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Title of the Thesis: Investigation on Versatile Cascade Latent Heat Storage System for Solar Cooking Applications

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Abstract: Food is vital for human existence, supplying energy and nutrients for daily activities and overall health. A significant proportion of the global population relies on polluting fuels (firewood, animal dung, and agriculture waste) for daily cooking energy needs, which causes household air pollution. Adoption of clean cooking fuels (Liquified petroleum gas, natural gas, biogas, electricity, and solar) is necessary to prevent health hazards (respiratory and cardiovascular diseases) due to household air pollution. Moreover, the depletion of fossil fuel reserves and geopolitical instabilities are significantly increasing the cost of cooking fuels in developing countries. Utilization of solar energy (clean energy) for daily cooking applications can address these challenges appropriately. Solar energy can be utilized for cooking in the form of heat (from solar thermal collectors) or in the form of electricity (from solar photo-voltaic collectors). Although solar energy is abundantly present on Earth, its intermittency (diurnal and seasonal) and nocturnal unavailability create a considerable hindrance in its adoption for cooking applications. Furthermore, operational challenges, restrictions on food types, and the inability to prepare any kind of meal at any time of the day, regardless of weather conditions, pose significant technological barriers to the widespread adoption of existing community-scale indoor solar cooking systems. The integration of a suitable energy storage system, along with design modifications in existing cooking systems, is essential to increase the acceptability of solar cooking systems among people. Storing solar energy in thermal energy storage is more feasible than storing it in an electrochemical battery in terms of efficiency, operational simplicity, life cycle, economics, and ecological footprints. Therefore, collecting solar energy using solar thermal collectors and storing it in a thermal energy storage system for off-sun cooking applications is a viable option.

Latent heat storage technology excels among other technologies, such as sensible and thermochemical energy storage, owing to its high energy density, operational simplicity, environmental feasibility, easy availability, and cost-effectiveness. Latent heat storage stores thermal energy as phase transition enthalpy of phase change materials. The poor thermal conductivity of phase change materials significantly affects the thermal performance of the latent heat storage systems. This highlights the need to incorporate heat transfer augmentation techniques during their integration in any application.

The necessity of the present work originates from the paucity of studies exploring the possibility of developing a latent heat storage technology for supporting multi-temperature-based indoor solar cooking applications. Various food items require different temperatures during cooking, i.e., baking, frying, and boiling, which require an end-use temperature of 453-493 K, 383-443 K, and 373-393 K, respectively. The foundation of the design of the latent heat storage system is laid on a few requisites, i.e., storage should be compact, cost-effective,

efficient, should have a faster charging rate (it is necessary while coupling the storage with solar thermal collectors due to diurnal variation of solar radiation), should require less maintenance, and can maintain a stable supply of thermal energy at different temperatures. The research is initiated with the comparative assessment of single and multiple-phase change material-based storage systems using the enthalpy porosity technique-based numerical approach. It has been observed that in comparison to single-phase change material-based storage using NaNO3 and NaNO2, a two-stage cascade latent heat storage system incorporating both phase change materials reduces the charging time by 35.23% and 10.52%, respectively. The cascade latent heat storage system maintains an augmented heat transfer rate between the heat transfer fluid and phase change materials during charging. It can also facilitate end-use applications at different temperatures.

Furthermore, numerical investigations are performed to find the simple, passive, economical, low-cost heat transfer augmentation methods for the cascade latent heat storage systems that are feasible for their commercial implementation. In this context, the effect of modification of the shell, change of orientation of the storage, and eccentric repositioning of the heat transfer fluid passage on the thermal behavior of the shell and tube-based latent heat storage system are investigated. Changing the cylindrical shell to frustum in the latent heat storage system reduces the charging time by 18.42%. However, it adversely impacts the charging performance of the cascade latent heat storage system. The horizontal cylindrical cascade storage completes the charging in 39.04%, 15.78%, 24.70%, and 5.9%, respectively, less charging time than the other storage configurations, i.e., single-stage NaNO3 storage, single-stage NaNO2 storage, vertical frustum cascade storage, and vertical cylindrical cascade storage.

Based on the design guidelines that originated from numerical investigations, a state-of-the-art versatile cascade latent heat storage system is developed. Furthermore, three innovatively designed cooking units, i.e., cooking plate, frying pan, and cooking vessel, are developed for baking, frying, and boiling-related cooking operations and integrated with the developed storage. This work thoroughly discusses the real-time cyclic (charging and discharging) thermal behavior of cascade storage, along with its capabilities to support different temperature-based end-use applications. The developed cascade latent heat storage system maintains the stable end-use temperature of 473 K, 452 K, and 373 K, respectively, at the cooking plate, frying pan, and cooking vessel for baking, frying, and boiling food products. Cooking time for baking a chapati (60 g), frying potato chips (80 g), and boiling potatoes (500 g) is observed as 4 minutes, 4 minutes, and 13 minutes, respectively. The cyclic and end-use efficiency of the cascade storage are obtained as 55.82% and 38.24%, respectively. The recommendations of the present research work will pave the way for the commercial establishment of cascade latent heat storage technology for multi-temperature-based solar thermal and industrial applications.