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Thermodynamic Analysis of a Diesel Engine Integrated with a PCM Based Energy Storage System

K.Nantha Gopal[1*], Rayapati Subbarao[2], V.Pandiyarajan[3] and R. Velraj[4]

[1]School of Mechanical and Building Sciences, VIT University, Vellore -14, Tamilnadu, India
[2]Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai - 25, India.
[3]A.C.College of Technology, Anna University, Chennai - 25, India.
[4]Institute of Energy Studies, Anna University, Chennai - 25, India.
E-mail: [1]nanthagopalk@yahoo.com; [2]rsubbarao@hotmail.com; [3]vprajan@annauniv.edu;[4]velrajr@annauniv.edu

Abstract

This work describes the energy and exergy analysis of a diesel engine integrated with a PCM based energy storage system, and provides more realistic and meaningful assessment than the conventional energy analysis. Using actual system data, the assessments of energy and exergy saved, and energy and exergy efficiencies are done. The exergy saved in the overall system is quantified and illustrated using an exergy flow diagram. Also, energy and exergy flow diagrams are compared. It is observed through the analysis that 6.13% of the total energy of the fuel is saved using the TES system. From the exergy analysis, it is identified that only 0.47% of the chemical availability of the fuel is saved. The energy efficiency of the integrated system is found to be varying between 3.19% and 34.15%. In contrast, the exergy efficiency, which incorporates the second law of thermodynamics for the integrated system, ranges from 0.25% to 27.41%.

Keywords: *Thermal energy storage, phase change material, exhaust heat exchanger, heat of fusion, low density polyethylene, waste heat recovery.*

1. Introduction

Large diesel engines are one of the most efficient power generation units. In addition to less maintenance and high efficiencies, these can burn a wide range of fuels derived from fossil or organic sources. Nearly two-thirds of input energy is wasted through exhaust gas and cooling water of diesel engines. Energy recoveries from such installations have become of worldwide interest because of the energy crisis. Such waste heat recovery would ultimately reduce overall fuel consumption and production of carbon dioxide. Depending on the temperature of the exhaust gas and the proposed application, different heat exchange devices, heat pipes and combustion equipment can be employed to facilitate the use of the recovered heat. Major technical constraints that prevent successful implementation of heat recovery systems are intermittent and time-mismatches between the demand and availability of energy.

Thermal energy storage (TES) in general and phase change materials (PCMs) in particular, have been an area of interest of researchers for the last two decades. Latent heat storage system has the advantages of high-energy storage density and isothermal behavior during the charging and discharging processes. The utilization of TES systems reduces energy consumption and provides an alternative as fossil fuels are getting depleted. Three types of TES systems are common in practice: sensible, latent and thermo-chemical. The selection of TES is generally dependent on the storage period required, economic viability and operating conditions. The choice of storage media depends on the amount of energy to be stored per unit volume or weight of the storage medium and the temperature range at which it is required for a given application.

Zalba et al. (2003) reviewed the phase change materials, heat transfer and applications of thermal storage systems with solid–liquid phase change. Paraffin wax has been used in many latent thermal energy storage applications because of its advantageous thermal performance. PCMs that are used as storage media in latent thermal energy storage can be classified into two major categories: inorganic and organic compounds. Inorganic PCMs include salt hydrates, salts, metals and alloys, whereas organic PCMs comprise paraffin, fatty acids/esters and poly alcohols. Paraffin is taken as the most promising phase change material because of its high latent heat, low cost, stability, non-toxicity and non-corrosive characteristics, and negligible degree of subcooling during nucleation. Also, the phase change process results in only a small volume change (He et al., 2004). Zukowski (2007) described a short term TES unit based on an enclosed PCM in a polyethylene film bag. Paraffin wax was used as a storage medium. He presented the experimental results that included charge, discharge and pressure drop of the tested unit. The total enthalpy storage in the module was dependant on the PCM temperature change and ranged from 240 to 262 kJ/kg.

TES systems have the potential to produce significant benefits and savings, particularly in low temperature heating and cooling applications. They are widely used in heat pumps, solar engineering and spacecraft thermal control applications. Use of PCMs for heating and cooling applications in buildings has been investigated in the past few years. There are large numbers of PCMs that melt and solidify at a wide range of temperatures, making them attractive in a number of applications (Sharma et al., 2009).

Several researchers have carried out experimental and theoretical investigations on the application of diesel engine exhaust for drying of clay minerals and driving absorption

*Corresponding Author

refrigeration systems and heat pumps. Rabghi et al. (1993) presented the waste heat in different branches of industry and new ways to recover the discharged heat from industrial equipment. It was concluded that there exists numerous opportunities for recuperating and using waste heat. Use of paraffin as a PCM was investigated by Fieback and Gutberlet (1998) for the development of compact units, which provides high thermal energy storage capacity for many thermal applications.

Desai et al. (2002) experimentally studied the method of extracting waste heat from the exhaust gas of an IC Engine. A shell and tube heat exchanger to extract the heat from the exhaust gas of a diesel engine as per TEMA and ASME standards was designed and fabricated. It was observed that such a heat exchanger had an effectiveness of 80-82%. Smith et al. (2001) conducted a second law analysis for a domestic purpose cogeneration plant with a heat pump. He discussed the development of combined heat and power concept and described the construction of an experimental unit while identifying the areas of improvement needed in the performance of the plant using the second law that could not be examined by first law of thermodynamics.

Dincer (2002) conducted experiments on the applications of various TES systems with a number of illustrative examples. He carried out energy-exergy modeling for a TES system and demonstrated how exergy analysis provides more realistic and meaningful assessment than the conventional energy analysis in the performance of a sensible energy storage system. Sahin et al. (2007) investigated the thermodynamic characteristics of photovoltaic cells (PV) from an exergy based perspective. They developed an efficiency term that is useful in the study of PV performances and identified possible improvements. Saidur et al. (2007) applied energy and exergy principles for different modes of transport in Malaysia and compared the results with several other countries. Kanoglu et al. (2007) provided an extensive overview of various energy and exergy efficiencies used in the analysis of power cycles.

In the present work, water is considered as the sensible energy storage material and paraffin as the latent energy storage material (PCM). Also, water is treated as heat transfer fluid to extract heat from the exhaust gases of the diesel engine.

2. Thermodynamic Analysis of Systems

For better energy utilization, it is important to take care of the quantity and quality of energy. This can be accomplished by applying the laws of thermodynamics. Thermodynamic analysis (energy and exergy analyses) is a standard measure to understand a system's behavior and to acquire practical and theoretical knowledge in designing commercial systems. Use of this analysis allows the identification of losses that degrade the quality and quantity of energy transfer.

It is a systematic approach that can be used to identify sites of real losses of valuable energy in a thermal device (Najem et al., 1992). Exergy analysis uses the conservation of mass and energy principles together with the second law of thermodynamics for the design analysis of energy systems. In a diesel engine, the first law analysis identifies significant energy losses because of cooling and heat lost in the exhaust gas of the engine. But, when these losses are analyzed using the exergy method, the actual exergy loss is insignificant compared to the thermodynamic losses within the engine (Najem et al., 1992). The present work is aimed at illustrating the capability of exergy analysis to provide a systematic approach to pinpoint the waste and lost energy in a diesel engine and the TES system. This leads to significant improvement in energy utilization.

2.1 System Description

The experimentation unit consists of a diesel engine, exhaust heat exchanger (EHE) and a TES system as shown in Figure 1. A four stroke, water-cooled, twin cylinder diesel engine rated at 10.3kW@1500 rpm is considered for the analysis. EHE (Figure 2) consists of horizontal and elliptical shape heater core made of mild steel that is wounded by copper tube at gradual intervals across its length. Lathe scrap is filled over this surface and is wound by glass wool. The entire surface is covered with aluminum sheet. Lathe scrap acts as an additional heat transfer surface to increase the heat transfer rate. Glass wool is used to reduce the heat lost to the surroundings. The entire set up is fit to the exhaust pipe of the engine to extract waste heat from the exhaust gas, using water as the heat transfer fluid.

The storage tank is a stainless steel vessel, which contains water as the sensible energy storage material and paraffin as the latent storage material. Water also acts as a heat transfer fluid to extract heat from the flue gas. TES tank is filled with spherical containers made of low density polyethylene, which contains paraffin. The engine is operated with and without the heat exchanger. Water from the storage tank enters the heat exchanger and extracts heat from the exhaust gas and this energy is stored in the storage system. Water in the copper tube is heated and circulated by natural circulation to the storage tank. Due to the circulation of water through the heat exchanger, the temperature in the storage tank increases. PCM melts when the water temperature is increased beyond the melting temperature of the PCM. Water is heated until it reaches the temperature of $80^{\circ}C$ during the charging period. The properties of paraffin are summarized in Table 1.

2.2 Charging of PCM

Water in the copper tube is heated as water circulates by natural circulation in the storage tank. The temperature in the storage tank increases due to circulation of water through the heat exchanger. Initially, the water temperature rises at a faster rate and during the phase change the rise in temperature is very low. Water is heated until it reaches a temperature of $80^{o}C$. Temperature readings are taken at a regular interval of 10 minutes throughout the charging period.

3. Energy and Exergy Analysis

The following sections will explain the energy and exergy analysis of the diesel engine and energy storage system as shown in Figure.1. A second law analysis is carried out to examine the various aspects of plant operation that could not be dealt with using first law techniques. By assessing the maximum available work (exergy) that could be obtained from mass flow or an energy transfer, the quality of energy transfer can be evaluated. As the second law of thermodynamics implies that work energy has a greater value than thermal energy, the analysis of quality of energy has practical and economic implications.

This method examines the properties of mass transfer and calculates the maximum work that can be theoretically carried out by bringing it to a reference state. Exergy analysis is carried out using the following assumptions:

- Changes of potential, kinetic, electromagnetic and electrostatic exergies are negligible and are not included in the analysis.
- Atmospheric environment at a pressure of 1 bar and a temperature of 301 K (28ºC) as reference state.
- Engine and the TES system are steady flow devices.
- Losses in EHE are negligible.
- Maximum storage temperature is 80ºC.

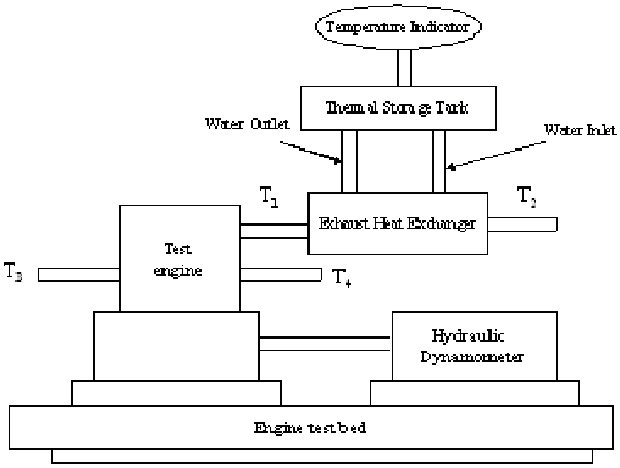

Figure 1. Schematic Diagram of the Experimental Setup.

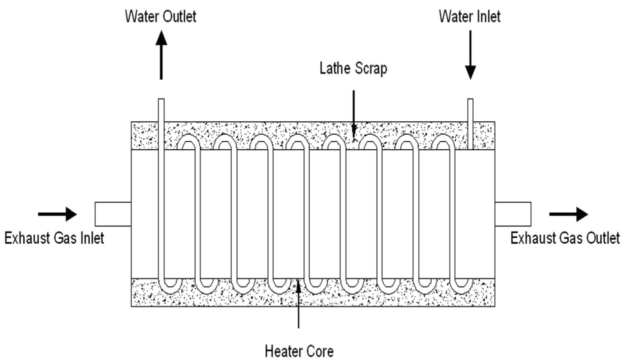

Figure 2. Schematic Diagram of Exhaust Heat Exchanger.

Table 1. Thermo- physical Properties of PCM (paraffin).

Latent heat of fusion[kJ.kg^{-1}]	214
Specific heat capacity (solid) [kJ.kg^{-1} K^{-1}]	1.85
Specific heat capacity (liquid)[kJ.kg^{-1} K^{-1}]	2.348
Thermal conductivity (solid)[W.m^{-1}.K^{-1}]	0.4
Thermal conductivity(liquid))[W.m^{-1}.K^{-1}]	0.15
Density (solid)[kg. m^{-3}]	856
Density (liquid)[kg. m^{-3}]	775
Phase transformation temperature range[ºC]	58-60

3.1 Energy Analysis of the System

All energies are evaluated on the basis of the first law of thermodynamics (Eqs 1-10). Input energy to the diesel engine is the amount of energy content of the fuel and is given by:

$$E_f = \dot{m}_f \times LCV \tag{1}$$

The energy carried by exhaust gases is:

$$E_{ex} = \dot{m}_{ex} \times C_{p_{ex}} (T_1 - T_0) \tag{2}$$

The energy recovered by EHE is:

$$E_{ehe} = \dot{m}_{ex} \times C_{p_{ex}} (T_1 - T_2) \tag{3}$$

The energy lost to cooling water is:

$$E_{cw} = \dot{m}_{cw} \times C_{p_{cw}} (T_4 - T_3) \tag{4}$$

The charging rate is the rate of energy storage in the storage system. It is the ratio of energy required to increase the temperature of water and paraffin in the tank from 28ºC to 80ºC to the time required to attain the temperature of 80 ºC. The charging rate is:

$$E_{ch} = \frac{\dot{m}_w \times C_{pw}(80-28) + \dot{m}_p \times L + \dot{m}_p \times C_{pp}(80-28)}{t} \tag{5}$$

The charging efficiency is the ratio of energy stored in the storage tank to the energy recovered by the EHE,

$$\eta_{ch} = \frac{\left(\dot{m}_w \times C_{pw}(80-28) + \dot{m}_p \times L + \dot{m}_p \times C_{pp}(80-28)\right)}{\dot{m}_{ex} \times C_{pex}(T_1 - T_2) \times t} \tag{6}$$

where L is the latent heat of paraffin.

Total useful energy is:

$$E_t = W_d + E_{st} \tag{7}$$

Energy efficiency of the diesel engine is:

$$\eta_d = W_d / E_f \tag{8}$$

Energy efficiency of the integrated system is:

$$\eta_i = E_t / E_f \tag{9}$$

Energy saved,

$$E_s = \frac{\left(\dot{m}_w \times C_{pw}(80-28) + \dot{m}_p \times L + \dot{m}_p \times C_{pp}(80-28)\right)}{\dot{m}_f \times LCV \times t} \tag{10}$$

3.2 Exergy Analysis of the System

Kotas (1995) gave a simple expression for computing the chemical availability of a fuel as

$$A_f = 1.04 \times \dot{m}_f \times LCV \tag{11}$$

The exergy lost in exhaust gas without EHE is:

$$A_{ex} = \dot{m}_{ex} \{(h_i - h_o) - T_o(s_i - s_o)\} \tag{12}$$

The exergy recovered by EHE is:

$$A_{ehe} = \dot{m}_{ex} \times C_{pex} \{(T_1 - T_2) - T_o \ln(T_1 / T_2)\} \tag{13}$$

The exergy lost to cooling water is:

$$A_{cw} = \dot{m}_{cw} \times C_{pcw} \{(T_4 - T_3) - T_o \ln(T_4 / T_3)\} \tag{14}$$

The exergy of the storage in the system is:

$$A_{st} = \frac{\begin{Bmatrix} \dot{m}_w \times C_{pw}[(80-28) - T_0 \ln(353/301) + \dot{m}_p \times Cpp[(80-28) \\ -T_0 \ln(353/301)] + \dot{m}_p[(L - T_0(L/T_{pc})] \end{Bmatrix}}{t} \quad (15)$$

where, T_{pc} is the phase change temperature of paraffin (60ºC).

Total useful exergy is:

$$A_t = W_d + A_{st} \quad (16)$$

Exergy efficiency of the diesel engine is:

$$\psi_d = \frac{W_d}{A_f} \quad (17)$$

Exergy efficiency of the integrated system is:

$$\psi_i = \frac{A_t}{A_f} \quad (18)$$

Exergy saved is:

$$E_s = \frac{A_{st}}{A_f} \quad (19)$$

Exergy efficiency of charging is:

$$\psi_{ch} = \frac{A_{st}}{A_{ehe}} \quad (20)$$

4. Results and Discussion

4.1 Energy and Exergy balance of the Diesel Engine and the Integrated System

The efficiency of the diesel engine according to first and second laws of thermodynamics with respect to brake power is shown in Fig. 3. It shows that the exergy efficiency of the diesel engine is slightly lower than the energy efficiency of the diesel engine for the same power output. This is due to the fact that the chemical availability of the fuel is slightly higher than its input energy.

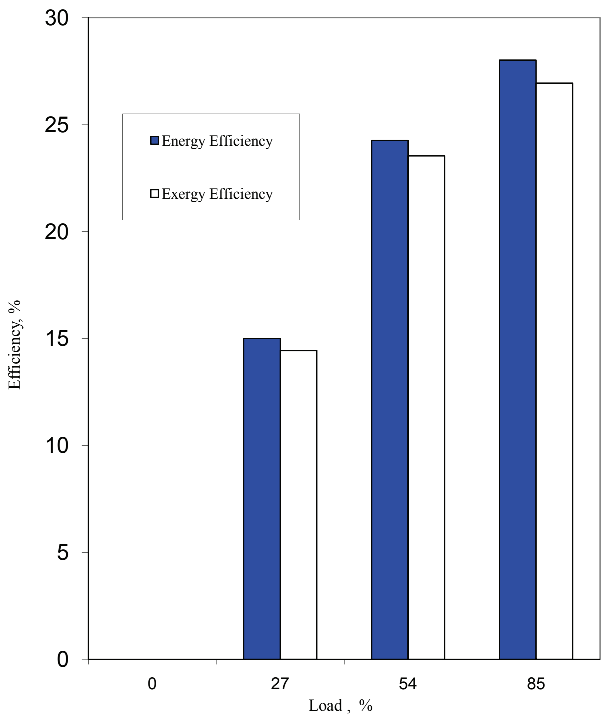

Figure 3. Efficiency of Diesel Engine with Load.

Figure 4 shows the efficiency of the integrated system (diesel engine with TES system) at various loads. It is seen from the graph that the exergy efficiency of the integrated system is lower than its energy efficiency. It is due to low exergy stored in the storage tank at low temperature level as shown in Fig. 5. This can be further improved by storing energy at a higher grade by selecting the proper phase change material and using heat transfer fluids such as oil.

The energy and exergy recovered by heat exchanger from the exhaust gas are shown in Fig. 6 and values are tabulated in Tables 2 and 3. From these analyses the energy recovered from the exhaust gas varies from 1.22 to 3.86 kW at various loads. However, only 0.33 to 2.23 kW of exergy of fuel is available to produce useful work.

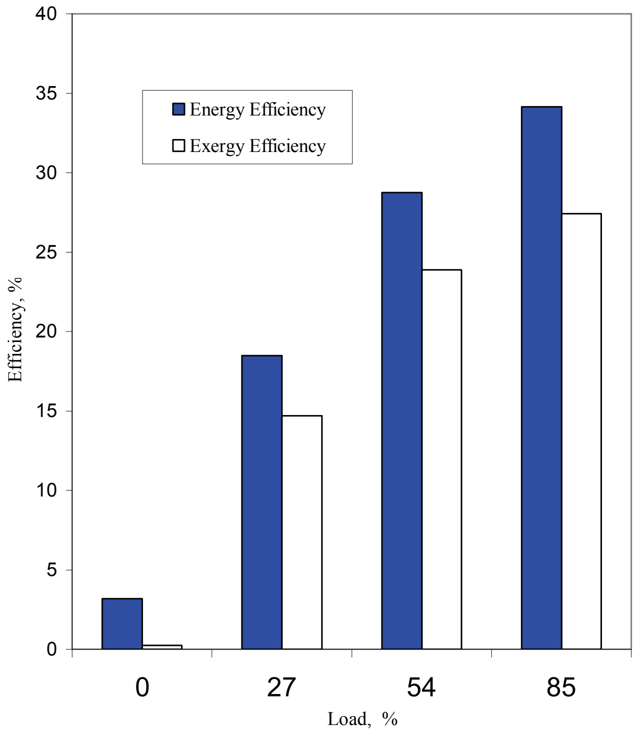

Figure 4. Efficiency of Integrated System with Load.

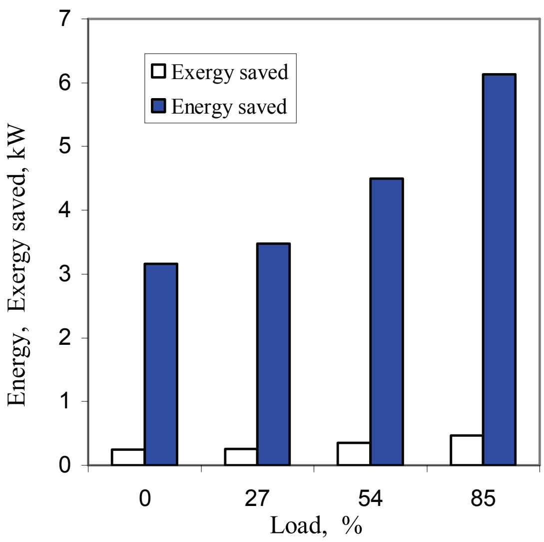

Figure 5. Energy and Exergy Saved with Load.

Figure 7 shows the overall exergy efficiency of the engine with and without the integrating the storage system. It is seen from the figure that there is only a marginal increase in exergy efficiency with the storage system compared to the system without the storage system. Hence it is construed that more focus should be given to improve the efficiency of engine rather than recovering heat at lower temperature.

In order to represent the energy and exergy level at every stage of the energy conversion and recovery process, the energy and exergy balance diagram for the diesel engine integrated with PCM storage system are shown in Figs. 8 and 9. From the energy analysis, it is found that the losses in energy due to cooling water and exhaust gases are about 51% of the total input fuel energy, and 21 to 34% is lost due to unaccounted factors.

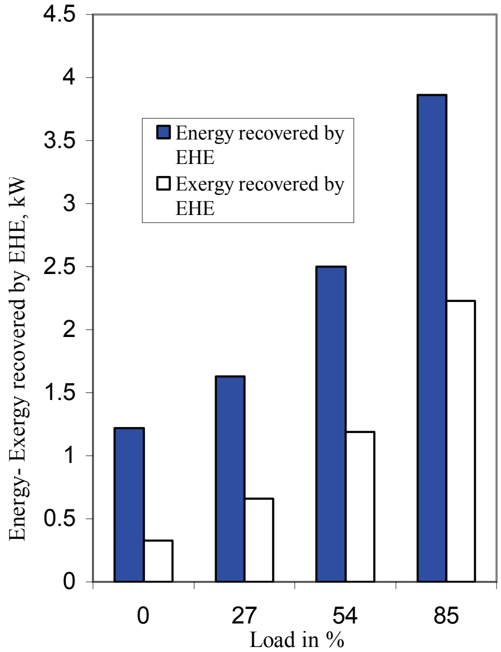

Figure 6. Energy and Exergy recovered by EHE (in kW).

Table 2. Energy Analysis.

Description	A	B	C	D
Load[%]	0	27	54	85
Fuel input(E_f) [kW]	13.5	18.4	22.7	31.48
Brake power(W_d) [kW]	0	2.76	5.51	8.82
Energy lost in exhaust without EHE(E_{ex}) [kW]	2.16	3.16	4.51	6.05
Energy recovered by EHE(E_{ehe})[kW]	1.22	1.63	2.5	3.86
Energy lost in exhaust with EHE(E_{lt})[kW]	0.94	1.53	2.04	2.19
Energy of storage medium(E_{ch}) [kW]	0.43	0.64	1.02	1.93
Energy lost in cooling water(E_{cw})[kW]	3.32	6.38	7.76	9.96
Total energy used from fuel input(E_t) [kW]	0.43	3.4	6.53	10.75
Energy efficiency of charging (η_{ch}) [%]	35	39.26	40.8	50
Energy efficiency of diesel engine (η_d) [%]	0	15	24.27	28.02
Energy efficiency of integrated system(η_i) [%]	3.19	18.49	28.75	34.15
Energy saved(η_s) [%]	3.15	3.48	4.5	6.13

Table 3. Exergy Analysis.

Description	A	B	C	D
Load [%]	0	27	54	85
Chemical availability of fuel(A_f)[kW]	13.91	19.12	23.31	32.74
Brake Power(W_d))[kW]	0	2.76	5.51	8.82
Exergy lost in Exhaust without EHE(A_{ex}) [kW]	0.4	0.83	1.4	2.356
Exergy recovered by EHE(A_{ehe}) [kW]	0.329	0.66	1.19	2.23
Exergy lost in Exhaust with EHE(A_{lt})[kW]	0.075	0.17	0.212	0.126
Exergy of storage medium(A_{ch}) [kW]	0.035	0.052	0.083	0.155
Exergy lost in cooling water(A_{cw}) [kW]	0.027	0.104	0.199	0.346
Total exergy used from fuel input(A_t) [kW]	0.035	2.81	5.64	8.98
Exergy efficiency of charging(ψ_{ch}) [%]	10.64	7.58	6.97	6.95
Exergy efficiency of diesel engine(ψ_d) [%]	0	14.44	23.54	26.94
Exergy efficiency of integrated system(ψ_i) [%]	0.25	14.69	23.88	27.41
Exergy saved (ψ_s) [%]	0.25	0.26	0.35	0.47

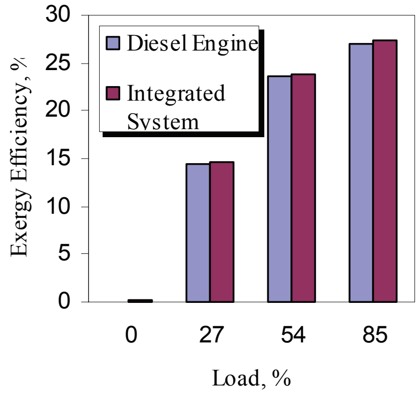

Figure 7. Exergy Efficiency of Diesel Engine and Integrated System.

According to the first law of thermodynamics, the energies of cooling water and exhaust gas seem to be identical, regardless of their temperature differences. The amount of energy in exhaust gas and cooling medium can be usefully utilized in a heat recovery system to produce power or to use it in other processes. From the exergy analysis, it is identified that only 8.25% of the exergy of the fuel is lost in the cooling water and exhaust gas and at the same time 64.78% is destroyed due to irreversibilities (Fig. 9). When this exhaust heat energy is recovered by EHE and stored in TES system using PCM, 6.81% of the total input energy can be saved (Fig. 5).

This stored energy can be used to heat up the water stream for a specific application. But, the exergy analysis shows that only 0.5% of the exergy of the fuel is available to produce useful work. This is because of irreversible losses due to the quality of energy degradation while the heat is transferred over a finite temperature difference and the energy stored in the storage tank is at a low temperature (80ºC). Hence, the maximum useful work obtainable from the stored energy is low (Fig. 5). However, if these energies

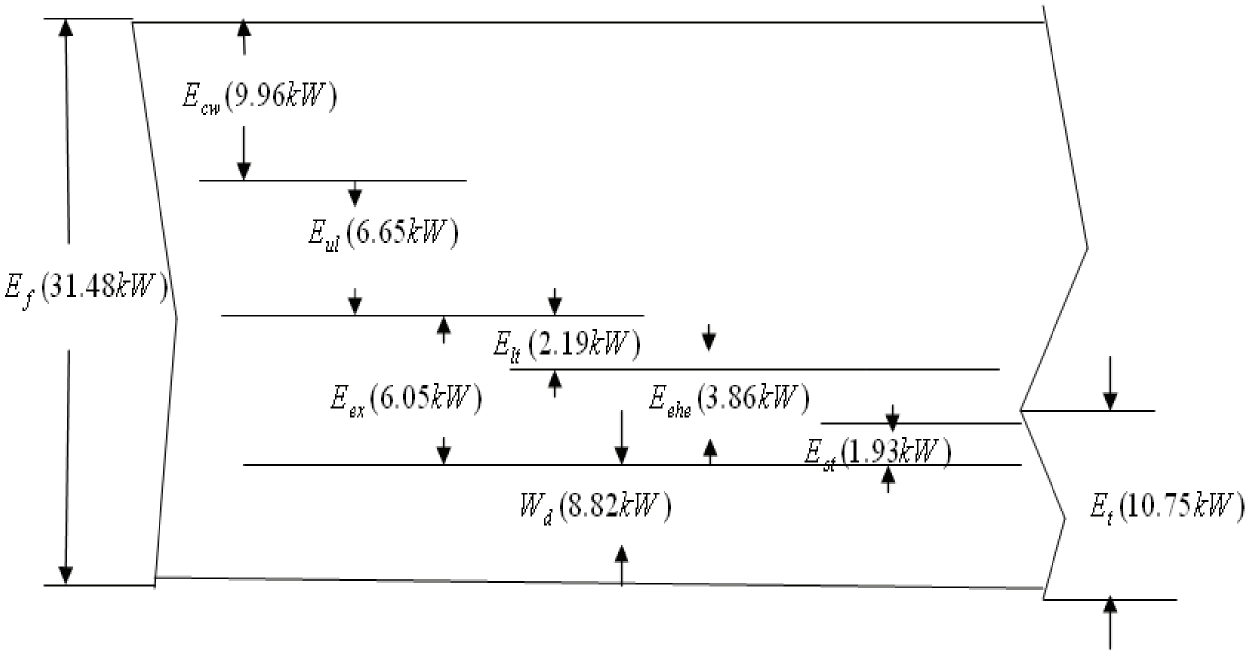

Figure 8. Energy Flow Diagram for the Diesel Engine Integrated with PCM system.

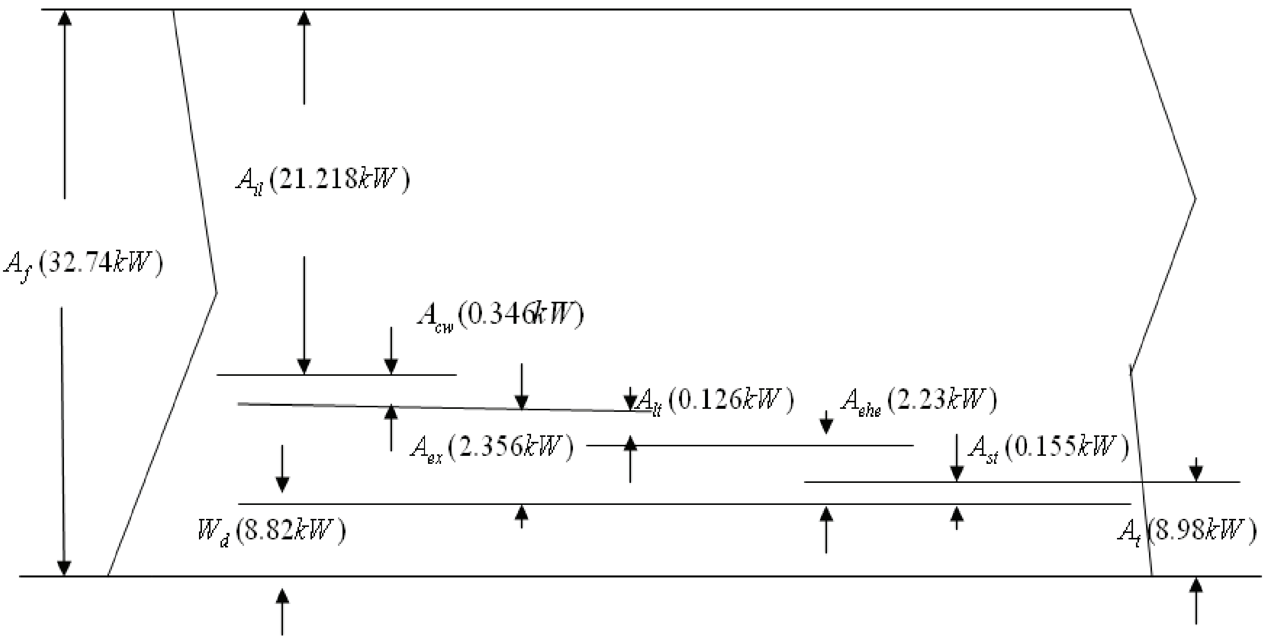

Figure 9. Exergy Flow Diagram for the Diesel Engine Integrated with PCM system

are considered for the production of electricity, then the temperature is considered as a major factor in our selection. From the exergy point of view, 8.25% of the exergy of the fuel is available in the exhaust gas and cooling water to produce useful work.

5. Conclusion

First and second laws of thermodynamics are employed to analyze the quality and quantity of energy in a diesel engine and the thermal energy storage system. The energy and exergy analyses enable us to develop a systematic approach that can be used to identify the sites of real losses of valuable energy in thermal devices. The first law analysis shows that significant losses occur in the exhaust gas and cooling water. However, when analyzed using the exergy method, it is found that the actual exergy losses are insignificant compared to the irreversibility losses in the engine. This indicates that improving the performance of the engine is of more importance than the recovery of low-grade energy loss. In this work, the assessment of energy and exergy saved, and energy and exergy efficiencies are carried out. The exergy saved in the overall system is quantified and illustrated using an exergy flow diagram. Furthermore, energy and exergy flow diagrams are drawn for comparison. It is observed through the analysis that 6.13% of the total energy from fuel input is saved using the TES system. But from the exergy analysis, it is identified that only 0.47% of the chemical availability of the fuel is saved. Results also show that the exergy saved by the energy storage device is low because of its low temperature range. This can be further improved by storing energy at higher temperature. The energy efficiency of the integrated system is seen to be varying between 3.19% and 34.15%. In contrast, the exergy efficiency, which incorporates the second law of thermodynamics for integrated system ranges from 0.25% to 27.41%.

It is concluded from the results that the phase change material should be selected such that it can work at high temperatures and fluids like oil can be used as heat transfer fluids to store heat at that temperature. Therefore, more research should be devoted to minimize such losses by choosing a suitable PCM.

Nomenclature

EHE	Exhaust Heat Exchanger
PCM	Phase Change Material
TES	Thermal Energy Storage
WHR	Waste Heat Recovery
A	exergy [kW]
C_P	specific heat at constant pressure [$kJ.kg^{-1}\ K^{-1}$]
E	energy [kW]
h	specific enthalpy [$kJ.\ kg^{-1}$]
L	latent heat of fusion of Paraffin [$kJ.kg^{-1}$]
LCV	lower Calorific Value [$kJ.\ kg^{-1}$]
M	mass [kg]
$\dot{m}$	mass flow rate [$kg.s^{-1}$]
rpm	revolutions per minute
s	specific entropy [$kJ.kg^{-1}\ K^{-1}$]
T	temperature [K or ^oC]
t	time required to attain 80^oC [s]
W	power output [kW]
η	first law efficiency (energy efficiency) [%]
ψ	second law efficiency (exergy efficiency) [%]

Subscripts

1	temperature of exhaust gas entering EHE
2	temperature of exhaust gas leaving EHE
3	inlet cooling water temperature of the engine
4	outlet cooling water temperature of the engine
amb	ambient
ch	charging
cw	cooling water
d	diesel engine
ehe	exhaust heat exchanger
ex	exhaust gas
f	fuel
i	integrated
in	inlet
ir	irreversible losses
lt	lost energy
o	reference state
out	outlet
p	paraffin
pc	phase change
s	saved
st	stored energy
t	total
ul	unaccounted losses
w	water

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