Performance Characterization of a Microchannel Liquid/Liquid Heat Exchanger Throughout an Extended Duration Life Test

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ABSTRACT

Liquid/Liquid Heat Exchangers (L/L HX) are an integral portion of any spacecraft active thermal control system. For this study the X-38 L/L HX was used as a baseline. As detailed in a previous ICES manuscript, NASA paired with Pacific Northwest National Laboratory to develop a Microchannel L/L HX (MHX). This microchannel HX was designed to meet the same performance characteristics as the aforementioned X-38 HX. The as designed Microchannel HX has a 26% and 60% reduction in mass and volume, respectively. Due to the inherently smaller flow passages the design team was concerned about fouling affecting performance during extended missions. To address this concern, NASA has developed a test stand and is currently performing an 18 month life test on the MHX. This report will detail the up-to-date performance of the MHX during life testing.
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Nomenclature

\( A \) = total surface area (m\(^2\))  
\( C_c \) = heat capacity rate of cold fluids (W/°C)  
\( C_h \) = heat capacity rate of hot fluids (W/°C)  
\( C_{\text{min}} \) = minimum heat capacity rate of the two working fluids (W/°C)  
\( c_p \) = specific heat of the fluid (J/kg-°C)  
\( \Delta T_{\text{lm}} \) = log-mean temperature difference (K)  
\( m \) = mass work rate of the working fluid (kg/s)  
\( q \) = heat transfer rate  
\( t_2 \) = inlet temperature (°C)  
\( t_1 \) = outlet temperature (°C)  
\( T \) = inlet and outlet temperatures of the heat exchanger on the cold and hot sides (°C)  
\( T_{h,i} \) = temperature for the hot side, \( h \), inlet, \( i \)  
\( U \) = overall heat transfer coefficient (W/K-m\(^2\))

I. Introduction

In an effort to address the mass and volume concerns associated with space flight hardware, the Thermal Control System Development for Exploration Project at the NASA Johnson Space Center partnered with Pacific Northwest

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National Laboratory (PNNL) to develop a microchannel liquid/liquid heat exchanger. PNNL expected that its technology would provide considerable mass and volume savings over state-of-the-art plate and fin heat exchangers.

PNNL designed and fabricated a microchannel liquid/liquid heat exchanger based on the performance criterion of a flight qualified plate and fin X-38 heat exchanger. The X-38 vehicle was designed to be used as an emergency crew return vehicle for the International Space Station. The microchannel heat exchanger was designed to transfer the same amount of heat as the X-38 heat exchanger and have equal or lower pressure drops for both the hot and the cold fluid sides. To corroborate PNNL’s claims of volume and mass savings, the X-38 heat exchanger was tested at the design point and its performance was used as a baseline to compare with the microchannel heat exchanger’s performance.

II. MICROCHANNEL LIQUID/LIQUID HEAT EXCHANGER

The microchannel heat exchanger was designed to meet or exceed the previously described X-38 heat exchanger requirements. PNNL fabricated the microchannel heat exchanger using stainless steel. The microchannel heat exchanger core measures 1.9 inches in length, 3 inches in width and 3.3 inches in height as shown in Figure 1. Channels inside the microchannel heat exchanger measure approximately 0.1 – 0.3 mm, creating more wetted surface area and thus resulting in a higher thermal conductance.

Conventional plate and fin heat exchangers usually have low pressure drops because of the wider flow channels that allow the fluids to flow freely without added flow restrictions. Heat exchanger pressure drop is a strong function of the fluid selection and the fluid viscosity (which is a function of the fluid temperature). Despite PNNL’s claim to the contrary, the Thermal Control System Development for Exploration Project was concerned that the microchannel heat exchanger would experience a higher pressure drop caused by the smaller flow channels.

Table 2 provides a comparison of the geometric specifications for the X-38 and microchannel heat exchangers. The mass and volume savings of the microchannel heat exchanger are evident. Figure 2 shows the two heat exchangers side by side. The difference in volume is noticeable.

Table 1. Heat exchangers geometric specifications

<table>
<thead>
<tr>
<th>Heat Exchanger</th>
<th>Mass</th>
<th>Core Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-38</td>
<td>2.7 kg</td>
<td>48 in³</td>
</tr>
<tr>
<td>Microchannel</td>
<td>2 kg</td>
<td>19 in³</td>
</tr>
</tbody>
</table>

III. TEST SETUP

Figure 3 shows the mechanical schematic of the test loop for the heat exchanger test apparatus. The test loop was developed using two fluid loops. The main loop also called the hot loop used deionized water as the working fluid at a heat exchanger inlet temperature of approximately 27°C. The chiller loop was nominally chilled to an inlet temperature of 4°C and used 50:50 by mass ethylene glycol and water mixture as the working fluid. The inlet...
temperatures were based on the design point for the X-38 heat exchanger. The X-38 and the microchannel heat exchangers were both individually tested in the test loop.

Figure 3. Microchannel test schematic

IV. Test Results

The results discussed are taken from the primary test point: 350 lb/hr at an inlet temperature of 27°C on the main loop and 600 lb/hr at an inlet temperature of approximately 4°C on the cold loop. The X-38 and microchannel heat exchangers were designed to have a heat transfer rate of 3.1 kW and a maximum pressure drop of 0.5 psid across both the hot and cold sides. Table 3 shows the baseline test data for the X-38 and microchannel heat exchangers.

The X-38 heat exchanger failed to produce a heat transfer rate of 3.1 kW, while the microchannel produced a higher heat transfer rate for the prescribed inlet conditions. It’s failure to produce the designed heat transfer rate can possibly be attributed to the cleanliness of the heat exchanger or to possible fouling within the X-38 heat exchanger. However, the project has every reason to believe the X-38 heat exchanger did indeed meet its performance requirements when it was delivered to NASA. As mentioned above, the

<table>
<thead>
<tr>
<th></th>
<th>( q_{\text{hot}} ) (W)</th>
<th>( q_{\text{cold}} ) (W)</th>
<th>( \varepsilon )</th>
<th>( UA ) (W/k)</th>
<th>( \Delta P_{\text{hot}} ) (psid)</th>
<th>( \Delta P_{\text{cold}} ) (psid)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>X-38</strong></td>
<td>2423 ± 42</td>
<td>2662 ± 40</td>
<td>.65 ± .01</td>
<td>261 ± 10</td>
<td>0.35 ± .005</td>
<td>0.54 ± .012</td>
</tr>
<tr>
<td><strong>Microchannel</strong></td>
<td>3138 ± 51</td>
<td>3317 ± 44</td>
<td>.84 ± .01</td>
<td>553 ± 10</td>
<td>0.48 ± .029</td>
<td>0.95 ± .028</td>
</tr>
<tr>
<td><strong>Design Point</strong></td>
<td>3100 W</td>
<td></td>
<td>.75</td>
<td>415</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

X-38 heat exchanger was fabricated and intended to serve as flight hardware. NASA would not have taken delivery of the hardware if it was not shown to meet its performance requirement. The X-38 heat exchanger did meet the pressure drop requirement of less than 0.5 psid on both sides of the heat exchanger. In fact, the X-38 heat exchanger had a pressure drop of 0.35 psid across the hot side and 0.54 psid across the cold side. The microchannel heat
exchanger met the pressure drop requirement across the hot side with a pressure drop of 0.48 psid, but failed across
the cold side at 0.95 psid. This data was shared with PNNL who used the test data to correlate their design model.
PNNL has subsequently claimed that they could deliver another heat exchanger that would meet the pressure drop
requirements while sacrificing on heat transfer performance, which would be acceptable because their heat
exchanger performance exceeded the design requirement. To be exact, PNNL claims that they can deliver a new
heat exchanger that meets all of the design requirements and has a mass of only 1.2 kg and a core volume of 188
\( \text{cm}^3 \).

To determine how efficient the heat exchangers were, effectiveness and overall heat transfer coefficient were
calculated. The microchannel heat exchanger had a higher effectiveness and heat transfer coefficient than the X-38
heat exchanger. Effectiveness is a measure that determines how well a heat exchanger is able to transfer heat from
one fluid to the other. As shown in Table 3, the microchannel heat exchanger’s effectiveness was 0.84 compared to
0.65 for the X-38 heat exchanger. This increase in effectiveness was due to the microchannel heat exchanger having
larger temperature differences between the inlet and outlet temperatures than the X-38 heat exchanger. The
microchannel heat exchanger overall heat transfer coefficient was 553 W/K, which was more than double the overall
heat transfer coefficient of the X-38 heat exchanger which was calculated to be 261 W/K. The difference in overall
heat transfer coefficient is due to either a higher thermal resistance between the working fluids in the X-38 heat
exchanger or a much higher surface area in the microchannel heat exchanger, or a combination of both.

V. Conclusion

A plate and fin liquid/liquid X-38 heat exchanger was originally designed to have a heat transfer rate of 3.1 kW
and pressure drops not to exceed 0.5 psid across both the hot and cold sides of the heat exchanger. Performance
specifications from this heat exchanger were used to design a microchannel liquid/liquid heat exchanger. A test
apparatus was designed and used to test both the X-38 and the microchannel heat exchangers. The microchannel
heat exchanger met all of its performance requirements, with the exception of the pressure drop across the cold side
of the heat exchanger. The microchannel heat exchanger’s heat transfer rate, effectiveness, and UA were higher
although it weighs less and is smaller than the X-38 heat exchanger. The microchannel heat exchanger design
achieved a mass reduction of 26%. In addition, its core was reduced by 61% as compared to that of the X-38 heat
exchanger.

The test data have been shared with PNNL. The project was especially concerned about PNNL’s failure to meet
the pressure drop requirements. To that end, PNNL has used the test data to develop correlated thermal models.
These models were then used to conceptually design a next generation microchannel heat exchanger. The
conceptual design shows improved mass and volume as compared to the first generation microchannel heat
exchanger. This was achieved while sacrificing the unit’s thermal performance. This sacrifice was acceptable
because the first unit exceeded the thermal performance specifications. The mass and core volume for the
conceptual design is 1.2 kg and 188 \( \text{cm}^3 \), respectively.

The project is in the process of developing a life test for the microchannel heat exchanger. This test is scheduled
to run the baseline test point continuously for at least 6 months. The life test will provide insight into the
performance of a microchannel heat exchanger over a long test duration. The project is concerned that the
microchannel heat exchanger may be susceptible to performance degradation because of the extremely small flow
passages.
## Appendix

X-38 heat exchanger test data with varying flow rates:

<table>
<thead>
<tr>
<th>Flow Rate hot (lb/hr)</th>
<th>Flow Rate cold (lb/hr)</th>
<th>$q_{hot}$ (W)</th>
<th>$q_{cold}$ (W)</th>
<th>$\epsilon$ (UA (W/K))</th>
<th>$\Delta P_{hot}$ (psid)</th>
<th>$\Delta P_{cold}$ (psid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>351</td>
<td>600</td>
<td>2423 ± 42</td>
<td>2661 ± 40</td>
<td>0.65 ± .01</td>
<td>261 ± 10</td>
<td>0.36 ± .005</td>
</tr>
<tr>
<td>355</td>
<td>558</td>
<td>2220 ± 39</td>
<td>2470 ± 38</td>
<td>0.63 ± .01</td>
<td>256 ± 10</td>
<td>0.24 ± .005</td>
</tr>
<tr>
<td>354</td>
<td>499</td>
<td>2224 ± 39</td>
<td>2498 ± 38</td>
<td>0.61 ± .01</td>
<td>251 ± 10</td>
<td>0.23 ± .005</td>
</tr>
<tr>
<td>357</td>
<td>443</td>
<td>2161 ± 39</td>
<td>2388 ± 37</td>
<td>0.59 ± .01</td>
<td>258 ± 10</td>
<td>0.25 ± .005</td>
</tr>
<tr>
<td>354</td>
<td>400</td>
<td>2068 ± 38</td>
<td>2287 ± 36</td>
<td>0.60 ± .01</td>
<td>251 ± 10</td>
<td>0.25 ± .005</td>
</tr>
<tr>
<td>350</td>
<td>200</td>
<td>1476 ± 32</td>
<td>1597 ± 41</td>
<td>0.84 ± .01</td>
<td>248 ± 10</td>
<td>0.29 ± .005</td>
</tr>
<tr>
<td>350</td>
<td>151</td>
<td>1198 ± 29</td>
<td>1270 ± 43</td>
<td>0.90 ± .02</td>
<td>238 ± 10</td>
<td>0.37 ± .005</td>
</tr>
<tr>
<td>300</td>
<td>600</td>
<td>2278 ± 43</td>
<td>2521 ± 40</td>
<td>0.70 ± .01</td>
<td>248 ± 10</td>
<td>0.22 ± .005</td>
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<tr>
<td>250</td>
<td>600</td>
<td>2045 ± 44</td>
<td>2299 ± 39</td>
<td>0.75 ± .01</td>
<td>230 ± 10</td>
<td>0.17 ± .005</td>
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<tr>
<td>199</td>
<td>600</td>
<td>1672 ± 44</td>
<td>1902 ± 37</td>
<td>0.81 ± .01</td>
<td>209 ± 10</td>
<td>0.22 ± .005</td>
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<tr>
<td>150</td>
<td>600</td>
<td>1393 ± 47</td>
<td>1594 ± 36</td>
<td>0.87 ± .01</td>
<td>185 ± 10</td>
<td>0.05 ± .005</td>
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</table>

Microchannel heat exchanger test data with varying flow rates:

<table>
<thead>
<tr>
<th>Flow Rate hot (lb/hr)</th>
<th>Flow Rate cold (lb/hr)</th>
<th>$q_{hot}$ (W)</th>
<th>$q_{cold}$ (W)</th>
<th>$\epsilon$ (UA (W/K))</th>
<th>$\Delta P_{hot}$ (psid)</th>
<th>$\Delta P_{cold}$ (psid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>601</td>
<td>3136 ± 51</td>
<td>3285 ± 44</td>
<td>0.84 ± .01</td>
<td>547 ± 10</td>
<td>0.48 ± .028</td>
</tr>
<tr>
<td>351</td>
<td>557</td>
<td>3060 ± 50</td>
<td>3284 ± 43</td>
<td>0.82 ± .01</td>
<td>551 ± 10</td>
<td>0.46 ± .023</td>
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<tr>
<td>350</td>
<td>499</td>
<td>2944 ± 48</td>
<td>3089 ± 42</td>
<td>0.80 ± .01</td>
<td>555 ± 10</td>
<td>0.46 ± .023</td>
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<td>452</td>
<td>2811 ± 47</td>
<td>2965 ± 42</td>
<td>0.77 ± .01</td>
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<td>0.46 ± .027</td>
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<tr>
<td>350</td>
<td>406</td>
<td>2782 ± 46</td>
<td>2935 ± 43</td>
<td>0.76 ± .01</td>
<td>552 ± 10</td>
<td>0.47 ± .030</td>
</tr>
<tr>
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<td>357</td>
<td>2565 ± 44</td>
<td>2680 ± 43</td>
<td>0.82 ± .01</td>
<td>562 ± 10</td>
<td>0.45 ± .036</td>
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<tr>
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<td>2359 ± 41</td>
<td>2479 ± 45</td>
<td>0.87 ± .01</td>
<td>563 ± 10</td>
<td>0.45 ± .042</td>
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<tr>
<td>350</td>
<td>247</td>
<td>2058 ± 38</td>
<td>2163 ± 46</td>
<td>0.92 ± .01</td>
<td>610 ± 10</td>
<td>0.45 ± .046</td>
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<tr>
<td>351</td>
<td>209</td>
<td>1748 ± 34</td>
<td>1833 ± 46</td>
<td>0.95 ± .01</td>
<td>1006 ± 10</td>
<td>0.64 ± .048</td>
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<tr>
<td>300</td>
<td>599</td>
<td>2834 ± 51</td>
<td>2990 ± 42</td>
<td>0.88 ± .01</td>
<td>520 ± 10</td>
<td>0.63 ± .028</td>
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<tr>
<td>251</td>
<td>598</td>
<td>2464 ± 52</td>
<td>2620 ± 40</td>
<td>0.91 ± .01</td>
<td>469 ± 10</td>
<td>0.36 ± .031</td>
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<tr>
<td>201</td>
<td>598</td>
<td>2016 ± 52</td>
<td>2196 ± 38</td>
<td>0.94 ± .01</td>
<td>395 ± 10</td>
<td>0.30 ± .032</td>
</tr>
<tr>
<td>149</td>
<td>598</td>
<td>1517 ± 52</td>
<td>1655 ± 36</td>
<td>0.95 ± .01</td>
<td>282 ± 10</td>
<td>0.23 ± .032</td>
</tr>
</tbody>
</table>

## References