short Columns. In spite of high-strength material and improved methods of dimensioning members, most column including slender columns are considered (designed) as short column.

2.2 Joint arrangement of the Piston rod assembly - existing piston

The welding has to be done between the piston rod assembly and the existing conventional piston. The existing piston top crown is machined suitably and welded to the aluminium bottom cap. It is strength welded from the top and inside the current piston so it will not fail [6].

2.3 Intermediate insert assembly

The Intermediate insert assembly is the intermediate or middle portion of the entire modification setup of the conversion engine. The intermediate insert assembly is entirely made of stainless steel grade 304 material. It consists of three sub-assemblies: the skeleton structure, gusset mounting arrangement, and bearing mounting arrangement [7]. The purpose of the intermediate insert assembly is to guide the piston rod with the help of six bearings. The gussets are fixed on both sides of the skeleton structure. Gussets support the bearing.

2.4 Skeleton structure

The Skeleton structure is a sub-assembly of the intermediate insert assembly. It consists of a top flange(Part-1), a bottom flange (Part-2), support pillars (Part-3 and Part-4), and additional reinforcement rods (Part-5). Four support pillars, viz., Front pillar, rear pillar, left-side pillar, and right-side pillar, are welded between the top and bottom flanges in such a way as to have perfect parallelism between the top and the bottom flanges. The top cylinder fits inside the top flange. The bottom flange fits into the existing conventional engine.

The top flange has dimensions of 120 mm x 120 mm x 10 mm thick with a drawing weight of 0.7713 kg. The bottom flange has 120 mm x 120 mm x 13 mm thick dimensions with a drawing weight of 1.1156 kg. The Front, rear, left-side, and right-side support pillars all have the exact dimensions of 105 mm x 22 mm x 8 mm thick. Four additional reinforcement rods were welded in four corners between the top and bottom flange to improve strength and reduce vibration with dimensions of Ø5 mm x 105 mm long, with a total drawing weight of 0.0647 kg. All dimensions and tolerances are in mm. TIG WELDING does all metal joining. The top and bottom flanges must be kept parallel by maintaining an equal overall height on all sides.

The gusset mounting arrangement consists of gusset mounting studs, washers, spring washers, nuts, and split pins. Gussets are fixed between support pillars and mounted on the support pillars by locking nuts and with the help of spring washers and washers [8]. The thirty-two numbers washers have dimensions of Ø15 mm x 1 mm thick with a total drawing weight of 0.0317 kg. The Sixteen numbers of split pins are used for extra care to avoid failure. The spring washers are made of high-carbon steel that suits M8 Studs [9].

The bearing mounting arrangement consists of bearing mounting studs, washers, spring washers, nuts, and split pins. The Bearing mounting stud has long threads on both ends and is machined. The six numbers bearing mounting studs have the exact dimensions of Ø8 mm x 50 mm with a total drawing weight of 0.1146 kg. Bearings are mounted inside using studs with the help of locking nuts, spring washers and washers [10]. Washers are used to avoid loosening or to distribute the load from the nut or bolt head over a larger area. The twenty-four numbers of washers are used and have dimensions of Ø15 mm x 1.5 mm thick with a total drawing weight of 0.0355 kg. For extra care, twelve numbers of mild steel split pins are used. The spring washers that suit M8 Studs are made up of high-carbon steel.

2.5 Top Cylinder assembly

The top cylinder assembly is used in the hot zone or top portion of the entire modification setup of the converted engine. The top cylinder assembly is entirely made of stainless steel grade 304 material. It consists of two sub-assemblies viz., top cylinder and insulation details. The top cylinder assembly aims is to hold the gas under pressure and guide the piston. It is in direct contact with the combustion products and must be cooled. The top piston is placed inside a cylinder with a combustion chamber and is exposed to high temperatures of burning gases. Combustion of fuel takes place inside the cylinder. The cylinder is filled with a mixture of air and fuel. The clearance between the top piston and the existing cylinder head is about 3mm [11].

The top cylinder is fully made up of stainless steel grade 304, and it consists of the top flange (Part-1), the bottom flange (Part-2), and the cylinder (Part-3). The top flange fits into the existing cylinder head using locating pin. The top flange has dimensions of 120 mm x 120 mm x 10 mm thick with a drawing weight of 0.7713 kg. The bottom flange fits inside the intermediate insert assembly. The bottom flange has dimensions of 120 mm x 120 mm x 10 mm thick with a drawing weight of 0.7713 kg. The cylinder is welded between the top and bottom flanges, and the site TIG is welded. The overall dimensions of the cylinder are Ø94 mm x 132 mm in length. All dimensions and tolerances are in mm. All metal joining is done by TIG welding. The top and bottom flanges align parallel automatically. Four bolt holes are provided at four corners of flanges for overall assembly through tie bolts of equal size.

Reduced heat loss rates and the ensuing rise in flame temperature are primarily responsible for insulation. Insulation is well-known for lowering heat losses, resulting in energy and financial savings[12]. A heat transfer analysis and an economic analysis to calculate the "monetary worth" of energy loss are used to decide how much insulation is needed.

Insulation needs to be thick enough to be effective—60mm to 80mm (three inches) is suggested. The insulation on the cylinders is properly attached, with no flaws that would not allow the heat to escape[13]. Mild steel wire, insulation strips, insulation wool, and an aluminium cover sheath constitute insulation. The insulating wool on the outside of the top cylinder is held in place by the aluminium cover sheath. The entire size of the aluminium cover sheath is 105 mm long by 105 mm wide. The 12 insulating strips attached to the cylinder wall are stainless steel SS304 grade. The aluminium sheath covering the insulation uses tightened mild steel wire, 530 mm overall length.

3 Results and Discussion

3.1 Thermal Design Calculation 50 per cent overload conditions[4,14]

Table 1. Thermal Design Calculation

Stainless steel cylinder	73.1 mm
Stroke length (L)	74 mm
Engine brake power (P)	4.41 kW
Engine speed	1800 rpm
Type of engine	4
Frictional loss	400 W
Total work done	320.66 J/cycle
No. of cycle/sec.	15
Bore area (A)	0.004
Stroke length (L)	74 mm

Heat energy to be supplied (Qs) = Total work done/Assumed n cycle

= 3320.66 /0.65

= 493.33 J/cycle

Stroke volume (Vs) = Stroke length (L) x Bore area (A)

= 0.074 x 0.0041974

= 0.000310608 m^3

Compression ratio = (Vs+ Vc) / Vc = 22

(Vs/Vc) = 21

Clearance volume (Vc) = (Vs)/21

= 0.000310608 /21

Vc = 0.000014790 m^3

V_1 = Vs + Vc

V_1 = 0.000310608 + 0.000014790

V_1 = 0.000325399 m^3

Estimation of (T_2) & (T_3)

$T_2/T_1 = (V_1/V_2)^{0.4}$

$T_2 = T1\ (V_1/V_2)^{0.4}$

$T_2 = 303\ (0.000325399 /0.000014790)^{0.4}$

T_2 = 1043.305 K
Mass flow rate/ cycle (m) = Stroke volume (Vs) x Density of air (kg/m^3)
= 0.000310608 x 1.128
= 0.000347 kg/cycle
Qs = m cp (T_3-T_2)
493.33 = 0.000347 x 1005 (T_3-1043.305)
T_3 = 2454.36 K
Estimation of (V_3)

$$P_3\, V_3 = P_2\, V_2 \tag{1}$$

$mRT_3 = mRT_2$

$$T_3 = T_2 \tag{2}$$

Dividing equations (1) & (2),
P_3V_3 / T_3 = P_2V_2/ T_2 (P_2 = P_3)
V_3 / T_3 = V_2/ T_2
i.e., V_3 = (V_2/T_2) x T_3
= (0.000014790/1043.305) x 2454.36
V_3 = 0.000034795 m^3
Estimation of (T_4)
$T_4/T_3 = (V3/V4)^{0.4}$
Therefore $T_4 = T_3\ (V_3/V_4)^{0.4}$
= 2368.112 x $(0.000034795\ /0.000325399)^{0.4}$
T_4 = 1003.644 K
Estimation of (Q_R)
Q_R = m cv (T_4 – T_1)
= 0.000347 x 718 x (1003.644 – 303)
Q_R = 175.00 J/cycle
Determination of cycle Efficiency
W = Q_S - Q_R
= 493.33 – 175.00
= 318.327 J/cycle
Efficiency = (Work done/heat supplied) x 100
= (318.327/ 493.33) x 100
Cycle Efficiency = 64.525 %
Determination of Overall Efficiency
Shaft work/cycle = Brake power at rated load/ No. of cycle/sec.
= 4410 /15
= 294 J/cycle
Overall Efficiency = [(Shaft work/cycle) /heat supplied] x 100
= [(274 / 493.33) x 100]
Overall Efficiency = 59.59 %

3.2 Thermal performance

The various performance data calculated are displayed in Table 2. In Table 2, the approximated material temperature of the stainless steel piston is 611°C, corresponding to a 40% load condition. Hence, as per the data generated by us theoretically, the stainless steel piston and cylinder made of SS304 grade can not be used at loads more than 40% of rated load, and for loads between 40% to 130% of rated output, Inconel material can be made use of, and that can withstand up to 850°C. The approximated material was calculated as an average of T_1, T_2, T_3, and T_4.

Where
T_1 - Inlet air temperature
T_2 - Temperature at the end of the compression stroke

T_3 - Temperature at the end of constant pressure heat addition
T_4 - Exhaust gas temperature

Table 2. Data pertaining to engine performances

S.No		Inlet air temperature	Temperature at end compression stroke	Temperature at theend of constant pressure process	Exhaust gas Temperature	Approximated Material Temperature	Cycle Efficiency	Overall Efficiency
	%	T1 oC	T2 oC	T3 oC	T4 oC	Tave oC	%	%
1. 1.	0	29.85	770.155	879.117	75.059	438.54	70.35	0
1. 2.	20	29.85	770.155	1039.291	144.659	496.13	69.52	41.66
1. 3.	40	29.85	770.155	1354.91	291.79	611.66	67.99	55.95
1. 4.	60	29.85	770.155	1376.976	302.542	620.030	68.70	55.43
1. 5.	80	29.85	770.155	1541.861	384.655	681.78	67.15	58.11
1. 6.	100	29.85	770.155	1720.725	384.655	749.62	66.38	58.97
1. 7.	120	29.85	770.155	1905.008	576.014	820.40	65.61	59.27
1. 8.	130	29.85	770.155	1989.949	622.73	853.32	65.27	59.27
1. 9.	140	29.85	770.155	2094.962	681.467	894.25	64.86	59.24
1. 10.	150	29.85	770.155	2181.21	730.49	928.077	64.52	59.27

Hot cylinder ID = 73.1 mm; Stroke Length = 74 mm; RatedEngine speed = 1800 rpm; Rated power = 2.94 kW
Calculations havebeen made assuming the speed of the engine equal to the rated speed (1800 RPM),for all cases

Figure 3 shows the exhaust gas temperature values calculated theoretically over a % load, assuming the engine runs at rated speed. It can be seen in the graph that the exhaust gas temperature is a maximum of 400^{o}C and beyond 100%. The exhaust gas temperature steeply rises, and it may require exhaust manifolds made up of costlier materials like stainless steel, etc., making the conversion uneconomical.

Figure 4 displays the values of approximated material temperature (T average) over % load. At 100% of the rated load condition, the material temperature of the added piston and cylinder is predicted to be ≈ 750^{o}C.

Figure 5 displays the values of cycle efficiency (almost equal to air standard efficiency) over % load. It may be noticed that the above-rated load condition (100%). It shows a decreasing trend.

Figure 6 indicates that the overall efficiency of the converted engine reaches about 59% and then has a flat trend.

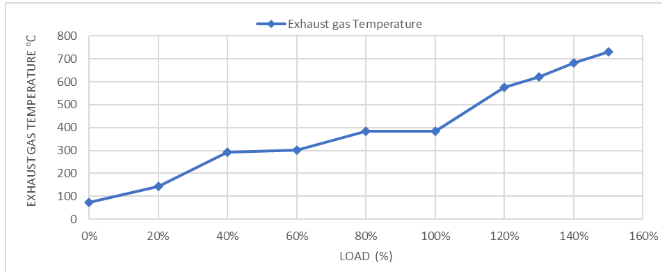

Fig 3. Exhaust gas temperature Vs Load (%)

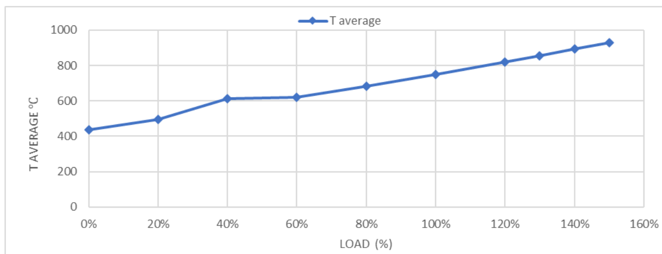

Fig 4. T average Vs Load (%)

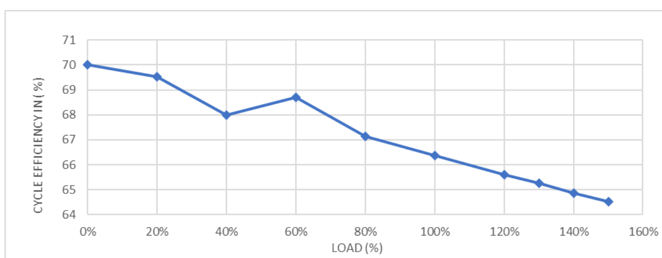

Fig 5. Cycle Efficiency (%) Vs Load (%)

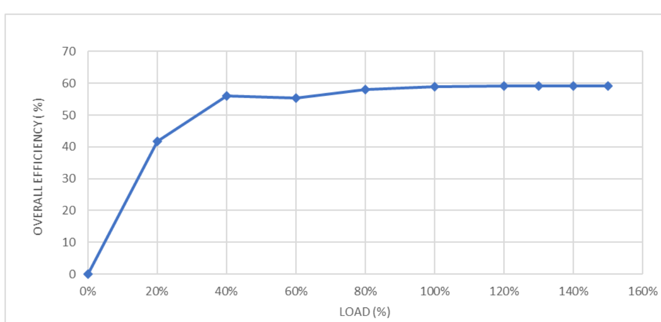

Fig 6. Overall Efficiency (%) Vs Load (%)

4 Conclusion

Engineering drawings were made after the shaping and sizing of various parts involved. The drawings also detail the various tolerances for which the parts are to be machined. Overall assembly drawing of the converted engine shows the constituting parts and illustrates the complete design. Figure 7 shows a fabricated converted conventional engine[(14)].

It may be concluded that it is not considered to use the engine above-rated load (100%) condition as the exhaust gas temperature shows a steep increasing trend requiring costlier materials (stainless steel) for the fabrication of exhaust manifolds, and it can be found that the approximated material temperature of the added piston and the added cylinder is around 750°C. Inconel material may be made use of safely. Current efforts aim to raise performance and durability without increasing costs.

Fig 7. Fabricated converted conventional engine

The scope of future research is to be:

1. Comparison of an insulated and non-insulated converted conventional engine
2. Performance and emission achievement with an un-cooled modified single-cylinder diesel engine
3. Endurance testing of a high-output converted conventional engine
4. Methods of heat transfer and thermal analysis in an insulated cylinder of a converted conventional engine.
5. Fabrication of a converted piston in Inconel material as Prototype 2.

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