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Carbon Dioxide Two-Phase Closed Thermosyphon for Ground Freezing Applications

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Abstract

Two-phase closed thermosyphons (TPCTs) are efficient heat transfer devices widely used in various applications, including artificial ground freezing, energy storage, and geothermal energy extraction. A TPCT is a gravity-assisted heat pipe and a natural circulation system, transferring heat from a heat source to a heat sink. TPCTs have recently gained notable attention due to their low maintenance costs and high effectiveness in transferring heat, even over small temperature differences. Despite the growing industrial-scale use of TPCTs, significant challenges remain in accurately modeling their detailed transient behavior and developing a comprehensive physics-based understanding. Continuous and cyclic boiling, evaporation, and condensation processes inside the closed pipe introduce uncertainties, particularly when operating conditions, installation depth, or working fluid properties change. Therefore, extensive mathematical modeling, laboratory experiments, and pilot studies examining design parameters, including both geometric and operational aspects, are necessary to enrich TPCT research. This study investigates the application of a TPCT filled with carbon dioxide as the working fluid, intended for passive cold energy storage in shallow ground regions in cold climates. A Multiphysics analysis of the TPCT, combining reduced-order analytical modeling, computational fluid dynamics (CFD) numerical modeling, and laboratory-scale experimental studies, is conducted in this research. Preliminary results indicate acceptable TPCT performance, and the analytical and numerical models have been successfully verified and validated against existing literature data. The experimental setup is currently in the commissioning phase, and it will be utilized to demonstrate and validate the mathematical frameworks and provide insights into the Multiphysics phenomena occurring inside the TPCT. Evaluation on the effect of hydrostatic pressure on boiling of the working fluid reveals that phase change phenomena are primarily confined to the first few centimeters (or meters, depending on the dimensions) of the liquid pool, while the remaining fluid mass is predominantly subjected to natural convection. As a result, in many studies where this effect is overlooked, particularly under high filling ratios, there is a notable tendency to overestimate the TPCT's performance in heat extraction due to the assumed lower thermal resistance in the evaporator. This overestimation is associated with the substantial difference in heat transfer coefficients between boiling and natural convection. Furthermore, large uncertainties can arise from empirical correlations used to represent phase change heat transfer. The expected outcomes of this work are to validate empirical convective heat transfer coefficients for boiling, evaporation, condensation, and the secondary refrigerant flow through a helical coil around the condenser.