**INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI**
**SHORT ABSTRACT OF THESIS**

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**SHORT ABSTRACT**

Energy plays a major role for the existence of humanity. For a quite long period, much of the energy needs of the humankind are fulfilled from the non-renewable energy sources such as coal, oil and natural gas. The gruesome point of usage of non-renewable energy sources in the power generation, heating and cooling, and transportation sector is the greenhouse gas emissions, which has several adverse effects like climate change, global warming, ozone depletion, sea level rise, etc. Hence, several countries ramped their investments on renewable energy based technologies to combat these harmful environmental outcomes.

Concentrated solar power (CSP) is one of the promising large-scale power generation technologies among the renewables, which is being widely commercialized now. The major problem that all solar power plants face is the intermittent solar radiation that can be solved by adding storage. Of all the storage options, thermal energy storage (TES) is the most economical, which gives an advantage to CSP plants over solar PV plants since TES can be integrated with CSP to ensure power 24/7. The TES systems are broadly classified into sensible heat storage, latent heat storage (LHS) and thermochemical heat storage. LHS systems using phase change materials (PCMs) are highly attractive due to their high volumetric heat storage capacity, compactness, moderate cost, near constant temperature heat storage/retrieval and adaptability over wider temperature ranges.

In general, LHS system consists of a regenerator type heat exchanger wherein the heat transfer fluid (HTF) is passed through the storage media for charging and discharging processes. During charging, the high-temperature HTF transfers the heat to the storage medium. The stored energy is released during discharging as the low-temperature HTF passes through it. Design and optimization of LHS prototypes require exhaustive analysis on heat transfer characteristics between the PCM and HTF. The number of HTF tubes and fins on the HTF tube's outer surface play a major role in transferring the heat between them. Un-optimized prototype with more number of HTF tubes and fins

would lead to higher material inventory. Additionally, the overall weight of the system will increase too. Hence, a detailed optimization study is needed to have a cost-effective LHS system.

The main objectives of the present work are (i) to study the charging and discharging characteristics of a LHS prototype by considering the natural convection effect, (ii) to develop a 2D mathematical model for optimizing the number of tubes and fins in the shell-and-tube type lab-scale LHS prototype, (iii) to develop a 3D thermal model for predicting the charging and discharging characteristics of the LHS prototype with the optimized number of tubes and fins at different operating conditions and (iv) to test the storage performances of the LHS prototype at various operating conditions.

A numerical study of conjugate heat transfer and phase change process in a shell-and-tube type prototype of 10 MJ LHS capacity filled with a PCM is presented. The PCM used in the present study is a ternary mixture of potassium nitrate, sodium nitrate and sodium nitrite in the weight proportion of 53:7:40. Effective heat capacity method is used in the model to integrate the latent heat of the PCM with the specific heat and Boussinesq approximation is applied to incorporate the buoyancy effect of the molten layer of the PCM. For proper modeling of velocities in the PCM, Darcy law's source term is added. The governing equations involved in the model are solved using a finite element based software product, COMSOL Multiphysics 4.3a. To optimize the number of HTF tubes and number fins on the tubes, a 2D thermal model is developed and the performance is compared by varying the number of HTF tubes (19, 22, 25, 28) and number fins on the tubes (0, 2, 4, 6). Thermal model with 25 tubes and 4 fins is found to be the optimized configuration.

Based on the results of optimization study, a lab-scale shell-and-tube based LHS prototype of 10 MJ LHS capacity is fabricated and the computational study is extended to a 3D thermal model for evaluating the performance of the prototype. Charging and discharging characteristics are investigated at different HTF inlet temperatures (157 / 162 / 167 °C during charging and 117 / 122 / 127 °C during discharging) and flow rates (0.3, 0.45, 0.6 $m^3$/hr). It is observed that the charging/discharging rate is faster for higher/lower HTF inlet temperature. Similarly, the charging/discharging rate is faster for higher HTF flow rates. The numerical and experimental results are found to have a good agreement.

It is observed that the charging process is faster than the discharging process due to the additional natural convection, which takes place after the phase change temperature. For an HTF inlet temperature of 162 / 122 °C during charging/discharging and HTF flow rate of 0.3 $m^3$/hr, it took about 124 / 131 min for charging/discharging of the LHS prototype in the experiments. Similarly, it took about 111 / 117 min for charging/discharging of the LHS prototype in the numerical simulations. It is also seen that partial charging/discharging process is efficient than complete charging/discharging process. It took only 73 / 70 % of the complete charging/discharging time for 90 % of heat storage/discharge. In addition, it is found that varying HTF inlet temperature has a greater effect on charging/discharging time when compared with HTF flow rate. Still, the effect of HTF flow rate is more prominent at lower/higher HTF inlet temperature during charging/discharging process.

Based on the above discussions, one can conclude that the shell-and-tube based LHS prototype with multiple tubes and fins can be effectively used for storing the heat. Further, the results presented in this thesis will be useful for developing the commercial LHS devices for industrial applications. Using the developed thermal model, one can predict the performances of shell-and-tube based LHS prototype with fins filled with different PCMs without performing the expensive experimental studies.

In addition to the major objectives of the thesis, two novel concepts namely novel encapsulation and novel fin are proposed in this thesis. The numerical model used for the performance evaluation of the LHS prototype is slightly modified to study the storage characteristics of the novel concepts.

The concept of novel encapsulation technique is intended to achieve better heat transfer in LHS capsules, which has a wide application in steam accumulators. A comparison of the heat transfer characteristics of the basic and novel capsules is done using the numerical model. It is found from the numerical study that it took about 64 / 33 min and 158 / 57 min for the basic/novel capsules for complete charging/discharging. The reduction in the charging/discharging time achieved by the novel capsule when compared with the basic capsule is about 48.4 / 63.9 %. Effect of operating temperature range is also studied and it is observed that the novel capsule with the least temperature difference (20 °C) itself charges/discharges faster than the basic capsule with a higher temperature difference (30 / 40 °C). The scope for commercial viability of the novel concept is also explored and the results showed a positive step towards the commercialization of the novel concept. While upscaling, the reduction in the charging and discharging time achieved by the novel capsule (1 MJ capacity) when compared with the basic capsule (0.5 MJ capacity) are 4.7 % and 19 %. Different arrangements of novel and basic capsules in circular and rectangular forms are studied for less volume occupancy and it is found that the novel capsules arranged in the rectangular fashion occupies the least volume. In addition, a mass reduction of approximately 21.4 % can be achieved with the novel capsule when compared with the basic capsule in the current study.

The concept of novel fin is envisioned to accomplish an efficient heat transfer in tube-in-tube LHS modules. A comparison of the storage characteristics of the novel fin configuration with no fin and standard fin configurations is made using the numerical model. It is found from the numerical study that it takes about 548 / 788 min, 514 / 742 min and 487 / 665 min for complete charging/discharging of the LHS module with no fin, standard fin and novel fin. It can be noted that the charging/discharging time has decreased by about 11.1 / 15.6 % and 5.25 /10.4 % when using novel fin configuration with respect to no fin and standard fin configurations. The novel fin proposed has also an additional advantage of weight and cost reduction of fins by a factor of 0.5.