ISSN (Online) : 2319 -8753
ISSN (Print) : 2347 -6710

International Journal of Innovative Research in Science, Engineering and Technology

Volume 3, Special Issue 3, March 2014

2014 International Conference on Innovations in Engineering and Technology (ICIET'14)
On 21st & 22nd March Organized by

K.L.N. College of Engineering and Technology, Madurai, Tamil Nadu, India

Experimental Investigation Of Heat Recovery From Diesel Engine Exhaust Using Compact Heat Exchanger And Thermal Storage Using Phase Change Material

S.P.Raja[#1], R.Rajavel[#2], D.Navaneethakrishnan[#3]
[#]Department Of Mechanical Engineering, Velammal engineering college, Chennai, India.

ABSTRACT: The exhaust gas from an internal combustion engine carries away about 20% of the heat of combustion. The energy available in the exit stream of many energy conversion devices goes as waste, if not utilized properly. The major technical constraint that prevents successful implementation of waste heat recovery is due to its intermittent and time mismatched demand availability of energy. In the present work, heat recovery system consisting of a compact shell and tube heat exchanger and a thermal energy storage (TES) tank with paraffin and ethylene glycol as phase change material (PCM) storage has been designed and fabricated for waste heat recovery from diesel engine exhaust. Castor oil is used as heat transfer fluid (HTF) in the tube side to extract heat from exhaust gas. Cascading mode of heat recovery is tested using those two phase change materials. Heat recovered both during the endothermic and exothermic reactions of phase change material. About 14% of waste heat through the diesel engine exhaust is recovered using this cascaded mode of thermal storage system.

KEYWORDS*:* Waste heat recovery, Thermal storage, Phase change material, Heat recovery heat exchanger

I INTRODUCTION

The rapid industrial and economic growth in India increased the need for energy. Although variety of sources of energy available, uncertainty existing in these sources, makes attention on the utilization of sustainable energy sources. High capacity diesel engines are one of the most widely used power generation units. Nearly 30% of the input energy is wasted through exhaust and cooling water of these engines. It is necessary to conserve this energy through waste heat recovery techniques. Waste heat is generated in a process by the way of fuel combustion. If this waste heat could be recovered, a considerable amount of primary fuel can be saved. This system is to employ the modern technique to recover the waste heat and to store the recovered heat in a thermal storage system which can be utilised for variety of applications. Latent heat storage is majorly concentrated since its ability to provide high energy storage density and its characteristics to store heat at constant temperature.

Dincer [1] presented a detailed investigation on the energy and exergy analysis of sensible heat storage systems with lot of illustrative examples and also defined various terminologies related to storage systems such as energy and exergy efficiencies for charging, storing and discharging periods. Zalba et al. [2], Sharma et al. [3] and Jagadheeswaran and Pohekar [4] presented a thorough review on thermal energy storage with phase change materials, heat transfer analysis and applications. The parametric studies during solidification of PCM inside an internally finned tube were presented by Velraj et al. [5]. The performance of a natural circulation air heating system with phase change material based energy storage was analyzed by Enibe [6]. Cheralathan et al. [7] have investigated the performance of an industrial refrigeration system

Integrated with encapsulated PCM based cool thermal energy storage system. Nallusamy et al. [8] have experimentally studied the thermal performance of a packed bed latent heat thermal energy storage unit integrated with solar flat plate collector in which paraffin as PCM filled in spherical capsules are placed in a cylindrical storage tank. Schatz [9] introduced the concept of a heat battery which stores engine waste heat using a PCM. The possibility of recovering waste heat from engine coolant and storing the heat in a PCM heat battery is experimentally attempted. This stored heat is used during engine cold start condition by transferring heat from PCM to the engine coolant which ensures the engine to attain operating temperature substantially faster. The concept of integrating thermal energy storage in motor vehicles has been proposed as an alternative short term technological solution for controlling cold-start emission. Vasiliev et al. [10] have experimentally investigated and mathematically modeled the heat storage system for pre heating a petrol engine operated under real condition in cold winter time. Korin et al. [11] have experimentally studied the reduction of cold-start emission from IC engine by means of a catalytic converter embedded in a PCM. They concluded that under normal engine operating conditions some of the thermal energy of the exhaust gases was stored in the PCM. When the vehicle was not in use, the PCM underwent partial solidification and the latent heat produced was exploited to maintain the catalyst temperature with in the desired temperature for maximum catalytic conversion efficiency. Subramanian et al. [12] have done experiment on waste heat recovery from diesel engine exhaust and they mentioned the advantages of combined sensible and latent heat storage system. V.pandiarajan et al. [13] use single PCM paraffin and suggested multiple PCM in a cascaded storage medium for improved heat recovery. Wu et al. [14] made comparison between single stage and cascaded system and found cascaded system is more effective.

In the present work, heat recovery system consisting of a compact shell and tube heat exchanger and a thermal energy storage (TES) tank with paraffin and ethylene glycol as phase change materials (PCM) storage has been designed and fabricated for waste heat recovery from diesel engine exhaust. Castor oil is used as heat transfer fluid (HTF) in the tube side to extract heat from exhaust gas.

II EXPERIMENTAL INVESTIGATION

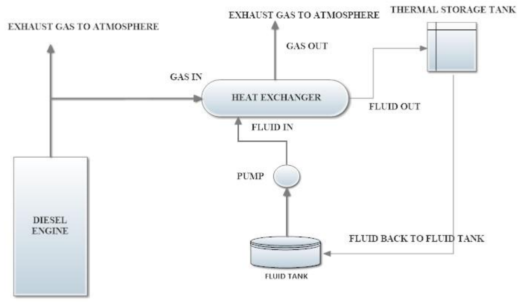

Fig. 1. Schematic diagram of the experimental setup

The major criterion in the design of waste heat recovery system is the proper selection of heat exchanger with optimum conditions in the present investigation, the objective is to extract heat from the exhaust gas and to store it in the storage tank. This could be achieved by providing a separate heat exchanger through which HTF is circulated to extract heat from exhaust gas and deliver it to the storage medium present in the TES tank. TES tank contains cascaded system in which paraffin wax and ethylene glycol is filled as shown in fig. 3. Castor oil is used as a heat transfer fluid (HTF).

A. Selection of heat exchanger and storage tank configuration:

In the present work a shell and tube heat exchanger is selected to extract heat from the exhaust gas and a separate storage tank filled with ethylene glycol and paraffin containers to store the heat.. In general the surface convective heat transfer coefficient for gases will be very low and hence heat transfer surface on the gas side needs to have a much larger area for better heat transfer. This requirement cannot be achieved by embedding the heat exchanger coil inside the storage tank. Hence a separate heat exchanger is designed with tubes in which the exhaust gas is allowed to through the shell side to achieve higher surface area on the gas side. There are two reasons for the selection of such a storage tank filled with PCM containers and oil. The first reason is that a separate shell and tube heat exchanger is already selected for heat recovery due to the above said reason and hence a heat transfer fluid is required to be circulated to extract heat from the heat recovery heat exchanger. The second reason is that the PCM cannot be packed separately inside the storage tank due to its poor thermal conductivity which varies the resistance for heat transfer during charging and discharging. When the PCM solidifies on the convective heat transfer surface, the solidified layer act as an insulator and as the thickness of the solidified layer increases with respect to time the resistance for heat transfer between the HTF and liquid PCM in the storage tank increases. This in turn decreases the heat transfer rate appreciably and causes a non-uniform rate of discharging characteristics in the storage tank which may restrict the usage for any application. This effect is most significant during the discharging process. In order to avoid the above said problems, the storage tank is filled with PCM encapsulated small containers and the heat transfer fluid which receives heat from HRHE is also used as a sensible heat storage material in the storage tank. This type of storage system increases the heat storage capacity compared to the sensible heat storage system and eliminates the problem of varying thermal resistance across the solidified PCM layer that usually encounter in the separate LHTS unit. The details of experimental setup and the methodology adopted are explained in the following section.

Fig. 2. Photographic view of the experimental setup

B. Experimental setup:

The experimental setup consists of a twin cylinder, four stroke, water cooled, Kirloskar make diesel engine (bore 87.5 mm, stroke110 mm, rated power 7.4 kW at 1500 rpm) integrated with a heat recovery heat exchanger (HRHE) and a thermal storage system. Figs. 1 and 2 show the schematic diagram and the photographic view of the experimental setup. The heat recovery system is a shell and tube heat exchanger, made up of mild steel and copper respectively with shell side fluid as exhaust gas and tube side fluid as castor oil.

The HRHE is fitted into the exhaust pipe of the engine. The exhaust gas from the engine is allowed to flow either to the heat exchanger or to the atmosphere by using valves. Castor oil is circulated through tube side of the heat exchanger using gear pump and is passed through thermal energy storage tank. Castor oil from HRHE enters the storage tank from the top and leaves at bottom. A pump maintains the circulation of castor oil in this setup. The TES tank is well insulated using glass wool and covered with Aluminium cladding. A control valve fitted at the exit of TES tank is used to vary the oil flow rate in the system.

C. Experimental methodology:

The experiments are conducted by operating the engine at various load conditions. A rheostat type electrical dynamometer is used to vary the load on the engine. First the experiment is conducted at 25% load condition. Initially the exhaust gas is not allowed to flow through the heat exchanger to avoid carbon deposition on the tube surface. After a short duration from the start of engine, the exhaust gas is allowed to pass through the shell side of the heat exchanger while ensuring the oil circulation through the tube side. A Tachometer is used to measure the speed of the engine to ensure the rated speed of 1500 rpm. The ammeter and voltmeter readings are taken for the evaluation of the brake power. The temperature readings are continuously monitored in the TES tank, inlet and outlet temperature of the HRHE and TES tank. The above said measurements are used to evaluate the heat recovered, charging rate and charging efficiency. Several experiments are conducted to check the repeatability of the results. The experiments are conducted for 50%, 75% and full load condition. The results along with the evaluated parameters are analysed and discussed in the following section.

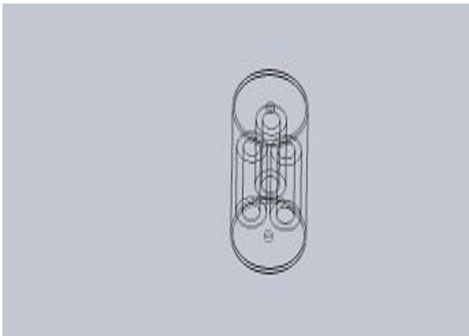

Fig. 3. PCM container

III RESULTS AND DISCUSSION

The results obtained from the experimental investigation for the engine operated at various load conditions are studied in detail and presented. The exhaust gas in an internal combustion engine carries about 30% of the heat of combustion. In the present work, attempts have been made to recover the maximum possible heat from the exhaust gas through a shell and tube heat exchanger and to store it in a

TES tank filled with cylindrical PCM capsules.

A. Performance of heat recovery heat exchanger:

The temperature variation of the exhaust gas and the oil at the inlet and outlet of the HRHE with respect to time for various engine load conditions (25%, 50%, 75% and full load) is shown in Figs. 4a–4d.In a diesel engine normally the temperature of exhaust gas will attain steady state within a period of 5 min at a given load. However it is observed in the present work that at all loads, the temperature of the gas at the inlet of the heat exchanger attain a steady state after a time interval of 25 min. It is due to the thermal inertia of the exhaust gas pipe along with insulation material from exhaust manifold to the HRHE. As the engine load increases the exhaust gas temperature also increases due to its higher heat release from the engine. At all loads it is observed from the oil and the gas outlet temperature variation that the temperature increases at the beginning and the slope decreases when the temperature of the oil attains approximately 60 °C and further increases at a higher rate after a certain interval of time. At 25% load a near constant temperature around 60 °C is observed for a longer duration and this duration decrease with increase in load. It is also observed from the figures that there is a large temperature drop in the exhaust gas at all times and the increase in temperature of the oil is very low since the heat capacity of the oil ($m_{oil}\, c_{p\cdot oil}$) is much higher than the heat capacity of the exhaust gas ($m_g c_{p.g}$). In all the four loads the exit temperature of the exhaust gas from HRHE approaches the inlet temperature of the oil and they are almost equal at the end of the experiment. This shows the of the effectiveness heat exchanger approaches 99% at the end of the experiment in all the cases.

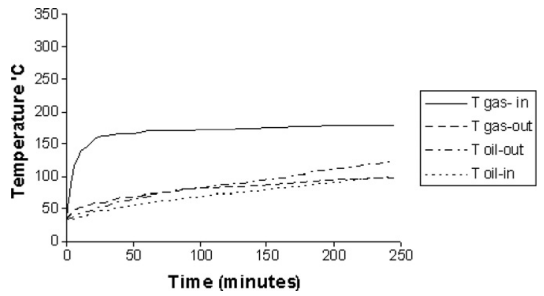

Fig. 4a. Temperature variation of the exhaust gas and the oil at the inlet and outlet of HRHE at 25% load

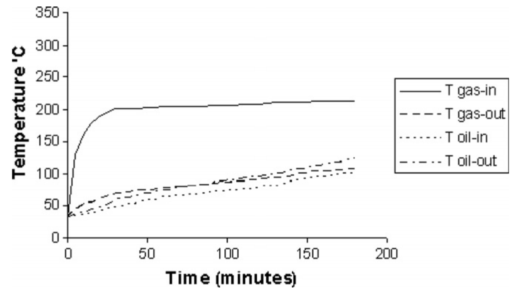

Fig. 4b. Temperature variation of the exhaust gas and the oil at the inlet and outlet of HRHE at 50% load

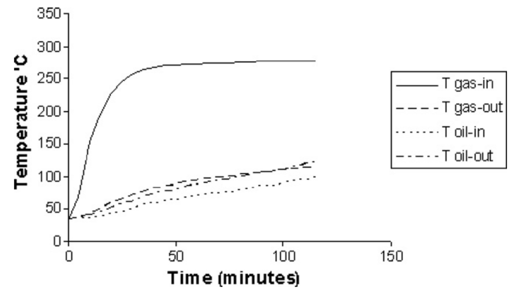

Fig. 4c. Temperature variation of the exhaust gas and the oil at the inlet and outlet of HRHE at 75% load

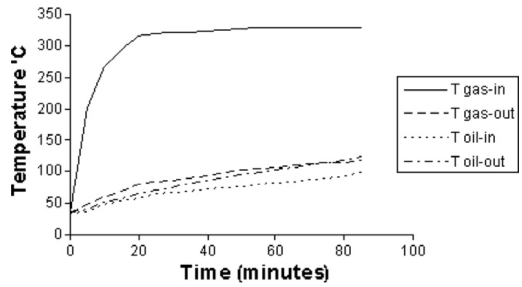

Fig. 4d. Temperature variation of the exhaust gas and the oil at the inlet and outlet of HRHE at full load

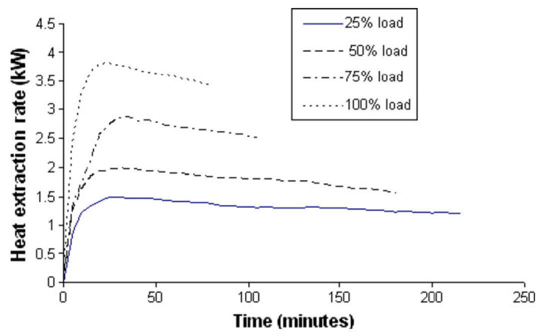

Fig. 5. Heat extraction rate from exhaust gas at different load conditions

Fig. 5 shows the variation of the heat extraction rate from the exhaust gas through the WHR heat exchanger evaluated at different loads using by:

$$Q_e = m_g c_{p.g} (T_{g1} - T_{g2}) \quad (1)$$

where m_g– mass flow rate of the exhaust gas T_{g1},T_{g2}– exhaust gas temperature at the inlet and outlet of HRHE.

At full load condition the maximum heat extracted is around 3.6 kW which is very high when compared to all other engine load conditions due to very high heat release rate from the engine at maximum load. It is observed from the figure that at all loads, the heat extraction rate decreases as time increases. It is due to the increasing temperature of the oil at the inlet of HRHE which reduces the average temperature difference between the exhaust gas and the oil. However it is seen that at 25% load, the decrease in heat extraction rate is very low and hence further analysis is made to determine LMTD and the overall heat transfer coefficient of the exchanger at various load conditions which is explained in the following section.

The variation of heat extraction and LMTD with time for 25%,50%, 75% and full load conditions are shown in Fig. 6a–6d respectively. It is observed from the Figs. 6c and 6d (75% load and full load) that the decrease in heat extraction rate and LMTD has a similar trend. However at 25% load the decrease in heat extraction rate is much smaller whereas the decrease in LMTD with respect to time is appreciable. This trend is also seen at 50% load (Fig. 6b) with variation marginally lesser than 25% load. The near uniform heat extraction rate with higher LMTD with respect to time at 25% load reveals that the overall heat transfer coefficient is increasing with respect to time. This could be due to condensation of water vapour from the exhaust gas in most part of the heat exchanger at 25% and 50% loads. The condensation of water vapour on the surface of the tubes increases outside surface convective heat transfer coefficient and hence there is an increase in overall heat transfer coefficient. The increasing heat transfer coefficient at lower loads which is due to the condensation of water vapour increases the possibility of extracting The variation in overall heat transfer coefficient with respect to time at all loads is the latent heat of water vapour present in the exhaust gases. Hence by decreasing the exhaust gas temperature much below 100 °C, it is possible to recover the heat which is liberated during the burning of fuel (HCV–LCV). This heat recovery is possible only if the fuel has negligible sulphur content, otherwise the acid formed during the condensation of sulphur may corrode the heat exchanger.

B. Performance of the thermal energy storage tank:

The performance of the thermal storage tank is evaluated by analyzing the heat loss coefficient of the TES tank, temperature distribution inside the TES tank and also by evaluating the various parameters like charging rate, charging efficiency and percentage energy saved at various load conditions during the charging process and also the storage efficiency of the TES tank.

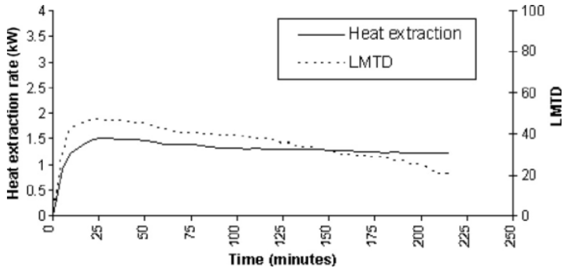

Fig.6a. Heat extraction rate and LMTD at 25% load

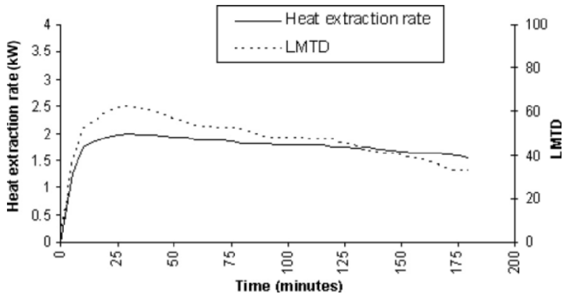

Fig 6b. Heat extraction rate and LMTD at 50% load

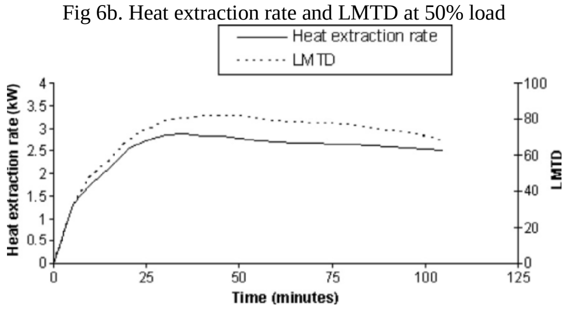

Fig 6c. Heat extraction rate and LMTD at 75% load

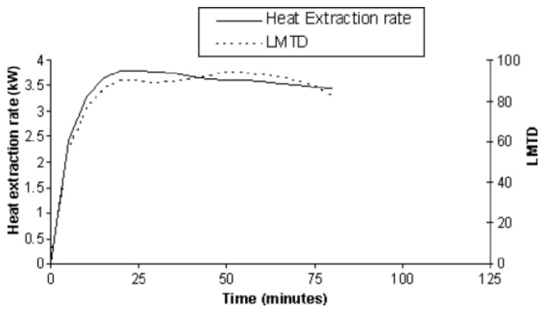

Fig 6d. Heat extraction rate and LMTD at full load

A. Overall heat loss coefficient:

The castor oil in the TES tank is raised to a higher value of 120 °C and left undisturbed in order to determine the overall heat loss coefficient thereby the duration of energy retention is studied. The temperature in the storage tank decreases slowly and the average temperature inside the storage tank is recorded at a regular interval of time and the variation of temperature with respect to time. It is seen from the figure that the temperature drop is very high during the initial period, and it decreases slowly with respect to time. The heat loss coefficient is evaluated using the Eq. (2) in two stages. In the first stage, only the sensible heat loss from 120 °C to 65 °C is evaluated and by noting the time required for this temperature reduction the U value is determined. The same is evaluated for the second stage (from 65 °C to 50 °C) Where the major heat removed is the latent heat of the PCM. The heat loss coefficient estimated at two stages are U_1= 1.085 W/m^2K and U_2= 0.81 W/m^2K, respectively. At a higher temperature, the overall heat loss coefficient is high as the outer surface of the insulated tank attains a temperature well above the ambient temperature that increases the surface convective heat transfer Coefficient.

$$m_{oil}c_{p.oil}(T_1 - T_2) + m_{pcm}c_{p.pcm}(T_1 - T_2) + (m_{pcm}L_{pcm}) / t = U_L A_S LMTD \quad (2)$$

$U_L$is the time averaged overall heat loss coefficient which is used for the evaluation of heat transferred from the TES tank during the charging period. It is evaluated using by:

$$UL=(U_1t_1+U_2t_2)/(t_1+t_2) \quad (3)$$

t_1, t2 corresponds to the time taken for the temperature of oil to drop from (120–65 °C and 65–50 °C), respectively.

B. Temperature distribution in the TES tank:

The temperature distribution inside the TES tank as measured from T_1–T_{12} with respect to time for all the loads is discussed in this section. Shows the increase in temperature of the oil in the storage tank during the charging process at 25% load and full load conditions. It is seen from that the increase in temperature of the oil at the beginning of the charging process is high (sensible heating) and when the temperature of the oil attains above the melting temperature of the PCM, there is a decrease in slope (due to latent heat removal) and further increase in temperature is observed when the oil temperature increases above 80 °C (sensible heating). This shows that when the oil temperature is in between 60 °C and 80 °C, a large portion of heat is absorbed by phase change material and hence the increase in temperature of the oil is very small during this period. However this trend is not distinctly seen at full load condition as the charging rate is very high and hence the phase change occurs at a very short interval of time.

The total heat stored in the TES tank is 19,500 kJ in which the heat stored in the oil is 13,150 kJ with a temperature raise of 86 °C (120–34 °C) and heat stored in the PCM is 6390 kJ. The total heat storage capacity in the PCM is due to its sensible heat (3100 kJ) and latent heat (3290 kJ). In the storage system the contribution of latent heat is only 17% of the total heat storage capacity. Hence the isothermal behaviour is not visible during the charging period. However at 25% load condition, the increase in oil temperature from 60 °C to 80 °C is very slow compared to the initial increase in temperature from 34 °C to 60 °C due to the absorption of heat from the PCM at its melting temperature of 58–60 °C.

It is also seen from the figure that there is no temperature variation between the layers (i.e., no stratification inside the tank). This uniform temperature is due to the presence of stainless steel PCM containers and storage tank wall which transfers the heat by conduction in the axial direction of the storage tank. Hence a near uniform temperature is observed throughout the TES tank.During the charging process at all loads considered in the present work. Since the oil temperature is nearly constant at all heights at any instantaneous time, only the second layer temperature (average of three thermocouple measurements) is shown for all the loads. The experiments were conducted till the temperature (5) inside TES tank attains 120 °C during the charging process for all the loads. When the storage tank attains 120 °C, the total energy stored in the storage tank is 19,500 kJ with respect to environment. Though the energy stored is same at all load conditions, it is observed that the duration of charging is 245 min at 25% load and it decreases to 180 min, 150 min and 85 min, respectively for 50%, 75% and full load conditions. This shows that there is a variation in the charging rate.

The charging rate is defined as the average rate at which the heat is supplied to the TES tank at a particular load. It is ratio of the total heat stored in the tank to the duration of charging and is evaluated using by:

$$Q_c = (m_{oil}c_{p\cdot oil}\Delta T_{oil}) + (m_{pcm}c_{p.pcm}\Delta T_{pcm}) + (m_{pcm}L_{pcm}) / t_c \quad (4)$$

The faster charging at higher loads reduces the losses encountered during the charging process. In order to account the above, the charging efficiency is introduced which is defined as the ratio of change in energy content (DE_C) in the storage tank to the actual energy supplied during the charging process (Q_a). It is evaluated using by:

$$\eta_c = \Delta E_c / Q_a \quad (5)$$

Where $\Delta E_c = E_f - E_i$, $Q_a = \Delta E_c + Q_r$, E_f – energy content of the storage tank at the end of charging process with respect to environment,

E_i- energy content of the storage tank at the beginning of charging process with respect to environment, Q_a- actual energy supplied for charging, $Q_r = (U_L A_S LMTD)t$, U_L– time averaged overall heat loss coefficient when the temperature changes from 34 °C to 120 °C and t_c– time of charging.

A.Percentage energy saved:

This is the indicative of percentage of fuel power saved by introducing the storage system when the system is employed for replacing the conventional one which requires either fuel or electric power.

$$E_s = Q_c / (m_f \times CV) \quad (6)$$

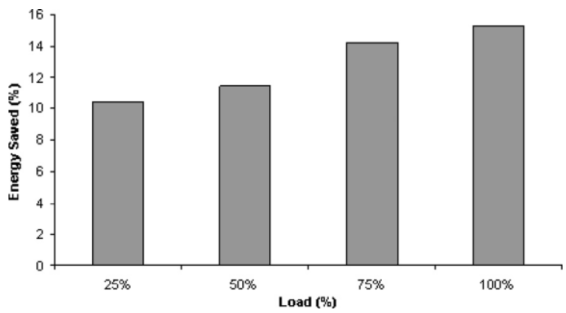

Fig. 7. Percentage energy saved at various loads.

The percentage energy saved at different loads is given in Fig. 7. It is a direct measure of overall efficiency improvement of the system. It is noted from the graph that a considerable amount of energy in the fuel can be saved. The percentage energy saved varies from 10% to 15% as the load increases from 25% to full load. At lower loads the percentage energy saved is less due to high specific fuel consumption (SFC) at part load condition and also higher heat loss encountered during the charging process with longer duration of charging.

IV CONCLUSIONS

The exhaust gas of a diesel engine carries a lot of heat and this energy can be recovered efficiently using HRHE. However the major technical constraint that prevents successful implementation of such a system is intermittent and time mismatched demand and availability of energy. The thermal energy storage system will eliminate the above constraint. A suitable WHR system with a large capacity of TES tank can store heat energy and this energy can be utilized for many applications like process heating etc., in industries.

In the present work a shell and tube heat exchanger and a PCM based TES tank of capacity were designed and fabricated and tested by integrating them with a diesel engine of capacity 7.4 kW.
The investigation has shown the following conclusions:

Nearly 10–15% of total heat (that would otherwise be gone as waste) is recovered with this system. The maximum heat extracted using the heat exchanger at full load condition is around 3.6 kW.

By decreasing the exhaust gas temperature below 100 °C it is possible to recover the heat which is liberated from the fuel along with the exhaust gas during the burning of fuel (HCV–LCV).

The presence of stainless steel containers and the high conductivity storage wall transfer the heat by conduction in the axial direction of the storage tank and hence there is no stratification found and a near uniform temperature is observed throughout the TES tank.

Both the charging rate and charging efficiency are very high at higher load and they decrease with respect to load.

REFERENCES

[1] Dincer Ibrahim. Thermal energy storage as a key technology in energy conservation. Int J Energy Res 2002; 26:567–88.
[2] Zalba Belen, Jose Marin M, Cabeza Luisa F, Mehling Harald. Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. Appl Thermal Eng. 2003; 23:251–83.
[3] Sharma Atul, Tyagi VV, Chen CR, Buddhi D. Review on thermal energy storage with phase change material and applications. Renew Sustain Energy Rev 2009; 13:318–45.
[4] Jagadheeswaran S, Pohekar Sanjay D. Performance enhancement in latent heat thermal storage system: a review. Renew Sustain Energy Rev 2009; 13:2225–44.
[5] Velraj R, Seeniraj RV, Hafner B, Faber C, Schwarzer K. Heat

transfer enhancement in a latent heat storage system. Int J Solar Energy 1999; 65(3):171–80.
[6] Enibe SO. Performance of a natural circulation solar air heating system with phase change material energy storage. Renew Energy 2002; 27:69–86.
[7] Cheralathan M, Velraj R, Renganarayanan S. Performance analysis on industrial refrigeration system integrated with encapsulated PCM based cool thermal energy storage system. Int J Energy Res 2007; 31:1398–413.
[8] Nallusamy N, Sampath S, Velraj R. Study on performance of a packed bed latent heat thermal energy storage integrated with solar water heating system. J Zhejiang Univ Sci A 2006; 7:1422–30.
[9] Schatz Oskar. Cold start improvement by use of latent heat stores. Automotive Eng. J 1992:1458–70.
[10] Vasiliev LL, Burak VS, Kulakov AG, Mishkinis DA, Bohan PV. Latent heat storage modules for preheating internal combustion engines: application to bus petrol engine. Appl Thermal Eng. 2000; 20:913–23.
[11] Korin E, Reshef R, Tshernichovsky D, Sher E. Reducing cold start emission from internal combustion engines by means of a catalytic converter embedded in a phase change material. Proc Inst Engrs 1999; 213:575–83.
[12] Subramanian SP, Pandiyarajan V, Velraj R. Experimental analysis of a PCM based IC engine exhaust waste heat recovery system. Int Energy J 2004; 5(2):81–92.
[13] Pandiarajan V, chinnapandiyan M, velraj R. Experimental investigation on heat recovery from diesel engine exhaust using finned shell and tube heat exchanger and thermal storage system. Applied Energy- 2011:88:77-87.
[14] wu et, al. Transient behaviour and dynamic performance of cascade heat pump water heater with thermal storage system. Applied energy-2011.