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Thermal performance of a polymer composite webbed-tube heat exchanger

Juan Cevallos, Avram Bar-Cohen, David C. Deisenroth *

University of Maryland, Department of Mechanical Engineering, College Park, MD 20740, United States

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ABSTRACT

This paper presents an in-depth study of the thermal performance of a gas-to-liquid "webbed tube" polymer heat exchanger. The heat exchanger was fabricated from a thermally enhanced polymer composite, consisting of a Nylon 12 matrix filled with carbon fibers. A laboratory-scale prototype heat exchanger was built using injection molding and tested on a cross-flow air-to-water heat exchange apparatus. The thermal performance of this laboratory webbed-tube polymer composite heat exchanger is studied in depth through an extended set of experiments, application of existing empirical correlations, and detailed computational fluid dynamic (CFD) simulations. The laboratory webbed-tube heat exchanger prototype provided a maximum UA value of 1.8 W/K and a volume-specific heat transfer coefficient of 14 kW/m^3 K. The experimental results, in conjunction with numerical simulations, were used to determine an "effective" thermal conductivity of 1.8 W/m K for the injection-molded Nylon-carbon composite material in the webbed-tube heat exchanger configuration.

1. Introduction

Polymer heat exchangers (PHXs) have received considerable attention since their invention more than 40 years ago due to their corrosion resistance, low weight, and low manufacturing cost. New polymer composites with higher strengths, thermal conductivities, and thermal stability promise to bridge the performance gap between polymers and corrosion resistant metals. This paper introduces a novel "webbed-tube" heat exchanger (WTHX) configuration and provides the first-reported empirical data for a laboratory prototype, polymer composite heat exchanger. This polymer heat exchanger design offers reduced mass, compared to more classical designs, while taking advantage of the process-induced anisotropy to yield favorable heat transfer characteristics. A numerical exploration of the process-induced anisotropy of carbon fiber reinforced polymer composite is used to set the expected bounds on the wall thermal conductivity. The thermal performance of this laboratory "webbed-tube" polymer composite heat exchanger is studied in depth through an extended set of experiments, application of existing empirical correlations, and detailed computational fluid dynamic (CFD) simulations.

Polymer heat exchangers (PHXs) were introduced first by DuPont in 1965 [1]. These heat exchangers consisted of bundles of many flexible, thin, small-diameter polytetrafluoroethylene (PTFE) tubes that were joined at their ends to form a honeycomb structure that could be used in shell-and-tube and immersion heat exchanger configurations. These early designs were adopted for specific industrial applications, such as pickling in steel manufacturing, heating of agitated reactor vessels and heating/cooling of distilled water. The wide availability and versatility of polymers has since driven the interest of the research community toward the use of these materials in a broad range of heat exchanger applications [2–4].

When corrosive fluids are present in the heat exchange process, polymers are an increasingly popular material choice as an alternative to exotic metals and graphite [5], especially when strong acidic solutions are present [6]. In addition, due to their low surface energy and smooth surface, fouling deposits have a lower propensity to adhere to polymers, which reduces the fouling thermal resistance. In seawater heat exchangers, fouling is generally a costly problem due to the many modes of fouling that occur in seawater: corrosion, biological, crystallization and particulate [7]. Therefore, the material properties of polymers make them good candidates to replace costly exotic metals, such as copper-nickel alloys and titanium in this important future application.

Several reviews of the latest advancements in PHX technology have been published. Zaheed and Jachuck [8] reviewed the use of polymers in compact heat exchangers, paying special attention to designs made of high temperature polyetheretherketone (PEEK) with 100-μm-films fabricated with corrugations to enhance

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* Corresponding author.

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boundary layer mixing. A review by T'Joen et al. [9], aimed to assess the merits of PHXs for heating, ventilation, air-conditioning and refrigeration applications. Notable heat exchanger applications are reviewed in detail, and special attention is paid to polymer matrix composites, which can offer vast improvements in thermal conductivity. Most notably, fiber-filled composites show the most promising results because of their availability as injection molding resins. Composites with thermal conductivities up to two orders of magnitude higher than unreinforced polymers have been made possible by the use of pitch-based carbon fibers, which offer fiber thermal conductivities of approximately 800 W/m K, which are intermediate to PAN-based fibers at approximately 160 W/m K and CVD fibers at 1950 W/m K. Effective utilization of carbon nanotubes, with reported conductivities of 2000–6600 W/m K, could further enhance the thermal properties of polymer composites [10]. It is noteworthy that with improved fiber conductivity, polymer composites approach the thermal properties of common corrosion resistant metals (e.g. titanium and stainless steel) and thus, can be considered as replacements for metals in applications where seawater is used as a direct coolant for industrial processes.

2. Webbed-tube heat exchanger

A webbed-tube heat exchanger consists of a stack of thin rectangular plates that are separated from each other in the thickness direction to allow one of the fluids (Fluid 1) to flow between the plates. Embedded in the plates is an array of tubular channels that can span the length of the plate. This tubular array serves as the passage for the second fluid (Fluid 2). In practice, the diameter of the tubes can be substantially larger than the thickness of the plate itself, effectively creating a "bumpy" plate or webbed-tube array, as shown in Fig. 1. The effects of these bumps on the flow field and thermal transport will be discussed in later sections of this paper.

When Fluid 1 and Fluid 2 flow parallel to each other, the heat exchanger can operate in the co-current (same direction) or countercurrent (opposite direction) mode. When the flows are perpendicular, the heat exchanger is in a cross-flow configuration. Contiguous tube plates can be fully aligned or displaced in the lateral direction, relative to each other, to create staggered arrays of tubes (see Fig. 2).

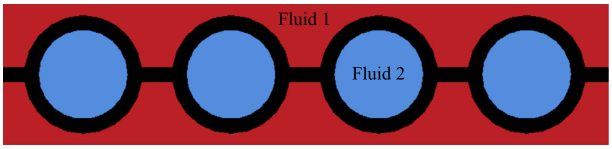


Fig. 1. Profile view of webbed-tube heat exchanger plate.

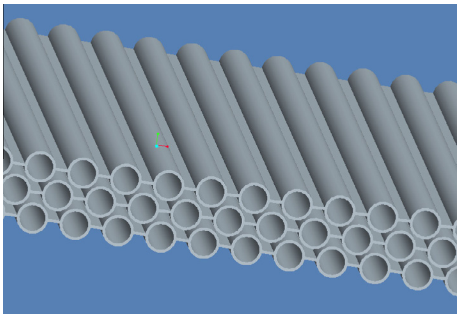
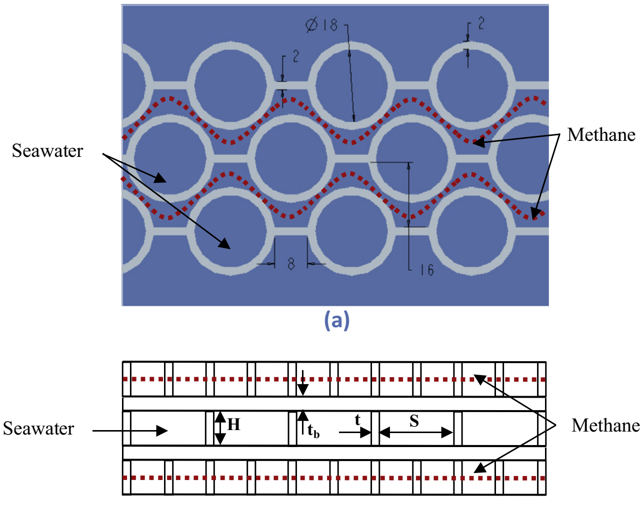


Fig. 2. 3D rendition of the WTHX geometry.



(a)

(b)

Fig. 3. Sketches of heat exchangers used in performance comparison (a) webbed-tube heat exchanger module (all dimensions in mm, overall plate length and width = 1 m). (b) Plate-fin heat exchanger module (H = 10 mm, S = 3 mm, $t = t_b$ = 2 mm, plate length and width = 1 m).

3. Thermo-fluid performance comparison of a WTHX to a plate-fin heat exchanger

In order to illustrate the value of the WTHX design, its heat transfer performance was benchmarked against the more classical plate-fin design. For the example discussed here, which is based on heat exchange needs of a particular stage in a natural gas liquefaction process, both heat exchangers were assumed to be fabricated of a polymer composite and utilize a counter-flow configuration, with hot methane gas at 90 °C and 500 kPa being cooled by seawater at 35 °C and 400 kPa [29]. The volumetric flow rates of the two fluids were approximately equal, with the seawater flow rate kept constant at 0.02 m^3/s, and the gas flow rate varying from 0.02 to 0.1 m^3/s. Cross-sectional views of both HX designs are shown in Fig. 3. The plate-fin heat exchanger design was derived from configurations investigated in previous work and optimized for material and manufacturing cost [12] as well as total coefficient of performance [13]. The dimensions of the WTHX were then chosen such that methane and water velocities, within their respective channels, were comparable to those in the plate-fin design.

It is to be noted that, for the WTHX heat exchanger, the methane gas flows between the tube plates while the seawater flows inside the tubes. The control volumes used to calculate the heat transfer rate and pumping power are outlined with red dashed lines in the Fig. 3. These constitute building blocks for a larger heat exchanger. In both cases, the control volume consists of a single set of seawater channels, which receives heat from the methane "half channels" above and below, so that the methane channels also transfer heat to the water channels on the opposite side.

Since the heat exchangers were designed to be constructed from fiber-filled polymer, the wall thermal conductivity was modeled with thermal conductivity anisotropy [14]. For purposes of this preliminary investigation, we assumed that the fibers mostly lie parallel to the plane of the wall, resulting in an in-plane conductivity of 10 W/m K and through-plane conductivity of 0.65 W/m K. For the plate-fin design, the described anisotropy results in the rectangular fins having an axial conductivity of 10 W/m K, while the plate itself will have a conductivity of 0.65 W/m K for