International Journal of ChemTech Research
CODEN (USA): IJCRGG ISSN: 0974-4290
Vol.8, No.6, pp 711-717, 2015

# A study of waste heat recovery from diesel engine exhaust using phase change material

**S. Senthur Prabu, Asokan M.A***

**School of Mechanical and Building Sciences, Vellore Institute of Technology, Vellore – 632014, India**

**Abstract:** The exhaust gas from the diesel engine exhausted to the atmosphere as waste carries approximately 30% of the heat of combustion. By providing proper Waste Heat Recovery System (WHRS), a considerable amount of heat can be saved. In the present study, the shell and tube heat exchanger and Thermal Energy Storage System (TESS) contained Paraffin Phase Change Material (PPCM) incorporated with a diesel engine system to extract heat from the exhaust gas. The performance of the heat exchanger and thermal storage tank were investigated under the different loading condition. It is found that 86.45 kJ/kg of heat energy extracted from the heat exchanger and 0.54 kW of heat energy–is saved at full load condition; it is nearly 7% of fuel power is stored as heat in the storage system, and the water can be utilized for suitable applications which are available reasonably at higher temperature.
**Keywords:** Phase Change Material, Waste heat recovery, Heat exchanger, Thermal storage tank, Diesel engine, Exhaust gas.

## 1. Introduction

Energy is an important mania for the economic development of any country. The energy requirement drastically increases in the recent years because of the rapid industrial growth. Nowadays worldwide concern is about the best ways of using the depletable sources of energy and of developing techniques to reduce pollution. This interest has encouraged research and development efforts in the field of alternative energy sources, cost-effective use of the exhaustible sources of energy, and the reuse of the usually wasted forms of energy. Moreover as the fuel prices continues to escalate, the relevance of efficient energy management is apparent to companies everywhere, from the smallest concern to the largest multinationals. A large number of industrial processes covering most industrial sectors, use significant amounts of energy in the form of heat, which are rarely, used efficiently. The methods and techniques adopted to improve energy utilization will vary depending on circumstances, but the basic principles of reducing energy cost relative to productivity will be same. Thus there is considerable scope for the use of heat exchangers and other form of heat equipment to enable waste heat to be recovered. Waste heat is generated by the way of fuel burning and then it is exhausted into the environment as a waste. The potential savings possible are greatest for the temperatures ranges from 200°C to 500°C. The developed countries are the pacesetters in energy consumption, discharging at the same time vast amounts of waste energy. The industry in these countries consumes the largest share of energy.

Diesel engine is the one of the most efficient and versatile prime movers used in automobiles, stationary power generating plants, air compressors, construction machinery etc. Nearly about two- third of the heat generated by the engine is wasted through exhaust gas and cooling water and lost in to the surroundings. If some of this waste heat could be recovered, a considerable amount of primary fuel could be saved. Such a waste heat recovery would ultimately reduce the overall energy requirement and also the impact on global warming.

Also the recovered energy can be utilized to reduce the cost of waste disposal. Much effort has been expended during the past two decades to re-use the waste heat. But the energy lost in waste gases cannot be fully recovered. Waste heat is usually but not always characterized by low temperature. There are many methods through which this energy can be recovered and utilized. Waste energy can be recovered by the installations of special combustion equipment to utilize the unburned fuel, and the provision of heat recovery equipment to regain sensible and latent heat. Depending on the temperature level of the wasted heat and the proposed application, different heat exchangers can be employed to facility the use of recovered heat. The application of heat recovery should be physically close to the source of waste heat for maximum benefits from recovered energy. Energy storage is needed when there is a time span between energy recovery and use.

A low-cost PCM-used in the thermal storage system with heat exchanger is used to collect waste heat from exhaust gas of a diesel engine and conducted an experiment utilizing waste heat as energy and recovered about 10–15% of the total waste heat for each engine load condition[1]. The natural convective heat transfer efficiency of phase change material is somewhat low, the heat transfer efficiency drastically decreases as the PCM starts to melt and a layer of liquid matter develops. To avoid a liquid layer from developing, the space between the heat transfer surfaces where the PCM is charged should be as thin[2]. Melting and solidification of PCM RT35 were experimentally investigated; using five various heat exchangers as heat storage systems and working at two different flow rates and two different water inlet temperatures. The obtained results are Reynolds numbers in the turbulent regime are desirable for faster phase change processes, considerable amount of the phase change time decreased (between 30% and 60%) and consequently, an increase of the average phase change power[3]. The amount of energy can be extracted from four different nanocomposite PCMs (graphene–paraffin, MWCNT–paraffin, Al–paraffin and $TiO_2$–paraffin, each at 20 % loading. Remarkably, the amount of thermal energy that can be recovered from the graphene–paraffin nanocomposite PCM in application is roughly 11% more than that which can be recovered from the base paraffin, while each of the other nanocomposite PCMs exhibit at least 15% decrease in the amount of thermal energy that can be recovered from the PCM vs the base paraffin[4]. The numerical modeling of solidification of nano-enhanced phase change material inside an enclosure with two wavy walls using nano-particle lowers the freezing time; it reduces the capacity of energy storage/release in phase change material. Therefore surface waviness can be used to improve the performance of PCM without reducing their capacity of energy storage[5]. The amount of heat stored in the composite phase change material in the form of latent heat is depends on the percentage of paraffin in the composite and the difference in temperature imposed (15-50°C) and also shows that the amount of latent heat stored by the paraffin sample RT 27 is higher than stored by the paraffin sample RT 21[6].

In this study, heat recovery system consisting of a shell and coiled heat exchanger and a thermal energy storage system with paraffin as PCM has been designed and fabricated for waste heat recovery from diesel engine exhaust gas. Pure water is used as Heat Transfer Fluid (HTF) in both heat exchanger and thermal energy storage system. Heat energy stored in the thermal storage tank and thermal performance of heat recovery heat exchanger has been studied for various engine load conditions.

## 2. Experimental Setup and procedures

The main objective is to extract heat from the exhaust gas of a diesel engine and to store it in the thermal storage tank. This could be achieved by the heat exchanger and the thermal Storage System separately. The heat exchanger coil is not embedding inside the storage tank due to the very low convective heat transfer coefficient for gases, because of this larger surface area is needed on the gas side for better heat transfer. Also due to poor thermal conductivity, the PCM cannot be packed directly inside the storage tank, which varies the resistance for heat transfer during charging and discharging, so that the PCM encapsulated in separate containers inside the storage tank to store the heat. When the PCM solidifies on the convective heat transfer surface inside the storage tank, the solidified layer itself act as an insulator and as the thickness of the layer increases with respect to time, the resistance for heat transfer increases between the liquid PCM and the HTF in the storage tank, in turn decreases the heat transfer rate and causes a non-uniform rate of discharging characteristics in the storage tank. The experimental setup is shown in the figure 2.1 consists of a six cylinders Ashok Leyland diesel engine, heat recovery heat exchanger and the thermal storage system.

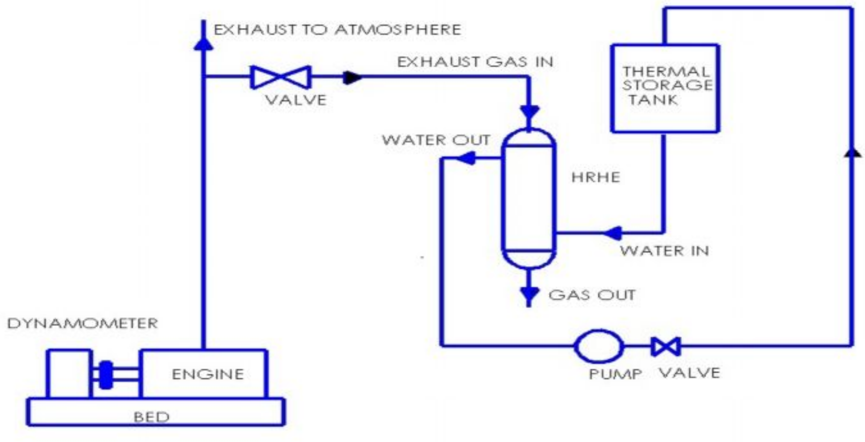
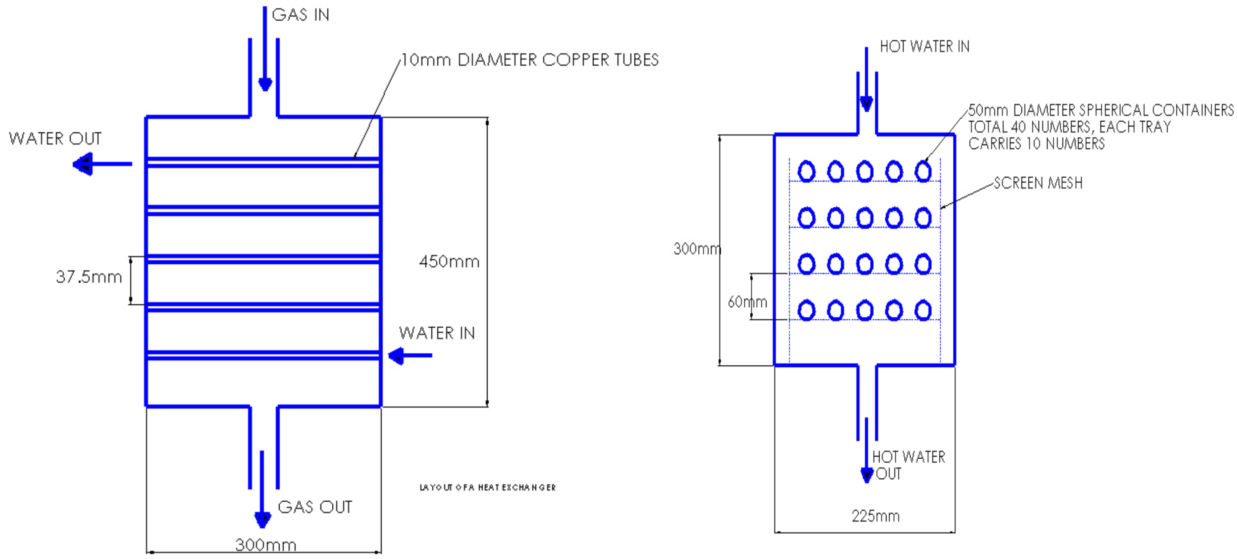



**Fig 2.1 Schematic diagram of the experimental setup**




(a) (b)

**Fig 2.2 Schematic diagram of (a) Heat recovery heat exchanger and (b) Thermal storage system.**

### 2.1 Engine Setup

The engine used for this study is a four stroke, water cooled, six cylinder diesel engine. The rated power of the engine is 61kW at 1500rpm. The engine is mounted on the bed with suitable connections for fuel and cooling water supply. The engine is coupled with an electrical dynamometer to vary the load on the engine.

### 2.2 Heat Recovery heat Exchanger

In all energy conversion methods due to thermodynamic constraints and other reasons, large quantity of heat available in the exit streams discharge into the atmosphere without proper utilization and these results in a major loss in thermal efficiency. Air preheater using WHRS and co-generation are successful techniques to improve the overall thermal efficiency of a system to certain extent. By the efficient implementation of suitable WHRS, the exit stream energy can be stored and utilize and there by improve the overall thermal efficiency.

The schematic diagram of the heat recovery heat exchanger is illustrated in fig 2.2 (a) consists of a vertical cylindrical shape heater core made of mild steel, with a circumference of 300 mm and an active length of 450 mm. A copper tube of size 10 mm is wound over this heater core at gradual intervals across its length. The copper tube is connected into the thermal storage tank that is filled with water and phase change material. The water inside the copper tube circulated as natural circulation. The above said setup is fitted in the exhaust pipe of the engine to extract the waste heat from engine exhaust gas using water as heat transfer fluid.

### 2.3 Thermal Storage Tank

Thermal storage units have received greater attention in solar and waste heat recovery thermal applications because of the large heat storage capacity and their isothermal behavior during charging and discharging process. The major technical constraint, which prevents successful implementation of heat recovery system, is intermittent and time mismatched demand and availability. In order to overcome the above constraint WHRS integrated with thermal storage unit can be adopted. Thermal energy storage provides one practical means of storing energy during availability and use this energy when need arises.

Fig 2.2 (b) shows the schematic diagram of the thermal storage system consists of stainless steel vessel of diameter 250 mm and height 300 mm and it is well insulated by using fiber coir to prevent heat radiation to the surroundings. It contains water as the sensible heat material and paraffin as the latent heat material. Hence it is called combined sensible and latent heat storage system. The water also acts as the heat transfer fluid to extract the heat from the exhaust gas. The tank is filled with 40 Nos. of spherical containers made of Low Density Polyethylene (LDPE) having a diameter of 50mm whose melting Point is 110$^{o}$C and density 0.910 – 0.940 g/cm$^3$, each spherical container contains approximately 100 grams of paraffin phase change material. Table-1 shows the property of paraffin material.

**Table-1 Property of paraffin phase change material**

| Sl. No. | Property | Values |
|---|---|---|
| 1 | Latent heat of fusion | 147 kJ/kg |
| 2 | Specific heat capacity (solid) | 1.85 kJ/kg K |
| 3 | Specific heat capacity (liquid) | 2.13 kJ/kg K |
| 4 | Density ( solid) | 856 kg/m$^3$ |
| 5 | Density ( liquid) | 775 kg/m$^3$ |
| 6 | Phase transformation temperature range | 58-60°C |

## 3. Results and discussion

The results of the diesel engine operated at various load conditions were studied. The exhaust gas from the diesel engine carries approximately 25 to 30% of the heat of combustion. In this study, many attempts has been made to extract the maximum possible heat energy from the exhaust gas through a shell and tube heat exchanger and to store this heat energy in TES tank filled with spherical LDPE.

### 3.1 Performance of heat recovery heat exchanger.

The temperature variation of the exhaust gas and the water at the inlet and outlet of the HRHE with respect to time for different engine load conditions (25%, 50%, 75% and full load) is shown in figures 3.1.1– 3.1.5.

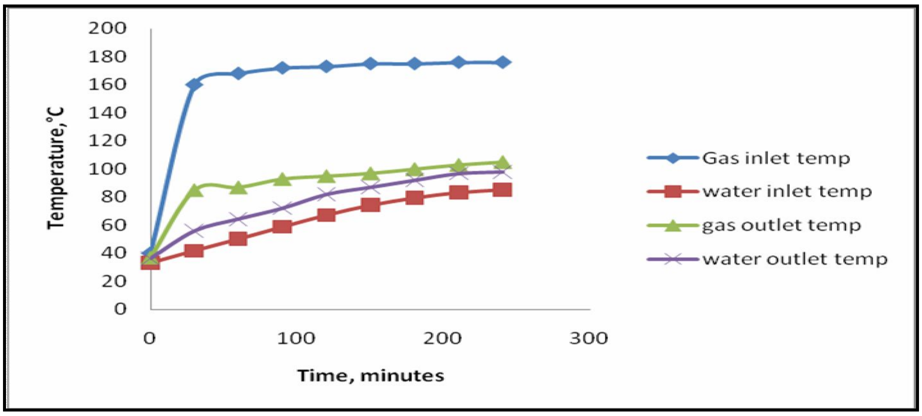



**Figure-3.1.1 Temperature variation of the exhaust gas and the water at the inlet and outlet of the HRHE at 25% load.**

From the fig 3.1.1 at 25% load, a constant temperature around 60°C is obtained after 90 minutes and this duration decrease with increase in load and also the maximum temperature of water attained 98°C after 240 minutes. This duration also decreases when the load of the engine increases.

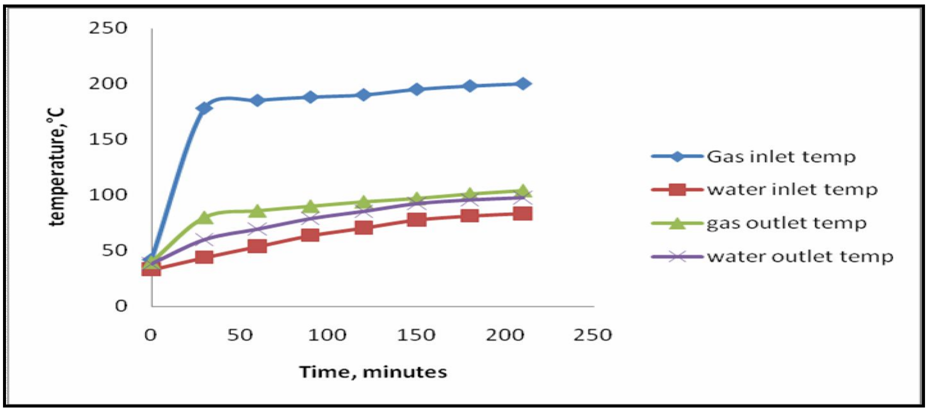



**Figure-3.1.2 Temperature variation of the exhaust gas and the water at the inlet and outlet of the HRHE at 50% load.**

From the fig 3.1.2 at 50% load, a constant temperature around 60°C is obtained after 80minutes and the maximum temperature of water attained 98°C after 210 minutes.

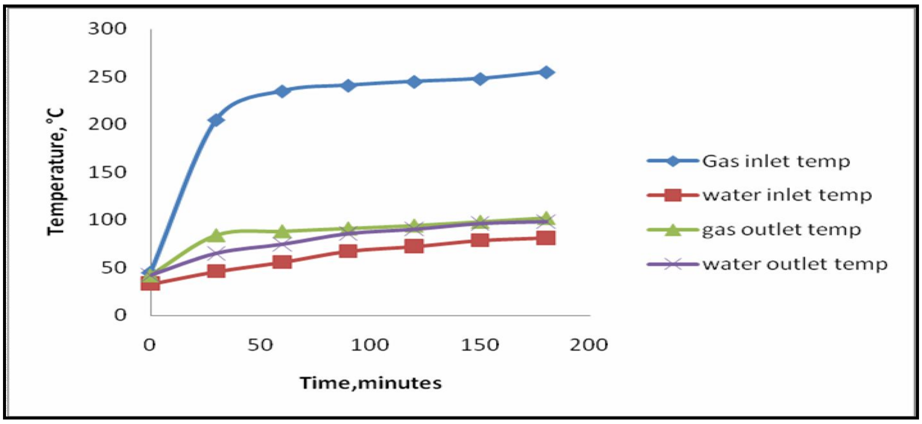



**Figure-3.1.3 Temperature variation of the exhaust gas and the water at the inlet and outlet of the HRHE at 75% load.**

From the fig 3.1.3 at 75% load, a constant temperature of 60°C is obtained nearly at 70minutes and the maximum temperature of water reached 98°C at 180 minutes.

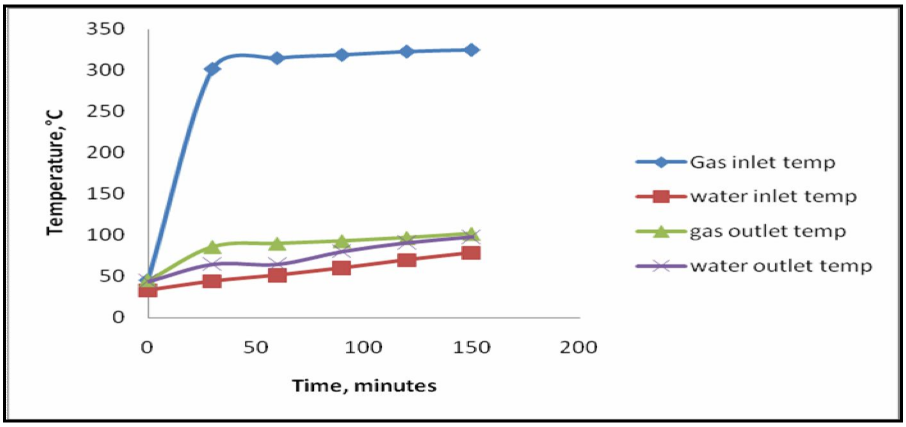



**Figure 3.1.4 Temperature variations of the exhaust gas and the water at the inlet and outlet of the HRHE at full load.**

From the fig 3.1.4 at full load, a constant temperature of 60°C is obtained at around 65minutes and the maximum temperature of water attained 98°C at 150 minutes. From the graph, it is clear that as the load on the engine increases the exhaust gas temperature also increases accordingly. However, initially during starting of the engine and auxiliaries will absorb a part of the incremental heat till the system attains steady state. Thereafter the temperature of exhaust gas coming from the engine will be approximately at a constant high temperature. At all of the loading conditions the temperature difference of the water and gas outlet is same and the slope decreases when the temperature of the water reaches nearly 60°C and further increases gradually.

Fig. 3.1.5 shows the variation of the heat extraction rate from the exhaust gas through the HRHE evaluated at different loads. The average heat extracted values at 25%, 50%, 75% and full load condition are 50.68kJ/kg, 51.84kJ/kg, 70.92kJ/kg and 86.45kJ/kg respectively. At full load condition the heat extraction is maximum when compared to all other engine load conditions due to high heat release rate from the engine. From the figure it has been observed that at all the loads, the heat extraction rate decreases as time increases. It is due to the increasing temperature of the water at the inlet of HRHE which reduces the average temperature difference between the exhaust gas and the water.

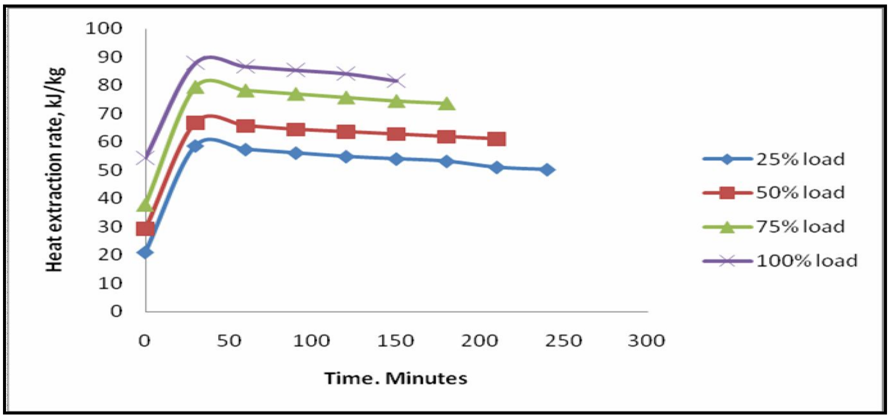



**Figure 3.1.5 Heat extraction rate in HRHE at different load conditions.**

### 3.2 Performance of the Thermal Energy Storage Tank

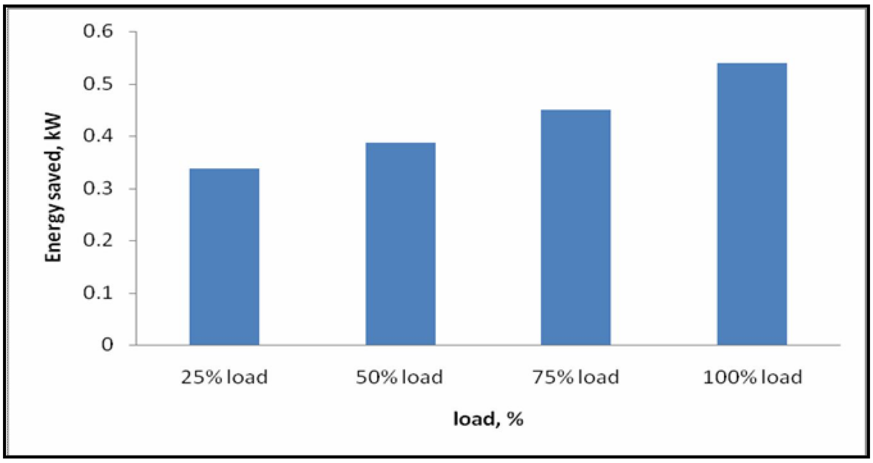



**Figure 3.2.1 Heat Energy saved in the storage tank for different loading conditions**

Fig 3.2.1 shows heat energy stored in the storage tank, it is seen from the above graph that the heat energy storing capacity increases while load of engine increases. The total heat stored in the TES tank is 4863kJ in which the heat stored in the water is 4003 kJ with a temperature raise of 65°C (98–33°C) and heat stored in the PPCM is 860 kJ. The total heat storage capacity in the PPCM is due to its sensible heat (272 kJ) and latent heat (588 kJ). In the storage system the contribution of latent heat is only 12% of the total heat storage capacity. When the storage tank attains 98°C, the total energy stored in the storage tank is 4863 kJ with respect to environment. Though the energy stored is same at all load conditions, it is observed that the duration of charging is 240 min at 25% load and it decreases to 210 min, 180 min and 150 min, respectively for 50%, 75% and full load conditions. This shows that there is a variation in the charging rate. The energy saving at 25%, 50%, 75% and full load condition are 0.337kW, 0.386kW, 0.450kW and 0.540kW respectively which is evaluated by,

$$Q_S = \frac{(m_{water} \; X C_p \, water \; X \, \Delta T_{water}) + (m_{pcm} \; X C_p \, pcm \; X \; \Delta T_{pcm}) + (m_{pcm} \; L \, pcm)}{t_c}$$

## 4. Conclusion

The exhaust gas of a diesel engine carries a considerable amount of heat and this energy can be recovered efficiently by using HRHE and TES tank. A suitable waste heat recovery system with a TES tank can store heat energy and this energy can be utilized for many applications like process heating etc., in industries. In the present study a shell and tube heat exchanger and a PPCM based TES tank were designed and fabricated and tested with a diesel engine. The investigation has shown the following conclusions:

1. Nearly 4–7% 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 86.45kJ/kg.
2. The maximum energy saved at full load condition in the thermal storage tank is 0.540 kW.
3. The presence of LDPE it conducts heat uniformly and found uniform temperature throughout the TES tank.
4. The percentage of heat recovered can be increased further by increasing the surface area of the HRHE.
5. The charging efficiency of the storage tank and the percentage of energy saved can be improved further with proper insulation and also increasing the Nos. of LDPE containers.

## References:

1. V. Pandiyarajan, M. Chinna Pandian, E. Malan, R. Velraj, R.V. Seeniraj, “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.
2. Jungwook Shon, Hyungik Kim, Kihyung Lee, “Improved heat storage rate for an automobile coolant waste heat recovery system using phase-change material in a fin–tube heat exchanger”, Applied Energy, 2014, 113, 680–689
3. M. Medrano, M.O. Yilmaz, M. Nogués, I. Martorell, Joan Roca, Luisa F. Cabeza, “Experimental evaluation of commercial heat exchangers for use as PCM thermal storage systems”, Applied Energy, 2009, 86, 2047–2055
4. Ronald J. Warzoha , Amy S. Fleischer, “Improved heat recovery from paraffin-based phase change materials due to the presence of percolating graphene networks”, International Journal of Heat and Mass Transfer, 2014, 79, 314–323
5. M. Abdollahzadeh, M. Esmaeilpour, “Enhancement of phase change material (PCM) based latent heat storage system with nano fluid and wavy surface”, International Journal of Heat and Mass Transfer, 2015, 80, 376–385
6. Moussa Aadmi, Mustapha Karkri, Mimoun El Hammouti, “Heat transfer characteristics of thermal energy storage for PCM (phase change material) melting in horizontal tube: Numerical and experimental investigations", Energy, 2015, 85, 339–352.

*****