Heat and mass transfer in porous materials for passive energy-conversion devices

Abstract

In the contemporary transition scenario, optimizing the water-energy nexus is crucial to reducing the environmental impact of several essential energy-intensive applications. For example, state-of-the-art desalination plants require up to 750 MWh/day to operate, while traditional cooling and heating systems account for 10.5% of total energy used in the US. In addition, large-scale plants require significant investment and maintenance, which may not be affordable or feasible in some areas of the world. In stark contrast, passive devices based on water wicking and evaporation offer a sustainable alternative to several traditional technologies, ranging from cooling to water treatment. Taking advantage of material-driven transport mechanisms, they do not require high-grade energy inputs and their working principle does not rely on mechanical moving parts. These features make passive devices particularly cost-effective, robust, and optimal for off-grid installation.

In this context, this dissertation focuses on the design, analysis, and application of porous media in passive technologies, with the aim of demonstrating the feasibility of high-performance devices with a new and more sustainable approach. Starting from the development of a comprehensive theoretical framework to analyze their heat and mass transfer performance, the discussion advances to their experimental characterization and, finally, to their perspective application in laboratory-scale prototypes, developed from a proof-of-concept perspective. Following this line, this thesis focuses on three different applications.

First, a novel polyethylene fabric with engineered transport properties is proposed for personal thermal management. Theoretical models, solved both analytically and numerically, were used to relate the micro-structure and chemistry of the fabric surface to the resulting performance. Experimentally, the created fabric reported better thermoregulation capabilities than conventional commercial textiles, such as polyester and cotton, which were used as a reference throughout the characterization process. Thus, the use of the proposed material for garments promises to reduce the internal cooling demand during hot seasons and, at the same time, the properties of polyethylene allows reducing the environmental footprint of its production, use and disposal phases.

Successively, the issue of thermal management was addressed shifting from a single user application (namely, engineered textiles for personal thermal management) to a system-level approach (e.g., a cooling system for buildings); that is, by proposing a modular multistage device capable of generating a net cooling capacity driven solely by the salinity difference between two solutions. The concept was investigated both theoretically and experimentally: a 4-stage laboratory-scale device was fabricated and characterized; the results were used to validate a theoretical 0-D model, which was subsequently employed to optimize the device performance. The

tested device, despite being far from optimality, has demonstrated considerably better performance than other passive cooling approaches, proving the potential of this technology.

Both discussed applications exploit capillary transport to achieve the desired performance: comfortable fabrics are required to effectively wick and evaporate sweat, while the cooling device must self-supply distilled water to be considered entirely passive. Therefore, the final application proposed focuses on the structure itself of porous media, envisioning a novel class of textured, ultra-thin and rigid materials. The concept was tested on aluminum sheets, which were machined by femtosecond laser to obtain V-shaped grooves and, subsequently, covered with silica. The obtained material was able to exhibit stable capillary properties even when exposed to saline solutions for more than 250 hours. Therefore, it was envisaged for use in a passive device for solar desalination: an analytical model was used to investigate the productivity and optimal size of the device depending on the properties of the used capillary materials. By providing general guidelines for the design of passive device based on wicking and evaporation, this section aims to demonstrate the potential of using structured materials to improve the scalability and performance of passive technologies.

Concluding, by proposing novel materials, functioning principles and design layouts, this thesis seeks to create a bridge between fundamental research on heat and mass transfer phenomena and applied engineering challenges.