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Research Paper

Experimental investigation on latent heat thermal energy storage system for stationary C.I. engine exhaust

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HIGHLIGHTS

- Thermal energy storage system is integrated with stationary CI engine.
- Erythritol is used as phase change material.
- Maximum 69.53% charging efficiency is obtained.
- Percentage energy saved is 11.33%.

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ABSTRACT

Increasing gap between demand and supply of energy has resulted in raised prices of conventional energy sources, and concern for clean environment has led to increase in use of renewable energy and focus on increased energy efficiency. In context of increased energy efficiency, energy storage and waste heat recovery play an important role as these systems improve overall efficiency of systems. In this study, a latent heat thermal energy storage system (LHTESS) for stationary C.I. engine exhaust heat was developed and integrated with engine. A shell and tube type heat exchanger having 346 mm diameter and 420 mm height with 45 numbers of tubes with 18 mm diameter was developed to store thermal energy, in which Erythritol ($C_4H_{10}O_4$) was used as a phase change material. The engine performance and the thermal energy storage system performance parameters such as amount of heat stored, and charging efficiency were evaluated. Slight decrease in the engine performance was observed when latent heat thermal energy storage system was integrated to engine but amount of energy which could be recovered was significant. At a load of 4.4 kW the maximum charging efficiency, recovery efficiency and percentage energy saved was 69.53%, 38% and 11.33% respectively.

1. Introduction

About 30% of the heat of combustion is carried out by exhaust gas from an internal combustion engine. The energy available in the exit stream of many energy conversion devices goes as waste; if not utilized properly. To achieve an optimal solution for the current energy crisis, the world needs to focus more on (a) renewable sources of energy or (b) look for recycling/appropriate utilization of energy being wasted [1]. Waste heat (as a by-product) from the prime mover is recovered and used to (a) drive thermally activated components such as vapor absorption system or adsorption chiller or desiccant dehumidifier and (b) to produce hot water, steam, warm air or other heated fluid through the use of heat exchanger [2,3]. The major technical constraint that prevents successful implementation of waste heat recovery is its intermittent and time mismatched demand and availability [4–6]. Thermal energy storage (TES) technology plays an important role to overcome this problem by way of rationale use of energy as it allows excess thermal energy to be stored for later use [7]. Thermal energy storage transfers heat to storage media during the charging period, and releases it at a later stage during the discharging step [8]. A lot of work has been carried out in the field of thermal energy storage. Iten and Liu [9] presented a review on procedure to design an effective short term thermal energy storage (TES) system using phase change materials. Stritih [10] experimentally studied heat-transfer characteristics of a latent-heat storage unit with a finned surface in terms of the solidification and melting processes by comparing them with those of a heat-storage unit with a plain

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surface. Paraffin with a melting point of 30 °C was used in the investigations. Nallusamya et al. [11] experimentally investigated the thermal behavior of a packed bed thermal energy storage unit of combined sensible and latent heat storage. Felix Regin et al. [12] presented a review on heat transfer characteristics of thermal energy storage system using PCM capsules. It was proposed that to achieve the objective of high storage density with higher efficiency, use of phase change material (PCM) capsules assembled as a packed bed is one of the important methods. Developments of available latent heat thermal energy storage technologies, different aspects of storage such as material, encapsulation, heat transfer, applications and new PCM technology was also studied. Butala and Stritih [13] presented an experimental study on buildings cooling using night time cold accumulation in a phase change material. PCMs suitable for summer cooling were also listed. Agyenim et al. [14] presented a review on the development of latent heat thermal energy storage systems (LHTESS) with various phase change materials (PCMs) investigated over the last three decades, the heat transfer and enhancement techniques employed in PCMs to effectively charge and discharge latent heat energy and the formulation of the phase change problem. The review also included the geometry and configurations of PCM containers and a series of numerical and experimental tests undertaken to assess the effects of parameters such as the inlet temperature and the mass flow rate of the heat transfer fluid (HTF). It was concluded that most of the research on phase change problems has been carried out within the temperature range of 0–60 °C suitable for domestic heating/-cooling. Medved et al. [15] presented a review on various Phase Change Materials, to find a suitable PCM for various purposes, suitable heat exchanger with ways to enhance the heat transfer and it will show a variety of designs to store the heat using PCMs for different applications, i.e. space heating and cooling, solar cooking, greenhouses, solar water heating and waste heat recovery systems. Pandiyarajan et al. [4] integrated a shell and finned tube heat exchanger with an IC engine setup to extract heat from the exhaust gas and a thermal energy storage tank used to store the excess energy available. Combined sensible and latent heat storage system for thermal energy storage using cylindrical phase change material (PCM) capsules was designed. Nomura et al. [16] described heat release performance of a direct contact heat exchanger using erythritol as a PCM. Hatami et al. [17] presented numerical study of finned type heat exchangers for ICEs exhaust waste heat recovery. Dubovsky et al. [18] analyzed a tubular heat exchanger which utilizes the latent heat of a phase change material with an assumption that sensible heat capacity of the liquid PCM and the tubes' material is considered small in comparison with the latent heat of melting of the PCM. Hatami et al. [19] presented a review of different heat exchangers' designs for increasing the diesel exhaust waste heat recovery and concluded that using fins is more applicable and appropriate than foam sand porous materials due to the lower pressure drop and higher heat transfer rate. Tay et al. [20] investigated useful latent energy that can be stored within a tube-in-tank phase change thermal energy storage system, with particular reference to off peak thermal storage applications for cooling buildings. Tay et al. [21] experimentally studied the effectiveness of a tube-in-tank design filled with PCM (salt hydrate) for cold storage applications. Hatami et al. [22] presented a comparative study of different exhaust heat exchanger's effect on the performance of a diesel engine. Hatami et al. [23] experimentally and thermodynamically analyzed diesel exhaust vortex generator heat exchanger for optimizing its operating condition. Wang et al. [24] experimentally studied charging process of a direct contact erythritol/ HTO energy storage system. In this system erythritol was used as energy storage media. Hatami et al. [25] carried out experimental investigations on diesel exhaust exergy recovery using delta winglet vortex generator heat exchanger. Hatami et al. [26] obtained an optimized design of finned type heat exchangers (HEX) to recover waste heat from the exhaust of a diesel engine using CFD and CCD techniques.

A lot of researches have been carried out in the field of thermal energy storage but very few studies related to latent heat energy storage are available for stationary C.I. engine exhaust. This study aims to develop a latent heat engine storage system for stationary C.I. engine exhaust and to integrate this system with stationary C.I. engine for carrying out experimental investigation related to engine performance, amount of heat stored, charging efficiency and percentage energy saved.

2. Selection of phase change material for latent heat thermal energy storage system

Several authors have carried out investigation into a wide range of PCMs, subdividing them into organic, inorganic, eutectics PCMs [14]. Factors that must be considered while selecting the phase change heat storage materials are that PCM must possess; a melting point in the desired operating temperature range, high latent heat of fusion per unit mass, high specific heat, high thermal conductivity, small volume changes during phase transition, chemical stability, corrosion resistance to container materials, and should be non-toxic, non-flammable and non-explosive.

Agyenim et al. [14] presented a list of PCMs investigated for different applications. Based on the engine exhaust gas temperature it was decided that selected PCM must possess a melting point temperature between 100 °C and 130 °C (because at part load condition the temperature of exhaust gas is lower hence it is not possible to achieve high melting point in LHTESS). From the available PCMs following two phase change materials (see Table 1) were selected.

Magnesium chloride hexahydrate is a toxic compound and also has a much lower latent heat compared to Erythritol, hence, erythritol was selected as PCM for this experimental investigation. Erythritol is a naturally occurring polyol produced by bacteria, yeast and fungi. Erythritol is biological sweetener and is used extensively in the food and pharmaceutical industries [27].

3. Development of latent heat thermal energy storage system (LHTESS)

In present work a finned shell and tube heat exchanger was used to extract heat from the exhaust gas of a stationary C.I. engine. Based on the amount of heat available in the engine exhaust gases and latent heat of selected PCMs (erythritol), LHTESS was developed. In this shell and tube type heat exchanger, cylindrical shell was made of mild steel with diameter 346 mm and height of 420 mm. 45 numbers of tubes of diameter 18 mm were fixed in the shell. 15 kg erythritol powder was filled in between the spaces of tubes and shell and the exhaust gas from the stationary C.I. engine was allowed to pass through the tubes. Four numbers of longitudinal fins were attached to each tube at equal intervals. The shell was insulated with layer of glass wool and a layer of plaster of Paris.

This tank had inlet and outlet (for exhaust gas) as diverging and converging sections respectively. Diverging section was used at bottom side of tank to expand the exhaust gas for better heat transfer between exhaust gas and tubes. Converging section was used at top of the bed to allow easy escape of the exhaust gas. The Photographic view of the finned shell and tube heat exchanger filled with erythritol, finned shell and tube heat exchanger with insulation, converging section, diverging section and tube with fins are shown in Fig. 1(a), (b), (c), (d) and (e) respectively.