INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI
SHORT ABSTRACT OF THESIS

Name of the Student	:	**GURPREET SINGH SODHI**
Roll Number	:	**156103007**
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Thesis Title: **Design, Development and Performance Investigations of High-Temperature Latent Heat Storage Systems**

Name of Thesis Supervisor(s)	:	**Prof P Muthukumar**
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SHORT ABSTRACT

The demand and supply of energy go hand in hand, however, major consequences of the increasing energy demands are the depletion of fossil fuel reserves and their impact on the environment. In the current scenario, the energy sector is plausibly dependent upon natural resources for minimizing the instability in the market. Among all the renewable energy resources, solar energy is one of the most prominent sources due to its ample availability and use in numerous applications such as thermal comfort in buildings, solar water heating, solar cooking, solar drying and power generation.

Due to the intermittent nature of solar energy, it cannot meet a continuous supply and storage of energy becomes essential. Thermal energy storage (TES) acts as a temporary reservoir to store energy and assist the operation of the application system during peak demand. This enables stable grid performance added with a decreased reliance on non-renewable energy resources. Concentrated solar power (CSP) technology integrated with TES is a promising solution to develop a stand-alone renewable power generation system. Thermal energy can be stored by various methods; Sensible, Latent and Thermochemical storage. Among all, latent heat storage (LHS) is the most customary storage technique due to its relatively high energy density and a

wide range of operating temperatures. LHS systems use phase change materials (PCMs) which absorb the energy due to phase change for energy storage. The isothermal behaviour of phase change leads to a stable power output delivered by the PCMs. Since the thermal conductivity of most PCMs is generally low (0.1-1 W m^{-1} K^{-1}), most of the research works have focused on improving the thermal performance of LHS systems.

The present research work explores the high-temperature LHS systems keeping in mind their integration to applications such as CSP and direct steam generation (DSG). The design, development and performance investigations of high-temperature LHS systems have been scarcely reported in the literature. The thesis work focusses on two major objectives;

(i) Thermal modelling, design, development and testing of high-temperature shell and multi-tube and fin and non-finned encapsulated PCM LHS systems.

(ii) Development of novel LHS system designs to improve the heat transfer rate in conventional high-temperature LHS systems.

To conduct the performance investigations of high-temperature LHS systems, we have designed and developed an experimental test facility at the Indian Institute of Technology Guwahati. The system uses air as the heat transfer fluid (HTF) suitable for maximum operating temperatures and flow rates of 450 ºC and 120 m^3/h, respectively. Sodium nitrate with a melting temperature of 305 ºC is chosen as the PCM. To study the charging and discharging heat transfer behaviour of the LHS system, experimentally validated 2-dimensional (2D), 2D axi-symmetric and 3D numerical models were developed for different geometries using the commercial modelling software COMSOL Multiphysics.

To develop a shell and multi-tube LHS system (storage capacity: ~20 MJ), a 2-dimensional (2D) numerical model was developed to study the heat transfer characteristics of a multi-tube heat exchanger. Three LHS configurations with 13 (1-inch), 17 (3/4-inch) and 25 (1/2-inch) HTF tubes were modelled by fixing the PCM quantity and the HTF tube surface area. The natural convection was neglected for the discharging model. It was found that by increasing the HTF tubes from 13 to 25, the charging and discharging times were reduced by 20% and 48%, respectively. Based on the modelling study, a multi-tube LHS module with 25 HTF tubes was fabricated and experimental investigations were conducted to study the axial/radial temperature distributions, and performance parameters such as charging/discharging time, energy stored/discharged and output power by varying the flow rate and inlet temperature of the air.

To test the performance of high-temperature cylindrical PCM encapsulations (storage capacity: ~0.6 MJ), five different designs were fabricated namely; basic capsule (Case 1), annular capsule (Case 2), annular capsule with straight longitudinal fins (Case 3), annular capsule with tapered longitudinal fins having a decreasing height (Case 4), and annular capsule with tapered longitudinal fins having an increasing height (Case 5). Experimental and numerical investigations were carried out to compare the charging and discharging performances of basic and annular capsules (capsule with hole). The results show that adding a hole in the basic capsule leads to better surface contact due to an increase in the heat transfer area and improves the flow dynamics of the incoming air. Further, experimental investigations were conducted to estimate the charging and discharging performances of all the Cases 1-5 by varying the air inlet flow rate and temperature during charging and discharging.

To improve the charging and discharging heat transfer rates in conventional shell and tube LHS systems, two heat transfer enhancement techniques with simple design modifications such as effective PCM and fin distribution along the length of conventional shell and tube LHS are proposed.

In the first enhancement technique, the design of the LHS system is modified from a cylindrical shell to a conical shell LHS system. A numerical model of the 3D geometry was developed to analyze the charging and discharging characteristics of both designs. The system comprises of single HTF tube system with Sodium Nitrate as the PCM in the shell side and air as the HTF. The shell dimensions were varied by changing the cone angle and fixing the total PCM volume (or fixed LHS capacity). The conical shell system with a cone angle of 3.4° was found to reduce the charging/discharging times by 17%/28% than the conventional cylindrical shell system. The improvements in the heat transfer rates occur due to the uniform melting and solidification along the system length due to the effective distribution of PCM. Further, the effect of adding straight or tapered fins attached to the HTF tube on the performance of the conical shell system was also analyzed.

In the second enhancement technique, a 2D axi-symmetric numerical model of a vertical shell and tube LHS system comprising of three blocks of PCMs having melting point temperatures (T_m) 360 °C, 335.8 °C and 305.4 °C, respectively, is developed. A non-uniform distribution of fins in three PCM blocks is initially employed to study the performance of the single PCM system ($T_m =$335.8 °C). The effect of inlet HTF temperature on the charging and discharging performances of the single PCM and multiple PCM (m-PCM) systems were analyzed by varying a Stefan number (Ste_{ref}) parameter, calculated based on the single PCM system. The charging and discharging times for the m-PCM system are either similar or lesser than the single PCM system for $Ste_{ref} \geq 1$, however, there is an improvement of 21-25% in the specific energy charged and discharged by the m-PCM system for all the Ste_{ref} values (0.5, 1, 1.5 and 2) considered. By employing a compound enhancement technique, which is a combination of non-uniform fin-distribution and PCM blocks length ratio optimization for the m-PCM system, 30% and 9% reduction in the charging and discharging time, respectively, over the single PCM system is achieved.

The present thesis work highlights the performance of high-temperature LHS systems. The developed LHS systems can be integrated to high-temperature applications such as CSP and DSG. The important parameters affecting the performance of the LHS system are studied based on experimental and numerical investigations. The research works on high-temperature LHS systems are presently limited and the research output from the present investigations will serve as a benchmark for the development of high-temperature TES devices in the future. The different heat transfer enhancement techniques proposed in the thesis work are simple and can be effectively employed to improve the performances of high-temperature LHS systems.