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ENERGY AND EXERGY ANALYSIS OF DIESEL ENGINE BY VARYING COMPRESSION RATIO

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ABSTRACT

In this study, the energy and exergy analysis has been carried out by applying first law and second law of thermodynamics on a single cylinder conventional diesel engine at various compression ratios. The desired compression ratios were attained by changing the clearance volume. The test results indicated that the heat carried away by exhaust gases was 10% at compression ratio of 15.37:1. The unaccounted loss was more, 41.6% at a compression ratio of 14.5:1. The heat carried away by cooling water was 24% at compression ratio of 16.4:1. The energy analysis shows that the availability of brake power at compression ratio of 17.5:1 is 27%. The destructive availability is 57% at compression ratio of 13.7:1.

Keywords: Energy, Exergy, Analysis, Anergy, Diesel engine, Compression ratio.

INTRODUCTION

The use of energy resources has tremendously increased in the present day. The attention to think and device systems for optimum utilisation of energy has become inevitable. Hence, in-depth study and analysis to identify and eliminate the sources of inefficiency is required. The first law of thermodynamics throws light on equivalence of energy[1]. It emphasizes that energy is always conserved quantity wise. The second law of thermodynamics emphasizes that energy always degrades quality wise[2]. It also proves that heat energy cannot be completely converted into work energy. Where as vice-a-versa may happen. Work is considered as high grade energy and heat as low grade energy. The bulk of the high grade energy which is in the form of mechanical work is obtained from the sources of low grade energy, like fuels[3]. By virtue of second law, it is impossible to convert low grade enrgy completely into high grade energy[1]. The low grade energy, available for

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conversion is termed as Available energy and the form of energy that must be rejected is known as Unavailable energy[1,4]. Available energy is also called as exergy and unavailable energy is called as anergy. Energy is the sum of exergy and anergy.

$$\text{Energy} = \text{Exergy} + \text{Anergy} \qquad \ldots(1)$$

Available energy referred to a cyclic heat engine

The cyclic heat engine (Fig. 1), interacts between the source and sink. The source is at higher temperature of T_1 and the sink is at a lower temperature of T_2. The heat supplied to the engine is Q_1 and the maximum work obtained out of it, is the available energy (A.E), W_{max}.[1,5]

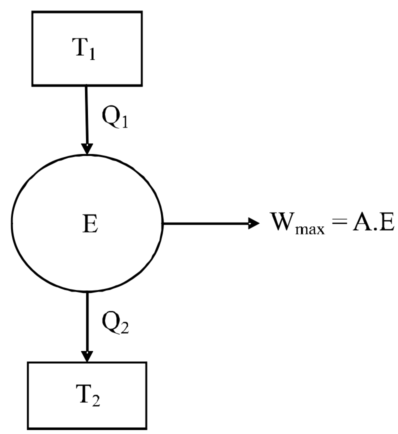


Fig. 1: Heat engine

$$W_{max} = \text{A.E.} \qquad \ldots(2)$$

The minimum energy (Q_2), which has to be rejected to the sink is the unavailable energy (U.E),

$Q_2 = \text{U.E}$

$Q_1 = \text{A.E} + \text{U.E}$

$W_{max} = \text{A.E} = Q_1 - \text{U.E}$

Efficiency of the reversible heat engine,

$$\sigma_{rev} = 1 - (T_2/T_1) \qquad \ldots(3)$$

Exergy

Exergy is an extensive property. Once the environment is specified, the value of exergy is fixed. It shall be numerically greater than or equal to zero for all the states of the system[6].

$$\text{Exergy} \geq 0$$

Exergy can be generated, destroyed and stored. It is destructed during the chemical reactions. It causes environmental problems, when it interacts with its surroundings[7].

Classification of exergy

(a) Thermo mechanical exergy

(b) Chemical exergy

Sub classification of thermo mechanical exergy

(a) Physical exergy

(b) Kinetic exergy and

(c) Potential exergy

Physical exergy is the work obtained by the reversible process. Kinetic exergy is equal to the kinetic energy when the velocity is considered relative to the surface of the earth[8]. Potential exergy is equal to the potential energy at the average level of the surface of the earth.

Chemical exergy is the work that is obtained by taking the system at ambient temperature and pressure to the state of thermodynamic equilibrium with environment and brings the system to the dead state. The state, at which the system and the environment are at mechanical, thermal and chemical equilibrium i.e. the thermodynamic equilibrium, is said as dead state. All spontaneous processes terminate at the dead state.

Exergy analysis

Thermodynamic system tends to attain equilibrium state by interacting with the surroundings. The maximum useful work that can be obtained during a process that ultimately brings the system to equilibrium state is termed as availability. In a thermal process, as per the law of loss of maximum work, the work obtained is always less than the maximum obtainable work due to the irreversibility[9]. Availability analysis or exergy analysis reveals the losses and imperfections in a thermodynamic process and indicates the possibilities to minimize the losses and improve the process.

Theoretical analysis

Energy analysis

An energy analysis on an engine gives the account of energy supplied and utilized in various ways. The total chemical energy of the fuel is consumed as effective work, heat transfer loss by cooling water, heat carried away by exhaust gas and unaccounted losses[10]. By optimizing the energy distribution, energy utilization efficiency can be improved.

The following assumptions are made for energy analysis:

1. The engine runs at a steady state.
2. The whole system is selected as a control volume.
3. The composition of air and exhaust gas forms ideal gas.
4. Potential and kinetic energy affects of the incoming and outgoing fluid streams are ignored.

Heat supplied to the engine in the form of fuel, (Qs in kW) is given as[1,11] –

$$Qs = m_f \text{ x L.C.V} \qquad \dots(4)$$

Where m_f is the mass of fuel supplied in Kg/sec and L.C.V is the lower calorific value of the fuel in kJ/Kg.

Heat equivalent to brake power (Q_{bp} in kW) is given as –

$$Q_{bp} = 2 \times \Pi \times N \times T_e \qquad \dots(5)$$

Where N is the crank revolution per second and T_e is the torque developed in kN-m.

Heat carried away by cooling water (Q_{cw} in kW) is given as –

$$Q_{cw} = m_{we} \times C_{pw} \times (T_2 - T_1) \qquad \dots(6)$$

Where m_{we} is the mass of cooling water circulated through the cooling jacket in Kg/sec.

C_{pw} is the specific heat of water in kJ/Kg.K

$T_2 - T_1$ is the rise in water temperature passing through the cooling jacket in the engine in K.

Heat carried away by exhaust gas (Q_{eg} in kW) is given as

$$Q_{eg} = m_{eg} \text{ x } C_{pe} \text{ x } (T_5 - T_a) \quad \ldots(7)$$

Where m_{eg} is the mass of exhaust gas = ($m_f + m_a$) in Kg/sec.

m_f is the mass of fuel in Kg/sec

m_a is the mass of air

C_{pe} is the specific heat at constant pressure of exhaust gas in kJ/Kg.K

T_5 is the temperature of exhaust gas to calorimeter in K

T_a is the ambient temperature in K.

Heat lost by the exhaust gases = Heat gained by the cooling water :

$$m_{eg} \text{ x } C_{pe} \text{ x } (T_5 - T_6) = m_{cw} \text{ x } C_{pw} \text{ x } (T_4 - T_3) \quad \ldots(8)$$

where m_{eg} is the mass of exhaust gases

m_{cw} is the mass of cooling water passing through the calorimeter in Kg/sec.

T_3 is the calorimeter water inlet in K

T_4 is the calorimeter water outlet in K

T_5 is the exhaust gas to calorimeter inlet temperature in K

T_6 is the exhaust gas from calorimeter outlet temperature in K

C_{pe} is the specific heat of exhaust gas in kJ/Kg K

C_{pw} is the specific heat of cooling water in kJ/Kg K

Unaccounted energy losses (Q_u)

Part of the power generated in the engine is utilised to run the accessories like lubricating pump, cam shaft, water circulating pump and also heat is lost by convection and radiation. These losses are termed as unaccounted losses.

Unaccounted losses,

$$Q_u = Q_s - (Q_{bp} + Q_{cw} + Q_{eg}) \quad \text{…(9)}$$

Exergy balance

It is the exergy change of a system during a thermodynamic process.

The availability of fuel supplied (A_{in}),

$$A_{in} = [LCV_f \times \{1.0401 + 0.1728\,(H/C) + 0.0432\,(O/C) + 0.2169\,(S/C) \times (1\text{-}2.0268\,(H/C))\}] \quad \text{…(10)}$$

Where H, C, O and S are the mass fraction of hydrogen, carbon, oxygen and sulphur[14].

Shaft availability (A_s),

$$A_s = \text{brake power of the engine in kW} \quad \text{…(11)}$$

Cooling water availability (A_{cw}),

$$A_{cw} = Q_{cw} - [m_{we} \times C_{pw} \times T_a \times \ln(T_2/T_1) \quad \text{…(12)}$$

Where T_1 is the temperature inlet water temperature passing through the cooling jacket in K. T_2 is the outlet water temperature of cooling jacket in K.

Availability of exhaust gas, A_{eg}

$$A_{ex} = Q_{eg} - [m_{eg} \times T_a \times \{C_{pe} \text{ x } \ln(T_5/T_a) - R_{eg} \times \ln(P_e/P_a)\}] + e_{ch} \quad \text{…(13)}$$

Where R_{eg} is the specific heat constant of exhaust gas in kJ/Kg K.

P_a is the ambient pressure in N/mm^2, P_e is the final pressure in N/mm^2

Destructive availability, A_d

$$A_d = A_{in} - (A_s + A_{cw} + A_{ex}) \quad \text{…(14)}$$

$$\text{Exergy efficiency, } \sigma_A = [1 - (A_d/A_{in})] \times 100 \quad \text{…(15)}$$

Experimental methods

The engine used was a four stroke single cylinder, vertical, water cooled, natural aspirated, direct injection diesel engine. The specifications of the engine are given in Table 1.

Table 1: Specification of the engine

Component	Specification
Make	Kirloskar Engines Ltd., Pune
Type of engine	Four stroke single cylinder water cooled engine
Bore and stroke	87.5 mm & 110 mm
Compression ratio	17.5 : 1
BHP and rpm	4.4 kW & 1500 rpm
Fuel injection pressure	200 N/mm^2
Fuel injection timing	23^0 BTDC
Dynamometer	Eddy current dynamometer

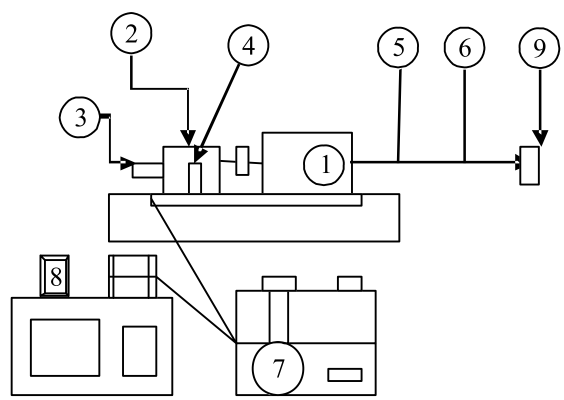


Fig. 2: Schematic diagram of experimental setup

1. Engine 2. Dynamometer 3. Crank angle encoder 4. Load cell 5. Exhaust gas analyzer 6. Smoke meter 7. Control panel 8. Computer 9. Silencer

The schematic diagram of the experimental setup is represented in Fig. 2. A pressure transducer is used to monitor the injection pressure. The engine apparatus was connected with an emission measurement device AVL Digas 444 a five gas analyser. The setup is provided with necessary instruments for measuring combustion pressure and crank angle. The signals from the above instruments are interfaced to the computer through engine indicator for P-V and P-θ diagrams with AVL INDIMICRA 602 –T10602A (V2.5). Atmospheric air enters the intake manifold of the engine through an air filter and an air box. An air flow sensor fitted with the air box gave the input for the air consumption to the data acquisition system. All the inputs such as air and fuel consumption, engine brake power, cylinder pressure and crank angle were recorded by the high speed data acquisition system, processed in the computer. A thermocouple in conjunction with a temperature indicator was connected at the exhaust pipe to measure the temperature of the exhaust gas. A counter flow type calorimeter is used to measure the specific heat of exhaust gas. Thermocouples are fitted at relevant positions for the measurement of temperatures at the required positions. A rotameter is used to measure the flow of water to the engine and the calorimeter. The smoke density of the exhaust was measured by the help of an AVL415 diesel smoke meter. A crank position sensor was connected to the output shaft to record the crank angle. The experimental test rig is shown in Fig. 3.

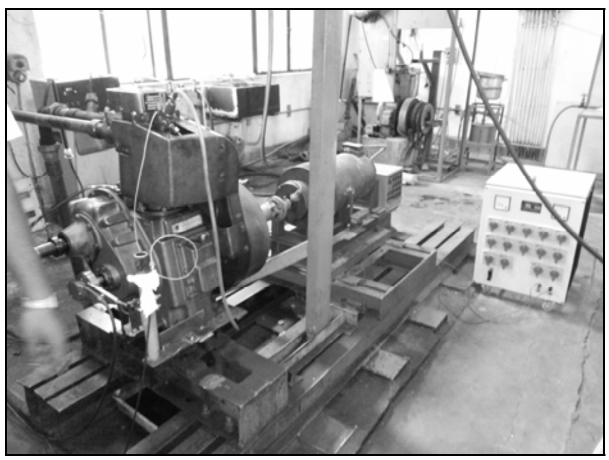


Fig. 3: Experimental test rig

Experimental procedure

The engine used in this study was a direct injection single cylinder engine manufactured by Kirloskar. The engine was run at different compression ratios to evaluate the performance and emission characteristics. Initially the engine was run on no load condition and its speed was maintained at a constant speed of 1500 rpm. The engine was tested at varying loads of 4.5 A, 9 A, 13.5 A and 18 A by means of an electrical dynamometer. For each loading conditions, the engine was run for at least 3 min after the data was collected. In the present study, thin copper spacers were used to vary the clearance volume to obtain compression ratios of 16.4:1, 15.37:1, 14.5:1 and 13.7:1 apart from the standard compression ratio of 17.5:1.

Experimental observations

Energy analysis

Table 2 shows the energy analysis at compression ratio of 17.5:1. As the load increase, the brake power increases and the unaccounted losses also increases.[12]

Table 2: Experimental observations based on energy analysis

5.1.1 CR 17.5:1

Load		Qin kW	%	W shaft kW	%	Q cooling kW	%	Q exhaust kW	%	Q unaccounted kW	%
4.8	25%	7.198	100	1.13	15.69	3.762	25.08	1.185	16.46	1.21	15.57
9.37	50%	9.798	100	2.29	23.37	3.762	25.08	1.665	16.99	2.081	21.23
13.94	75%	11.881	100	3.33	28.05	3.762	25.08	2.052	17.27	2.737	23.03
18.2	Full	15	100	4.226	28.17	3.762	25.08	2.666	17.77	4.346	28.97

Table 3 shows the energy analysis at compression ratio 16.5:1. As the load increases, the heat lost to exhaust also increases.[13]

Table 3: Experimental observations based on energy analysis

5.1.2 CR 16.5:1

Load		Qin kW	%	W shaft kW	%	Q cooling kW	%	Q exhaust kW	%	Q unaccounted kW	%
4.5	25%	7.838	100	1.105	14.09	3.511	23.88	1.146	14.62	2.076	26.48
9.36	50%	10.689	100	2.256	21.1	3.511	23.88	1.567	14.65	3.355	31.38
13.81	75%	13.567	100	3.299	24.3	3.511	23.88	1.677	12.36	5.096	37.56
18	Full	14.697	100	4.2	28.57	3.511	23.88	2.574	17.51	4.412	30.01

Table 4 shows the energy analysis at compression ratio of 15.37:1. As the load increase, the brake power increases and the unaccounted losses also increases.

Table 4: Experimental observations based on energy analysis

5.1.3 CR 15.37:1

Load		Qin kW	%	W shaft kW	%	Q cooling kW	%	Q exhaust kW	%	Q unaccounted kW	%
4.34	25%	7.198	100	1.089	15.12	3.521	20.16	1.413	19.63	1.175	16.32
9.3	50%	9.664	100	2.263	23.41	3.521	20.16	1.792	18.54	2.088	21.65
13.73	75%	12.598	100	3.264	25.9	3.521	20.16	2.359	18.72	3.454	27.41
18.1	Full	17.462	100	4.163	23.84	3.521	20.16	3.078	17.62	6.7	38.36

Table 5 shows the energy analysis at compression ratio 15.5:1. As the load increases, the heat lost to exhaust also increases.

Table 5: Experimental observations based on energy analysis

5.1.4 CR 14.5:1

Load		Qin kW	%	W shaft kW	%	Q cooling kW	%	Q exhaust kW	%	Q unaccounted kW	%
4.3	25%	7.838	100	1.055	13.46	3.26	18.48	1.339	17.08	2.183	27.85
9.0	50%	11.198	100	2.17	19.37	3.26	18.48	1.657	14.79	4.1106	36.7
13.4	75%	16.034	100	3.245	20.23	3.26	18.48	2.284	14.24	7.2446	45.17
18.1	Full	17.637	100	4.223	23.94	3.26	18.48	2.805	15.9	7.348	41.6

Table 6 shows the energy analysis at compression ratio of 13.7:1. As the load increase, the brake power increases and the unaccounted losses also increases.

Table 6: Experimental observations based on energy analysis

5.1.5 CR 13.7:1

Load		Qin kW	%	W shaft kW	%	Q cooling kW	%	Q exhaust kW	%	Q unaccounted kW	%
0	0	0	100	0	0	0	0	0	0	0	0
4.32	25%	7.348	100	1.08	14.69	3.009	17.06	1.8	24.49	1.459	19.85
9.26	50%	10.078	100	2.232	22.14	3.009	17.06	2.312	22.94	2.525	25.05
13.62	75%	16.797	100	3.162	18.82	3.009	17.06	3.027	18.02	7.598	45.23
18.1	Full	17.637	100	4.223	23.94	3.009	17.06	3.118	17.67	7.225	40.96

Exergy analysis

Table 7 shows the exergy analysis at compression ratio of 17.5:1. As the load increases, the availability of the shaft power and destructed availability increases.

Table 7: Experimental observations based on exergy analysis

5.2.1 CR 17.5:1

Load		Ain kW	%	A shaft kW	%	A cooling kW	%	A exhaust kW	%	A destroyed kW	%	Efficiency availability
4.8	25%	7.425	100	1.13	15.22	2.547	34.30	0.754	10.15	2.993	40.31	59.68
9.37	50%	10.105	100	2.29	22.66	2.547	25.21	0.941	9.31	4.327	42.82	57.1
13.94	75%	12.28	100	3.33	27.12	2.547	20.74	1.086	8.84	5.317	43.30	56.7
18.2	Full	15.5	100	4.226	27.26	2.547	16.43	1.52	9.81	7.207	46.50	53.5

Table 8 shows the exergy analysis at compression ratio of 16.4:1. As the load increases, the availability efficiency decreases.

Table 8: Experimental observations based on exergy analysis

5.2.2 CR 16.4:1

Load		Ain kW	%	A shaft kW	%	A cooling kW	%	A exhaust kW	%	A destroyed kW	%	Efficiency availability
4.5	25%	8.08	100	1.1	13.61	2.29	28.34	0.65	8.04	4.03	49.88	50.08
9.36	50%	11.05	100	2.25	20.36	2.29	20.72	0.9	8.14	5.59	50.59	49.35
13.81	75%	14.01	100	3.29	23.48	2.29	16.35	0.951	6.79	7.469	53.31	46.7
18	Full	18.23	100	4.2	23.04	2.29	12.56	1.47	8.06	10.26	56.28	43.69

Table 9 shows the exergy analysis at compression ratio of 15.37:1. As the load increases, the exhaust gas availability increases.

Table 9: Experimental observations based on exergy analysis

5.2.3 CR 15.37:1

Load		Ain kW	%	A shaft kW	%	A cooling kW	%	A exhaust kW	%	A destroyed kW	%	Efficiency availability
4.34	25%	7.425	100	1.089	14.67	2.306	31.06	0.669	9.01	3.361	45.27	54.73
9.3	50%	9.97	100	2.26	22.67	2.31	23.17	0.996	9.99	4.44	44.53	55.43
13.73	75%	13	100	3.26	25.08	2.31	17.77	1.27	9.77	6.16	47.38	52.63
18.1	Full	18.01	100	4.16	23.10	2.30	12.77	1.75	9.72	9.79	54.36	45.64

Table 10 shows the exergy analysis at compression ratio of 14.5:1. As the load increases, the destructive exergy and availability to exhaust gases increases.

Table 10: Experimental observations based on exergy analysis

5.2.4 CR 14.5:1

Load		Ain kW	%	A shaft kW	%	A cooling kW	%	A exhaust kW	%	A destroyed kW	%	Efficiency availability
4.3	25%	8.1	100	1.05	12.96	2.201	27.17	0.715	8.83	4.13	50.99	49.01
9.0	50%	11.55	100	2.17	18.79	2.2	19.05	0.823	7.13	6.356	55.03	44.9
13.4	75%	16.564	100	3.245	19.59	2.2	13.28	1.231	7.43	9.877	59.63	40.36
18.1	Full	18.22	100	4.22	23.16	2.20	12.07	1.665	9.14	10.145	55.68	44.35

Table 11 shows the exergy analysis at compression ratio of 16.4:1. As the load increases, the availability efficiency decreases and increased at full load.

Table 11: Experimental observations based on exergy analysis

5.2.5 CR 13.7:1

Load		Ain kW	%	A shaft kW	%	A cooling kW	%	A exhaust kW	%	A destroyed kW	%	Efficiency availability
0	0	0	100	0	0	0	0	0	0	0	0	0
4.32	25%	7.596	100	1.08	14.22	2.028	26.70	0.905	11.91	3.583	47.17	52.83

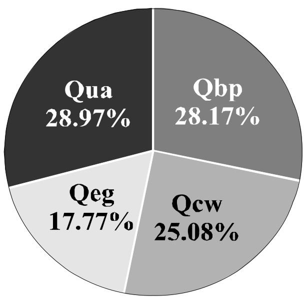
Cont…

Load		Ain kW	%	A shaft kW	%	A cooling kW	%	A exhaust kW	%	A destroyed kW	%	Efficiency availability
9.26	50%	10.412	100	2.232	21.44	2.028	19.48	1.154	11.08	4.998	48.00	51.99
13.62	75%	17.363	100	3.1628	18.22	2.028	11.68	1.056	6.08	13.145	75.71	24.29
18.1	Full	18.223	100	4.223	23.17	2.03	11.12	1.693	9.29	10.29	56.47	43.53

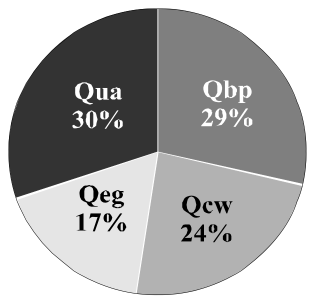
RESULTS AND DISCUSSION

The following results are drawn based on the energy and exergy analysis,

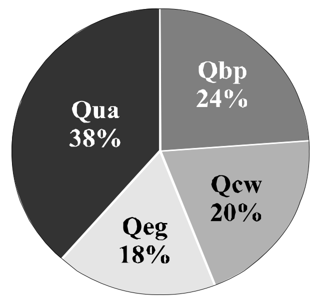
Energy analysis



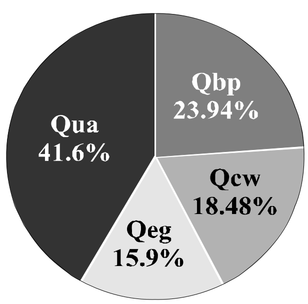
(a) Energy analysis at CR 17.5:1



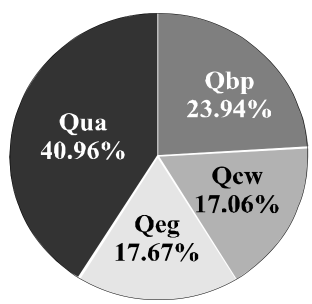
(b) Energy analysis at CR 16.4:1



(c) Energy analysis at CR 15.37:1



(d) Energy analysis at CR 14.5:1

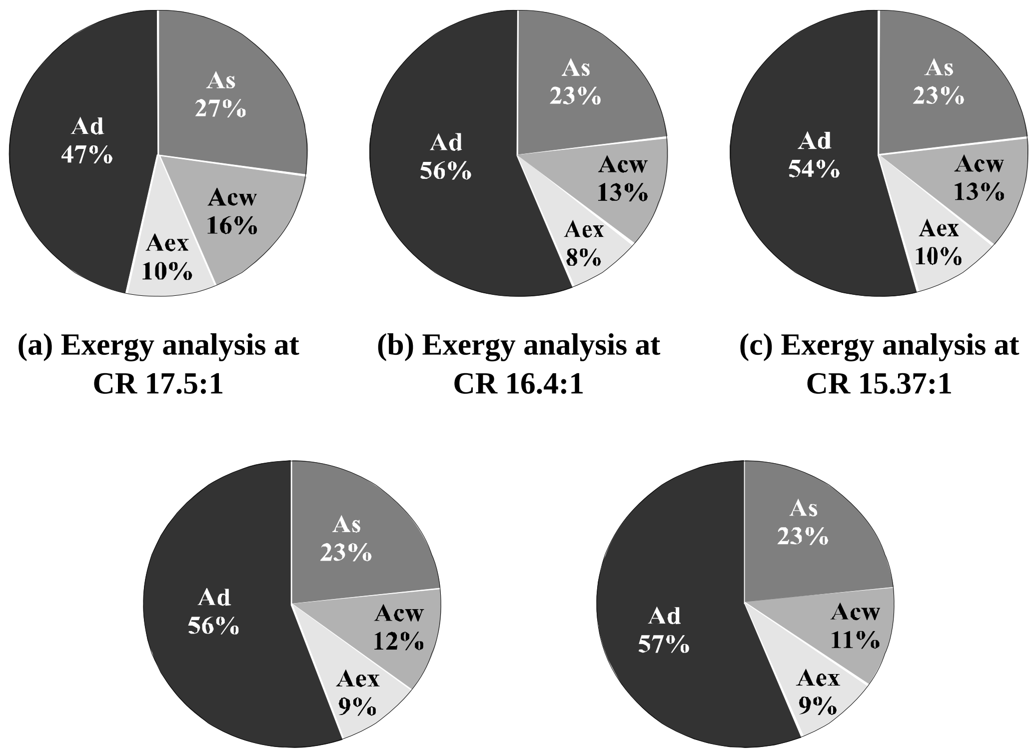


(e) Energy analysis at CR 13.7:1

Fig. 4: Energy distribution at various compression ratios

Fig. 4 shows the energy analysis of the input fuel energy and energy spent for brake power, energy lost through exhaust gases, cooling water and unaccounted losses. It was found from Fig. 4b that the fuel energy utilization for brake power was found to be 29% at compression ratio of 16.4:1. Fig. 4d shows that the fuel energy spent on brake power was 23.9% at compression ratio of 14.5:1 and 13.7:1. The fuel energy is directly proportional to the compression ratio. As the compression ratio reduces, the peak in-cylinder pressure reduces. This leads to the poor atomization of fuel. Figure 4a shows that the heat lost to the exhaust gases was found to be maximum, 17.77% at compression ratio of 17.5:1.

Exergy analysis



(a) Exergy analysis at CR 17.5:1 **(b) Exergy analysis at CR 16.4:1** **(c) Exergy analysis at CR 15.37:1**

(d) Exergy analysis at CR 14.5:1 **(e) Exergy analysis at CR 13.7:1**

Fig. 5: Exergy distribution at various compression ratios

Fig. 5 shows the exergy analysis. The heat transfer creates the irreversibility. Higher will be the exergy loss when the temperature of the engine surface is higher and the heat loss from the engine is proportional to the rate of heat rejection. From Fig. 5e, the exergy destruction is high, 57% at compression ratio of 13.7:1 and less, 47% at compression ratio of 17.5:1 from Fig. 5a. The exergy availability at shaft is high at compression ratio of 17.5:1.

CONCLUSION

In the study, the Energy and Exergy analysis were performed on a diesel engine at various compression ratios, by changing the clearance volume. The energy analysis is based on first law and exergy analysis is based on second law of thermodynamics. The fuel energy utilization to brake power is more, 29% at compression ratio of 16.4:1 and less, 23.94% at compression ratio of 13.7:1. The exergy availability is high, 57% at compression ratio of 13.7:1 and 47% at compression ratio of 17.5:1.

Nomenclature

A.E.	:	Available energy, kW
Ain	:	Input availability, kW
Acw	:	Cooling water availability, kW
Aex	:	Exhaust gas availability, kW
Ad	:	Destructed availability, kW
BP	:	Brake power, kW
Cpw	:	Specific heat of water, kJ/kg K
Cpe	:	Specific heat of exhaust gas, kJ/kg K
e	:	Flow exergy per unit mass
$e$tm	:	Thermo mechanical exergy
$e$ch	:	Chemical exergy
L.C.V	:	Lower calorific value, kJ/kg
mf	:	Mass of fuel supplied, kg/s
mwe	:	Mass of cooling water circulated through the cooling jacket, kg/s
mcw	:	Mass of cooling water passing through the calorimeter, kg/s
meg	:	Mass of exhaust gases ($mf + ma$), kg/s
N	:	Crank revolution per second
Q_{BP}	:	Heat equivalent of brakepower, kW
Qcw	:	Heat carried away by cooling water, kW
Qeg	:	Heat carried away by exhaust gases, kW

Qu	:	Unaccounted energy losses, kW
Ta	:	Ambient temperature, K
U.E.	:	Unavailable energy, kW
ηA	:	Exergy efficiency
CR	:	Compression Ratio

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