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Multi-Scale CFD Modelling of a Fan-Chiller-Tube-Bank Cooling System for Microclimate Control in a Solar-Powered Greenhouse under Hot-Arid Conditions

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Abstract

Greenhouse production in hot-arid regions is constrained by the high energy and water demands of cooling, and by the limitations of the fan-and-pad evaporative system, which raises indoor humidity and produces uneven temperature distribution. This study presents a validated multi-scale computational fluid dynamics (CFD) model of a fan–chiller–tube-bank (FCTB) cooling system, in which air is cooled by sensible heat exchange with chilled water flowing over a dense array of plastic tubes, without adding moisture. A detailed tube-bank sub-model was solved in ANSYS Fluent using the standard k–ε turbulence model with conjugate heat transfer, and validated against field measurements; it reproduced the measured outlet air and water temperatures to within approximately 1°C. The validated outlet condition was then used as the inlet boundary for a full three-dimensional greenhouse model that incorporated solar heating via the Solar Load model. A mesh independence study confirmed convergence at 1.2 million cells, where the predicted outlet velocity changed by less than 1% relative to the finest mesh. The results show that the FCTB system maintains a nearly uniform air temperature of about 21°C in the cultivation zone, with a spatial variation of less than 2°C over the 6 m greenhouse length, while the polycarbonate cover reaches nearly 49°C under solar load. The air velocity in the occupied zone remains low (about 0.2 m s^{-1}), which is favourable for the crop. Psychrometric analysis confirms that the absolute humidity is almost unchanged between inlet and outlet (about 8.5 g of water per kg of dry air), demonstrating that the FCTB system delivers sensible cooling without humidification, a key advantage over the fan-and-pad system. The validated model provides a reliable basis for the optimisation and scale-up of low-humidity cooling for sustainable greenhouse production in hot-arid climates.

Keywords—computational fluid dynamics, greenhouse cooling, hot-arid climate, microclimate uniformity, Oman, sensible cooling, tube-bank heat exchanger, water use efficiency.