Experimental Analysis of a PCM Based I. C. Engine Exhaust Waste Heat Recovery System

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ABSTRACT

The exhaust gas in an internal combustion engine carries away about 35% of the heat of combustion and it goes as a waste, if not utilised properly. Air pre heater using waste heat recovery system, cogeneration and concept of heat battery are successful techniques to improve the overall thermal efficiency of the system to a certain extent. However, there is still a large potential to store and utilise the exit stream energy by the efficient implementation of waste heat recovery system. The major technical constraint that prevents successful implementation of such a system is intermittent and time mismatched demand and availability of energy. In the present work, a heat recovery heat exchanger integrated with an I.C. engine and a combined sensible and latent heat storage system with spherical PCM (phase change material) capsules, as the latent heat material is designed, fabricated and tested. Performance characteristics of the system are also studied in detail. It is found that about 15% fuel power is stored in the combined storage system, which is available at higher temperature for suitable applications.

1. INTRODUCTION

The utilisation of exhaust waste heat is now well known and forms the basis of many cooling and power installations. Many difficulties that are experienced such as, starting the I.C. engine at low temperature, inefficient combustion during warm-up, high exhaust emissions and fuel consumption etc can be overcome by preheating the vehicle. Conventional preheating devices are expensive and require a source. Energy saving and performance improvement are possible, if the engine waste heat can be stored and utilised effectively. The heat recovery system also enhances the performance of engines that implement exhaust gas re circulation (EGR) method.

Energy storage can be achieved in the form of sensible heat of a solid or liquid medium or latent heat of a phase change substance. Sensible heat storage (SHS) units have very low heat capacity per unit volume. On the other hand, latent heat thermal storage (LHTS) units are particularly attractive due to their high-energy storage capacity and isothermal behaviour during charging and discharging processes.

Although LHTS systems possess desirable characteristics, they are not in commercial use as much as sensible heat storage systems. The main reason is the difficulty involved in the charging and discharging of the heat from the storage system. In LHTS unit, during the phase change, the solid liquid interface moves away from the convective heat transfer surface. In this process, the surface heat transfer rate decreases, due to the increasing thermal resistance of the growing solidified/melt layer of the medium. Combined sensible and latent heat storage system is a better alternative, which offers the following benefits:

- Higher heat capacity.
- Isothermal charging and discharging
- Variation in the surface heat transfer rate due to poor thermal conductivity of solid medium is minimised.
- Compact size.
- Economical operation.

Several investigators have studied, theoretically and experimentally, the advantages of thermal energy storage, employing a phase change material in variety of geometries. Belen Zalba et al. [1] 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 and Seeniraj. [2]. The performance of a natural circulation air heating system with phase change material based energy storage was analysed by Enibe. [3]. Ibrahim Dincer et al [4] presented a detailed investigation of the availability of sensible heat storage techniques for solar thermal applications. Various techniques for the utilisation of engine waste heat were presented by researchers viz Talbi et al [5], Desai et al. [6], Zhang [7] and Mostafavi et al [8].

Oskar Schatz et al. [9] introduced the concept of a Heat battery, which stores engine waste heat using a phase change material. During cold start, the engine coolant flows through the heat battery, extracting the stored heat. Korin et al. [10] made an experimental investigation in to the use of a catalytic converter, embedded in a phase change material to reduce cold start emissions.

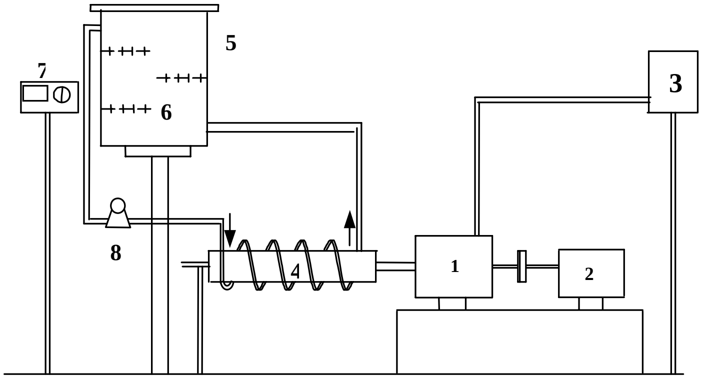
2. EXPERIMENTAL INVESTIGATION

The experimental set-up consists of a single cylinder, four-stroke, water-cooled, Texvel diesel engine (bore 80 mm, stroke 110 mm, rated power 3.7 kW at 1500 rpm), coupled to a hydraulic dynamometer, heat recovery heat exchanger (HRHE) and a thermal storage system. Figures 1 and 2 show the schematic diagram and the photographic view of the experimental set-up. The HRHE consists of a horizontal, elliptical shaped heater core, made of mild steel with a circumference 450 mm and active length 430 mm. A copper tube of diameter 10 mm is wound over the heater core across its length. The contact area of the copper tube over the heater core is 0.07 m^2. A schematic diagram and photographic view of the HRHE are shown in figures 3 and 4 respectively. The HRHE is fitted in to the exhaust pipe of the engine. The two ends of the copper tube are connected to the thermal storage tank. The tank is a stainless steel vessel of diameter 270mm and height 280 mm. It contains water as the sensible heat storage medium and paraffin filled in spherical capsules of diameter 50 mm made up of low-density polyethylene, as latent heat storage medium. The tank contains 5.2 kg paraffin filled in 100 spherical capsules and 8.5 kg water. A photographic view of the PCM filled containers in the storage tank is shown in figure 5. The thermo physical properties of the paraffin used are given in table 1. The temperatures at various locations are recorded using Ni Cr-Ni thermocouples (Type K). The thermocouples are connected to a temperature indicator, which provides instantaneous digital outputs. Twelve thermocouples are placed in three different horizontal planes in the storage tank. Four thermocouples are placed uniformly in each plane. In addition, thermocouples are placed at inlet and outlet of HRHE and storage tank. Water from the HRHE enters the storage tank through copper tubes at the bottom and leaves at the top. A pump maintains the circulation. The entire set-up is well insulated using glass wool.

The engine is started, run at no load condition, and the following observations are recorded.

1. Exhaust gas temperature at inlet and outlet of HRHE.
2. Water temperature at inlet and outlet of storage tank.
3. Temperatures at different locations inside the storage tank.
4. Mass flow rate of air and fuel for the engine.

The observations are repeated at 30% full load, 60 % full load and at full load. The following parameters are evaluated to analyse the performance characteristics of the system.



1. Texvel engine.
2. Hydraulic dynamometer.
3. Fuel tank.
4. Heat recovery heat exchanger.
5. Thermal storage tank.
6. PCM filled capsules.
7. Temperature indicator.
8. Circulating pump.

Fig. 1. Schematic diagram of the experimental set-up

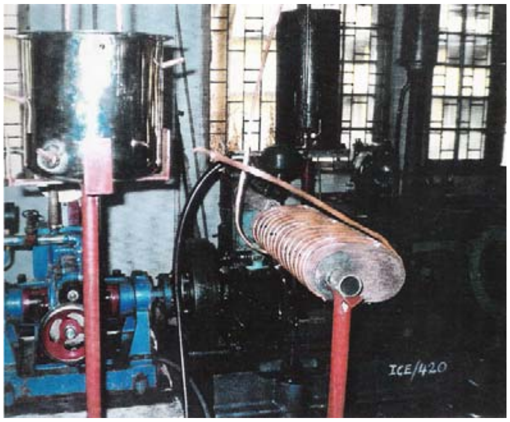


Fig. 2. Photographic view of the experimental set-up

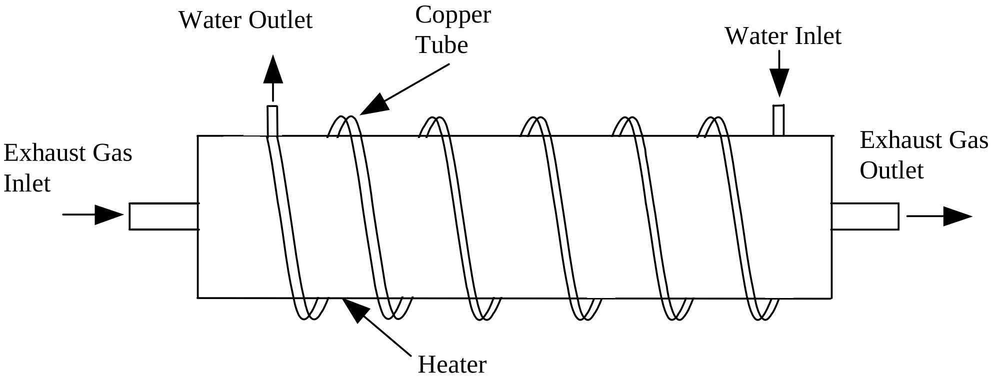


Fig. 3. Schematic diagram of the heat recovery heat exchanger

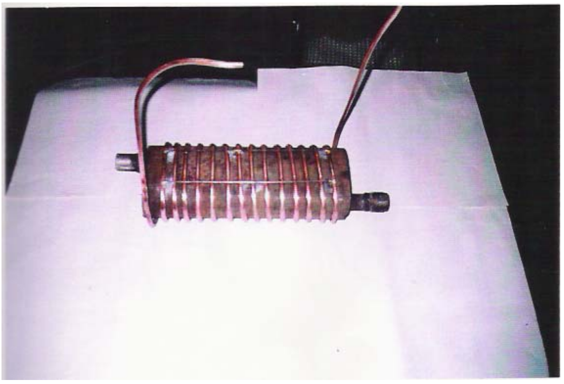


Fig. 4. Photographic view of the heat recovery heat exchanger

Fig. 5. Photographic view of PCM filled capsules in the storage tank

Table 1. Properties of Paraffin

Latent heat of fusion	214 kJ/kg
Specific heat capacity	2.9 kJ/kg K
Thermal conductivity	0.2 W/m K
Density (Solid)	850 kg/m^3
Density (Liquid)	775 kg/m^3
Phase transformation temperature range	60-70^{o}C

2.1 Heat loss coefficient

Experiments are conducted to determine the heat loss coefficient of the insulated storage tank that helps to evaluate the heat retention time of the container. During the experimental trial, the storage tank is filled with water and the temperature is raised to a higher value (85^{0}C) and left undisturbed. At regular intervals of time, the average temperature inside the storage tank is recorded for a specific duration. The final average temperature in the tank is also noted. The variation of temperature with time is shown in figure 6. The heat loss coefficient (h_L) is then calculated using the energy balance.

$$\frac{m_w c_{pw}(T_1 - T_2)}{t_1} = h_L A_s LMTD$$

$$\text{LMTD} = \frac{(T_1 - T_\infty) - (T_2 - T_\infty)}{\ln \frac{T_1 - T_\infty}{T_2 - T_\infty}}$$

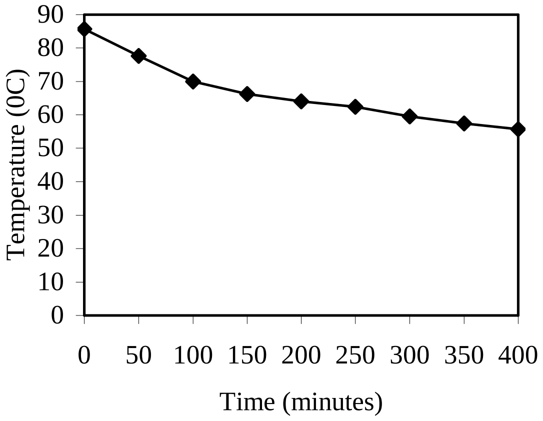


Fig. 6. Temperature Time graph for the determination of Heat loss coefficient

2.2 Heat extraction rate

It is the rate at which heat is extracted from the exhaust gases by the addition of the HRHE.

$$Q_e = m_g c_{pg} (Tg_1 - Tg_2)$$

2.3 Charging rate

It is defined as the average rate at which heat is supplied to the storage tank at a particular load. It is calculated as the ratio of total heat stored in the tank and the time of charging.

$$Q_c = \frac{\left[m_w c_{pw} (T_f - T_i) + m_P c_{PP} (T_f - T_i) + m_p L\right]}{t}$$

2.4 Charging efficiency

It is the ratio of charging rate to the average heat extraction rate.

$$\eta_c = \frac{Q_c}{Q_e}$$

2.5 Percentage energy saved

It is the percentage of fuel power saved by introducing the combined storage system.

$$E_s = \frac{Q_c}{m_f * C.V}$$

3. RESULTS AND DISCUSSION

The temperature-time variation of the exhaust gas at inlet and outlet of the HRHE are shown in figures 7,8 and 9 for 30%, 60% and at full load respectively. As the engine load increases, the exhaust gas temperature also increases due to higher heat release from the engine. As more heat is available at higher loads, the time required for attaining the required temperature in the storage tank is found to be less. Hence the duration of the trial is less at higher loads. It is observed that, as the engine load increases from 30% to 60%, the charging time is reduced to 80 minutes from 120 minutes. Further, when the engine runs at full load, the charging time required is 60 minutes. It is seen that the temperature drop of the exhaust gas across the HRHE decreases as the charging proceeds and about 50^0C difference in the drop in temperature is recorded during the initial and final period of the trial. This is due to the decreasing rate of heat extraction by water, as it enters the HRHE at higher temperatures.

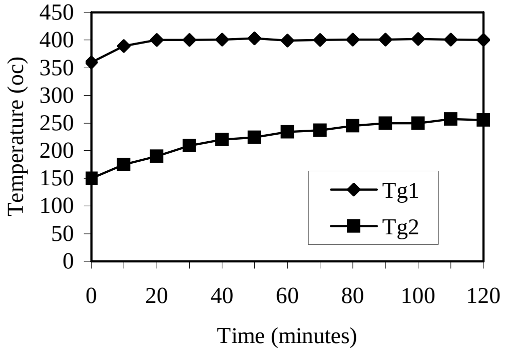


Fig. 7. Exhaust gas Temperature variation at inlet and outlet of HRHE at 30% load

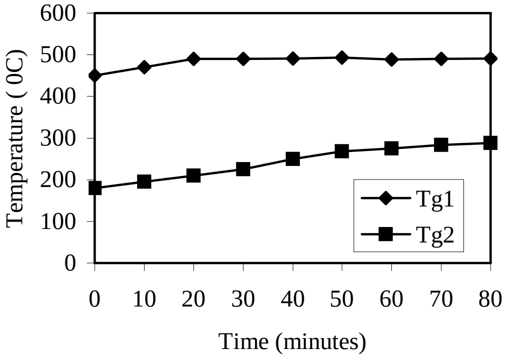


Fig. 8. Exhaust gas temperature variation at inlet and outlet of HRHE at 60% load.

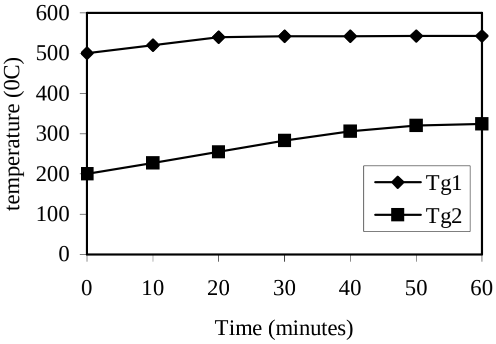


Fig. 9. Exhaust gas Temperature variation at inlet and outlet of HRHE at full load

Figures 10 to 15 show the variation of water temperature in the storage tank at three different loads. During charging, heat transfer takes place by mixing of the circulating water with the water in the storage tank and heat is stored in three distinct stages. In the first stage heat is stored as sensible heat in water and in PCM. During this period the temperature shows a steady rise and this continues until thePCM reaches the melting temperature. During the second stage, heat is stored as latent heat as PCM melts almost at constant temperature. Hence the slope of the graph is found to be less. In the third stage, heat storage is in the form of sensible heat in water and in PCM.

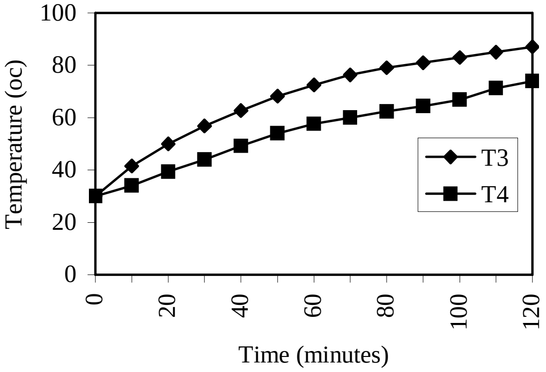


Fig. 10. Water temperature variation at inlet and outlet of the storage tank at 30% load

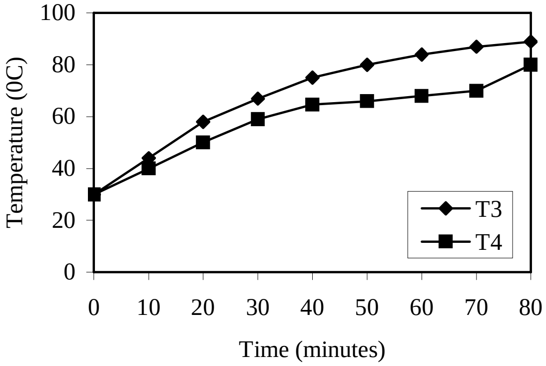


Fig. 11. Water temperature variation at inlet and outlet of the storage tank at 60% load

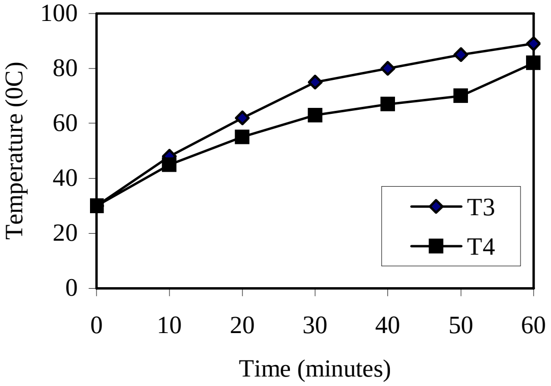


Fig. 12. Water temperature variation at inlet and outlet of the storage tank at full load

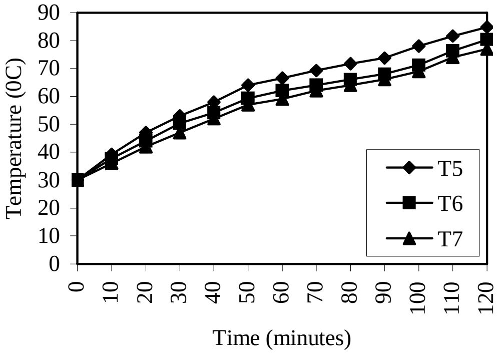


Fig. 13. Water temperature variation inside the storage tank at 30 % load

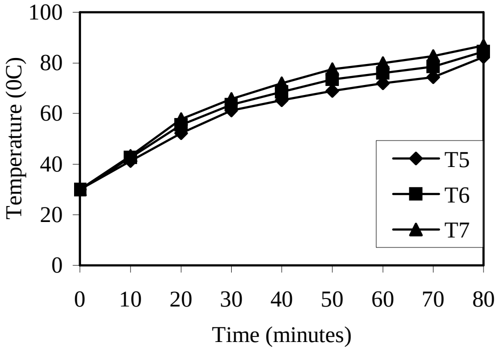


Fig. 14. Water temperature variation inside the storage tank at 60 % load

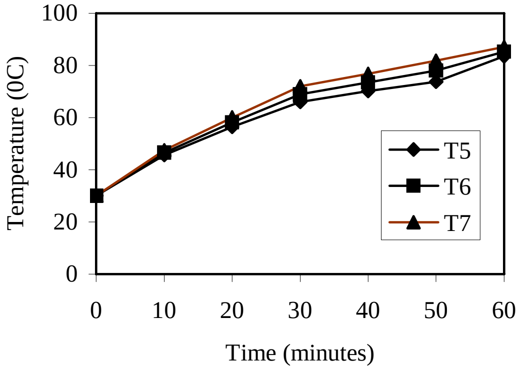


Fig. 15. Water temperature variation inside the storage tank at full load

Figure 16 shows the variation of heat extraction rate from the HRHE at three different loads. The heat extraction rate can be improved further by having a counter flow, double pipe heat exchanger in place of the copper tube wound HRHE. The exhaust gas can be made to flow through the inner pipe and the water through the outer annulus. This will increase heat transfer surface area and hence the heat extraction rate.

The percentage heat loss through the exhaust gas with and without HRHE under various loads is shown in figure 17. The difference between the two is the heat recovered through the HRHE and is shown in the same graph. It is observed that nearly 15 % of the fuel power can be recovered by the introduction of the HRHE.The heat loss can be further minimised by increasing the surface area of the heat exchanger.

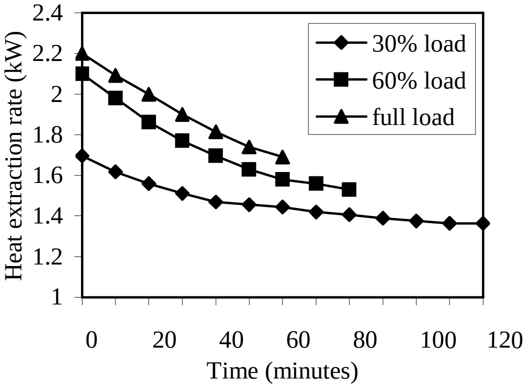


Fig. 16. Variation of heat extraction rate at different loads

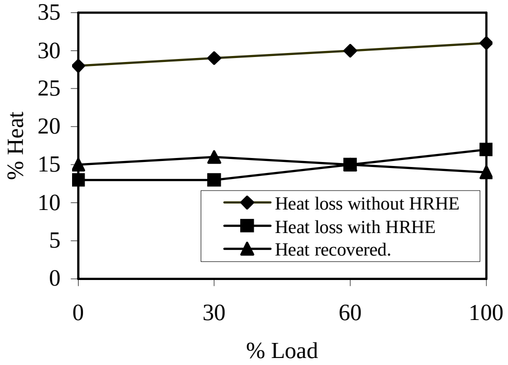


Fig. 17. Variation of heat loss and recovered at different loads

Figure 18 shows the variation of charging rate and charging efficiency with respect to load. The charging efficiency is found to increase from 25% to 50% when the engine runs from no load to full load condition. About 200% increase in the charging rate is observed during this period. This is due to the reduced charging time at higher loads. The heat loss is in direct proportion with time. Hence when the charging time is less, the heat loss is reduced, which shows an increase in both charging rate and charging efficiency. The percentage fuel energy saved, shown in figure 19 is also in line with the above graph. The performance of the storage system can be improved by better insulation for the storage tank, HRHE and the piping as well as by increasing the capacity of the storage tank.

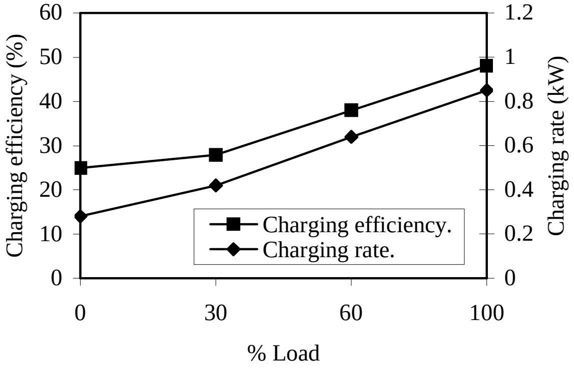


Fig. 18. Variation of charging rate and charging efficiency at different loads

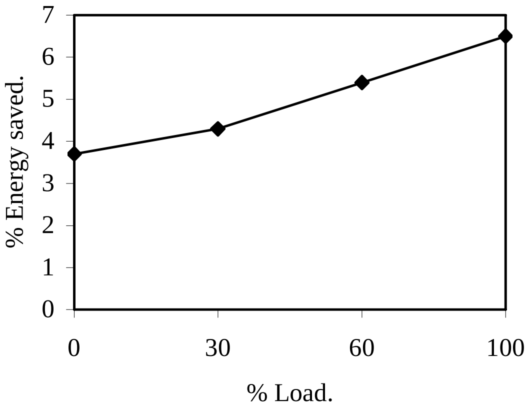


Fig. 19. Variation of percentage energy saved at different loads

The value of the heat loss coefficient of the storage tank is a useful parameter in the application design. For the thermal storage tank in use, heat loss coefficient is calculated as 1.5 W/m^2K. It is a measure of the capacity of the system to preserve the heat stored in it. For the given system the total heat stored is calculated, as about 3060 kJ at 85^0C during the trial at full load for 60 minutes. About 60% of this heat is stored in PCM and the remaining in water. About 38% of the total heat is stored in PCM as latent heat, which can be extracted at uniform temperature corresponding to the phase change temperature of PCM. It is calculated that, the system can preserve the stored heat for a total duration of about 64 hours. Providing better insulation can further increase the heat storage capacity of the system.

The concept of combined sensible and latent heat storage system is successfully introduced in air-conditioning applications. For domestic solar hot water applications, this concept can be successfully introduced. From the application side, hot water may be required at a higher rate for a short duration and the sensible heat of water in the storage tank can meet this requirement. Before its use next time, the temperature of water in the tank gradually increases again by slow extraction of latent heat from the PCM.Thereby the problem of non-uniform heat flux during the withdrawal of heat can be minimized.

The present work is focused to analyse the possibility of introducing the concept of combined storage system for I C Engine waste heat recovery applications. In case of automobile vehicles, the heat thus recovered can be released during the cold start, which will provide improved emissions and warm-up performance, fuel economy, cabin heating and wind shield clearing. In case of stationary Diesel power generation plants, the recovered heat can be utilised for suitable applications like process water heating, air pre-heating and vapour absorption unit. Storage devises based on the principle of latent heat storage, like catalytic converters embedded in phase change material, will have the main drawback of non-uniform heat storage and extraction. Combined storage system eliminates this difficulty to a great extent.

4. CONCLUSION

A combined sensible and latent heat storage system for I C engine waste heat recovery was fabricated and tested. The time wise variation of temperature for the HRHE and the storage system are experimentally studied. The performance parameters like heat extraction rate, charging rate and charging efficiency are analysed. The major advantages of the present system are,

1. The major quantity of heat is available at higher temperature for discharge applications almost at the PCM phase change temperature.
2. Combined storage system exhibits isothermal behaviour and provides uniform heat flux as compared to conventional systems.
3. The higher heat capacity of the combined system reduces the space and size requirements,

compared to conventional storage systems.

For the present analysis, water and paraffin are selected as the sensible heat and latent heat storage materials respectively. Such systems can be adopted, where the requirement of heat is within the temperature range of 50^{0}C to 80^{0}C. For higher temperature applications, suitable materials can be selected based on the exhaust gas temperature available and the application requirement. Commercial phase change materials like salt solutions and paraffin with phase change temperatures ranging from 33 ^{0}C to 112 ^{0}C are available in the market. Various compounds, eutectic and non-eutectic mixtures of inorganic substances, organic substances and fatty acids with phase change temperatures ranging from 0 ^{0}C to 900 ^{0}C have been studied by different researchers for their potential use as phase change materials.

Many applications are possible for the combined sensible and latent heat storage system utilising I C engine waste heat. Each application requires careful attention in the selection of the PCM and design of the storage system.

5. NOMENCLATURE

m_w - mass of water in the tank
m_p - mass of paraffin in the tank
c_{pw} - specific heat of water
c_{pp} - specific heat of paraffin
T_1 and T_2 - initial and final temperatures of water in the storage tank observed during time $t_{1,}$ for determining heat loss coefficient
LMTD - log mean temperature difference
L - latent heat of paraffin
h_L - heat loss coefficient
A_s - surface area of storage tank exposed to outside atmosphere
T_∞ - ambient temperature
m_g - mass of exhaust gas
c_{pg} - specific heat of exhaust gas
t - charging time
C.V - calorific value of the fuel
m_f - fuel consumption
Tg_1 and Tg_2 - exhaust gas temperature at inlet and outlet of the HRHE
T_3 and T_4 - water temperature at inlet and outlet of the storage tank
T_5, T_6 and T_7 - average temperatures at thermocouple locations 1,2and 3 respectively (from bottom) inside the storage tank
T_i and T_f - temperature of the storage tank at the beginning and at the end of charging

6. REFERENCE

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