Space Station Environmental Control & Life Support System
Pressure Control Pump Assembly Modeling and Analysis

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• Overview

• Integrated PCPA/Manifold Analyses

• Manifold Performance Analysis

• PCPA Motor Heat Leak Study

• Conclusions/Future Plans
Simplified Distillation Assembly/PCPA Block Diagram

- Product Water
- Waste Water
- Brine

Stationary Bowl Volume

Condenser

Evaporator

Compressor

Coolant In
(100 lbm/hr @ 65°F)

Flexhose

Manifold

PCPA

\[ V_{2,\text{dot}} = 3.895 \text{ ft}^3/\text{hr} \]

\[ X_1 \sim 1.0 \]

\[ P = P_{\text{sat}} \sim 0.95 \text{ psia} \]

\[ T = T_{\text{sat}} \sim 100^\circ \text{F} \]
Pressure Control Pump Assembly

- Drive Motor (minus cooling jacket)
- Outer Hub
- Cooling Jacket (housing)
- Tubes
- Inlet/Outlet (Manifold Mount)
PCPA Chiller Block and Attachment

Valve Locations

Purge Gas Inlet

Coolant Inlet

Coolant Exit

Inlet Manifold

Outlet Manifold

Chiller Block Attachment to the Pump

Bottom View
Inside the PCPA

- Fluid Volume per tube = 1.167 in³
- Volumetric displacement per tube (at 24 rpm) = 0.466 in³/sec
- Total displacement (4 tubes) = 1.87 in³/sec
PCPA Pump Cycle

1/2 Stroke

3/4 Stroke

1/4 Stroke

End of Cycle

Beginning of Cycle

- High Pressure (Outlet)
- Low Pressure (Inlet)
Opposing Piston-Cylinders used to Model Pump Cycle

- **Inlet**
- **Outlet**
- **Piston #1**
- **Piston #2**
- **Open**
- **Close**

Flow directions:
- **Q**

Pressures:
- **High Pressure (Outlet)**
- **Low Pressure (Inlet)**

Legend:
- Gray: High Pressure (Outlet)
- Black: Low Pressure (Inlet)
Piston-Cylinder Analogy for a Complete Cycle
A Derivation of the Pump Performance Equation

Piston Cylinder Expansion Stroke

\[
Q_{\text{dot}} = \frac{2\pi k \lambda_{\text{Norgren}}}{\ln\left(\frac{r_o}{r_i}\right)} \left( T_{\text{Piston}} - T_{\text{Coolant}} \right)
\]

Assume \( P, T \) inside the piston remain at \( P_{\text{sat}}, T_{\text{sat}} \)

The mass drawn into the volume over a timestep, \( \Delta \tau \), is equal to:

\[
\Delta M = \int \frac{V_{\text{dot}}}{v_f + x_2 v_{fg}} \, d\tau + \int \frac{2\pi k \Delta T}{\ln\left(\frac{r_o}{r_i}\right) h_{fg}} \, d\tau
= \int \frac{V_{\text{dot}}}{v_f + x_2 v_{fg}} \frac{2\pi k \Delta T}{\ln\left(\frac{r_o}{r_i}\right) h_{fg}} \, d\tau
\]

\[
\Delta M = \frac{V_{\text{dot}}}{v_f + x_2 v_{fg}} \Delta \tau + \frac{2\pi k \Delta T}{\ln\left(\frac{r_o}{r_i}\right) h_{fg}} \frac{(r_f^2 - r_i^2)}{2}
= \frac{V_{\text{dot}}}{v_f + x_2 v_{fg}} \Delta \tau + \frac{2\pi k \Delta T}{\ln\left(\frac{r_o}{r_i}\right) h_{fg}} \frac{(r_f + r_i)}{2} \Delta \tau
\]

\[
\frac{\Delta M}{\Delta \tau} = \frac{M_{\text{dot}}}{u} = \frac{V_{\text{dot}}}{v_f + x_2 v_{fg}} + \frac{\pi k \Delta T}{\ln\left(\frac{r_o}{r_i}\right) h_{fg}} \cdot \frac{L}{2} = \frac{(r_f + r_i)}{2}
\]

\[
V = AL = \pi r_o^2 L, \quad V_{\text{dot}} = A x_{\text{dot}} = Au
\]
Derivation of Manifold (Chiller Block) Performance Equation

Heat transfer between the coolant and purge gas passages in the manifold:

\[ Q_{dot} = \frac{1}{hA_{Coolant}} + \frac{1}{f(k, L, d)} + \frac{1}{hA_{Purge}} \]^{-1} (\text{T}_{Purge} - \text{T}_{Coolant})

\[ Q_{dot} = \overline{G} \Delta T \]

Mass flow in the purge gas passage is inversely proportional to the condensation rate:

\[ Q_{dot} = \overline{G} \Delta T = (x_1 - x_2) h_{fg} \text{Mdot} \]

\[ \text{Mdot} = \frac{\overline{G} \Delta T}{h_{fg} (x_1 - x_2)} \]

\[ \zeta = \frac{\overline{G} \Delta T}{h_{fg}} \]

Let \( \zeta \) = heat transfer rate/heat of condensation; expected values range between 0.02 and 0.1 for the chiller block per hand calculation; larger value indicates higher heat transfer rate.

\[ \text{Mdot} = \frac{\zeta}{(x_1 - x_2)} \]
Pump versus Manifold Parametric

$X_1=100\%, \ T_1=100^\circ F$

- $\xi = \frac{\overline{G}\Delta T}{h_{fg}}$

- $\xi$ is a dimensional parameter (units of mass flow rate) that describes the thermal performance of the manifold.
- A larger value of $\xi$ indicates a higher heat transfer rate between the coolant and purge lines.
- Per hand calculations, $\xi$ is expected to range between 0.02 and 0.1 for the manifold.
DA/PCPA Rack Interface Tubing Model
Steady State Results

PCPA Capacity with Chiller Block

PCPA Inlet Vapor Quality

Chiller Block Temperature (deg F) vs. Purge Flow (lbm/hr)

Chiller Block Temperature (deg F) vs. PCPA Inlet Vapor Quality
Steady State Results (Cont’d)

PCPA Inlet Temperature

![Graph showing the relationship between PCPA Inlet Temperature and Chiller Block Temperature (deg F). The graph indicates a linear increase in PCPA Inlet Temperature as the Chiller Block Temperature increases.]
PCPA Chiller Block Thermal Model

- Imported chiller block model directly from CAD file (stereo-lithography translation).
- Meshed as a solid with 10970 nodes and 43619 tetrahedrals.
PCPA Chiller Block Thermal Model Development

- Imported chiller block model directly from CAD file (stereo-lithography translation).
- Meshed as a solid with 10970 nodes and 43619 tetrahedrals.
PCPA Chiller Block Thermal Analysis Results

Note: inner solid volume removed for clarity to expose flow passages.
Boundary Conditions for PCPA Motor Heat Leak Study

### Cold Case (Motor Dissipation=18 watts)

<table>
<thead>
<tr>
<th></th>
<th>Motor Dissipation</th>
<th>Fluid Dissipation</th>
<th>Motor Cooling Jacket Temp</th>
<th>Outer Cooling Jacket Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Operational</td>
<td>4.5 (watts)</td>
<td>0.85 (watts)</td>
<td>67 (F)</td>
<td>66 (F)</td>
</tr>
<tr>
<td>Worst Case Operational</td>
<td>18.0 (watts)</td>
<td>3.38 (watts)</td>
<td>72 (F)</td>
<td>71 (F)</td>
</tr>
<tr>
<td>Loss of Cooling</td>
<td>18.0 (watts)</td>
<td>3.38 (watts)</td>
<td>95 (F)</td>
<td>95 (F)</td>
</tr>
</tbody>
</table>

### Hot Case (Motor Dissipation=55 watts)

<table>
<thead>
<tr>
<th></th>
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<th>Fluid Dissipation</th>
<th>Motor Cooling Jacket Temp</th>
<th>Outer Cooling Jacket Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Operational</td>
<td>13.8 (watts)</td>
<td>0.85 (watts)</td>
<td>65+ 6=71 (F)</td>
<td>65+ 4=69 (F)</td>
</tr>
<tr>
<td>Worst Case Operational</td>
<td>55.0 (watts)</td>
<td>0 (watts)</td>
<td>65+22=87 (F)</td>
<td>65+18=83 (F)</td>
</tr>
<tr>
<td>Loss of Cooling</td>
<td>NA (watts)</td>
<td>NA (watts)</td>
<td>NA (F)</td>
<td>NA (F)</td>
</tr>
</tbody>
</table>
PCPA Thermal Model

Nodes: 14612
Elements: 45508
PCPA Temperature Distribution for the Worst Case Operational Scenario

Temp °F

70.3
72.2
73.4
74.6
75.8
77.0
78.2
79.4
80.8
81.9
83.1
84.3
85.5
86.7
87.9
89.1
90.3
Steady State PCPA Motor Heat Leak Study Results

**Cold Case (Motor Dissipation=18 watts)**

<table>
<thead>
<tr>
<th></th>
<th>Harmonic Drive Outer Temp (F)</th>
<th>Minimum Peristaltic Tubing Temp (F)</th>
<th>Maximum Peristaltic Tubing Temp (F)</th>
<th>Motor Temp (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Operational</td>
<td>70.2</td>
<td>67.6</td>
<td>69.9</td>
<td>71.2</td>
</tr>
<tr>
<td>(25% Duty Cycle)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Worst Case Operational</td>
<td>86.2</td>
<td>76.4</td>
<td>85.5</td>
<td>91.6</td>
</tr>
<tr>
<td>(100% Duty Cycle)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loss of Cooling</td>
<td>109.8</td>
<td>100.3</td>
<td>109.3</td>
<td>113.8</td>
</tr>
</tbody>
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**Hot Case (Motor Dissipation=55 watts)**

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</thead>
<tbody>
<tr>
<td>Nominal Operational</td>
<td>78.5</td>
<td>72.3</td>
<td>77.8</td>
<td>80.4</td>
</tr>
<tr>
<td>(25% Duty Cycle)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Worst Case Operational</td>
<td>126.8</td>
<td>92.3</td>
<td>110.3</td>
<td>137.5</td>
</tr>
<tr>
<td>(100% Duty Cycle)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loss of Cooling</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
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Conclusions/Future Plans

- Preliminary results from a thermal/flow analysis of the PCPA indicate that the pump performance (mass flow rate) is enhanced via cooling of the housing and lowering of the inlet vapor quality.

- Under a nominal operational profile (25% duty cycle or less), at the maximum motor dissipation, it appears that the peristaltic tubing temperature will still remain significantly below the expected UPA condenser temperature (78°F max versus ~105°F in the condenser) permitting condensation in the pump head.

- Future plans include the development of numerical models to characterize the integrated behavior of the PCPA/Manifold with the Distillation Assembly.