Indo American Journal of Multidisciplinary Research and Review
ISSN: 2581 - 6292 / Website: www.iajmrr.com

PERFORMANCE EVALUATION OF PCM BASED WASTE HEAT RECOVERY SYSTEM

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Cite This Article: S. A. Ravi Verman, Dr. S. Babu & Dr. S. Balachandran, "Performance Evaluation of PCM Based Waste Heat Recovery System", Indo American Journal of Multidisciplinary Research and Review, Volume 3, Issue 2, Page Number 14-19, 2019.

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 paper, experiments are carried out to analyze the performance of thermal energy storage using PCM based compact shell and tube heat exchanger. In the current study, Paraffin RT 35 has been selected as the PCM, exhaust gas from the engine as hot fluid in tube side and water as cold fluid in shell side. The phase change in the shell-and-tube model was dominated by the effect of convective heat transfer. It is found that 0.35 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.

Key Words: Phase Change Material, Waste Heat Recovery, Heat Exchanger, Thermal Storage & Engine Exhaust Gas

1. Introduction:

Energy is an important mania for the economic development of a[...] energy requirement drastically increases in the recent years because of the rapid i[...] 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. 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. 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. 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. 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. In this study, heat recovery system consisting of a shell and tube heat exchanger combined thermal energy storage system with PCM was 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 shell and tube heat exchanger and thermal performance of heat recovery heat exchanger has been studied for various engine load conditions.

Double layer glass

2. Experimental Procedure:

2.1 System Description:

An experimental latent thermal energy storage unit was constructed. It has been isolated analysing the heat transfer phenomenon in the latent thermal energy storage system of the shell-and-tube type shown in Fig. 1.The heat exchanger system consists of a container and the HTF tubes, which are placed into the container. The heat transfer fluid flows by forced convection through the HTF tubes. The PCM has been filled with in the shell space between the container and the tubes. During the engine running condition i.e. the active phase, Exhaust gas heats the PCM, the PCM melts and the heat is stored. During the discharging phase, the PCM solidifies and the stored heat is delivered to the cold fluid. It can be seen from the Fig.1 that the HTF tubes are placed into the tube in such a way that around each of these tubes a circle can be drawn that bounds the region in which this tube exchanges the heat with the surrounding PCM. The experimental test unit consisted of two concentric tubes with 0.75 m length. The inside tube, with inner diameter of 0.016 m and outer diameter of 0.018 m, was made of mild steel while the outside tube, with inner diameter of 0.025 m and outer diameter of 0.028 m, was made of aluminium.

2.2 PCM Selection:

The PCMs having a suitable melting temperature should be selected for appropriate application. PCMs with high latent heat, high thermal conductivity and specific heat are desirable for waste heat recovery application. The values supplied by the manufacturer might be varied. Therefore, pre-characterization of PCM is recommended to get correct thermo physical properties of PCMs. Usually very small quantity of product is applied to the machine to measure the properties. Paraffin wax is the most suitable option due to its availability, non-corrosiveness, compatible melting temperatures, and low cost. Paraffin wax PCM was selected for this experiment.

The thermo physical properties of paraffin wax used in the experiment are presented in Table 1

Table 1: Thermo physical properties of paraffin wax

Descriptions	Value
Melting temperature	56.7^{0}C
Thermal conductivity (solid)	0.1383 W/m.^{0}C
Thermal conductivity (liquid)	0.1383 W/m. ^{0}C
Specific heat (solid)	2890 J/kg.K
Specific heat (liquid)	2890 J/kg.K
Density (solid)	947 kg/m3
Density (liquid)	750 kg/m3
Latent heat	209 kJ/kg

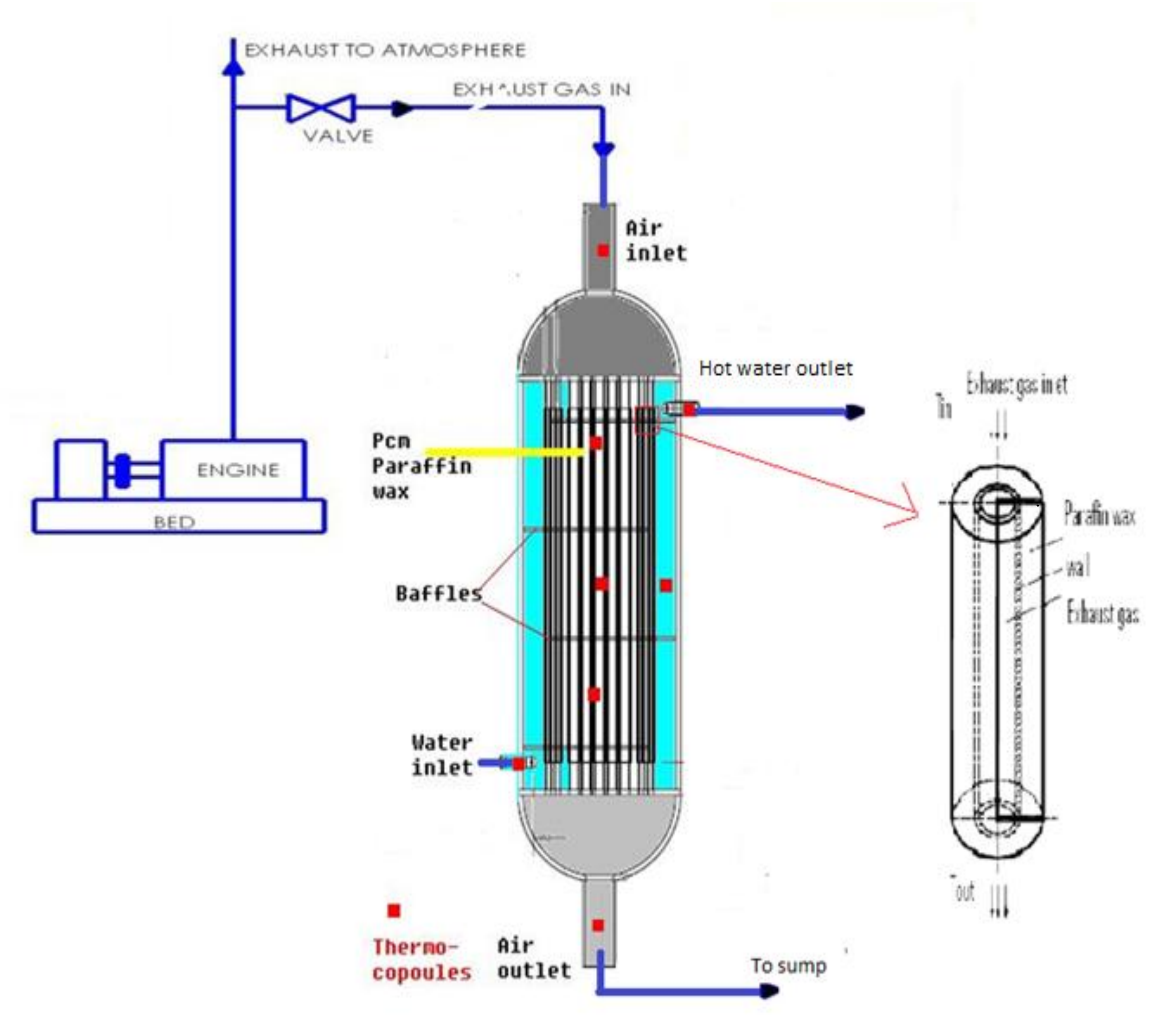

Figure 1: Schematic diagram of integrated shell and tube heat exchanger

2.3 Experimental Methodology:

The experiments are conducted by operating the engine at various load conditions. A few test runs are required in order to check the leakage of PCM and to calibrate the system. Charging experiment is performed when PCM comes in the solid state. The initial condition for charging is established when all thermocouples inside the paraffin shows the same temperature. During charging (melting of paraffin wax), hot air from the engine exhaust, over the melting range of PCM. The charging experiment is finished when the reading of all thermocouples is above the melting temperature range. The discharging (solidification of paraffin wax) experiment is then started with established conditions.Several experiments are conducted to check the repeatability of the results. The experiments are conducted for 25%, 50%, 75% and full load condition. The results along with the evaluated parameters are analysed and discussed in the following section.

The PCM-integrated shell and tube heat exchanger effectiveness is predicted from the energy and mass balances involved in the system. The useful energy from the exhaust gas is

Heat gain $Q_u = m\, c_p(\triangle T)$ 1

The useful heat gain general equation above can be further elaborate into three equations when involved PCM. Since PCM is a phase change material, it consists of sensible heat and latent heat. The equations are as below

Heat gain when PCM is in solid state:

Sensible heat $Q_u = \dot{m}\, c_{ps}\,(T_{s2} - T_s)$ 2

Heat gain during phase change:

Latent heat $Q_u = mc_{pl}$..................................3

Heat gain when PCM is in liquid state:

$Q = \dot{m}\, C_{pl}(T_{L2} - T_{L1})$ 4

Figure 2: Photographic view of the experimental setup

The shell and tube heat exchanger operation strategy is that the experiment is to use after the engine was stopped. During the charging time heat source is the exhaust gas whereas for discharging time the heat can be obtained from PCM.

3. Results and Discussion:

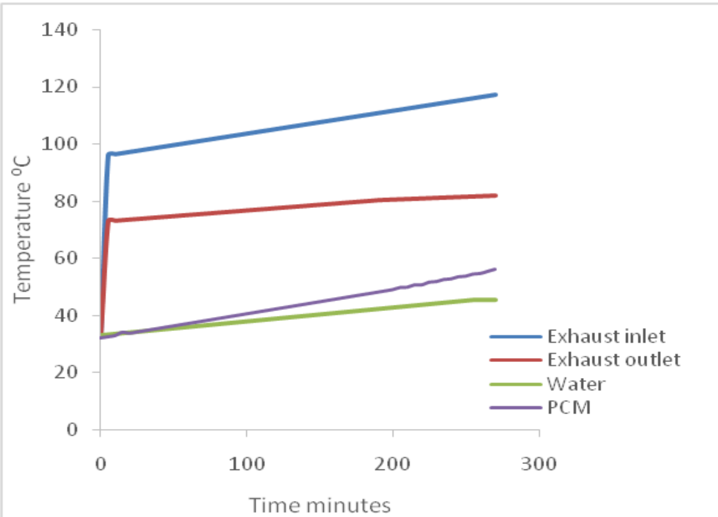

Figure 3: Temperature variation of the exhaust gas and the water at the inlet and outlet at 25% load

The temperature variation of the exhaust gas and the water at the inlet and outlet of the Heat exchanger with respect to time for various engine load conditions (25%, 50%, 75% and full load) is shown in Figures 3– 6.In a diesel engine normally the temperature of exhaust gas will attain steady state within a period of 5 min at a given load. 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 water and the gas outlet temperature variation that the temperature increases at the beginning and the slope decreases when the temperature of the water attains approximately 45 °C and further increases at a higher rate after a certain interval of time. 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 water is very low since the heat capacity of the water (mwatcp.wat) is much higher than the heat capacity of the exhaust gas (mgcp.g).

The time taken by the PCM to reach its melting point and the water to reach 45°C at 25%, 50%, 75% and full load are about 275, 245, 220, 190 minutes approx. Thus the charging time decreases with the load increases. The faster charging at higher loads reduces the losses encountered during the charging process.

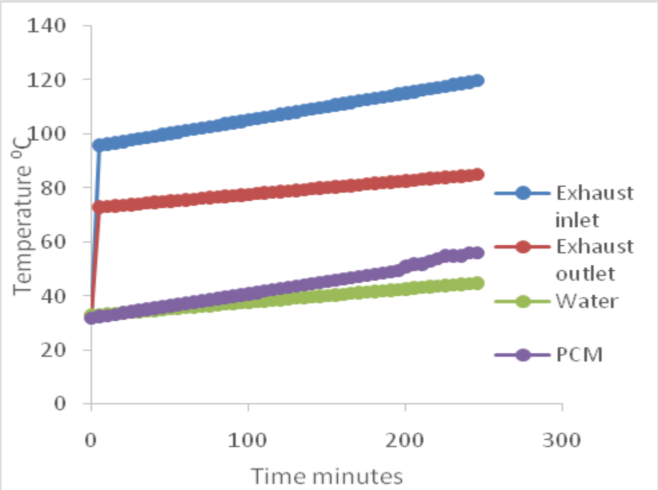

Figure 4: Temperature variation of the exhaust gas and the water at the inlet and outlet at 50% load

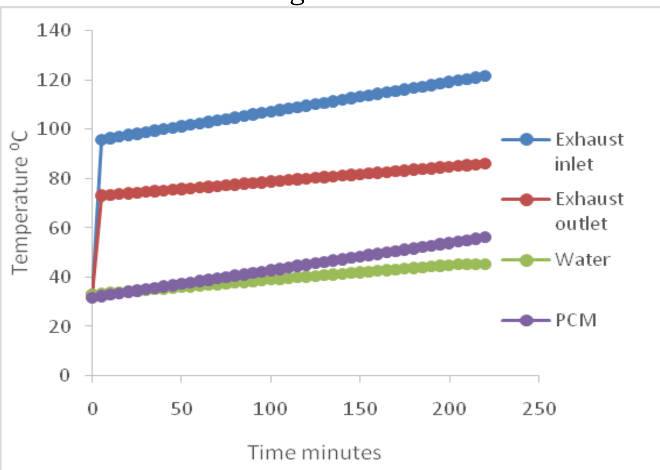

Figure 5: Temperature variation of the exhaust gas and the water at the inlet and outlet at 75% load

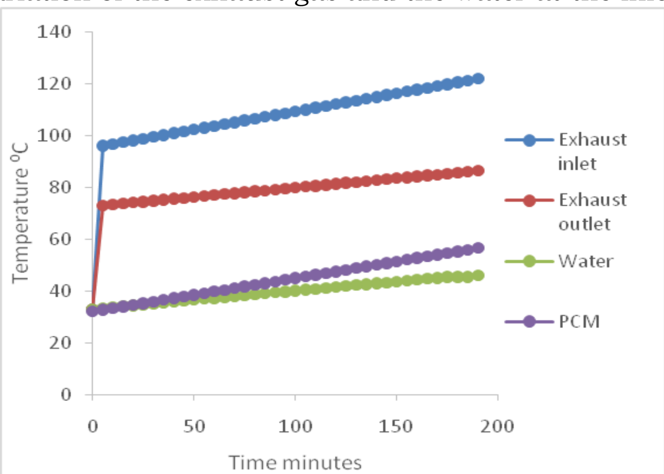

Figure 6: Temperature variation of the exhaust gas and the water at the inlet and outlet at 100% load

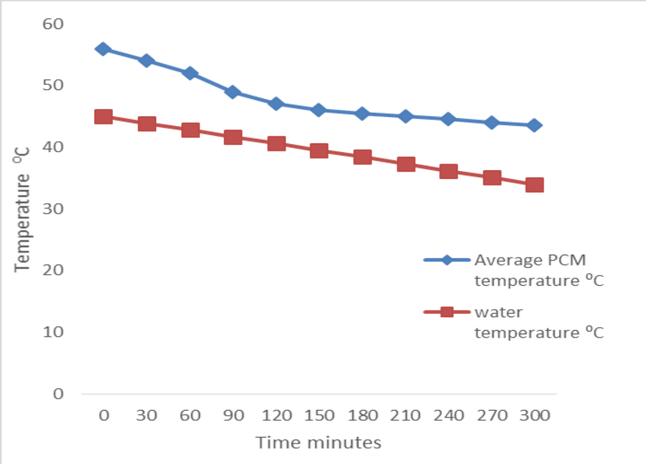

Figure 7: Energy discharging with time intervals

Figure 7 shows the temperature of PCM and water for different time intervals. The water temperature can be maintained for more time with proper insulation. The temperature can be maintained for about 5 hours.

The pressure drop can be calculated from the manometer reading connected at the exhaust gas inlet. The pressure drop inside the tubes through which the exhaust gas flowed need to be reasonable to avoid back pressure. Fig. 8 shows the pressure drops inside the tubes of the heat exchangers at different loads. At 25%, 50%, 75% and 100% loads, the pressure drops were 20.4, 25.7, 27.8 and 31.3 kPa respectively.

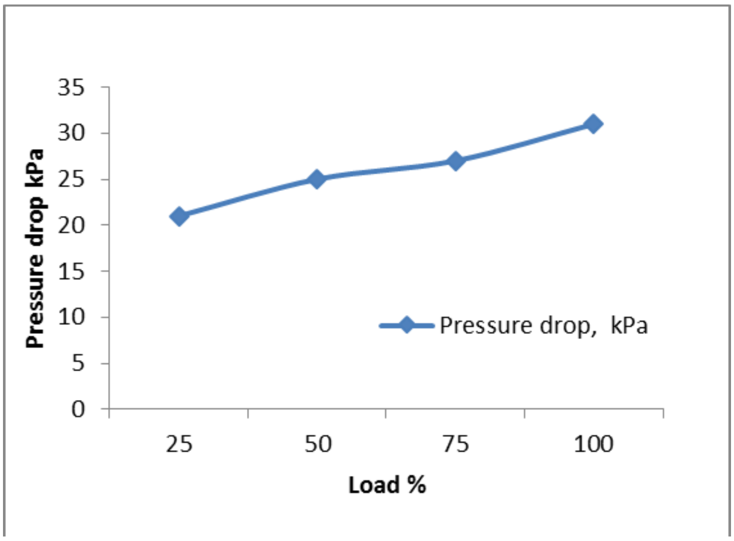

Figure 8: Pressure drop across the heat exchanger at various loads of the engine.

4. Nomenclature:

C_p	=	Specific heat (J/kg °C)
m PCM	=	Specific heat of PCM (J/kg °C)
C_{pWater}	=	Specific heat of water (J/kg °C)
C_{pl}	=	Specific heat of PCM during liquid phase (J/kg °C)
C_{ps}	=	Specific heat of PCM during solid phase (J/kg °C)
C_{pL}	=	Specific latent heat (J kg^{-1})
m PCM	=	Mass of PCM (kg)
$\dot{m}$	=	Mass flow rate (kg sec^{-1})
ΔT	=	Temperature difference (°C)

5. Conclusion:

The exhaust gas of a diesel engine carries a lot of heat and this energy can be recovered efficiently using Waste heat recovery system. 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 Thermal Energy Storage tank of about 80 litres were designed and fabricated and tested by integrating them with a diesel engine of capacity 3.7 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 0.35 kW. The PCM material integration helps in retaining the heat for longer time than normal shell and tube heat exchanger. Thus, it is concluded that integrated shell and tube heat exchanger systems are a commercially viable option for waste heat recovery systems where both the hot water and filtered exhaust gas can be laundry and industrial applications.

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