ABSTRACT

Diesel engines are used in automobiles, air compressors, stationary power plants, industries, etc. About one-third of the heat generated is despaired through the engine exhaust gases. CO_2, CO, NO_X, and other toxic gas emissions also impact the ecosystem. Renewable energy technologies are unreliable since they are entirely dependent on weather. The energy conversion and its utilization are essential, which can be achieved by using the heat recovery system to extract heat that would otherwise go to waste. Energy storage plays a vital role in conserving availed energy and improving its utilization. Latent heat thermal storage (LHS) using phase change materials (PCMs) are an efficient way to store thermal storage. Thus, the LHS method proved much higher storage energy and a slight temperature difference between storing and releasing heat.

In the present study, organic PCMs such as capric acid (CA), lauric acid (LA), paraffin wax (PW), and stearic acid (SA) based thermal energy storage systems integrated with the engine exhaust system were investigated in the first phase of the work. Due to phase change materials' low thermal conductivity properties, demerit for the TES system in performance has been observed. However, the TES system with nano-additives in phase change materials revealed satisfactory results. In the second phase of the work, the nano-enhanced PCM technique is used to enhance the thermal performance of TES systems through experimental analysis. The effects of natural convection during the melting and solidification process on 0.1% vol. fraction Al_2O_3 and CuO nano-additives in CA, LA, PW, and SA phase change materials have been investigated. Impact of performance parameters, i.e., Rayleigh number, Fourier number, Nusselt number, heat transfer coefficient, heat transfer rate, and total energy stored, on vol. fraction of nano-enhanced PCM has been considered. Also, using multi-walled carbon nanotubes (MWCNT) in organic PCMs shows drastic improvement in thermophysical properties. In the third phase, the thermophysical properties of multi-walled carbon nanotubes (MWCNT) based organic PCMs have been examined. In the fourth phase of the current study, the design and fabrication of a tube bundles-based TES system have been performed for the heating purpose of a cabin by using the PCMs mentioned above and NEPCMs. Based on the above theoretical study, two types of tube bundles, namely inline and staggered based TES systems, have been fabricated for the utilization of waste heat through above mention organic PCMs and NEPCMs. Furthermore, the thermal performance of inline and staggered tube bundles type TES systems integrated with IC engines were examined.

The energy and exergy analysis was performed for 0.1kg-0.4kg mass fraction of PCMs and revealed that the engine at full load enhances the charging time of CA, LA, PW, and SA PCMs by 51.35%, 53.85%, 129.16%, and 88.89%, respectively. However, CA, LA, and SA-based TES systems' energy saved increased by 122.84%, 5.66%, and 99.13%, respectively, for the mass fraction variation of 0.1kg-0.4kg. Furthermore, LA's 0.4kg mass fraction has 57.5% and 37.25% higher exergy efficiency than SA and PW PCMs. Also, the difference between discharging temperatures (within a time interval of 0–100minutes) of CA, LA, PW, and SA PCMs were 77.38%, 70.21%, 38.40%, and 40.35%, respectively, for 0.4kg mass of PCMs. However, CA, LA, and SA-based TES systems' energy saved increased by 122.84%, 5.66%, and 99.13%, respectively, for the mass fraction variation of 0.1-0.4kg. Furthermore, LA's 0.4 kg mass fraction has 57.5% and 37.25% higher exergy efficiency than SA and PW PCMs. Also, the energy and exergy efficiency of the integrated system with paraffin wax PCM decreased with an increase in mass variation from 0.1kg to 0.4kg.

In the case of nano-additives-based PCMs with a period of 40min., the heat extraction rate and the heat storage from the heat transfer fluid to 0.1% vol. fraction Al_2O_3nano additives-based LA-PCM was 7.69% and 74.3% higher than pure LA, respectively. Also, the LA-based 0.1% Al_2O_3nano-enhanced PCM-TES system saved 5.84%, 6.27%, and 2% energy compared to pure LA, pure PW-PCM, Al_2O_3–paraffin wax NEPCM based TES systems, respectively. The exergy saved from the exhaust for 0.1% vol. fraction Al_2O_3 nano-additives-based LA NEPCM has 34.24% and 35.22% higher values than the LA and PW PCM-based TES system, respectively, at an engine load of 7kg with 1500 rpm. Experimental analysis revealed that 0.1% vol. fraction CuO nano additives-based CA, LA, PW, and SA nano-enhanced phase change material (NEPCM) required 12%, 16%, 6.9%, and 29.34% less charging period than CA, LA, PW, and SA PCMs, respectively. Also, with a period of 50 min., the heat extraction rate and heat storage from heat transfer fluid to 0.1% vol. fraction CuO nano additives-based SA was 22% and 36% higher than pure SA, respectively.

The thermal conductibility (solid) of 0.02% MWCNT in CA, LA, PW, and SA composite PCMs was enhanced by 14.4%, 37.8%, 24.4%, and 13.5% than CA, LA, PW, and SA PCMs, respectively. Furthermore, the results obtained an optimum value for the energy analysis for integrated TES systems and found 0.02% MWCNT-based PW-PCM compared to others. The latent heat for 0.02% MWCNT based CA, LA, PW, and SA phase change materials was decreased by 51.5%, 8.55%, 35.95%, and 21.95%, respectively, compared to pure CA, LA, PW, and SA phase change materials. However, the maximum variation in heat transfer rate during charging of 0.02% MWCNT-based LA, PW, and SA composite PCMs is 61.16 %, 87 %, and 26.4 % higher than that of a thermal energy storage system based on LA, PW, and SA PCMs, respectively.

Also, theoretical comparison results of arranging tubes in an inline and staggered way based on TES systems revealed that the air outlet temperature increased by 1.52% and 1.68%, with tube length variation from 0.1m to 1m in inline and staggered tube arrangements. However, the energy transfer rate improved by 330.8% and 302.9% by increasing the tube diameter from 0.02m to 0.2m. Also, with an increase in upstream velocity from 1m/s-10m/s, the energy transfer rate was enhanced by 331.5% and 303.7%, respectively. Also, experimentation on thermal performance evaluation of inline and staggered tube bundles type TES systems integrated with IC engines has been carried out. Furthermore, the maximum energy storage in the case of a staggered tube arrangement was 14.28%, 11.25%, and 5.66% higher for 0.1% vol. fraction of CuO/ SA-PCM than SA-PCM TES system for inline, staggered, and CuO/SA with inline tube bundles type TES system, respectively. Also, the maximum temperature difference between outlet and inlet air was 8.6°C for LA phase change material with 0.1% vol. fraction of Al_2O_3 nanoparticles filled the TES system.

The present developed inline and staggered tube bundle-based TES system can be utilized for the waste heat from the exhaust side of the IC engine for heating a cabin space of 1m^3volume capacity. Present experimentation results in a temperature above 6.2°C from the ambient temperature for heating the cabin through the organic PCMs and NEPCMs based TES system integrated with engine exhaust. Also, the present developed organic PCM-based TES waste heat recovery system is eco-friendly with environmental concerns.