Entropy generation in the woven mesh regenerator filler of cryocoolers

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Introduction

- Regenerators are key components in regenerative cryocoolers. For good performance they should have high heat capacity, low axial thermal conduction, low friction and high porosity. Regenerator fillers come in various geometries, including powders composed of spheres, metal foams, wire mesh, and micro-manufactured structures.
- To optimize a regenerator filler, both first and second laws of thermodynamics must be considered. First law analysis aims to maximize the thermal performance; second law analysis is meant to minimize the entropy generation and energy destruction and losses.
- In this study, entropy generation is investigated by three-dimensional pore level CFD simulations in a woven mesh regenerator, (wire packing), for steady state and oscillating flow.
- For steady flow, the effects of geometric size, wire diameter, porosity, geometry irregularity and operating conditions are evaluated to optimize the regenerator and minimize exergy destruction.
- For oscillating flow, entropy generation is investigated for one geometry and for different Reynolds numbers.

Physical System

- Geometry

Figure 1. Woven mesh regenerator structure

- Unit cell concept as a computational domain

Figure 2. Computational domain and boundary conditions (a) solid part of unit cell for steady state condition, (b) fluid part of unit cell for steady state, (c) fluid part of domain for oscillating flow calculation

Sensitivity analysis on the unit cell

<table>
<thead>
<tr>
<th>Case number</th>
<th>𝜏 (µm)</th>
<th>𝐻𝑇 (µm)</th>
<th>𝑉 (µm)</th>
<th>Working fluid</th>
<th>𝜎 (unit)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>100</td>
<td>0</td>
<td>Stainless steel</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>100</td>
<td>0</td>
<td>Stainless steel</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>100</td>
<td>0</td>
<td>Stainless steel</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>100</td>
<td>0</td>
<td>Stainless steel</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>100</td>
<td>0</td>
<td>Stainless steel</td>
<td>100</td>
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</table>

Table 1. Unit cell geometry configurations for steady state analysis

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Heat flux from walls range (W/m²)</th>
<th>Mean pressure (MPa)</th>
<th>Reynolds number range</th>
<th>Working fluid</th>
<th>Wire material</th>
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<td>300</td>
<td>220-1800</td>
<td>0.1</td>
<td>2-4</td>
<td>Stainless steel</td>
<td>Stainless steel</td>
</tr>
</tbody>
</table>

Table 2. Operation conditions

Figure 3. Contour plots of case number 1 at Re= 18 and 𝑞” = 750 W/m², (a) temperature (K), (b) velocity magnitude (m/s), (c) local total volumetric entropy generation rate (W/m³K).

Figure 4. Viscous, heat transfer and total volume average volumetric entropy generation rate in case 1 for 𝑞”= 750 W/m².

Figure 5. Comparison of all 9 steady-flow cases at 𝑞” = 750 W/m², (a) normalized total volumetric entropy generation, (b) PEC, (c) Bejan number, (d) effect of irregularity on total entropy generation.

Figure 6. Contours of oscillating flow simulation at 1/8 cycle (left contours) and 1/4 cycle (right contours) for case 1 at Re=34, (a) velocity magnitude, (b) temperature (K), (c) total entropy generation (W/m³K).

Figure 7. Normalized total entropy generation for steady state with 𝑞” = 750 W/m² and oscillating flow for case 1 at Re=200Hz.

Results

- Steady state flow

Conclusion

- A pore-level CFD-assisted investigation was performed aimed at the elucidation of entropy generation in woven mesh regenerator fillers.
- Simulations show that the optimum operating conditions are determined by the relative magnitudes of viscous dissipation and entropy generation due to heat transfer.
- For steady flow simulations with constant wall heat flux the contribution of viscous irreversibility increases with Re, while the contribution of heat transfer irreversibility monotonically diminishes. Optimum working conditions occur when the two contribution terms become equal.
- Entropy generation is higher in periodic flow.
- Partial blockage of flow passages caused by particles can significantly increase entropy generation.