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"Experimental investigation of heat storage by using paraffin wax."-A Review

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Abstract*— A significant amount of heat is wasted in manufacturing process, electricity generation, chemical and industrial process. Recovery and reuse of this energy through storage can be useful in conservation of energy. In the present study, a double pipe type heat exchanger has been designed and fabricated for low temperature industrial waste heat recovery using phase change material (PCM) paraffin wax (PW). Experiments were performed for two different mass flow rates and inlet temperature of heat transfer fluid (HTF) is maintained at constant in charging process. In order to recovery of heat during discharging process temperature of HTF is maintained at atmospheric temperature.Heat transfer in the phase change problem waspreviously formulated using pure conduction approach but the problem has moved to a different level of complexity with added convection in themelt being accounted for. There is no standardmethod (such as British Standards or EU standards) developed to test for PCMs, making it difficult for comparison to be made to assess the suitability of PCMs to particular applications.The constrained and unconstrained melting of PCM inside a spherical capsule using paraffin wax (PW) is investigated. PCM melting is constrained in spherical capsule using thermocouples used to measure the temperatures in capsule. The visualization of melting process is obtained using digital camera. The qualitative and quantitative information on solid-liquid interface of phase change process is compared. It is observed that, the solid PCM is restricted from sinking to the bottom of the spherical capsule in constrained melting. The objective of this paper is to confirm suitability of PW for enhancing the performance of thermal storage capacity and utilizing PW for domestic solar water heating applications.The effect of mass flow rate on the performance of the system was studied. Calculations for amount of heat stored and released during charging (melting of PCM) and discharging (solidification of PCM) and heat discharging efficiency were also made. The experimental results show the feasibility of using PCM as storage media in heat recovery systems.

INDEX TERMS —CHARGING, DISCHARGING, PARAFFIN WAX, PHASE CHANGE MATERIAL.

I INTRODUCTION

The quest for new technologies to avert the growing concern about environmental problems, the imminent energy shortage and the high cost of energy and new power plants has been a scientific concern over the last three decades. Central to the problem is the need to store excess energy that would otherwise be wasted and also to bridge the gap between energy generation and consumption. Latent heat thermal energy storage is particularly attractive technique because it provides a high energy storage density. When compared to conventional sensible heat energy storage systems, latent heat energy storage system requires a smaller weight and volume of material for a given amount of energy. In addition latent heat storage has the capacity to store heat of fusion at a constant or near constant temperature which correspond to the phase transition temperature of the phase change material (PCM). It was extensively researched for use in different applications especially for solar heating systems[1], [2]. Studies have been conducted to assess the overall thermal behaviors of latent heat thermal storage systems. Studies of phase change systems have investigated design fundamentals, system and process optimization, transient behavior, and field performance. The research anddevelopment has been broad based and productive, concentrating on both the resolution of specific phase change materials and problems and the study of the characteristics of new materials. The major disadvantage, as reported by many researchers has been the low thermal conductivities possessed by many PCMs, leading to low charging and discharging rates (especially for the organic based materials). The development of a latent heat thermal energy storage system therefore involves the understanding of heat transfers/exchanges in the PCMs when they undergo solid-to-liquid phase transition in the required operating temperature range.The heat transfer and fluid movement during this process has an impact on performance. Experimental observations indicate that there is a difference in time for complete melting under constrained and unconstrained conditions. In TES system, a spherical container is most commonly used for storing PCM. This is mainly due to its low volume to heat transfer surface area ratio [3]. The density difference between the solid and liquid PCM causes a movement of solid up or down. Depending upon the densities, the melting phenomenon changes due to the movement of solid PCM [1]. Differences in the constrained and unconstrained melting of PCM inside the sphere under several constant surface temperature boundary conditions at several initial sub-cooled conditions are investigated by Tan [1]. It was found that under the same experimental condition, unconstrained melting inside the sphere seems to occur at a faster rate than the constrained melting. This is due to the larger rate of heat transfer by conduction from the solid PCM to the spherical glass.

Studies from Francis Agyenim a,*, Neil Hewitt a, Philip Eames b, Mervyn Smyth show that that to store the same amount of energy from a unit collector area, rock (sensible heat storage material) requires more than seven times the storage mass of Paraffin 116 Wax (P116-Wax), five times the storage mass of medicinal paraffin and more than eight times the storage mass of Na2SO4.10H2O.

Energy storage may be in the form of sensible heat in a liquid or solid medium, as heat of fusion (latent heat), or as chemical energy or products in a reversible chemical reaction. The classification of energy storage and the materials used are detailed in [6]. Chemical energy storage has not as yet been used in practical applications and both technical and economical questions have yet to be answered. Studies conducted to compare phase change and sensible heat storages have shown that a significant reduction in storage volume can be achieved using PCM compared to sensible heat storage.

2.1. PCMs investigated

Several authors have carried out investigation into a wide range of PCMs, subdividing them into organic, inorganic, eutectics PCMs [1]. The main criteria that govern the selection of phase change heat storage materials are [1]:

1. Possess a melting point in the desired operating temperature range (temperature range of application).
2. Possess high latent heat of fusion per unit mass, so that a smaller amount of material stores a given amount of energy.
3. High specific heat to provide additional significant sensible heat storage effects.
4. High thermal conductivity, so that the temperature gradients for charging and discharging the storage material are small.
5. Small volume changes during phase transition, so that a simple container and heat exchanger geometry can be used.
6. Exhibit little or no sub cooling during freezing.
7. Possess chemical stability, no chemical decomposition and corrosion resistance to construction materials.
8. Contain non-poisonous, non-flammable and non-explosive elements/compounds.
9. Available in large quantities at low cost

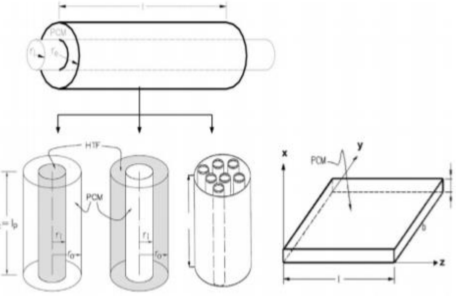
2.2. Classification of PCMs to melting temperature range and application area.

The selection of an appropriate PCM for any application requires the PCM to have melting temperature within the practical range of application. Several application areas have been proposed for PCMs studied. Some of the target application areas for the selection of PCMs for study, as provided by the references in the open literature. Most of the research on phase change problems have been carried out within the temperature range 0–65^0 C. Suitable for domestic heating/ cooling.

PCM containers

Once the PCM has been selected based primarily on the temperature range of application, the next most important factors to consider are:

(i) The geometry of the PCM container and (ii) The thermal and geometric parameters of the container required for a given amount of PCM. Each of these factors has a direct influence on the heat transfer characteristics in the PCM and ultimately affects the melt time and the performance of the PCM storage unit. To ensure long-term thermal performance ofany PCM system, the size and shape of the PCM container must correspond to the melting time of the PCM and the daily insulation at a given location, if the source of energy is a solar collector. PCMs are typically placed in long thin heat pipes [4]cylindrical containers [4] or rectangular containers [4]. Papers dealing with LHTES reveals that two geometries commonly employed as PCM containers are the rectangular and cylindrical containers. The most intensely analyzed LHTES unit is the shell and tube system. This is probably due to the fact that most engineering systems employ cylindrical pipes and also heat loss from the shell and tube system is minimal.



(a) Pipe model (b) Cylindrical model (c) shell or tube type model (d) rectangular type model

Fig 1: Classification of commonly used PCM containers in terms of the geometry and configuration

3.1. CONFIGURATIONS OF CYLINDRICAL PCM CONTAINERS

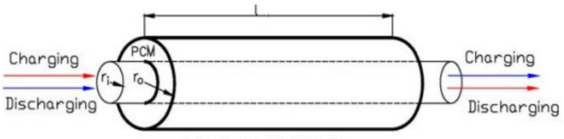
Three modes of cylindrical PCM container configurations are distinguished. The first is where the PCM fills the shell and the heat transfer fluid flows through a single tube (Fig. 1 a) designated the pipe model. In the second model the PCM fills the tube and the HTF flows parallel to the tube (Fig. 1b)

According to Esenet al. [8], who studied the two models theoretically by comparing the effects of various thermal and geometric parameters; cylinder radii, total PCM volume, mass flow rates and inlet temperatures of HTF on the storage time recommended the pipe model because it recorded a shorter melt time. This was because the thicker the PCM mass, the longer the melt time of the PCM. An added advantage for the pipe model not mentioned is the fact that the pipe model has a lower heat loss rate to the environment because most heat supplied from the center ends up heating the PCM. The third cylinder model is the shell and tube system commonly used to improve heat transfer in PCMs.

Agyenim et al. [4]conducted an experimental energy storage system to compare horizontal shell and tube heat exchanger (4 tubes) and a pipe model incorporating a medium temperature phase change material (erythritol) with a melting point of 117.7 8C. The thermal characteristics in the systems were analyzed using isothermal contour plots and temperature time curves. Temperature gradients along the three directions of the two systems; axial, radial and angular directions were also analyzed and compared. Heat transfer in the shell and tube system was found to be dominated by the effect of multiple convective heat transfer compared to conductive heat transfer in the pipe model. The temperature gradients recorded in the axial direction for both the pipe and shell and tube systems during the change of phase were reported to be 2.5% and 3.5% that of the radial direction respectively, indicating essentially a two-dimensional heat transfer in both systems. The onset of natural convection through the formation of multiple convective cells in the shell and tube system significantly altered the shape of the solid liquid interface fluid flow and indicated complete melt time within 5 h compared to more than 8 h for the pipe model. The authors recommended the shell and tube system for the charging of PCMs.

3.2. Counter-Current and Parallel HTF flow Directions

In a cylindrical container assembly, two possibilities exist for the flow direction of the heat transfer fluid during charging and discharging of the PCM energy. The two modes are either the hot and cold fluids are introduced into the tube from the same end (parallel flow) or the hot and cold fluids are introduced from the opposite ends (counter-current flow) of the heat transfer tube during charging and discharging respectively. Fig. 2 illustrates the schematic diagram of the parallel and counter-current flow principles. For each pair, the upper arrow represents the direction of HTF flow during charging and the lower arrow represents discharge direction of the HTF. Results from the numerical simulations conducted by Gong and Mujumdar[1] to investigate the effect of the parallel and counter-current flow modes using a mixture of 80.5% LiF and 19.5% CaF2 as a PCM and He/Xe mixture as a HTF showed that parallel flow increases the energy charge/discharge rate by 5% more than counter-current flow. This was because the penetration depth of the solid–liquid phase change interface during the charge/ discharge was larger due to higher temperature difference at the fluid inlet if hot and cold fluids enter from the same end. In addition, super cooling of the PCM did not occur in the fluid inlet region and heat transfer between the heat transfer fluid and the PCM did not deteriorate. On the other hand, counter-current flow for the charge/discharge processes produced significant super-cooling of the PCM in the inlet region of the cold fluid.



(a) Parallel HTF flow

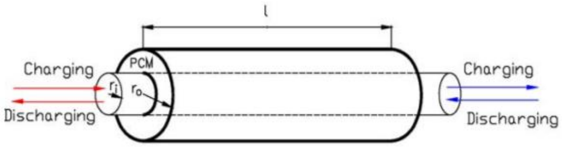


Fig 2: The physical model illustrating parallel and counter-current HTF flow in a shell and tube system.

3.3. Investigating parameters in PCM containers

Apart from the container geometry and configuration, various thermal and geometric parameters are known to affect the thermal performance of LHTES. The references to some of the operating parameters investigated and their key findings. Key findings from numerical predictions, tested against experimental data for various operating parameters have shown that, in order to optimize the performance of a PCM storage unit, the thermal and geometric parameters must be carefully selected.

Literature reviewed has shown a superior performance using the shell and tube configuration followed by the pipe model with the PCM at the shell side and the heat transfer fluid flowing through the center. It has therefore been recommended by many authors [5].

4. Heat transfer in PCMs and enhancement techniques

Most PCMs have unacceptably low thermal conductivity, leading to slow charging and discharging rates, hence heat transfer enhancement techniques are required for most LHTES applications. Several studies have been conducted to study heat transfer enhancement techniques in phase change materials (PCMs) and include finned tubes of different configurations, bubble agitation, insertion of a metal matrix into the PCM, using PCM dispersed with high conductivity particles , micro-encapsulation of the PCM [1] or shell and tube (multitubes). Majority of the heat enhancement techniques have been based on the application of fins embedded in the phase change material. This is probably due to the simplicity, ease in fabrication and low cost of construction. This is followed by the impregnation of metal matrix into the PCM using high conductivity materials such as carbon fiber and brushes and multitubes. The general observations drawn from the various studies demonstrate that, irrespective of the PCM used, the heat transfer characteristics of the PCMs can be improved using all of different enhancement techniques.

Choi and Kim, Horbaniuc et al. , Velrajet al. and Hamadaet al. , employed different experimental setups, different container materials, and different PCMs to investigate the heat transfer enhancement characteristics of PCMs.

In terms of performances of heat transfer enhancement techniques and systems used by Choi and Kim Horbaniucet al. ,Velraj et al. and Hamada et al. ,the best enhancement technique as reported in the literature was that due toVelraj et al. where the effective thermal conductivity calculated employing paraffin with lessing rings was ten times (2 W m1 K1) greater than the thermal conductivity of paraffin (0.2 W m1 K1). This must be qualified by the fact that different researchers employed different experimental setups, different container materials, and different PCMs to investigate the heat transfer enhancement characteristics. For example during the charging and discharging stages of the experiment, the heat transfer fluid in the experiment from Horbaniuc et al. passed over just a fraction of the whole setup rendering heat addition and removal inefficient. Results derived from any such setup cannot be considered to be optimal.

Different researchers used different parameters to assess the heat transfer enhancement in the PCMs. Velraj et al. evaluated the enhancement of the heat transfer using the effective thermal conductivity taken from a two-dimensional enthalpy-temperature governing equation which assumed no variation of temperature and thermal conductivity in the axial direction. Results were presented graphically using temperature–time curve and as such limits the application tending to other applications. Horbaniucet al. [1] measured performances of fins in terms of the interface freezing stage and the time taken for complete solidification to be achieved using parabolic and exponential approximations.

Hamada et al. used the effective thermal conductivity proposed byFukai et al. to assess and compare results with the control system with no heat transfer enhancement.

In the case of ChoiandKim, the key parameters used to assess the heat transfer enhancement of the circular finned system were the ratio of overall heat transfer coefficient in the finned and the unfinned tube systems. They reported a ratio of 3.5 for a surface area ratio of 3.2 between the finned and the unfinned tube systems. A comparison was also made by deriving a relationship for the ratio of the total amounts of heat recovered in the finned and unfinned tube systems correlated with dimensionless parameters of Fourier, Stefan and Reynolds with a correlation coefficient of 0.994 and a standard deviation of 0.023 and 0.028, respectively. The above discussion illustrate the fact that there is no unified international or national standard methods (such as British Standards or EU standards) developed to test PCMs, making it difficult for comparison to be made to assess the suitability of PCMs to particular applications. A standard platform such as British Standards, EU standards needs to be developed to ensure same or similar procedure and analysis (performance curves) to allow comparison and knowledge gained from one test to be applied to another. Also contradictions exist in the thermo physical properties of PCMs provided especially the latent heat of fusion, thermal conductivity and densities in solid and liquid states. This is again due to the absence of unified certification standards and procedures.

5. Characterizing the effect of melting and solidification rates in PCMs

To design PCM systems requires a good understanding of the fundamental heat transfer processes involved in accurately predicting the thermal performance of the PCM system. Based on both experimental and numerical investigations conducted to examine the thermal characteristics of LHTES systems, various correlations have been developed relating thermal performance and dimensionless numbers in given parametric domains. Dimensionless numbers are widely applied in modeling the PCM systems in order that the knowledge gained from one study can be extended beyond its source of acquisition. Among the thermal performance parameters for which correlations have been developed are melted volume fraction, temperature profile, melt time and melting rate. In spite of the significant literature available in quantifying melting and solidification rates, there has been no attempt to correlate available data. The two main reasons for this are:

1. Individual authors used different phase change materials with different heat transfer characteristics. In the case where the same PCM has been used, the researchers employed different dimensionless parameter ranges and presentations making it difficult to cross-correlate between the characteristics influencing the heat transfer in specific PCMs.
2. Some researchers presented results without using dimensionless parameters making it impossible to extend the knowledge to applications beyond the original source.

For example the empirical correlation for the melted volume fraction from Wang et al. ,for example predicted the experimental data with an average error of 9.3% and the deviation was attributed to the sensible heating that takes place at the very early times due to the presence of subcooling within the PCM. In the case of the time averaged Nusselt number, the correlation was found to fit the individual experimental data with an average error of 8.8%. The dependency of the melted volume fraction on Fo and Ste but minimal for Ra was that, the dimensionless groups Fo and Ste were the important factors to consider in the phase change process.

CONCLUSION

The experimental results show the feasibility of using PCM as storage media in heat recovery systems. Latent heat storage (LHS) system with PCM can be successfully used for recovery and reuse of waste heat.

REFRENCES

[1] Beasly, D.E. & Ramanarayanan, C. (1989). Thermal response of a packed bed of spheres containing a phase change material. Int. J. Energy Research, 13, 253-265.

[2] Buddhi, D., Bansal, K., Sawhney, R.L. & Sodha, M.S. (1988). Solar thermal storage systems using phase change materials. Int. J. Energy Research, 12, 547-555.

[3] Ettouney, H., El-Dessouky, H. & Amani Al-Ali. (2005). Heat transfer during phase change of paraffin wax stored in spherical shells. ASME Journal of Solar Energy Engg., 127, 357-365.

[4] X. Py, R. Olives, S. Mauran, Paraffin/porous-graphite-matrix composite as a high and constant power thermal storage material, Int. J. Heat Mass Transfer 44 (2001) 2727–2737.

[5] Farid MM, Mohamed AK. Effect of Natural convection on the process of melting and solidification of paraffin wax. Chem Eng Commun 1987; 57:297–316.

[6] Ismail, K.A.R. and Alves, C. L. F., 1986, "Analysis of shelland-tube PCM storage system", Prec.8thInt.Heat Transfer Conf., SanFrancisco, 1781-1786.

[7] Sari A, Karaipekli A. Thermal conductivity and latent heat thermal energy storage characteristics of paraffin/expanded graphite composite as phase change material. Appl Therm Eng 007; 27:1271–7.

[8] Velraj R, Seeniraj RV, Hafner B, Faber C, Schwarzer K. Experimental analysis and numerical modeling of inward solidification on a finned vertical tube fora latent heat storage unit. Sol Energy 1997; 60:281–90.

[9] Ettouney H, Alatiqi I, Al-Sahali M, Al-Hajirie K. Heat transfer enhancement in energy storage in spherical capsules filled with paraffin wax and beads. Energy Convers Manage 2006; 47:211–28.

[10] Farid MM, Mohamed AK. Effect of Natural convection on the process of melting and solidification of paraffin wax. Chem Eng Commun 1987; 57:297–316