Adaptable Single Active Loop Thermal Control System (TCS) for Future Space Missions

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Develop Adaptable Single-Loop Thermal Control System (ASL-TCS) that can tackle widely varying heat loads of different space missions and both cold and warm environments while improving system performance, reducing weight and volume, and ensuring reliable operation irrespective of gravity.
## Thermal Requirement for Different Missions

**Thermal loads and effective sink temperatures for different missions based on Orion Multi-Purpose Crew Vehicle (MPCV)**

<table>
<thead>
<tr>
<th>Mission</th>
<th>Thermal Load</th>
<th>Effective Sink Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch to LEO</td>
<td>1.2 kW</td>
<td>-93 to -66°C (180 to 207K)</td>
</tr>
<tr>
<td>TLC, TNEOC, TMC</td>
<td>1 kW</td>
<td>-198°C (75 K)</td>
</tr>
<tr>
<td>LLO</td>
<td>5 kW</td>
<td>-213 to 17°C (60 to 290 K)</td>
</tr>
<tr>
<td>LSO</td>
<td>6.25 kW</td>
<td>-56 to -34°C (217 to 239K)</td>
</tr>
<tr>
<td>NEO</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>MSO</td>
<td>6.25 kW</td>
<td>-123 to -23°C (150 to 250K)</td>
</tr>
<tr>
<td>LMO</td>
<td>5 kW</td>
<td>22°C (295 K)</td>
</tr>
</tbody>
</table>

**LEO:** Low Earth Orbit  
**LLO:** Low Lunar Orbit  
**TLC:** Trans Lunar Coast  
**TNEOC:** Trans Near Earth Objects Coast  
**TMC:** Trans Mars Coast  

**LSO:** Lunar Surface Operation  
**NEO:** Near-Earth Object  
**MSO:** Mars Surface Operation  
**LMO:** Low Mars Orbit  

LLO and LMO associated with heat sink temperatures that exceed lowest minimum fluid temperature of 2°C at inlet to cabin HX, therefore requiring heat pump mode
**Requirements for Heat Pump Mode**

\[ T_{\text{cabinHX,in}} = 2^\circ \text{C} : \] prevent frost formation on evaporator surfaces

\[ T_{\text{evap}} = 5^\circ \text{C} : \] evaporation temperature

Condenser pinch temp. = 5°C

LLO: \( T_{\text{sink}} = 17^\circ \text{C}, T_{\text{cond,out}} = 22^\circ \text{C} \)

LMO: \( T_{\text{sink}} = 22^\circ \text{C}, T_{\text{cond,out}} = 27^\circ \text{C} \)

Max \( T_{\text{lift}} = 80^\circ \text{C} \) when \( T_{\text{evap}} = 5^\circ \text{C} \) (60°C for R404a with \( T_{\text{crit}} = 72.07^\circ \text{C} \))

\( Q_{\text{cabinHX}} = 0.75 \text{ kW} \)

\( Q_{\text{avionicsHX}} = 0 – 5.5 \text{ kW} \)

**Pressure:**

Max pressure = \( P_{\text{sat}} \) at \( T_{\text{cond,sat}} = T_{\text{evap}} = 5^\circ \text{C} + T_{\text{lift}} = 80^\circ \text{C} \)

Min pressure = \( P_{\text{sat}} \) at \( T_{\text{cabinHX,in}} = 2^\circ \text{C} \)

**Radiator Area:**

\[ A_{\text{radiator,s}} = A_{\text{vapor}} + A_{\text{sat}} + A_{\text{liquid}} \quad , \quad T_{\text{cond,sat}} = T_{\text{evap}} + T_{\text{lift}} \]

\[ A_{\text{vapor}} = \frac{\dot{m}_{\text{hp}} c_p f (T_{\text{cond,in}} - T_{\text{cond,sat}})}{\varepsilon \sigma \left(\left(\frac{T_{\text{cond,in}} + T_{\text{cond,sat}}}{2}\right)^4 - T_{\text{sin}}^4\right)} \]

\[ A_{\text{sat}} = \frac{\dot{m}_{\text{hp}} h_f}{\varepsilon \sigma \left(\left(\frac{T_{\text{cond,sat}} + T_{\text{cond,out}}}{2}\right)^4 - T_{\text{sin}}^4\right)} \]

\[ A_{\text{liquid}} = \frac{\dot{m}_{\text{hp}} c_p f (T_{\text{cond,sat}} - T_{\text{cond,out}})}{\varepsilon \sigma \left(\left(\frac{T_{\text{cond,sat}} + T_{\text{cond,out}}}{2}\right)^4 - T_{\text{sin}}^4\right)} \]

**Coefficient of Performance:**

\[ COP = \frac{Q_{\text{cabinHX}} + Q_{\text{avionicsHX}}}{W_{\text{comp}} / \eta_{\text{comp}}} \quad , \quad \eta_{\text{comp}} = 85\% \]

\[ W_{\text{comp}} = \int_{P_{\text{avionicsHX,\text{out}}}^P_{\text{cond,\text{in}}}} V \, dP = \dot{m}_{\text{hp}} (h_{\text{cond,\text{in}}} - h_{\text{avionicsHX,\text{out}}}) \]
**Requirements for Heat Pump Mode**

**Mass Flow Rate:**
- **LLO:** Lower $T_{\text{cond, out}}$, lower enthalpy at inlet to cabin HX, higher evaporator enthalpy rise, lower mass flow rate
- **NH$_3$** requires lowest flow rate

**Pressure:**
- Max pressure highest for NH$_3$, lowest for HFE7000
Mass Flow Rate:
- Area decreases with increasing $T_{\text{lift}}$
- NH$_3$ requires smallest area but area differences among fluids are small
COP Trends
- Decreases with increasing $T_{\text{lift}}$ because of higher compressor work
- Higher for LLO because of lower evaporator inlet enthalpy
- Fairly equal for different fluids
1. **Chlorofluorocarbons (CFCs)**
   - Consist of chlorine, fluorine and carbon
   - Ex: R11, R12, R113, R114 and R115
   - High ozone depletion potential (ODP)
   - Already banned

2. **Hydrochlorofluorocarbons (HCFCs)**
   - Consist of hydrogen, chlorine, fluorine and carbon
   - Ex: R22, R123, R124 and R142b
   - Small but finite ODP
   - Being gradually phased out

3. **Hydrofluorocarbons (HFCs)**
   - Consist of hydrogen, fluorine and carbon
   - Ex: R404a, R134a, R245fa, HFE7000
   - Zero ODP; low global warming potential (GWP)
   - Currently preferred refrigerants

<table>
<thead>
<tr>
<th>Type</th>
<th>Rating</th>
<th>Critical Pressure (MPa)</th>
<th>Critical Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>-</td>
<td>B2</td>
<td>11.33</td>
</tr>
<tr>
<td>R404a</td>
<td>HFC</td>
<td>A1</td>
<td>3.73</td>
</tr>
<tr>
<td>R134a</td>
<td>HFC</td>
<td>A1</td>
<td>4.06</td>
</tr>
<tr>
<td>R245fa</td>
<td>HFC</td>
<td>B1</td>
<td>3.65</td>
</tr>
<tr>
<td>HFE7000</td>
<td>HFC</td>
<td>A1</td>
<td>2.48</td>
</tr>
<tr>
<td>R123</td>
<td>HCFC</td>
<td>B1</td>
<td>3.66</td>
</tr>
</tbody>
</table>

**Toxicity Rating:**
- Class A: no evidence of toxicity below 400 ppm
- Class B: evidence of toxicity below 400 ppm

**Flammability Rating:**
- Class 1: no flame propagation in open air
- Class 2: may propagate flame under certain conditions in open air
- Class 3: highly flammable
<table>
<thead>
<tr>
<th>Fluid</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH₃</td>
<td>Requires smallest flow rate but highest condenser pressure; exhibits toxicity and flammability</td>
</tr>
<tr>
<td>R404a</td>
<td>An HFC that requires high condenser pressure; exhibits no toxicity or flammability, zero ODP and low GWP</td>
</tr>
<tr>
<td>R134a</td>
<td>An HFC that provides compromise between reducing flow rate and reducing pressure; exhibits no toxicity or flammability, zero ODP and low GWP</td>
</tr>
<tr>
<td>R245fa</td>
<td>An HFC that provides compromise between reducing flow rate and reducing pressure; exhibits no flammability, zero ODP and low GWP, but some toxicity</td>
</tr>
<tr>
<td>HFE7000</td>
<td>An HFC that requires low condenser pressure but high flow rate; exhibits no toxicity or flammability, zero ODP and low GWP; used as replacement to R123</td>
</tr>
<tr>
<td>R123</td>
<td>An HCFC that requires low condenser pressure but high flow rate; exhibits no toxicity or flammability but some ODP</td>
</tr>
</tbody>
</table>

No significant differences among fluids in terms of radiator area or COP

**Preferred Coolant:** R134a *(1,1,1,2-Tetrafluoroethane, CH₂FCF₃)*
- LLSL-HX used high temperature of subcooled liquid exiting condenser to further superheat vapor before entering compressor
- Compared to basic heat pump: 8 to 8' and 4 to 4'
\[ \text{COP}' = \frac{Q_{\text{cabinHX}} + Q_{\text{avionicsHX}} + \Delta Q_{\text{cooling}}}{W_{\text{comp}} + \Delta W_{\text{comp}}} = \frac{1 + \frac{\Delta Q_{\text{cooling}}}{Q_{\text{cabinHX}} + Q_{\text{avionicsHX}}}}{1 + \frac{\Delta W_{\text{comp}}}{W_{\text{comp}}}} \text{ COP} \]
Heat Pump with LLSL-HX versus Basic Heat Pump Mode for R134a

Mass Flow Rate: appreciable reduction with LLSL-HX

COP: some degradation with LLSL-HX

Radiator Area: some improvement with LLSL-HX
Heat Pump Test Loop

Throttling Valve
($C_v = 0.73$)

Throttling Valve
($C_v = 1.8$)

Crew H/X

Avionics H/X

Turbine
Flow Meter

Filter

Liquid
Tank

Condenser

Fan

Solid-state
Controller

Variable
Frequency
Drive

Power
Meter

Compressor

T

P

Auto-
Transformer
Power
Meter

Auto-
Transformer
Power
Meter

Relief
Valve

Relief
Valve

Filter

Filter

Suction
Accumulator

Pressure
Switch

Power
Meter
<table>
<thead>
<tr>
<th></th>
<th>Max. Heat Load, Q (kW)</th>
<th>Max. Heat Flux, q&quot; (W/cm²)</th>
<th>Overall Dimensions</th>
<th>Number of Mini-Channels</th>
<th>Expected Pressure Drop (by correlation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabin HX</td>
<td>0.75 kW</td>
<td>3.13</td>
<td>Length : 152.4 mm (6”) Width : 152.4 mm (6”)</td>
<td>75</td>
<td>1.26 psi</td>
</tr>
<tr>
<td>Avionics HX</td>
<td>5.5 kW (LSO/MSO)</td>
<td>4.58</td>
<td>Length: 609.6 mm (24”) Width: 203.2 mm (8”)</td>
<td>100</td>
<td>6.34 psi</td>
</tr>
</tbody>
</table>
**Avionics HX: Cross Section and Temperature Measurements**

- **Polycarbonate Cover Plate**
- **G-7 Housing**
- **Copper block**
- **Heater**
- **G-10 Insulation**
- **Aluminum Cross Bars (H-Beam)**

**Thermocouples inside copper block**

- **Thermocouple at inlet**
- **Thermocouples inside copper block**
- **Thermocouple at outlet**

**Dimensions:**
- **2.79”**
- **2.28”** (repeated 7 times)

**Note:**
- Type-E, Miniature Thermocouple
Heat Transfer Characteristics and Dryout Effects
Avionics H/X: Heat Flux Effects

Avionics H/X (L = 609.6 mm)

\[ G_{\text{avionics}} = 283.53 \, \text{kg/m}^2\text{s} \]

\[ q_{\text{avionics}} \] [W/m²]

\[ h_{\text{tp}} \] [W/m²K]

\[ x_{di} = 0.445 \]

\[ x_e \]
- **Intermittent Dryout**: mostly in liquid film surrounding elongated slug flow bubble or due to vapor blanket formation within the liquid slug
- **Incipient Dryout**: dry wall patches in annular film
- **Dryout Completion**: annular flow replaced by mist flow, with cooling provided only by droplet deposition

\[
\text{Avionics H/X: } \begin{align*}
G_{\text{avionics}} &= 340.23 \text{ kg/m}^2\text{s} \\
q_{\text{avionics}} &= 44401.1 \text{ W/m}^2
\end{align*}
\]
Avionics H/X: Two-Phase Flow Patterns and Heat Transfer Mechanisms

(i) $x_e < 0.36$
- Liquid film
- Intermittent dryout due to vapor blanket formation in liquid slug
- Bubble formed by liquid bridging
- Intermittent dryout in liquid film

(ii) $0.36 < x_e < 0.50$
- Wavy annular liquid film shear driven by vapor core
- Liquid droplets entrained in vapor core

(iii) $0.50 < x_e < 0.74$
- Incipient dryout caused by formation of dry patches in liquid film
- Dry wall patches cooled only by droplet deposition
Macro-channel:

Chen (1966)

Liu & Winterton (1961)

Mini/Micro-channel:

Lazarek & Black (1982)

Tran et al. (1996)

Kandlikar (2004)

Lee & Mudawar (2005)

Bertsch et al. (2009)

Kim & Mudawar (2014)
Comparison of Present Average Two-Phase Heat Transfer Coefficient with Predictions of Universal Methodology

Kim & Mudawar (2014)

MAE = 21.19%, θ = 69.92%, ζ = 95.12%
Consolidated database:
10,805 saturated boiling heat transfer coefficient data points from 37 sources

- Working fluid:
  FC72, R11, R113, R123, R1234yf, R1234ze, R134a, R152a, R22, R236fa, R245fa, R32, R404A, R407C, R410A, R417A, CO₂, water

- Hydraulic diameter:
  0.19 < \( D_h \) < 6.5 mm

- Mass velocity:
  19 < \( G \) < 1608 kg/m²s

- Liquid-only Reynolds number:
  57 < \( Re_{fo} \) < 49,820

- Flow quality:
  0 < \( x \) < 1

- Reduced pressure:
  0.005 < \( P_{R} \) < 0.69


\[ h_{fp} = \left( h_{nb}^2 + h_{cb}^2 \right)^{0.5} \]

For nucleate boiling dominant regime:

\[ h_{nb} = \left[ 2345 \left( Bo \frac{P_H}{P_F} \right)^{0.70} P_R^{0.38} \left( 1 - x_e \right)^{-0.51} \right] \left( 0.023 Re_f^{0.8} Pr_f^{0.4} \frac{k_f}{D_h} \right) \]

For convective boiling dominant regime:

\[ h_{cb} = \left[ 5.2 \left( Bo \frac{P_H}{P_F} \right)^{0.08} We_{fo}^{-0.54} + 3.5 \left( \frac{1}{X_H} \right)^{0.94} \left( \frac{\rho_g}{\rho_f} \right)^{0.25} \right] \]

\[ \times \left( 0.023 Re_f^{0.8} Pr_f^{0.4} \frac{k_f}{D_h} \right) \]

where

\[ Bo = \frac{q_{\bar{H}}}{G h_f}, \quad P_R = \frac{P}{P_{crit}}, \quad Re_f = \frac{G(1 - x_e)D_h}{\mu_f} \]

\[ We_{fo} = \frac{G^2 D_h}{\rho_f \sigma}, \quad X_H = \left( \frac{\mu_f}{\mu_g} \right)^{0.1} \left( \frac{1-x_e}{x_e} \right)^{0.9} \left( \frac{\rho_f}{\rho_g} \right)^{0.5} \]

\( q_{\bar{H}} \): effective heat flux averaged over heated perimeter of channel

\( P_H \): heated perimeter of channel

\( P_F \): wetted perimeter of channel
Universal Predictive Methodology for Saturated Flow Boiling Heat Transfer in Small Diameter Tubes

Nucleate Boiling Dominant Data

- 8284 nucleate boiling dominant data
- MAE = 20.7%

Convective Boiling Dominant Data

- 2541 convective boiling dominant data
- MAE = 19.0%

Graphs show the relationship between predicted and experimental heat transfer coefficients ($h_{tp}$) for nucleate and convective boiling dominant conditions. The graphs are accompanied by visual representations of flow patterns including single-phase liquid, bubbly flow, slug flow, annular flow, and mist flow, highlighting incipience and completion points of dryout.
Parallel channel instability: Small amplitude, high frequency pressure drop oscillations (4,000 - 10,000 Pa over period of 1.33 s)

\[ \Delta p_{\text{crew}} = P_{\text{crew,in}} - P_{\text{crew,out}} \ [\text{Pa}] \]

- \( G_{\text{crew}} = 264.63 \ \text{kg/m}^2\text{s} \)
- \( q''_{\text{crew}} = 16146.9 \ \text{W/m}^2 \)
Pressure Drop Oscillations in Crew H/X

Discrete Fourier transform: pressure drop response in frequency domain
(power spectrum peak of 0.74 Hz (~ 1.33 sec)

R134a
$G_{\text{crew}} = 264.63 \text{ kg/m}^2\text{s}$
$q''_{\text{crew}} = 16146.9 \text{ W/m}^2$