Abstract

The continued rise in global energy demand, together with the need to limit greenhouse gas emissions, has increased interest in efficient renewable energy systems and reliable energy storage solutions. This trend calls for improvements in the efficiency and reliability of technologies based on renewable resources. In this context, concentrating solar power is particularly attractive, as it enables the production of high-temperature thermal energy. However, due to the intermittent nature of solar energy, thermal energy storage systems are essential to improve reliability and dispatchability. Among these, latent heat thermal energy storage systems are gaining attention due to their high energy density. Despite this potential, their widespread deployment remains limited by the very low thermal conductivity of phase-change materials, which results in slow charging and discharging rates.

This dissertation explores two approaches to improve heat transfer in concentrating solar power receivers and latent heat thermal energy storage systems. The first part focuses on the use of topology optimization to redesign the internal conductive structure of a compact latent heat thermal energy storage unit. The objective is to accelerate the phase-change process during discharge and achieve a more uniform temperature distribution without increasing the amount of highly conductive material. A density-based formulation is adopted, using the method of moving asymptotes together with adjoint sensitivity analysis to guide the optimization. The resulting design shows a measurable improvement in performance, reducing the time required to solidify 90% of the phase-change material (paraffin wax) by 12.3% compared to a well-performing reference case, while also promoting a more uniform temperature distribution.

The second part of the work examines the use of lattices based on triply periodic minimal surfaces to enhance heat transfer in concentrating solar power receivers. Four geometries—Diamond, Gyroid, SplitP, and Lidinoid—are analyzed numer-

ically in a tubular parabolic trough configuration under representative operating conditions. In addition to standard thermal metrics, entropy generation is used to assess thermodynamic performance. Based on these results, two designs—Diamond and SplitP—are selected for further experimental investigation using additively manufactured planar receiver mock-ups tested in a high-flux solar simulator. The findings indicate that structures based on triply periodic minimal surfaces can improve heat removal while keeping pressure losses at acceptable levels. In particular, the SplitP and Lidinoid geometries show a favorable balance, with lower entropy generation, reduced peak temperatures, and thermal efficiencies above 70%. These two mock-ups are further examined through numerical simulations to gain deeper insight into the temperature distribution on the heated surface and to identify which Reynolds-averaged Navier-Stokes turbulence models best predict their performance.

Overall, the results show that carefully designed internal geometries—whether obtained through topology optimization or implemented as lattices based on triply periodic minimal surfaces—can lead to tangible improvements in heat transfer. These findings contribute to the ongoing development of more efficient concentrating solar power receivers and latent heat thermal energy storage systems.