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"EXPERIMENTAL INVESTIGATION OF ENERGY AND EXERGY PERFORMANCE OF ZIRCONIUM OXIDE NANO-ENHANCED PARAFFIN WAX FOR THERMAL ENERGY STORAGE APPLICATIONS"

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ABSTRACT

The increasing demand for sustainable energy systems has intensified the need for efficient thermal energy storage technologies capable of supporting renewable energy integration and improving energy utilization. In this study, an experimental investigation was carried out to evaluate the thermal performance of zirconium oxide (ZrO_2) nano-enhanced paraffin wax used as a phase change material for thermal energy storage applications. The work focused on the preparation of nano-enhanced phase change material samples by dispersing ZrO_2 nanoparticles into paraffin wax at different concentrations, followed by the analysis of their charging, discharging, energy, and exergy characteristics in a dedicated test setup. The experimental system consisted of a PCM tank, heat source tank, helical coil heat exchanger, control unit, and data acquisition arrangement to monitor the thermal response of the storage medium under varying flow conditions. The results indicated that the incorporation of nanoparticles improved the thermal behaviour of paraffin wax by enhancing heat transfer during phase transition. The energy analysis showed that charging efficiency increased with increasing flow rate, whereas discharging efficiency gradually decreased because of reduced residence time of the heat transfer fluid. The exergy analysis further revealed that although energy efficiency improved at higher flow rates, exergy efficiency declined because of increased thermodynamic irreversibilities. The liquid fraction analysis also confirmed that nanoparticle addition accelerated melting and solidification behaviour, thereby improving the thermal responsiveness of the storage system. The study demonstrates that ZrO_2-based nano-enhanced paraffin wax is a promising thermal storage medium for improving the performance of latent heat energy storage systems used in solar thermal and related energy applications.

Keywords: *Thermal Energy Storage, Phase Change Material, Nano-Enhanced PCM, Zirconium Oxide Nanoparticles, Paraffin Wax, Energy Analysis, Exergy Analysis, Thermal Conductivity, Heat Transfer Enhancement, Latent Heat Storage, Thermophysical Properties, Renewable Energy, Experimental Investigation*

I. INTRODUCTION

Energy is central to modern civilization because it supports industrial production, transportation, residential needs, and technological development. However, the continued dependence on fossil fuels has created a dual challenge: depletion of conventional resources and severe environmental degradation. Rising fuel prices, increasing global demand, supply instability, and the adverse impact of carbon-intensive energy systems have intensified the global energy crisis [1]–[5]. In parallel, the accelerating effects of climate change have forced governments and researchers to shift attention toward sustainable and low-emission energy pathways [6], [7]. These concerns have made renewable energy integration and efficient storage technologies major priorities in contemporary energy research.

Renewable energy sources such as solar, wind, hydroelectric, and geothermal systems offer cleaner alternatives to conventional energy generation. Despite their environmental advantages, these sources are inherently intermittent because their output depends on climatic conditions, seasonal variation, and geographical location [6]–[10]. This intermittency creates operational challenges in maintaining grid stability, balancing supply and demand, and ensuring reliable power delivery. Therefore, energy storage systems have become indispensable in modern energy infrastructure. They help reduce generation variability, enable load shifting, improve peak management, strengthen grid resilience, and support large-scale renewable energy penetration [11], [12].

Among the available storage technologies, thermal energy storage (TES) has emerged as a practical and efficient approach for managing thermal loads and improving overall system efficiency. TES systems store surplus thermal energy during periods of low demand and release it during periods of high demand, thereby bridging the temporal mismatch between energy availability and energy utilization [12], [13]. Such systems are especially relevant in solar thermal applications, district heating and cooling, industrial waste heat recovery, and building energy management. Depending on the storage principle, TES systems are generally classified into sensible heat storage, latent heat storage, and thermochemical heat storage [13]–[15]. Of these, latent heat thermal energy storage has gained particular attention because it offers high storage density and near-constant temperature energy exchange during phase transformation [16], [17].

Latent heat storage systems rely on phase change materials (PCMs), which absorb and release significant amounts of thermal energy during melting and solidification. PCMs are attractive for thermal regulation because they can store large quantities of energy over a relatively narrow temperature range [16], [18]. However, conventional PCMs suffer from several limitations, including low thermal conductivity, slow charging and discharging behaviour, subcooling, and phase segregation in some systems [19], [20]. These drawbacks restrict their effectiveness in practical thermal energy storage applications and motivate the need for performance enhancement strategies. Recent studies have therefore focused on improving the thermal response of PCM systems through encapsulation, porous supports, heat transfer enhancement geometries, and nanoparticle incorporation [21], [22].

One of the most promising approaches for improving PCM performance is the development of nano-enhanced phase change materials (NEPCMs). By dispersing thermally conductive nanoparticles into base PCM, the overall heat transfer capability of the storage medium can be improved, thereby accelerating both melting and solidification processes. Among different additives, zirconium oxide (ZrO_2) nanoparticles are of particular interest because of their favorable thermal characteristics, chemical stability, and compatibility with advanced thermal storage media [21], [22]. Their incorporation can enhance the effective thermal conductivity of PCM-based systems and improve heat absorption and release characteristics, which are critical for practical TES performance. Based on this background, the present work focuses on thermal energy storage using ZrO_2-enhanced PCM and examines its charging and discharging behaviour under different operating conditions.

II. LITERATURE REVIEW

Thermal energy storage has been widely recognized as an enabling technology for sustainable energy systems because it improves energy utilization and allows excess thermal energy to be stored for later use. A large body of literature has examined TES for low- and medium-temperature applications, particularly in solar energy systems and heat recovery units. Munyalo and Zhang [12] reviewed the influence of particle size on the thermophysical properties of nanofluids and nanofluid-based PCMs and emphasized that material-scale tailoring can significantly affect thermal storage performance. Shah [13] further highlighted that nanomaterial-based PCM enhancement is an effective route for improving TES functionality, especially where heat transfer limitations dominate system behaviour. These studies establish that TES performance is strongly dependent on the thermophysical properties of the storage material.

TES systems are commonly categorized into sensible, latent, and thermochemical storage techniques. Sensible heat storage uses the temperature rise of a storage medium such as water, concrete, or sand, while latent heat storage relies on the enthalpy of phase transition [14]–[17]. Thermochemical storage, although promising because of its high energy density, is still under active development for practical deployment [18]. Among these options, latent heat storage has drawn the greatest research attention because PCMs can store and release a large amount of heat at nearly constant temperature, making them suitable for applications requiring controlled thermal management [16], [17]. This makes PCM-based TES especially attractive in buildings, HVAC systems, solar thermal devices, and thermal buffering applications.

A critical limitation of conventional PCM systems is their low thermal conductivity, which slows the rate of heat charging and discharging. Agyenim et al. [14] experimentally studied erythritol in a shell-and-tube latent heat storage system and showed that heat transfer enhancement is essential for improving the charging and discharging response. Similarly, several investigations reported that the design of the heat exchanger geometry, tube arrangement, and fluid circulation path strongly influences melting uniformity and total storage effectiveness [14], [18]. Mohamed et al. [19] and Cunha and Eames [20] noted that, although inorganic PCM systems may present issues such as corrosiveness, they often provide better thermal conductivity and thermal stability than many organic alternatives, particularly for low- to medium-temperature storage applications.

In parallel, researchers have examined the desirable thermophysical properties of energy storage materials, including latent heat, specific heat, melting temperature, density, thermal conductivity, and volume stability during phase transition. Studies compiled in the uploaded review indicate that high latent heat, stable phase transition temperature, low subcooling, and chemical reliability are key requirements for practical PCM selection [16], [18]. Inorganic materials generally offer higher storage density, whereas organic materials are often preferred for their chemical stability and compatibility. However, for both classes, low thermal conductivity remains a recurrent challenge. Because of this, numerous thermal enhancement strategies have been proposed, including metallic fins, porous matrices, encapsulation, graphite-based fillers, carbon nanotubes, and nanoparticle additives [19]–[22].

Nanoparticle-enhanced PCM systems have emerged as a major research direction for overcoming the heat transfer limitations of conventional TES media. Avid et al. [7] investigated paraffin/MWCNT nanocomposites and showed that surface-modified nanomaterials can alter PCM behaviour and improve composite properties. Other studies reported significant conductivity enhancement when nanofillers such as CNT, CNF, graphene nanoplatelets, metal particles, and ceramic additives were dispersed into waxes, salts, polyethylene glycol, and eutectic mixtures [21], [22]. Rezaie and Montazer [21] explored fatty acid–copper nanoparticle composites for low-temperature thermal management, while Gao et al. [22] reviewed confinement-based nano-enhanced PCM systems and emphasized that nano-confinement and shape stabilization can simultaneously address leakage, thermal conductivity, and storage durability. These studies collectively show that nanomaterials can improve PCM performance through both conductive network formation and microstructural stabilization.

Heat transfer enhancement in TES design has also been widely studied from a system-level perspective. Researchers have investigated microencapsulation, shell-and-tube arrangements, helical coils, porous metal supports, and hybrid storage structures to improve effective heat transfer area and reduce charging and discharging time [19]–[22]. Recent work has suggested that nano-enhanced phase change materials combined with optimized containment design and advanced exchanger geometries may offer substantial improvements in thermal responsiveness and storage efficiency. This is especially relevant in solar thermal systems, where rapid heat absorption and discharge are required to match fluctuating solar input and dynamic load conditions.

Among the different nanoparticles studied, ZrO_2 has emerged as a promising additive for TES applications. The uploaded source specifically notes that ZrO_2 nanoparticles can improve PCM thermal conductivity and can also enhance the thermal conductivity of heat transfer fluids used in solar thermal and concentrated solar power applications [21], [22]. Their high-temperature stability and compatibility with advanced storage configurations further increase their suitability for thermal storage systems. In addition, ZrO_2 has been discussed in the context of thermochemical storage and advanced heat storage devices, indicating that its functionality may extend beyond simple conductive enhancement [21], [22]. This makes ZrO_2-based NEPCM a valuable research direction for practical TES development.

Although the literature demonstrates clear progress in PCM enhancement, gaps remain in identifying optimum nanoparticle concentration, understanding charging-discharging performance under different flow conditions, and establishing experimentally validated TES behaviour in practical test rigs. Many published studies emphasize material synthesis or thermophysical property measurement, while comparatively fewer focus on integrated experimental charging and discharging analysis using ZrO_2-based PCM systems. Therefore, there remains a need for targeted experimental studies that evaluate the influence of ZrO_2 concentration on TES behaviour and quantify its effectiveness under realistic operating conditions. The present study addresses this need by examining the charging and discharging characteristics of ZrO_2-enhanced PCM in a dedicated thermal energy storage setup.

III. METHODOLOGY

A. Material used

The characterization of nano-enhanced phase change materials (NEPCMs) involves detailed analysis to understand their improved thermal properties and overall performance. For paraffin wax modified with molybdenum oxide nanoparticles, characterization techniques such as Scanning Electron Microscopy (SEM), Differential Scanning Calorimetry (DSC), and thermal conductivity measurements are employed. SEM analysis provides insights into the dispersion and uniformity of the nanoparticles within the wax matrix, ensuring proper integration and stability. DSC is used to determine the melting and freezing points, as well as the latent heat capacity, which indicates how effectively the NEPCM can store and release thermal energy. Thermal conductivity measurements assess the enhancement in heat transfer properties due to the nanoparticles.

The physical properties of the nano-enhanced PCM (NEPCM) are significantly influenced by the presence of molybdenum oxide nanoparticles. These properties include increased thermal conductivity, which allows for faster heat absorption and dissipation, enhancing the efficiency of thermal energy storage systems. The latent heat capacity, a crucial property for PCMs, remains high, ensuring that the material can store substantial amounts of thermal energy. Additionally, the melting and freezing points may be slightly adjusted due to nanoparticle integration, but they remain within a useful range for practical applications. Overall, the inclusion of nanoparticles aims to create a more effective and reliable thermal energy storage material, making NEPCMs a promising solution for energy-efficient systems.

B. Paraffin Wax

Paraffin wax, a commonly used phase change material (PCM), is valued for storing and releasing thermal energy during phase transitions between solid and liquid states. This property makes paraffin wax ideal for thermal energy storage applications. When heated, paraffin wax absorbs substantial heat as it melts, transitioning from solid to liquid. Conversely, when it cools, it releases stored thermal energy as it solidifies. This cyclical absorption and release of heat allow paraffin wax to regulate temperature effectively in various systems.

Paraffin wax is particularly advantageous as a PCM due to its high latent heat capacity, non- toxic nature, chemical stability, and wide availability. These characteristics make it suitable for diverse applications, including thermal management in buildings, electronics cooling, and temperature-controlled packaging. In building applications, paraffin wax can be integrated into construction materials or thermal storage units to enhance energy efficiency by stabilizing indoor temperatures and reducing heating and cooling demands show in figure 1.

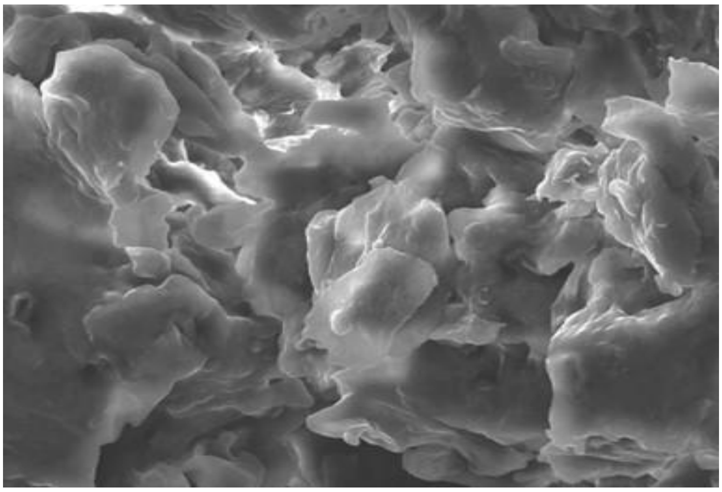

Fig.1. FESEM image of parA (nano-enhanced phase change material) NEPCM samples are first prepared by determining how much nanomaterial will be added to the paraffin solvent.

The authors here create numerous samples of ZrO2 doped PCM with volume concentrations of 0.1%, 0.2%, and 0.3% to examine the effects of nano inclusions in base paraffin. After 1.5 hours of magnetic stirring and 2.5 hours of ultrasonication, the samples are immersed in molten paraffin to ensure the complete diffusion of the nanomaterial. The PCM samples are kept in liquid state throughout the entire procedure by maintaining a constant temperature of 65 °C during both phases. Zirconium oxide nanoparticles and paraffin wax are combined to create a NEPCM, which improves thermal characteristics of wax. The general procedures for making a NEPCM sample using paraffin wax and zirconium oxide nanoparticles are listed below.

C. Experimental setup

An experimental setup, comprising a PCM tank, a heat source tank, a heat transfer fluid storage pipeline arrangement, a control unit, and a data recording unit, has been designed to investigate the temperature and performance of NEPCM samples in a heat exchanger. To maintain a constant temperature during the charging process, water heaters utilize a digitally regulated electric heater. The heat exchanger is built of copper tubes and a stainless-steel casing. The heat exchanger's dimensions are 140 mm in cell diameter, 2 mm in thickness, and 450 mm in length. The heat exchanger's helical copper tubes have a thickness of 8.6 mm with 17-18 turns. The goal is to document the sample temperature difference between the HTF and the NEPCM. The figure of experimental set-up as shown in figure 4 (a), and figure 4 (b) shows internal structure of the thermal store cylinder. RTD-based sensors are placed to record the temperature changes in HTF and the inlet and outlet temperatures of the NEPCM samples. At both ends of the spiral coil, another set of sensors has been attached. Water flow from HTF tank to heat exchanger is controlled manually, and both the hot as well as cold circuits of heat exchanger measure mass flow rate. The systems feature switches for controlling the various heating and pumping mechanisms as well as a control unit with a temperature display, a flow rate display, and these displays.

IV. RESULTS AND DISCUSSION

A. Exery and Energy Analysis

Figure 2 (a) Variation of flow rate vs Overall efficiency during charging and discharging (b) Exergy efficiency and HTF flow rate variationFigure 2(a) presents the variation of charging, discharging, and overall efficiencies as a function of flow rate ranging from 2 to 6 LPM. It is observed that the charging efficiency exhibits a consistent increasing trend, rising from approximately 53% at 2 LPM to nearly 67% at 6 LPM. This enhancement is primarily attributed to improved convective heat transfer at higher flow rates, where the increased mass flow of the heat transfer fluid (HTF) facilitates more effective heat exchange between the fluid and the storage medium. The higher velocity reduces thermal resistance and promotes better energy absorption during the charging process.

Conversely, the discharging efficiency shows a gradual decline with increasing flow rate, decreasing from about 57% at 2 LPM to nearly 52% at 6 LPM. This reduction can be explained by the reduced residence time of the HTF within the storage system at higher flow rates. As the fluid passes more quickly through the system, it is unable to extract the stored thermal energy effectively, leading to incomplete energy recovery during the discharging phase. This behavior indicates a limitation in heat extraction efficiency under high flow conditions.

As a combined effect of these opposing trends, the overall efficiency decreases significantly with increasing flow rate, dropping from approximately 74% at 2 LPM to around 59% at 6 LPM. This suggests that although higher flow rates enhance the charging process, the reduction in discharging efficiency has a more dominant influence on the overall system performance. Therefore, lower flow rates appear to be more favorable for achieving balanced thermal performance and maximizing overall efficiency.

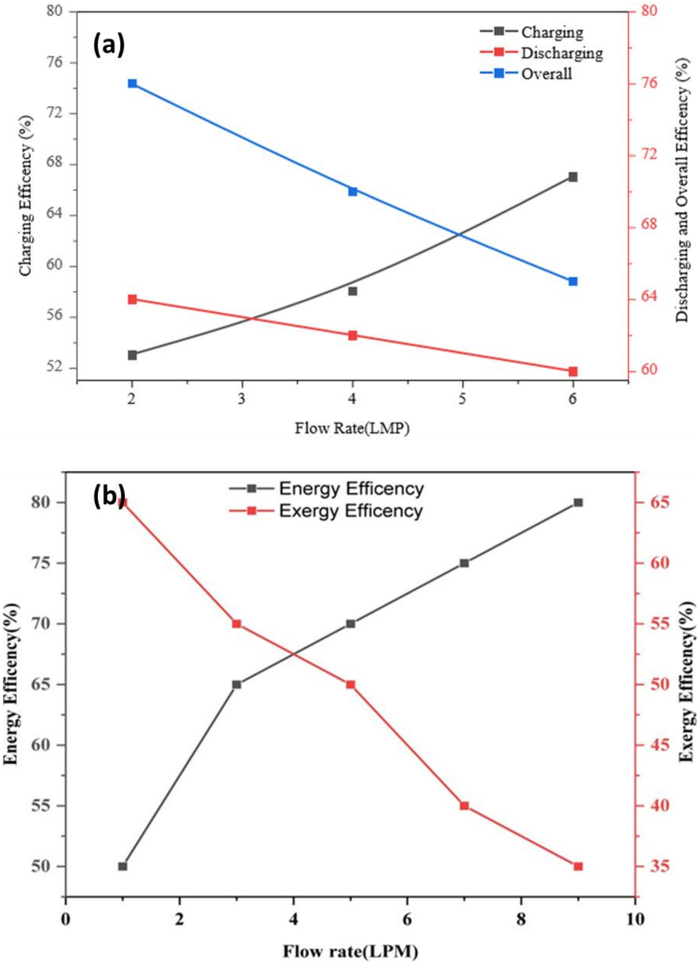

Fig. 2 (a). Variation of flow rate vs Overall efficiency during charging and discharging
Fig. 2 (b) Exergy efficiency and HTF flow rate variation

Figure 2(b) illustrates the effect of flow rate on energy efficiency and exergy efficiency over a wider range of 1 to 9 LPM. The energy efficiency increases steadily with flow rate, rising from about 50% at 1 LPM to nearly 80% at 9 LPM. This improvement is associated with enhanced heat transfer characteristics at higher flow rates, where increased turbulence and reduced thermal boundary layer thickness contribute to better utilization of input thermal energy.

In contrast, the exergy efficiency shows a sharp decreasing trend, declining from approximately 65% at lower flow rates to nearly 35% at higher flow rates. This behavior indicates a significant increase in thermodynamic irreversibilities within the system at higher flow rates. Factors such as increased entropy generation, fluid friction, and larger temperature gradients contribute to the degradation of useful energy (exergy), even though the total energy transfer improves.

Overall, the results from Figure 2(a) and 2(b) clearly demonstrate a trade-off between energy transfer enhancement and thermodynamic efficiency. While higher flow rates improve heat transfer and energy efficiency, they adversely affect exergy efficiency and overall system performance due to increased irreversibilities and reduced heat recovery during discharging. These findings highlight the importance of selecting an optimal flow rate that balances both energy and exergy performance for efficient thermal system operation.

B. Effect of liquid fraction variation in NEPCM (ZrO2 and PCM)

Figure 3 displays the results of simulation of the thermal storage cylinder with a single NEPCM for the liquid portion. Melting occurs faster at inlet than it does on the outlet side, as predicted.

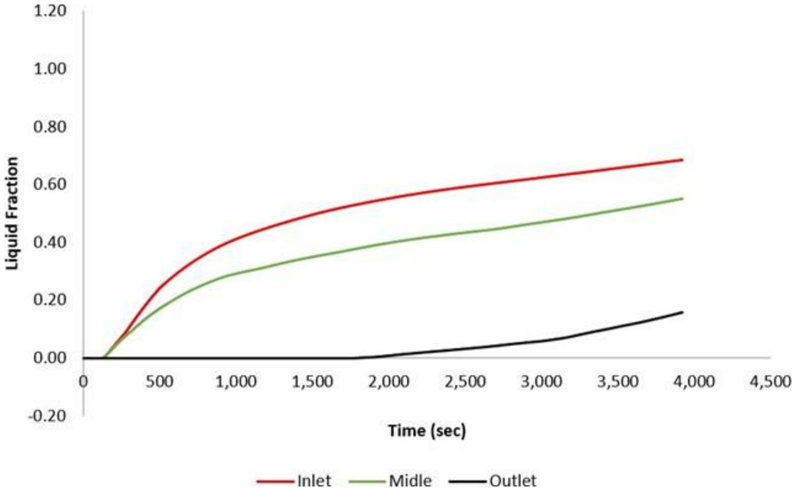

Fig. 3. Variation of liquid fraction vs time for NEPCM storage material

This is because natural convection lowers the temperature of the moving fluid while keeping the energy storage area constant. The quantity of latent heat stored or released by the NEPCM depends on the liquid fraction directly. The proportion of liquid in the PCM changes when it changes from a solid to liquid state (melting) or from a liquid to a solid state (solidification). NEPCM remains able to store and release more energy per unit mass than traditional materials maintaining stable temperatures because of the increased latent heat being stored or released when a higher liquid percentage is present. Therefore, the melting process is enhanced by the addition of the input side tube. Figure depicts the effects of liquid fraction application at the intake and outflow on PCM solidification. The findings suggest that the nanoparticles facilitate solidification and that their length decreases the phase transition time. Heat conduction and enhanced heat transfer surface area are responsible for the enhancement. The liquid fraction variation can influence the thermal response time of the NEPCM system. Higher liquid fractions during melting can lead to faster energy absorption and shorter response times, making NEPCM suitable for applications that require rapid thermal energy storage or release.

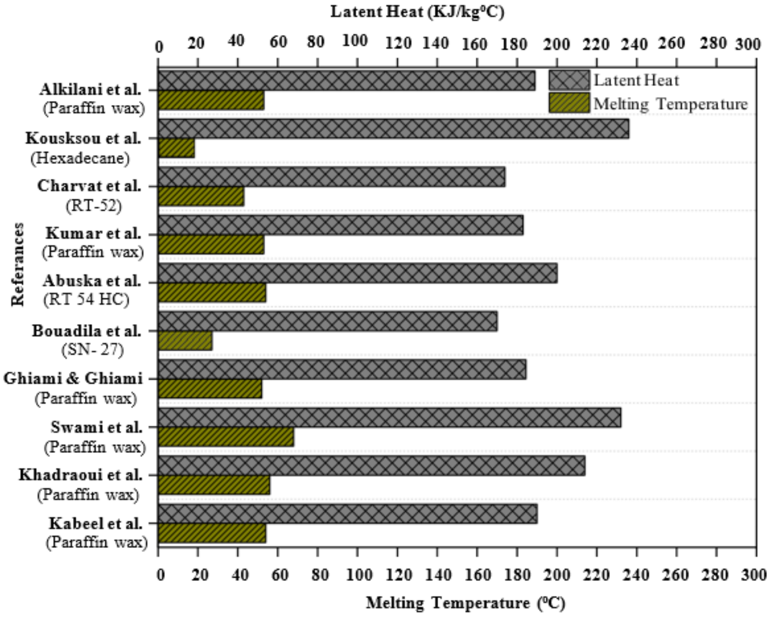

Fig. 4. Various paraffin waxes with respect to latent heat and melting temperature

Figure 4.6 exhibits the various types of paraffin wax utilized by the researchers, as well as analysis of latent heat and melting point. Because paraffin has limited heat conductivity, it must be used with a large heat transfer surface or heat transfer augmentation procedures.

V. CONCLUSIONS

The present study investigated the thermal energy storage performance of zirconium oxide (ZrO_2) nano-enhanced paraffin wax under different operating conditions and demonstrated its suitability for latent heat storage applications. The experimental analysis confirmed that the incorporation of ZrO_2 nanoparticles improved the thermal response of paraffin wax and supported more effective heat absorption and release during the phase change process. The prepared nano-enhanced phase change material exhibited stable charging and discharging behaviour, indicating that nanoparticle addition can be an effective approach for overcoming the low thermal conductivity limitation of conventional parafn-based PCM systems.

The energy analysis showed that the charging efficiency increased continuously with increase in heat transfer fluid flow rate, rising from nearly 53% at lower flow conditions to about 67% at higher flow conditions. This behaviour was associated with stronger convective heat transfer and faster thermal energy delivery to the storage medium. In contrast, the discharging efficiency decreased from about 57% to nearly 52% with increasing flow rate because the fluid had less residence time inside the storage unit and could not recover the stored heat effectively. As a result of these opposite trends, the overall efficiency declined from approximately 74% to nearly 59% with increasing flow rate, indicating that lower or moderate flow rates are more favorable for balanced system performance. The exergy analysis provided a deeper thermodynamic understanding of system behaviour. Although the energy efficiency improved at higher flow rates and reached nearly 80%, the exergy efficiency showed a strong decreasing trend, dropping from around 65% to nearly 35%. This decline indicates that high flow rates increase entropy generation, thermal irreversibility, and fluid friction losses within the system. Therefore, the study makes it clear that improvement in heat transfer rate alone does not guarantee better thermodynamic performance. An optimum operating range is required where both energy utilization and exergy efficiency remain reasonably high.

The liquid fraction analysis further confirmed that the presence of nanoparticles promoted faster melting and solidification of the NEPCM. The inlet region melted more rapidly than the outlet region, and the addition of ZrO_2 enhanced phase transition characteristics through better heat conduction and improved effective heat transfer within the storage domain. This faster thermal response is important for practical TES systems where rapid charging and discharging are required. The results therefore support the view that ZrO_2-enhanced paraffin wax can improve the operational responsiveness of thermal storage devices used in solar thermal systems, waste heat recovery, and related energy applications.

Overall, the study establishes that ZrO_2-based nano-enhanced paraffin wax is a promising material for thermal energy storage applications because it combines the latent heat storage capability of paraffin with the heat transfer enhancement provided by nanoparticles. However, system performance is strongly influenced by operating flow rate, and both energy and exergy perspectives must be considered while selecting working conditions. The findings of this work provide useful guidance for the design and optimization of nano-enhanced latent heat thermal energy storage systems and create a basis for future studies on concentration optimization, cyclic stability, and large-scale application of NEPCM-based storage units.

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