FLEXIBLE POLYMERIC HOLLOW FIBER HEAT EXCHANGERS

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ABSTRACT

Polymeric hollow fiber heat exchangers were proposed about a decade ago as an alternative to metal exchangers for low temperature application. Flexible polymeric hollow fiber heat exchangers were prepared and tested for liquid / air and liquid / liquid conditions. These heat exchangers use a plastic capillary with an outer diameter of 0.5 – 1.3 mm and a wall thickness of about 10% of the outer diameter. These heat exchangers are flexible and can be used in narrow slots and shaped channels. In experiments we obtained overall heat-transfer coefficients in water/air applications of up to 900 W/m² K. These heat exchangers are effective even in natural convection application where the advantage of high heat transfer coefficient on micro surfaces is utilized. The use of plastic and non-corrosive materials is advantageous in applications where the weight of the heat exchanger is important (about 50% reduction in weight in comparison to classical metal products) and in difficult chemical environments. The paper presents the results of laboratory tests of the developed prototypes of polymeric hollow fiber heat transfer surfaces for various applications.

KEY WORDS: microscale, convection, moisture condensation, compact heat exchanger, polymer, hollow fiber

1. INTRODUCTION AND THEORY

Polymeric hollow fiber heat exchangers (PHFHEs) can be considered light-weight because they can weigh up to 50% than traditional metal heat exchangers. The narrow fibers have thin walls and a large surface area, intensifying heat transfer. Applications for the PHFHE have been identified in several sectors, for example heat recuperation, air heaters and fan-coils; car radiators with the same thermal power as traditional radiators [1]; heat transfer units for cooling compact electronic devices; water desalination; energy storage in hollow fibers for encapsulating phase-change material. The implementation of PHFHE provides cost-effective and recyclable materials and a significant reduction in energy consumption and carbon emission.

Nowadays heat exchangers are mainly made of metals such as copper, steel and aluminum. Polymer materials offer many advantages in comparison with metals. Easy shaping, chemical resistance, lower density, and lower price are the most important of them. The energy consumed to produce a kilogram of the polymer is two times lower than to produce the same amount of a commonly used metal such as stainless steel or aluminum [2]. Their main disadvantages are a low temperature limit (approx. 100 °C for polypropylene and 250 °C for advanced polymers) and low thermal conductivity - about 0.1-0.4 W/ (m K) [3].

The PHFHE [3] is a novel technology with the potential not only to significantly improve current products but to enable entirely new applications and markets. This new approach to the enhanced functionality of polymeric fiber materials used in heat transfer surfaces already has the potential in its current development stage to be competitive in large segments of commercial heat exchangers.
thanks to its cost [4], weight, mass scalability, recyclability, resistance to corrosion [5] and low pollution.

PHFHEs are a type of thin-wall polymer heat exchanger which were first proposed by Zarkadas [3] as a useful alternative for lower temperature applications. Small devices containing several hollow PP-based fibers with the liquids in parallel flow at temperatures of up to 74 °C were studied. The overall heat transfer coefficients of these devices were 647-1314 W/(m²K) for water-water applications. Furthermore, the proposed heat exchangers had large numbers of transfer units (NTUs) for comparably short devices, and were very effective in heat exchange. Their other advantage is their quick response to changes in the flow rate. They are therefore suitable for temperature control [6]. PHFHEs achieve a large packing density (heat transfer area to volume ratio).

This paper presents new information about two of the most typical uses of hollow fiber heat transfer surfaces. The first is the performance of shell and tube types of heat exchangers for liquid / liquid application. Tubes inside the shell are made from thousands of polymer hollow fibers. The second example is for air / liquid cross-flow heat exchangers where the heat transfer surface is formed by layers of polymer hollow fibers. The results for performance and pressure losses in this type heat exchanger are presented. In addition, the results of measurements in a condensation mode on the outer surfaces of hollow fibers are discussed and the influence of the wettability of the surface of the fibers is shown.

2. SHELL AND TUBE LIQUID-TO-LIQUID UNITS

Several examples of shell-and-tube heat exchangers were made and tested (for details see Fig. 1 and Table 1). The shells were made of aluminum, and fiber bundles were placed inside. For units AB1, HE2 and HE3 fibers in the shell were not parallel- there was a 45° angle between fibers in neighboring layers. Such a structure was used to ensure uniform distribution of shell-side liquid and intensify heat transfer. This structure is similar to the one used for mass transfer in commercially available membrane contactors. O-rings were used to seal the gap between the aluminum shell and epoxy (see Fig. 1, centered). Epoxy with fibers was cut and milled to open entrances to fibers and create a tube sheet.

Before thermal performance tests, all heat exchangers were successfully tested for leaks with 6.5 bar pressure (pressurized by nitrogen, immersed in 80 °C water), and both sides (fibers and shell) were pressurized for 4 hours. During the leakage testing, the pressure was gradually increased to 6.5 bars during the first 30 minutes.
Fig. 1 Tested shell-and-tube heat exchangers (left), tube sheet of unit HE2 (centered) and hollow fiber tube bank without a shell (right). For the tube sheet, we can see free entrances to 2000 tubes.

Table 1 Tested shell-and-tube heat exchangers.

<table>
<thead>
<tr>
<th>Fiber number</th>
<th>OD, mm</th>
<th>ID, mm</th>
<th>Heat transfer area, m²</th>
<th>Potting area diameter, mm</th>
<th>Type of fiber structure</th>
<th>Effective length, mm</th>
<th>Fiber material*</th>
<th>Fiber potting area, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB1</td>
<td>740</td>
<td>0.8</td>
<td>0.65</td>
<td>0.52</td>
<td>40</td>
<td>280</td>
<td>PC</td>
<td>30%</td>
</tr>
<tr>
<td>AB2</td>
<td>820</td>
<td>0.8</td>
<td>0.65</td>
<td>0.54</td>
<td>40</td>
<td>260</td>
<td>PC</td>
<td>33%</td>
</tr>
<tr>
<td>HE2</td>
<td>2000</td>
<td>1.3</td>
<td>1.05</td>
<td>1.96</td>
<td>80</td>
<td>240</td>
<td>PA</td>
<td>53%</td>
</tr>
<tr>
<td>HE3</td>
<td>4240</td>
<td>0.8</td>
<td>0.65</td>
<td>2.56</td>
<td>80</td>
<td>240</td>
<td>PA</td>
<td>42%</td>
</tr>
</tbody>
</table>

* PC – polycarbonate, PA – polyamide.

Figure 2 shows the schematic diagram of the experimental setup. Cold water was supplied on the tube side of the heat exchangers (secondary) and hot water at a constant temperature was pumped from the tank on the shell side (primary). The connecting piping was insulated to reduce heat losses from the system. The heat exchanger system heated water at a constant temperature using steam. The inlet and outlet temperatures, differential pressure and flow rates of the shell-side and fiber-side were measured and recorded every 10 seconds using a datalogger for a period of 30 minutes. Averaged values were used to carry out the performance calculations. The accuracy of temperature sensors was estimated to be ± 0.4% of the measured values, pressure and differential pressure transducers ± 0.014 bars and flow meter ± 0.5% of reading. All measuring instruments were calibrated and calibration curves were created with which measured data was conditioned during the data-processing stages.
HE2 and HE3 are similar to HE in their dimensions. They differ in the number and type of fibers. HE2 has 2000 thicker fibers with 1.96 m$^2$ of heat transfer area. HE3 has 4240 thinner fibers with 2.56 m$^2$ of heat transfer area. The large amount of fibers in HE3 caused the large pressure drop on the shell side which led to the decrease in the shell flow rate and that caused the decrease in the heat load. Therefore, better of these two HE seems to be HE2. Its maximum measured power is 36 kW.

There is no difference between the results for AB1 and AB2. Both modules seem to be useful but they can be operated only up to a 600 l/h fiber flow rate (pressure drop 50 kPa) resp. 1000 l/h fiber flow rate (pressure drop 100 kPa). This is limiting their power up to 18 kW resp. 22 kW.

HE2 has no limit on the fiber flow rate and achieves a higher heat load than AB1 and AB2, but its dimensions and weight are greater. AB1 and AB2 could be used as an effective HE for small flow rate applications.

Table 2 Conditions of tests.

<table>
<thead>
<tr>
<th></th>
<th>shell temperature (°C)</th>
<th>fiber temperature (°C)</th>
<th>shell flow rate (l/h)</th>
<th>fiber flow rate (l/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB1</td>
<td>80</td>
<td>20</td>
<td>1080</td>
<td>96; 205; 752; 1001; 1495; 1679</td>
</tr>
<tr>
<td>AB2</td>
<td>80</td>
<td>20</td>
<td>1080</td>
<td>102; 203; 752; 1001; 1506; 1673</td>
</tr>
<tr>
<td>HE2</td>
<td>80</td>
<td>24</td>
<td>960</td>
<td>100; 198; 745; 994; 1506; 1832</td>
</tr>
<tr>
<td>HE3</td>
<td>80</td>
<td>24</td>
<td>760</td>
<td>99; 203; 747; 1005; 1492; 1756</td>
</tr>
</tbody>
</table>

Fig. 2 Experimental setup scheme
Another field of possible application for PHFHEs is the automotive industry. Modules P3 and P4 were developed for such a purpose. Modules P3 and P4 were tested in a wide range of air velocities in the calorimeter of an automotive company and a NETME Centre calorimeter. They have significantly higher values for compactness. For module P3, the ratio of width fiber pitch $b_1 = 1.8$ mm and depth pitch $b_2 = 2$ mm; and, for module P4, $b_1 = 1.6$ mm and $b_2 = 2$ mm. Thus, the ratio $b_1/D_o ≈ 2$ and $b_2/D_o ≈ 2.5$ for both modules. All the module’s properties are listed in Table 3. Figures 6, 7 and 8 show the results of pressure drops obtained in experiments, and the heat transfer rates and OHTC of these modules. There is mostly linear dependence of the heat transfer rate on air velocity for low velocities (up to 2 m/s, see Fig. 7) measured in HeatLab. This is caused by the large NTU numbers (the heat exchanger is too large for such small air quantities).
Table 3 Properties of module P3 and P4

<table>
<thead>
<tr>
<th>module</th>
<th>$N$</th>
<th>$L$ (mm)</th>
<th>$D_o$ (mm)</th>
<th>$D_i$ (mm)</th>
<th>$b_1$ (mm)</th>
<th>$b_2$ (mm)</th>
<th>$A_o$ ($m^2$)</th>
<th>$A_f$ ($m^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P3</td>
<td>1960</td>
<td>250</td>
<td>0.6</td>
<td>0.48</td>
<td>1.8</td>
<td>2</td>
<td>0.92</td>
<td>0.060</td>
</tr>
<tr>
<td>P4</td>
<td>1904</td>
<td>220</td>
<td>0.8</td>
<td>0.64</td>
<td>1.8</td>
<td>2</td>
<td>1.05</td>
<td>0.053</td>
</tr>
</tbody>
</table>

Fig. 5 Photo of module P3 (module P4 looks the same as module P3)

Fig. 6 Air pressure drop vs air velocity in cross-section (flow rate is 220-2200 m³/h).
Fig. 7 Heat transfer rate vs air velocity.

Fig. 8 OHTC vs air velocity. There is a trend showing that PHFHEs achieve high OHTC values starting from relatively low values of air velocity (1 m/s).

4. CROSS-FLOW LIQUID-TO-GAS UNITS WITH HUMIDITY CONDENSATION

Next prototypes were designed and made to test air humidity condensation on hollow fibers. The aim was to observe the condensation on the outer surface of the fiber and determine the influence of condensation on heat transfer. Phase change contains a lot of energy which can be exploited during heating or cooling. Such units can be used for example in air conditioning systems. An example of such an HE can be seen in Fig. 9. The prototypes vary with regard to the material of the fiber. Polypropylene and polyamide were used. Both prototypes have the same geometry and therefore the same amount of fibers (total heat transfer area).
The experimental setup scheme is shown in Fig. 10. The air test conditions were 27°C, 50% humidity. The liquid inside the fibers was water with a temperature of 10°C. The input and output humidity and temperatures were measured. The air and water flow rate, differential pressure on the air side, and amount of condensation was recorded. The placement of the measuring probes is shown in Fig. 10.

As was expected, the type of material has a significant influence on the process of condensation. The hydrophobic polypropylene had a tendency to create larger droplets, whilst the hydrophilic polyamide created a larger amount of smaller droplets. The comparison of these two phenomena is in Fig. 11. The air-flow conditions were the same- 3 m/s velocity, 27 °C inlet temperature, 50% relative humidity, water temperature 11 °C.
4. CONCLUSIONS

The perspective of PHFHEs follows from the presented experiment results. The prototypes had no problems tolerating the conditions which are typical in HVAC and automotive applications. They achieved comparable or even better results than the commonly used metal HE. Their big advantage, which can be exploited, is their weight and resistance to corrosion and aggressive liquids.

The results of the experiments were compared with the predictions made using the Grimson equation and the Churchill and Bernstein approach [7]. It was verified that the Grimson equation is sufficient for predicting outer HTC and can be used for engineering calculations.

Heat exchangers in liquid / liquid application with 45 degrees twisted micro size hollow fiber achieved a competitive performance. The highest overall heat transfer coefficient obtained under test conditions is about 1100 W/m²K, which is comparable with typical metallic shell and tube heat exchangers.

These heat exchangers have the potential to be used in low temperature and low flow rate applications. Most importantly, the fiber materials are made from PP, PC, PA, which are cheap to produce, environmentally friendly, and flexible for recycling.
It was found that these devices in liquid / air mode are able to achieve thermal performances comparable to metal heat exchangers, and can be successfully used as a replacement for metal exchangers in the automotive industry. These devices can achieve high overall heat transfer coefficients (up to 335 W/m²K) and efficiencies (up to 0.8). It can be concluded that the low thermal conductivity of polymers is not an obstacle to using hollow fibers for gas-to-liquid heat transfer because of the extremely thin heat transfer wall. Moreover, it was confirmed that air-side convective coefficients rise with a decrease in tube (fiber) diameter.

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REFERENCES