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Thermodynamics of Internal Combustion Engines - To Improve Performance & Efficiency

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Abstract: Internal combustion (IC) engines are still being developed to improve performance and efficiency. Theoretical thermodynamics is an important part of increasing performance and efficiency. The laws of thermodynamics provide solutions towards increasing as well as decreasing engine thermal efficiency, respectively. The proposed study shows how thermodynamics may be used to boost an IC engine's performance, reliability, and efficiency. The purpose is to evaluate LHR engine concepts and emphasize the complexity of utilizing thermodynamics to improve efficiency.

Keywords: low heat rejection, performance, theoretical, internal combustion

1. INTRODUCTION:

Reciprocating engines or IC Engines (ICE) are widely employed throughout the entire globe in several applications. Reciprocating engines (ICE) can be found for a wide range of purposes, including outdoor knife sharpeners and removers, recreation, farming, architecture, light-duty automotive, commercial vehicles, maritime, and electricity production.The factors that contributed to the IC engine's breakthrough have been extensively documented (refer, for particular, [1–3]). A low capital cost and increased power output, appropriate performance, the ability to meet environmental limits, and a perfect challenge with readily available fuels are among these characteristics. For the chief reason, this is doubly true. The IC engine can operate for extended periods with little replenishment since diesel fuels have greater specific energy. Refilling fuel duration for many automobiles is now in the range of 5 minutes or less. In the transportation business, these traits are critical.

Even though perhaps the mainstream media occasionally offers opinions on the IC engine's demise (— for example, [4]), the IC engine continues to be a major product. Auxiliary power plants are continuously being investigated, but neither has yet been shown to be capable of replacing the IC engine. For these solutions to be desirable to customers, energy storage and battery packs will still need to advance in the future. As a consequence, for most of the other above applications, the reciprocating engine is expected to be the prevailing power plant for future decades.

Finally, reciprocating engines must continue to be the prevailing innovation throughout industrial naval platforms, tractor-trailers, and aviation for the conceivable future. Other choices exist, but none offer the very same combination of minimum cost and maximum power output as a standard fuel container with nothing but an IC engine.

IC engine innovation is now focused on improving performance & brake thermal efficiency. Thermodynamic principles are one of the most important aspects of engine performance and reliability. The effectiveness of an engine is limited by both thermodynamic first and second laws. Our research uses cycle modeling to provide precise illustrations of engine thermodynamics. This cycle model combines most aspects of both principles of thermodynamics.

The purpose mainly is to evaluate LHR concepts and emphasize the complexity of utilizing thermodynamics to make it more efficient. This study contains a summary of the engine cycle simulation as well as thermodynamic principles. The paper concludes with both a summary and results.

2. QUICK REVIEW OF THERMODYNAMICS

For this topic, The most important rules of thermodynamics have been the first and second laws. These rules are fully discussed in many thermodynamic (— for example, [5,6]) and automotive reading materials [1,2,7]. Here's a short recap of what went down.

James Joule and Julius Mayer are commonly credited with inventing the first law of thermodynamics [5]. Researchers realized how thermal transmission, as well as action, were two very different representations of the same item in the mid-nineteenth century. This discovery immediately led to the understanding that while energy is stable, it can present itself in a multitude of ways. The conservation of energy is the first law of thermodynamics. There is no method to create or annihilate energy. This means that the value among all energy interfaces for a boundary condition must match the energy change.

The second law of thermodynamics is likely to be far more sophisticated and difficult than the first. This rule is commonly attributed to Carnot [8]'s 1824 book. The second law is determined by a variety of physical findings that have huge repercussions for thermal system development and operation. The second rule should be utilized to establish a steady-state, describe the optimal thermal system performance, and implement necessary elements that are very damaging to performance. There is no easy, single conclusion that captures the whole complexity of the moment due to the obvious huge range of linked observations.

Due to the enormous number of connected observations, there is no simple, unique decision that encompasses the whole spectrum of the second law of thermodynamics. Even though the Kelvin-Planck and Clausius discoveries are usually quoted as statements of the second rule in thermodynamic literature, they are just two portions of such law. The second law is simply a collection of facts that all have a similar premise about energy integrity. Establishing a characteristic (exergy or availability) that encompasses this notion.

3. THE ENGINE CYCLE SIMULATION IS OUTLINED HERE

3.1 The Basics of Simulation

This study's engine cycle simulation is a zero-dimension idea that encompasses complete 4 strokes, employs 3- region combust, and necessitates the employment of many empiric sub-models. Descriptions of this cycle modeling may be found in a booklet [9] as well as many scientific articles (— for example, [10–13]). The simulation is detailed in the following lines. The needed parts for conclusions, specifications of the engine, and working circumstances, or techniques for the subsequent estimates will be followed by subcategories.

Figure 1 shows the cycle model for the three-districts model. The three distrincts are the incomplete combustion region, adiabatic core, and border layer. The last two regions make up the charred region. Chamber heat transmission is governed by several of many thermal transfer relations (described below). The Chamber temperature distribution has been apportioned between both the incomplete combustion region and the border layer (of the burned region) caused by temperature changes and volumes of both regions [9].

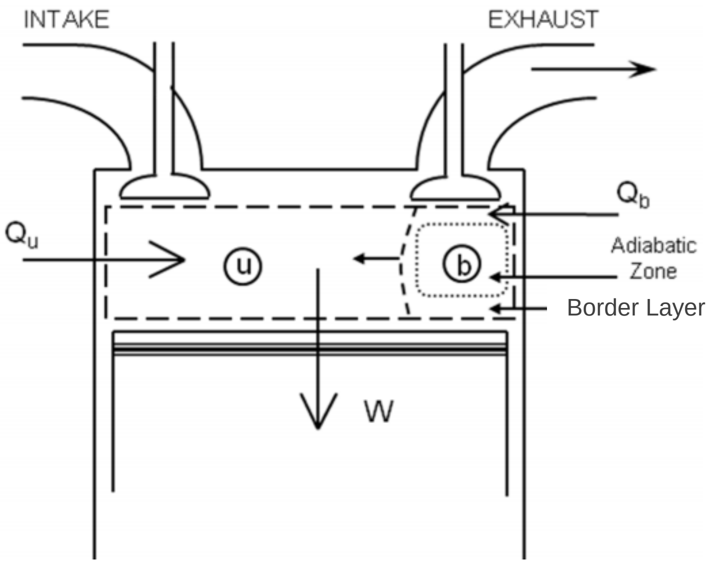


Figure 1. describes the three-region architecture of the cycle modeling. The dotted lines indicate control volumes, whereas the arrow directions show transfer of energy that highlight two of each regions.

3.2. FORMULATIONS

The first rule of thermodynamics is utilized to generate formulae for duration (crank angle) variations of the temperatures, volumes, pressures, and masses under considerations of engine performance characteristics, and performance criteria, including sub-model constants. In this evolution, simply stable flow functionality is taken into account. The diesel fuel is expected to have evaporated. All blow-by is disregarded, therefore combustion is assumed to be final (notice that according to the Wiebe function, The fuel (0.7 percent) is still not burned). A series of a partial differential equations is quantitatively determined as a consequence of crank angle.

The answers need the use of thermodynamic parameters, piston-cylinder kinematics, burning process formulations, Engine chamber heat exchange, mass flux, and mechanically frictional computations. Below is a short overview of each of these.

3.3 SOLUTIONS-RELATED STUFF

3.3.1 *Properties*

The qualities of airflow, fuel vapor, and burning determine the working fluid's characteristics. Under thermodynamic conditions, the working fluid of IC engines can be formulated to follow the ideal gas model. Some amounts of combustion products could have been "cooled" at reduced (lower) temperatures, and they might be dependent on spontaneous (change) reactant concentrations at higher temperatures. Even during the compression stage before combustion, the incomplete combustion mixture is made up of airflow, fuel vapor, exhaust emissions (as necessary), and residual gases. All burnt gases are calculated using a stoichiometric ratio or maybe the freezing or balanced content. Again when the content of the combinations is defined, the thermodynamic properties of the combinations may be estimated. To identify the attributes of each type, the polynomial model fits that the same information available is employed.

3.3.2. *Kinematics*

The geometry and kinematics are predicated on the geometry and kinematics of common internal combustion engines [9]. Combustion chamber size, stroke, connecting rod length, and volumetric efficiency are all important factors to consider.

These inputs may be used to determine the immediate chamber volume, chamber volume expansion rate, or area of the instantaneous surface.

3.3.3 *Combustion*

The combustion reaction starts when diesel fuel is fed into the combustor, and at the end of this stroke, fuel is pumped at significantly higher rates within one or perhaps more jets. The fuel atomizes and vaporizes due to the high-velocity injection and high temperature. Combustion happens whenever the fuel reaches a certain temperature where everything ignites. The sequences of combustion that take place during the expansion stroke in Compression ignition engines are classified into different distinct stages:

Ignition delay -The period between the initiation of direct injection of fuel and the onset of combust.

Premixed or instantaneous combustion phase - The fuel inside the engine cylinder ignites when it reaches its self-ignition temperature. A significant rate of heat release is produced during this phase.

Phase of mixing regulated combustion - The combustion rate is limited and the thermal output is decreased in the mixing regulated combustion phase.

Late combustion phase - The rate of heat release is lowest in this phase due to the limited amount of fuel available for combustion.

The Rayleigh regime occurs when fuel particles are larger than the size of the injector when sprayed into the combustion chamber of a CI engine at a lower jetting speed. Surface tension causes surface waves to form in an unsteady way, causing the regime to disintegrate. Forces related to the relative motion of the jet as well as its surrounds increase as the jet velocity increases, and these forces are stronger than the surface tension force, leading the fuel to break up into droplets the same size as the jet diameter. The "first wind-induced breakdown regime" is what it's called. The drop diameter diminishes as the jet velocity increases, atomizing the drop.

3.3.4 *Heat Transfer from Cylinder*

Heat transfer within chambers is a complicated process which has been under investigation. In this research, the chamber (cylinder) temperature difference is computed using actual convective heat transfer formulae from the domain, that are given by,

$$\mathbf{Q = hA(Twall - Tgas)}$$

Consider

h - Heat transfer coefficient

A - Surface area of Cylinder

Twall - Temperature of wall

Tgas - Temperature of gas

Heat transfer coefficient can be correlated in a variety of ways (e.g., [15,16]).

The connection from Hohenberg [16] is employed in the study presented here. For simplicity, the thermal transfer data from either the gases to that same walls will be reported being positive.

3.3.5 *Mass Flux*

Mass fluxes can be predicted using a common one-dimensional flow model [1,9]. An actual coefficient of discharge is utilized to account for actual consequences. At each computing phase, overall flow conditions are reviewed to assess whether the flowing is generally highest or sub-sonic. Sonic flow can occur when the upstream pressure has been substantially high in comparison to the downstream pressure. In addition to flow parameters, data on valve operation of the engine is required to determine the streamflow open area.

3.3.6 *Mechanical Friction*

To estimate brake parameters with desired calculations, mechanical frictional data is necessary. Mechanical friction is determined using several different approaches developed for vehicle engines [17]. The frictional values for sliding or rubbing are calculated using these methods.

3.4 ENGINE FEATURES

Because implementing the necessary alterations should not be difficult, Kirloskar four-stroke diesel engine was chosen as an experiment engine. The geometric features and parameters are determined by the engine arrangement. Table 1 lists the features of the engine.

Make and Model	Kirloskar VA320-2
Engine type	Single cylinder
Cooling type	Air cooled
Stroke	4
Fuel	Diesel
Bore	74 mm
Stroke	74 mm
cc	0.318 litres
CR	22
Maximum power Output kW	2.94 kW at 1800rpm
Engine Speed	1800 rpm
Fuel Tank Capacity	4.5 Litres
Governing	Class"B1"
Rotation while looking at the flywheel	Clockwise
Starting up	Hand
Physical dimensions of bare engine (Length X Width X Height)	366 X 623 X 402 mm

Table 1. Features of the engine

4. LOW HEAT REJECTION ENGINE - THERMODYNAMICS

4.1 Overview

In IC engines, the importance of cylinder heat transport cannot be emphasized. The metal components of the cylinder (combustion chamber head, chamber walls, and piston head), as well as the lube oil in the engine, must always be kept at substantially reduced temperatures than that of the combustion gases, therefore they were cooled to temperatures far lower than the gases. Heat is transmitted from either the gases to the same components even during the high-temperature phases of the cycle. Heat transfer, inefficiency, move thermal energy outside the cylinder, making it unavailable for work output. Even though the heat transfer energy might be stored in the cylinder chamber, as shown below, only a small amount of it could be put to use.

Engines with low heat rejection (LHR) are designed to have lower heat losses. Although some past research related to such a concept as adiabatic engines, no engine can be entirely adiabatic. Prior attempts to create LHR engines have been discussed extensively in the literature (– for example, [19–22]). Since LHR engines are projected to have greater gas temperatures, those principles will not apply to SI engines.

Many concepts have been researched to develop LHR engines. Ceramic and other lesser conducting materials have been used in these attempts to minimize chamber heat losses. Most of these materials aren't as ductile as the cast iron and steel components they're designed to accommodate. As a result of this feature, these materials have limited endurance and have repeatedly failed to endure the extreme conditions of the engine cylinder [19–22]. Aside from increased efficiency, the LHR engine concept also allows for the reduction or removal of the cooling systems

It could lead to weight reduction as well as the removal of a necessary component. If the coolant pumps were removed, the mechanical frictional would be decreased.

Higher exhaust gas temperatures might also assist turbochargers and other emissions after treatment systems. This section will look at how increasing the temperature of the chamber wall can affect the chamber heat transfer rate. To reduce cylinder chamber heat losses, most earlier attempts used high-temperature materials (— for example, ceramic materials) and therefore greater lubricating fluids. Several techniques are effective at increasing component temperatures.

The majority of prior research towards enhancing thermal efficiency has failed. The thermodynamics results in this article assist to explain why past initiatives failed and the difficulties of considerably enhancing thermal efficiency by lowering heat losses.

4.2 Redesigned Engine

In our study, an SS304 stainless steel piston is surmounted by a normal Al piston through an SS304 grade stainless steel conduit, dubbed the piston rod, in the hopes of greatly improving fuel economy.

We labeled the surmounted piston as a hot piston so the fire is carried above a hotter SS304 austenitic stainless steel piston. As a result, the engine has been redesigned. In the new diesel engine, lubricating oil will not be accessible between the heated piston as well as the heated chamber (cylinder), and only a minimal vacuum gap will be kept. Between both the heated piston and the heated cylinder, gas leakage was virtually eliminated.

Heat loss due to cooling inside the conventional engine cylinder portion has been carefully disregarded after the reconfiguration, and the environment surrounding the hot cylinder is firmly protected (insulated), so the hot piston doesn't transfer any heat thru the hot cylinder chamber, and only presence of loss of heat must be through the bottom surface of the hot piston. The overall assembly drawing of the redesigned engine is shown below Figure 2.

Radiator cooling wastes approximately 35 to 40% of the gasoline supplied. The radiator lowers the temperature of the engine materials less than 140°C, which prevents the lubricant from being scorched and sticky, as well as the piston and cylinder from seizing.

4.3 Materials

Austenitic Cr-Ni stainless steel (SS 304 grade) is selected because of its resistance to corrosion, excellent mechanical properties, and excellent drafting, trying to shape, and machining capabilities. Low carbon concentration implies less carbide precipitation in the high-temperature region but less inter - granular corrosive environment weaken during welding. The SS304 grade has strong oxidation resistance at 870°C with unwavering support and 925°C uneven support.

SS 304 grade is also used in various household and business hardware, including screw components for food manufacturing equipment, kitchenware, and automotive headers. It's frequently used as a coil material in vaporizers.

The signatory Element (by weight percent) of Grade SS 304 material is shown in Table 2.

The mechanical and physical parameters (values) of Grade SS 304 are listed in Table 3.

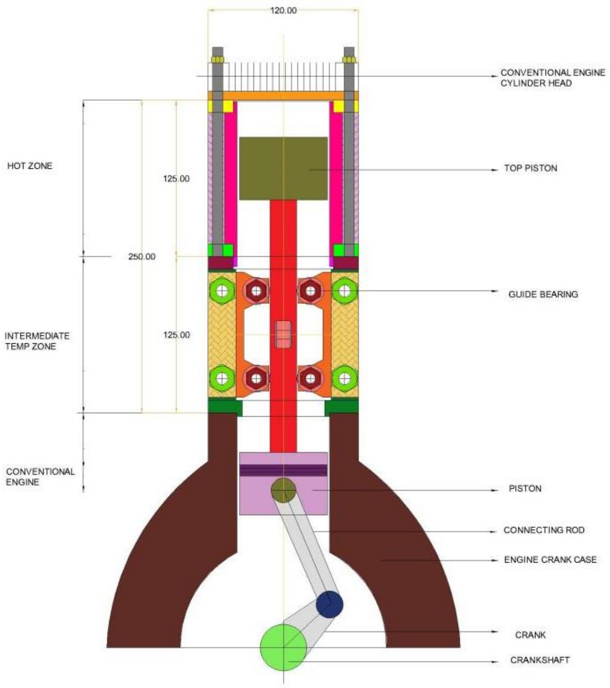


Figure 2.The overall assembly drawing of the redesigned engine

Element	C	Cr	Fe	Mn	Ni	P	S	Si
Present(%)	0.08	18 - 20	66.3 - 74	2	8 - 10.5	0.045	0.03	1

Table 2 shows the chemical concentration of stainless steel grade 304

Physical and Mechanical Parameters	Value
Poisson ratio	0.265 - 0.275
Density kg/m^3	7850 - 8000
Melting Point °C	1450
Youngs Modulus Gpa	193
Electrical Resistivity Ω.m	0.072 x 10^{-6}
Thermal Conductivity W.m -1.K-1	16.2
Thermal Expansion m/mK	17.2 x 10^{-6}
Comprehensive strength MPa	210
Tensile Strength MPa	520-750
Min Proof strength MPa	205
Min Elongation (%)	45

Table 3.Mechanical and Physical parameters of Grade SS 304 material

4.4 Thermal Performance Theory & Calculations

Full load condition:

SS304 Grade cylinder (ID) = 73.1 mm

Stroke length (L) = 74 mm

Engine brake power (P) = 2.94 kW = 2940 W

Engine speed = 1800 rpm

Variables involved

V_1 = 0.000325399 m^3

V_2 = 0.000014790 m^3

V_3 = 0.000028260 m^3

V_4 = 0.000325399 m^3

T_1 = 30 °C + 273 = 303 K

T_2 = 1043.305 K

T_3 = 1993.875 K

T_4 = 657.805 K

T_{ave} = 1022.62 K = 749.62 °C

m = 0.0003478 kg/cycle

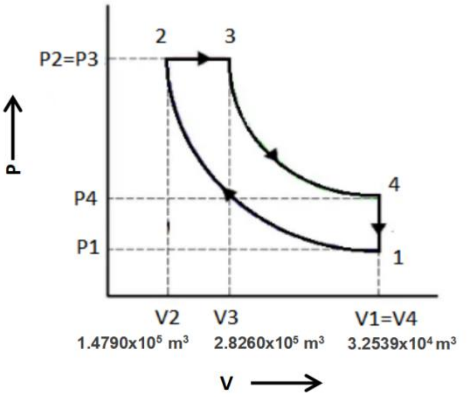
Q_S = 332.33 J/cycle

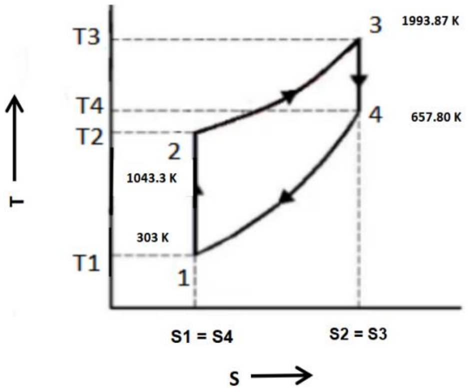
Q_R = 111.72 J/cycle

Assumed η cycle = 67 %

Calculated η cycle = 66.380 %

η Overall = 58.97 %





Design Calculation:

Engine brake power = 2.94 kW

Engine speed = 1800 rpm

No. of cycle/min. = (1800/2) = 900 cycle/min

No. of cycl/sec. = (900/60) = 15 cycle/sec

Type of engine = 4 stroke

Total work done = Shaft work + Frictional loss/cycle

Frictional loss = 400 W = (2940 + 400)/15

= 222.666 J/cycle

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

= 222.666 /0.67

= 332.33 J/cycle

Bore diameter (ID) = 73.1 mm = 0.073 m

Bore area (A) = $\pi/4\ (0.073)^2$

= 0.0041974 m^2

Stroke length (L) = 74 mm = 0.074 m

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

= 0.074 x 0.0041974

= 0.000310608 m^3

Compression ratio of the diesel engine = (Vs+ Vc) / Vc = 22

Therefore, (Vs/Vc) = 21

Therefore, 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

Where,
V_1 = 0.000325399 m^3
V_2 = Vc = 0.000014790 m^3
T_1 = 30 °C + 273 = 303 K

<u>*Estimation of (T_2) & (T_3)*</u>

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

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

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

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

Where,
Q_S = 332.33 J/cycle
m = 0.000347 kg/cycle
cp = 1005 J/kg.K
T_2 = 1043.305 K

Heat supplied (Qs) $= m\ cp\ (T_3 - T_2)$

332.33 $= 0.000347 \times 1005\ (T_3 - 1043.305)$

$T_3 = 1993.875$ K

Check for heat supplied (Q_S)

Heat supplied (Qs) $= m\ cp\ (T_3 - T_2)$

$= 0.000347 \times 1005\ (1993.875 - 1043.305)$

$Q_S = 332.33$ J/cycle

Where,
$V_2 = Vc = 0.000014790\ m^3$
$T_2 = 1043.305$ K
$T_3 = 1993.875$ K

Estimation of (V_3)

$P_3V_3 = P_2V_2$ -------------- (1)

$mRT_3 = mRT_2$------------ (2)

$P_2 = P_3$

Dividing equation (1) & (2),

$P_3V_3 / T_3 = P_2V_2 / T_2$

$V_3 / T_3 = V_2 / T_2$

ie.,

$V_3 = (V_2 / T_2) \times T_3$

$= (0.000014790/1043.305) \times 1993.875$

$V_3 = 0.00002826\ m^3$

Where,
$V_3 = 0.00002826\ m^3$
$V_1 = V_4 = 0.000325399\ m^3$
$T_3 = 1993.875$ K

Estimation of (T_4)

$T_4/T_3 = (V_3/V_4)^{0.4}$

Therefore

$T_4 = T_3\ (V_3/ V_4)^{0.4}$

$= 1993.875 \times (0.00002826 / 0.000325399)^{0.4}$

$T_4 = 750.314$ K

Estimation of (Q_R)

Rate of Heat Rejection

$Q_R = m\ cv\ (T_4 - T_1)$

$= 0.000347 \times 718 \times (750.314 - 303)$

$Q_R = 111.729$ J/cycle

Where,
$m = 0.000347$ kg/cycle
$cv = 718$ J/kg.K
$T_4 = 750.314$ K
$T_1 = 30\ °C + 273 = 303$ K

Determination of η

Work done $= Q_s - Q_R$

$= 332.33 - 111.729$

$= 196$ J/cycle

η = (Work done/ heat supplied) x 100

$= (196 / 332.33) \times 100$

η cycle = 66.380 %

Where,
$Q_S = 332.33$ J/cycle
$Q_R = 111.729$ J/cycle

Determination of η Overall

Shaft work/cycle = Brake power at rated load/ No. of cycle/sec.

$= 2940 / 15$

$= 196$ J/cycle

Therefore,

$\eta_{Overall}$ = [(Shaft work/cycle) /heat supplied] x 100

Where,
P = 2.94 kW = 2940 J/sec
No. of cycle/sec. = 15 cycle/sec
$Q_S = 332.33$ J/cycle

$= [(196 / 332.33) \times 100]$

$\eta_{Overall} = 58.97\ \%$

5. Summary and Conclusions

This research looks at the function of thermodynamics in internal combustion engines. A lot of the work, which was done using engine cycle modeling, was done utilizing the first and second laws of thermodynamics. The primary goal of this project was to increase thermal performance and efficiency. Some of the data corroborated generally held assumptions about how to boost productivity. Other sections of the study provided deeper insights and information on critical efficiency-boosting measures. The sections that follow emphasize some of the most key insights and results. Especially for modern engines or operations that lead to reduced combustion temperatures and greater thermal energy conversions to output work.

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