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Simultaneous Optical and Electrical Impedance-Based Monitoring Of the Liquid Fraction during Solidification inside a Vertical Enclosure

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Extended Abstract

Latent thermal energy storage (LTES) with phase change materials (PCMs) plays a critical role in the decarbonization of the cooling and heating sectors. The real-time monitoring of the liquid fraction during phase transitions—melting and solidification—offers essential insights into optimizing LTES design and facilitating the implementation of smart control strategies that maximize the utilization of renewable energy sources [1]. However, monitoring the liquid fraction during solid-liquid phase change poses a trade-off between accuracy and ease of implementation. Conventional methods for sensing thermal and flow variables, such as temperature, pressure, and flow rate, often exhibit limited precision in estimating the liquid fraction [2]. More advanced techniques, such as optical, X-ray, and ultrasonic imaging, can provide detailed information regarding the phase distribution but can be difficult to implement in real-world LTES [3], [4], [5]. Within this framework, electrical impedance-based sensing appears to be an accurate and easy-to-implement approach for liquid fraction measurement [6], [7], [8], [9].

The current study evaluates the feasibility of an electrical impedance-based sensor for liquid fraction measurement. The experimental study analyses the solidification of demineralized water inside vertical rectangular enclosure. A novel and specifically designed test section has been developed, incorporating Peltier cooling modules to regulate the temperature of the enclosure's side walls. Demineralized water is contained in a vertical enclosure with a width of 10 mm, a height of 100 mm and a depth of 100 mm. The complex impedance between two 90 mm x 90 mm square electrodes located on the side walls of the enclosure is measured with an LCR meter. Furthermore, the front and back walls of the test section are transparent, facilitating direct visualization of the phase distribution with a USB optical camera. For the solidification experiments, the water is allowed to reach thermal equilibrium at 10 °C. Then, the external temperature of the side walls suddenly changed to -12 °C. Optical images and electrical impedance measurements are continuously acquired until the solidification process is complete.

During solidification, a layer of ice starts forming on each of the side walls. The ice layers grow until they merge in the centre of the enclosure. The development of ice layers on the electrode surface results in a continuous increase in electrical impedance between the electrodes, attributable to the electrically insulating properties of ice as opposed to those of liquid water. An equivalent electrical circuit model is employed to estimate the temporal evolution of the liquid fraction based on electrical impedance measurements. Concurrently, image processing techniques are used to estimate the liquid fraction from the optical images, in which the solid-liquid interface is clearly distinguishable. Both measurement methodologies demonstrate a nearly linear decrease in liquid fraction over time, with the liquid fraction estimates from each technique showing excellent concordance, exhibiting a maximum deviation of approximately 0.08. Hence, electrical impedance-based sensing is found to be an accurate and nonintrusive approach to determine the liquid. The relative simplicity of impedance-based sensing as compared with direct optical visualization favours its implementation in real-world LTES.

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