System trade-off analysis of two-phase mechanically pumped fluid loop for thermal control of future deep space missions

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Future deep space missions

• Exploring to the outer space
  – Extreme environment
  – Low solar power

• Requirements for thermal control system
  – Low power consumption & waste heat reclamation
  – Light weight system
  – Keeping science instruments isothermal

• Current thermal control technology
  – Loop Heat Pipe
    • Flight system integration and distance issues, Evaporator shape
  – Single-Phase Mechanically Pumped Fluid Loop
    • Large ΔT in cold plate and across loop, large mass

• Two-Phase Mechanically Pumped Fluid Loop
  – Potential ability to meet requirements
Two-Phase Mechanically Pumped Fluid Loop

• **Working Principle**
  – Fluid driven by pump
  – Liquid absorbs heat in evaporator and changes to two-phase flow
  – Two-phase flow dissipates heat in condenser and changes to liquid
  – Accumulator controls temperature

• **Merits**
  – Pump driving
    • Long heat transport distance
    • Robust start-up
  – Phase change
    • Light weight
    • Low power consumption
    • Small ΔT on the evaporator

<table>
<thead>
<tr>
<th></th>
<th>LHP</th>
<th>SPMPFL</th>
<th>2PMPFL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>✗</td>
<td>〇</td>
<td>〇</td>
</tr>
<tr>
<td>Robustness</td>
<td>△</td>
<td>〇</td>
<td>〇</td>
</tr>
<tr>
<td>Isothermality</td>
<td>△</td>
<td>✗</td>
<td>〇</td>
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<tr>
<td>Low mass</td>
<td>〇</td>
<td>✗</td>
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</tbody>
</table>

TFAWS 2016 – August 1-5, 2016
Researches

• Experiment project at JEM in ISS
  – To clarify effects on heat transfer and critical heat flux in flow boiling

• AMS-2
  – The first full-size 2PMPFL in space
  – Searching for dark matter at ISS
  – The working fluid is CO₂

• Working fluid selection
  – A lot of criteria
    • Heat transport performance
    • Mass of system
    • Power consumption of pump
    • Others…

• Problem
  – Considering whether the working fluids satisfy the requirements of system

Figure of Merit of low pressure drop
H.J. Gerner et al,
ICES-2014-136, 2014
Evaluating the working fluids by total mass of system with 1D steady model of Two-Phase Mechanically Pumped Fluid Loop

- Contents
  - Evaluating method
  - Mathematical model of 2PMPFL
  - System analysis
  - Evaluating the working fluid
Evaluating method

• Requirements
  – Heat input 500W
  – Payload bench 0.5m²
  – Spatial uniformity on evaporator < 3°C

• Constraint
  – Mass without evaporator and radiator <10kg
    *Evaporator and radiator are made with structure panel of spacecraft

• Objective function
  – Mass of system
    \[ M_{system} = F(\lambda, \rho, \mu, c_p, k, T, P, \sigma) \]
    \[ M_{system} = M_{pump} + M_{accumulator} + M_{fluid} + M_{tube} \]
Mathematical model of 2PMPFL
• Assumptions
  – Not considering conduction of tube wall
  – Not considering degree of super heat for boiling
  – Constant heat flux in evaporator

• Modeling
  1. Input assumed pressure and temperature
  2-4. Liquid evaporates in the evaporator
  5. Two-phase flows into radiator
  5-7. Two-phase is cooled by radiator
  8. Accumulator controls the temperature
  9. Pump provides the driving pressure
  1. New initial value
Equations

- **Single-phase**
  - Pressure: \( P_{SP}^i = P_{SP}^{i-1} - \frac{f_{SP}L\rho_{SP}u_{SP}^2}{2D_h} \)
  - Temperature: \( T_{SP}^i = T_{SP}^{i-1} + \frac{Q_{in}}{mC_{p,SP}} \)

- **Two-phase**
  - Pressure: \( P_{2P}^i = P_{2P}^{i-1} - \left\{ \left(1 + x \frac{\rho_l - \rho_g}{\rho_g}\right)\left(1 + x \frac{\mu_l - \mu_v}{\mu_v}\right)^{-0.25} \right\} \frac{f_l\rho_l u_l^2}{2D_{in}} \)
  - Temperature: \( T_{2P}^i = T_{sat}(P_{2P}^i) \)
  - Quality: \( x = \frac{H^{i-1} + \frac{Q_{in}}{m} - H_{sat,l}}{\lambda} \)
Evaporator Design

• Requirements
  – Large flat area for flexible heat load placement
  – Dimensionally and temporally isothermal benches for science instruments

• Design
  – Wick structure for uniformly supplying the liquid
  – Heat is transferred through the pillars
  – Liquid evaporates at the whole area
  – Subcooled liquid is heated in wick and liquid chamber

Evaporator design
Eric Sunada et al, ICES-2016-129, 2016
• Assumption
  – All heat input is consumed for temperature rise and evaporation of fluid
  – All heat is transferred through the pillars
  – Liquid flows uniformly through the wick
  – Retreat of the meniscus in the wick is neglected
  – Pressure at the vapor-liquid junction is equal to pressure of the liquid
• **Modeling**

1. Liquid flows into evaporator
2-3 Some liquid flows top of evaporator
   - Temperature of liquid rises by heat leak \( T_3 = T_2 + \frac{Q_{HL}}{m_l c_p} \)
4. The wick absorbs the rest of liquid
   - Heat input evaporates liquid at the surface of wick
4-5 Vapor flows bottom of wick
6. Liquid and vapor are mixed
   - \( T_6 = T_3 \), \( P_6 = P_3 \)
• Modeling
  – Tube-on-plate radiator
  – One side radiating to the cold space
  – Area is enlarged to fulfill the Net Positive Suction Head (NPSH) requirement
• Modeling
  – Accumulator size is driven by these two cases
    • Startup = Liquid occupies the entire loop with some reserve fluid in accumulator ($\beta$)
    • Worst hot case = Vapor volume is maximized with some reserve vapor space in accumulator ($\alpha$)

→ Calculating the accumulator volume

\[ V_{acc} = \frac{V_{2\phi} + V_{evap,vapor} + V_{rad}}{\alpha - \beta} \]
Mass calculation

- **Pump**
  
  \[ M_{\text{pump}} = 0.25W_{\text{pump}} \]  
  (Power: \( W_{\text{pump}} = \frac{\Delta P \dot{m}}{\rho \eta_{\text{pump}}} \))

- **Accumulator**
  
  \[ M_{\text{acc}} = \rho_{\text{acc}} \pi \delta_{\text{acc}} D_{\text{acc}} L_{\text{acc}} \]  
  (Thickness: \( \delta = \frac{PD_{\text{out}}}{2(S+0.4P)} \))

- **Fluid**
  
  \[ M_{\text{fluid}} = \rho_l (0.15V_{\text{acc}} + V_{\text{tube-in}} + V_{\text{evaporator}}) \]

- **Tubing**
  
  \[ M_{\text{tube}} = \rho_{\text{tube}} V_{\text{tube}} \]

Not including the mass of evaporator and radiator which is made with panel of structure.
System analysis
Calculating condition

• Inputs
  – Fluid: Ammonia
  – Mass Flow rate: 0.003kg/s
  – Whole loop
    • Thermal transporting length: 1.7m
    • Inner diameter of pipe: 3.87mm
    • Outer diameter of pipe: 6.35mm
  – Evaporator
    • Heat load: 500W
    • Temperature of surface: 20°C
    • Area: 0.5m²
    • Wick pore diameter: 60μm
    • Pillar: 7.87 × 7.87 × 5.08mm³
  – Radiator
    • Sink temperature: 4K
    • Length of fin: 25.4mm
    • Thickness of fin: 1mm
  – Pump
    • Net Positive Suction Head: 138kPa
Results: Whole loop

- Radiator length → Mass of Tubing, Fluids
- Absolute pressure → Mass of Accumulator
- Pressure drop → Mass of Pump
Results: Evaporator

- Liquid is heated from subcooled to saturation
- Spatial temperature of surface fulfills the requirement $< 3^\circ\text{C}$
• Total Mass is 9.96 kg
• Mass of fluid is the largest
Evaluating the working fluid
Working fluid selection

• Criteria
  – Saturation pressure < 1.4 MPa at 20 °C
  – Freezing point < -70 °C
  – Availability

• Working fluids
  – AMMONIA – BUTANE
  – R12 – R245FA
  – R134A – R245CA
  – R152A – R114
  – R124 – R11
  – ISOBUTANE – R123
  – R142B – R141B
  – C318 – R113
  – R236FA – PROPYLENE
  – WATER
Fluids occupy the mass of system

Density of working fluid is critical for mass of system

Propylene, Isobutane, Ammonia and Butane fulfil the requirement of mass < 10kg

<table>
<thead>
<tr>
<th>Name</th>
<th>Density [kg/m³] (at 20 °C)</th>
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<tbody>
<tr>
<td>PROPYLENE</td>
<td>515.02</td>
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<tr>
<td>ISOBUTANE</td>
<td>557.04</td>
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<tr>
<td>AMMONIA</td>
<td>610.42</td>
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<tr>
<td>BUTANE</td>
<td>578.76</td>
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<td>R152A</td>
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<tr>
<td>R134A</td>
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<td>1377.2</td>
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<td>R123</td>
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</table>
Conclusion

• Evaluating the working fluids by total mass of system with 1D steady model of 2PMPFL
  – 1D steady 2PMPFL model for mass of system is developed
  – System analysis has been done.
  – Evaluating the working fluid
    • Working fluid drives the mass of system with the assumed evaporator design.
      – Density of working fluid is the key factor of mass of system
    • Propylene, Ammonia, Isobutane and butane fulfil the requirement of mass < 10kg

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