FEW0233: Additive Manufacturing of New Structures for Heat Exchange

Crosscutting Research Program Portfolio Review Meeting

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Objective: develop a heat exchanger for sCO$_2$ power cycles with radically improved material efficiency and higher temperature tolerance than current technology.

Approach: 3D-printing of nickel alloys in novel gyroid-like geometries.

<table>
<thead>
<tr>
<th>FY18</th>
<th>FY19</th>
<th>FY20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I</td>
<td>Phase II</td>
<td></td>
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</tbody>
</table>

Three milestone in Phase I:

- Print coupons of target alloys.
- Determine the material properties at ambient conditions and 700°C for the alloy coupons.
- Develop a model framework for structural and flow properties of designs; identify a workable design.
The project combines additive manufacturing of superalloys with new, efficient geometries.
Candidate gyroid-like geometries

AKA: Triply Periodic Minimal Surfaces (TPMS)

Surface defined by, e.g.:

\[
\sin \left( \frac{2\pi}{L} x \right) \cos \left( \frac{2\pi}{L} y \right) + \sin \left( \frac{2\pi}{L} y \right) \cos \left( \frac{2\pi}{L} z \right) + \sin \left( \frac{2\pi}{L} z \right) \cos \left( \frac{2\pi}{L} x \right)
\]
Expecting order-of-magnitude improvement in heat transfer performance over tubes and flat plates.

Hierarchies are common in nature for high interfacial area with low pressure drop and are now achievable with AM.
Prototypes printed in polycarbonate, ABS, and nylon
Original proof of concept printed in stainless steel
Five alloys considered, Inconel 625 most developed.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Powder available</th>
<th>Printed in literature</th>
<th>Powder obtained</th>
<th>Coupons printed by LLNL/partners</th>
<th>Reactor printed by LLNL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inconel 625</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Haynes 282</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Inconel 617</td>
<td>✓</td>
<td>✓</td>
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<td></td>
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<tr>
<td>Haynes 230</td>
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</tr>
<tr>
<td>Inconel 740H</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Vendor data shows good strength from printed Haynes 282

**Hanes 282 DMLM (Build #140570_11)**

<table>
<thead>
<tr>
<th>X-Direction</th>
<th>Yield Strength (ksi)</th>
<th>Tensile Strength (ksi)</th>
<th>Modulus of Elasticity (Mpsi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>99</td>
<td>144</td>
<td>24.7</td>
</tr>
<tr>
<td>2</td>
<td>98</td>
<td>142</td>
<td>23.0</td>
</tr>
<tr>
<td>3</td>
<td>97</td>
<td>142</td>
<td>23.6</td>
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<tr>
<td>4</td>
<td>98</td>
<td>142</td>
<td>24.5</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>145</td>
<td>22.9</td>
</tr>
<tr>
<td>6</td>
<td>97</td>
<td>141</td>
<td>24.5</td>
</tr>
</tbody>
</table>

Average 98.2 142.7 23.9

MDS ? ? ?

**Z-Direction**

<table>
<thead>
<tr>
<th>Yield Strength (ksi)</th>
<th>Tensile Strength (ksi)</th>
<th>Modulus of Elasticity (Mpsi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>121</td>
</tr>
<tr>
<td>2</td>
<td>82</td>
<td>119</td>
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<tr>
<td>3</td>
<td>82</td>
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<tr>
<td>4</td>
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<td>120</td>
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<tr>
<td>5</td>
<td>84</td>
<td>120</td>
</tr>
<tr>
<td>6</td>
<td>83</td>
<td>120</td>
</tr>
</tbody>
</table>

Average 82.7 120.0 19.8

MDS ? ? ?

Test cylinders being printed.

Data from i3D MFG
Test cylinders printed in Inconel 625
Nearly full density achieved at several spacings. Low powers is an artifact of through-porosity.
Reactor and test blocks in Inconel 625
Schwarz-D geometry meshed in StarCCM
Heat exchange model test case

Inlet 1
- $U \sim 0.01-1 \text{ cm/s}$
- $T = 300\text{K}$

Inlet 2
- $U \sim 0.01-1 \text{ cm/s}$
- $T = 350\text{K}$

- Extrusions provide stable flow at boundaries.
- Water as liquid phase
- Aluminum as solid phase

Computational domain: 4 repeat Units (4cm long)
- 11.6M Cells,
- $\sim 150$ um resolution
- Convergence in 15K iterations after 80h on 8 core
Flow characteristics

Variation in flow path size

\[ D_H = 4 \times \text{area} / \text{perimeter} \approx 7\text{mm} \]

Temperature in Fluid 2 (flow direction)

\[ U = 0.01 \text{ m/s}, \ Re = 87, \ Pe = 521 \]
Stable temperature profiles developed

Axially Averaged Temperature Variation

- Fluid 1
- Wall on Fluid 1 side
- Wall on Fluid 2 side
- Fluid 2

Temperature in Fluid 2 (flow direction)

U = 0.01 m/s
Re = 87
Pe = Re Pr = 87 * 6.0 = 521
Heat transfer coefficient varies with position and flow rate.

Axial variation of heat transfer coefficient, $h$

\[ q_{j \rightarrow W, i} \]

\[ \langle T_j \rangle - \langle T_{W, i} \rangle \]

Heat transfer coefficient: heat transferred normalized by surface area and temperature difference.

Fluid 1, $Re = 87$

\[ <h> = 1541 \text{ W/m}^2\text{-K} \]

Fluid 2, $Re = 5$

\[ <h> = 664 \text{ W/m}^2\text{-K} \]

Fluid 2, $Re = 87$
Comparing Heat Transfer Correlations

Heat Transfer Correlation (this work)

\[ Nu = 1.32 Re^{0.4765} Pr^{0.3333} \]

\[ Nu = 0.664 (D/L)^{0.5} Re^{0.5} Pr^{0.3333} \]

Experimental Correlation (literature)

\[ Nu = \frac{hD}{k} \]

\[ Nu = 1.20 Re^{1.81} Pr^{0.3333} \]

Schwarz-D from Femmer

shows higher \( Nu \), and stronger dependence on \( Re \).

Possibly due to smaller channels (1mm) and different, dependent on Nu formulation.

\(^1\)Femmer et al. 2015
Coupled heat transfer and solid mechanics modeled in Comsol

Uniform heating 300 → 1000 K
Computational domain size = 2 x 2 x 2 cm
Wall thickness = 0.85 mm

Material is Inconel 625 (properties from literature)

⇒ von Mises stresses are negligible for uniform heating
Thermal stress during heat exchange is manageable.

\[ T_{\text{hot}} = 1000K, \ T_{\text{cold}} = 300K, \ h = 1570 \ W/(m^2\text{-K}) \]

Solid temperature varies between 500 K to 800 K

von Mises stress concentration is about 120 MPa
(yield strength for printed Inconel 625 is \( \sim 400 \) MPa)
Summary

- Printed TPMS heat exchangers remain a very promising concept for sCO$_2$ power cycles.
- Feasibility of fabrication is confirmed in-house and through literature and commercial vendors.
- Superior heat exchange performance is supported in early modeling.
Phase II

Tasks in two tracks:
Refine design through computational optimization
Test additional alloys and select

Objective: demonstrate a prototype heat exchanger at 750°C and 300 bar ΔP with superior performance to a microchannel design.
Acknowledgements

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Team members: Philip Depond
              Victor Beck
              Pratanu Roy
              Omer Dogan (NETL)
              Du Nguyen

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