Introduction to Loop Heat Pipes

Jentung Ku
NASA/ Goddard Space Flight Center

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Outline

• From Heat Pipe to Loop Heat Pipe (and Capillary Pumped Loop)
• LHP Operating Principles
• LHP Components Sizing and Fluid Inventory
• LHP Operating Temperature Control
• LHP Start-up
• LHP Shutdown
• LHP Analytical Modeling
• Recent LHP Technology Developments
From Heat Pipe to Loop Heat Pipe and Capillary Pumped Loop
Heat Pipes - Heat Transport Limit

- For proper heat pipe operation, the total pressure drop must not exceed its capillary pressure head.
  \[ \Delta P_{tot} \leq \Delta P_{\text{cap, max}} \]
  \[ \Delta P_{tot} = \Delta P_{\text{vap}} + \Delta P_{\text{liq}} + \Delta P_{g} \]
  \[ \Delta P_{\text{cap, max}} = \sigma \cos \theta / R_p \]

- Heat Transport Limit
  - \((QL)_{\text{max}} = Q_{\text{max}} L_{\text{eff}}\)
  - \(L_{\text{eff}} = 0.5 L_e + L_a + 0.5 L_c\)
  - \((QL)_{\text{max}}\) measured in watt-inches or watt-meters

- Capillary pressure head:
  \[ \Delta P_{\text{cap}} \propto 1 / R_p \]

- Liquid pressure drop:
  \[ \Delta P_{\text{liq}} \propto 1 / R_p^2 \]

- An optimal pore radius exists for maximum heat transport.
  - Limited heat transport capability
  - Limited pumping head against gravity
• Wicks are present only in the evaporator, and wick pores can be made small.
• Smooth tubes are used for rest of the loop, and can be separately sized to reduce pressure drops.
• Vapor and liquid flow in the same direction instead of countercurrent flows.
• Operating temperature varies with heat load and/or sink temperature.
The reservoir stores excess liquid and controls the loop operating temperature.

The operating temperature can be tightly controlled with small heater power.

The loop can be easily modified or expanded with reservoir re-sizing.

Pre-conditioning is required for start-up.

Evaporator cannot tolerate vapor presence, may be prone to deprime during start-up.

Polyethylene wick with pore sizes ~ 20 µm
Capillary Two-Phase Thermal Devices

- Reservoir
- Evaporator
- Condenser/Subcooler
- Liquid Line
- Vapor Line
- Heat In
- Heat Out
- Heat In/Out
- Wick Structure
- Container Wall
- Q_{IN}
- Q_{OUT}
- Evaporation
- Condensation
- Liquid Flow
- Vapor Flow
CPL and LHP Flight Applications – NASA Spacecraft

TERRA, 6 CPLs
Launched Dec 1999

HST/SM - 3B; 1 CPL
Launched Feb 2002

AURA, 5 LHPs
Launched July 2004

ICESat, 2 LHPs
Launched Jan 2003

SWIFT, 2 LHPs
Launched Nov 2004

GOES N-Q, 5 LHPs each
Launched 2006

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GOES R-U, 4 LHPs each  
To be launched

ICESat-2, 1 LHP  
To be launched

SWOT, 4 LHPs  
To be launched

- LHPs are also used on many DOD spacecraft and commercial satellites.
Introduction to Loop Heat Pipes
• **Main design features**
  - The reservoir (compensation chamber or CC) forms an integral part of the evaporator assembly.
  - A primary wick with fine pore sizes provides the pumping force.
  - A secondary wick connects the CC and evaporator, providing liquid supply.
Main Characteristics of LHP

- **High pumping capability**
  - Metal wicks with ~ 1 micron pores
  - 35 kPa pressure head with ammonia (~ 4 meters in one-G)
- **Robust operation**
  - Vapor tolerant: secondary wick provides liquid from CC to evaporator
- **Reservoir** is plumbed in line with the flow circulation.
  - Operating temperature depends on heat load, sink temperature, and surrounding temperature.
  - External power is required for temperature control.
  - Limited growth potential
    - Single evaporator most common
LHP Operating Principles – Pressure Balance

- The total pressure drop in the loop is the sum of viscous pressure drops in LHP components, plus any pressure drop due to body forces:
  \[ \Delta P_{tot} = \Delta P_{groove} + \Delta P_{vap} + \Delta P_{cond} + \Delta P_{liq} + \Delta P_{wick} + \Delta P_g \]  \hspace{1cm} (1)

- The capillary pressure rise across the wick meniscus:
  \[ \Delta P_{cap} = 2\sigma \cos \theta / R \]  \hspace{1cm} (2)

- The maximum capillary pressure rise that the wick can sustain:
  \[ \Delta P_{cap, \text{max}} = 2\sigma \cos \theta / r_p \]  \hspace{1cm} (3)

  \( r_p \) = radius of the largest pore in the wick

- The meniscus will adjust its radius of curvature so that the capillary pressure rise matches the total pressure drop which is a function of the operating condition:
  \[ \Delta P_{cap} = \Delta P_{tot} \]  \hspace{1cm} (4)

- The following relation must be satisfied at all times for proper LHP operation:
  \[ \Delta P_{tot} \leq \Delta P_{cap, \text{max}} \]  \hspace{1cm} (5)
Evaporator core is considered part of reservoir.

- $P_6$ is the reservoir saturation pressure.
- All other pressures are governed by $P_6$.
- All pressure drops are viscous pressure drops.
Thermodynamic Constraints in LHP Operation (1)

• For the working fluid in a saturation state, there is a one-to-one correspondence between the saturation temperature and the saturation pressure.

• There are three LHP elements where the working fluid exists in a two-phase state, i.e. evaporator, condenser and reservoir.

• There is a thermodynamic constraint between any two of the above-mentioned three elements, i.e. the pressure drop and the temperature drop between any two elements are thermodynamically linked. E.G.

\[ P_E - P_{cc} = \frac{dP}{dT} (T_E - T_{cc}) \]

• The derivative \( \frac{dP}{dT} \) can be related to physical properties of the working fluid by the Clausius-Clapeyron equation:

\[ \frac{dP}{dT} = \lambda / (T_{cc} \Delta v) \]
Thermodynamic Constraints in LHP Operation (2)

\[
P_E - P_{\text{cond}} = (dP/dT) (T_E - T_{\text{cond}})
\]

\[
P_{\text{cond}} - P_{cc} = (dP/dT) (T_{\text{cond}} - T_{cc})
\]

\[
P_E - P_{cc} = (dP/dT) (T_E - T_{cc})
\]

- Gravity affects the pressure drop, and hence the temperature difference.

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\[ Q_{IN} = Q_E + Q_L \]
\[ Q_L = G_{E,CC}(T_E - T_{CC}) \]
\[ Q_E = m \lambda \]
\[ Q_{c,2\phi} = m \lambda = 2\pi D_c L_{c,2\phi} h_{c,2\phi}(T_{CC} - T_{c,wall}) \]

\[ T_{c,\text{out}} = f(m, L_{c,2\phi}, T_{c,\text{wall}}) \]
\[ T_{IN} = f(T_{c,\text{out}}, m, L_{LL}, D_{LL}, T_{amb}) \]
\[ Q_{\text{sub}} = m C_P(T_{CC} - T_{IN}) \]
\[ Q_{\text{leak}} - Q_{\text{sub}} + Q_{RA} = 0 \]
Simplified LHP Thermal Network

- **Reservoir**
- **Heat In**
- **Condenser/Subcooler**
- **Vapor Line**
- **Liquid Line**
- **Evaporator**
- **Heat In/Out**
- **ambT**
- **Q_e**
- **Q_cce**
- **Heat Out**
- **Compensation Chamber**
- **Evaporator**
- **m, h_e, T_e, q_e = 1**
- **T_amb**
- **Q_vat**
- **Inactive Condenser (Subcooler)**
- **Active Condenser**
- **m, h_i, T_i, q_i = 0**
- **T_amb**
- **m, h_i, T_i, q_i = 0**
- **Q_{vat,at}**
- **Q_{vat}**
- **Q_{cc,at}**
- **Q_{cc}**
- **m, h_{cc}, T_{cc}, q_{cc}**

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LHP Reservoir Sizing and Fluid Inventory

- The fluid inventory must satisfy the following relation under the cold start-up/operation ($\beta > 0$):
  \[ M = \rho_{l,c} (V_{loop} + \beta V_{cc}) + \rho_{v,c} (1 - \beta) V_{cc} \]
  \[ V_{loop} = \text{Loop volume excluding CC} \]

- The fluid inventory must also satisfy the following relation under the hot operating condition ($\alpha > 0$):
  \[ M = \rho_{l,h} [V_{liq} + V_{pw} + V_{sw} + (1 - \alpha) V_{cc}] + \rho_{v,h} (V_{gr} + V_{vap} + V_{con} + \alpha V_{cc}) \]

- The values of $\alpha$ and $\beta$, selected at the designer’s discretion, determine $V_{cc}$ and $M$.

- The loop must contain all liquid volume at the maximum non-operating temperature:
  \[ M \leq \rho_{l,\text{max}} (V_{loop} + V_{cc}) \]
ICESat-2 ATLAS LHP Charge Analysis
15% Fill in Cold Case

- Charge to maintain 15% CC fill fraction in the cold case startup conditions
- LHP requires 193.4 grams of ammonia

<table>
<thead>
<tr>
<th>Volume</th>
<th>Cold Start-up</th>
<th>Non-Operating Case</th>
<th>Operating Hot Case</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>liquid fraction</td>
<td>temp</td>
<td>liquid dens</td>
</tr>
<tr>
<td></td>
<td>in3</td>
<td>cc</td>
<td>in3</td>
</tr>
<tr>
<td>Evaporator (vapor)</td>
<td>0.43</td>
<td>7.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Evaporator (liquid)</td>
<td>4.67</td>
<td>76.5</td>
<td>4.7</td>
</tr>
<tr>
<td>Liquid Core</td>
<td>0.69</td>
<td>11.2</td>
<td>0.7</td>
</tr>
<tr>
<td>Vapor transport line</td>
<td>1.28</td>
<td>21.0</td>
<td>1.3</td>
</tr>
<tr>
<td>Condenser</td>
<td>4.92</td>
<td>80.6</td>
<td>4.9</td>
</tr>
<tr>
<td>Liquid Transport Line</td>
<td>2.00</td>
<td>32.8</td>
<td>2.0</td>
</tr>
<tr>
<td>Hydro-accumulator Wicks Liquid</td>
<td>0.24</td>
<td>3.9</td>
<td>0.2</td>
</tr>
<tr>
<td>Hydro-accumulator Free Volume</td>
<td>23.50</td>
<td>385.1</td>
<td>23.5</td>
</tr>
<tr>
<td>TOTAL</td>
<td>37.72</td>
<td>618.27</td>
<td>37.7</td>
</tr>
</tbody>
</table>

- 15% required reservoir liquid fraction at cold startup ($\beta = 0.15$)
- Design has 70% void volume in hot non-operational (processing) case at 60C
- 51.8% max fill at hot operating condition ($\alpha = 0.482$)

Typical values:
- $\alpha \geq 0.15$ ($\leq 0.85$ liquid fraction)
- $\beta \geq 0.15$ (0.15 liquid fraction)

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LHP Operating Temperature

- The LHP operating temperature is governed by the CC saturation temperature.
- The CC temperature is a function of
  - Evaporator power
  - Condenser sink temperature
  - Ambient temperature
  - Evaporator/CC assembly design
- As the operating condition changes, the CC temperature will change during the transient, but eventually reaches a new steady temperature.
LHP Operating Temperature
No Active Control of CC Temperature

- For a well insulated CC, $T_{cc}$ is determined by energy balance between heat leak and liquid subcooling.
- $T_{cc}$ changes with the evaporator power, condenser sink temperature, and ambient temperature.

\[ Q_{\text{leak}} - Q_{\text{sub}} = 0 \]
\[ Q_{\text{leak}} = G_{E,cc} (T_E - T_{cc}) \]
\[ Q_{\text{sub}} = mC_p(T_{cc} - T_{in}) \]
Effect of Sink Temperature on CC Temperature - Theory

\[ T_{\text{sink}3} > T_{\text{amb}} > T_{\text{sink}2} \]

\[ T_{\text{sink}2} > T_{\text{sink}1} \]

\[ T_{2\text{min}} \]

\[ T_{1\text{min}} \]

Q_2 Q_1

Net Evaporator Power
Ground Test Results of Thermacore miniLHP at Various Sink Temperatures

Operating Temperature vs Power
(New Chiller, Evaporator above Condenser by 0.25")

- Heater on large TM (Tsink = 293K)
- Heater on large TM (Tsink = 273K)
- Heater on large TM (Tsink = 253K)
- Heater on Evap. (Tsink = 293K)
- Heater on Evap. (Tsink = 273K)
- Heater on Evap. (Tsink = 253K)
LHP Operating Temperature
CC Temperature Controlled at $T_{set}$

- $Q_{cc}$
- $Q_{leak}$
- $-Q_{sub}$

CC, $T_{cc} \equiv T_{set}$

\[ Q_{leak} - Q_{sub} + Q_{cc} = 0 \]
\[ Q_{cc} = Q_{sub} - Q_{leak} \]

- CC is cold biased, and electrical heaters are commonly used to maintain $T_{cc}$ at $T_{set}$.
- Overall thermal conductance decreases.
- $Q_{cc}$ varies with $Q_{sc}$, which in turns varies with evaporator power, condenser sink temperature, ambient temperature and number of coupling blocks.
- $Q_{cc}$ can be large under certain operating conditions.
- Electrical heaters can only provide heating, not cooling, to CC.
LHP Temperature Control Methods

- All methods involve cold-biasing the CC and use external heat source to maintain CC temperature
  - Electric heater on CC only (Aura TES, GOES-R GLM)
  - Electric heater on CC and coupling blocks placed between vapor and liquid lines (ICESat GLAS)
  - Electric heater on CC and VCHP connecting the evaporator and liquid line (Swift BAT)
  - Pressure regulator on the vapor line with a bypass to liquid line (AMS)
  - TEC on CC with thermal strap connecting to the evaporator (heating and active cooling) – no electric heater (ST8)
  - Heat exchanger and separate subcooler (GOES-R ABI, ICESat-2 ATLAS)
LHP Operating Temperature Control
Electric Heater on CC

\[ Q_{leak} - Q_{sub} + Q_{cc} = 0 \]
\[ Q_{cc} = Q_{sub} - Q_{leak} \]

- The electrical heater attached to the CC provides the necessary control heater power to the CC.
- Advantages: simplicity, direct heating
- Disadvantage: required control heater power could be large.
CCHPs and LHPs manage equipment power dissipation from:

- 2 Mechanical Cooler Compressors
- Cooler electronics
- Signal Chain and Laser Head electronics
- Integrated Electronics Module (IEM)
EOS-Aura TES Components Thermal Performance

![Graph showing temperature variations over time for Cryocooler Electronics Power Boards and Cryocooler Compressor]
The coupling blocks serve as a heat exchanger which transfers heat from the vapor line to the liquid line.

- Re-distribution of LHP internal heat
- The reduction of liquid subcooling, $Q_{sub}$, leads to reduced $Q_{cc}$.
- The contact area of coupling blocks is determined by the LHP hot operational condition; the CC heater is then sized to accommodate the worst subcooling condition.

\[
Q_{leak} - Q_{sub} + Q_{cc} = 0
\]
LHP Operating Temperature Control
Use Coupling Blocks

- Advantages
  - Easy to implement
  - Efficient in reducing CC control heater power

- Disadvantages
  - Increases the natural operating temperature at low and high powers
  - May add difficulty to low power start-up
  - May still require high CC control heater power under the cold condition.

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LHPs on ICESat

- GLAS has high powered lasers to measure polar ice thickness
- First known application of a two-phase loop to a laser
- 2 LHPs; Laser altimeter and power electronics
  - Propylene LHPs
- Launched January, 2003
- Both LHPs successfully turned on
- Very tight temperature control ~ 0.2 °C
Coupling Blocks on ICESat GLAS LHPs

- There are eight coupling blocks between the vapor and liquid lines for each LHP.
  - Liquid subcooling is reduced by about one half.
- The ICESat spacecraft was launched in January 2003.
- Both LHPs have been working very well.
GLAS Laser Temperatures

- LLHP active control is finer than can be measured in the laser telemetry when the LHP is at full 110 W of power
LHP Operating Temperature Control
Use VCHP to Couple Evaporator and Liquid Line

\[ Q_{leak} - Q_{sub} + Q_{cc} = 0 \]

\[ Q_{cc} = Q_{sub} - Q_{leak} \]

- The VCHP transmits heat from the evaporator to the liquid line when the return liquid is too cold, reducing the amount of liquid subcooling, \( Q_{sub} \).
  - The required CC control heater power \( Q_{cc} \) is reduced.
- The VCHP is shut down when more subcooling is needed.
LHP Operating Temperature Control
Use VCHP to Couple Evaporator and Liquid Line

- **Advantage**
  - Active control of heating the liquid line versus passive heating when compared to the coupling blocks

- **Disadvantages**
  - Needs a VCHP, which may not be ground testable.
  - Needs an additional control device for the VCHP.
  - VCHP reservoir requires cold biasing.
LHPs on SWIFT BAT

- Burst Alert Telescope, a gamma ray detector array, is one of three instruments on Swift.
- Launched: November 20, 2004
- Detector array has 8 CCHPs for isothermalization and transfer of 253 W to dual, redundant, LHPs located on each side.
Swift BAT LHP Evaporator Assembly

- G-10 washers for thermal isolation
- Titanium bracket support of hydro-accumulator
- Saddle soldered to VCHP
- Aluminum clamps for VCHP
- Saddle attached to evaporator saddle with Eccobond
- CCHPs attached to evaporator saddle with Eccobond
- Heat exchanger swaged over VCHP condenser
- Titanium support bracket for VCHP reservoir

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• Temperature fluctuations of detectors < 0.4 °C
• Frequent spacecraft slews have no noticeable effect on LHP operation.
• Flight results verify satisfactory operation of dual LHPs for tight temperature control.
The subcooler is separated from the condenser.

The liquid line is coupled with the vapor line through a heat exchanger, where liquid is allowed to vaporize. The liquid line then enters the subcooler.

With proper sizing, the heat exchanger will take away most of the subcooling, and the subcooler will provide slightly subcooled liquid to the CC.

Results of TV testing of ABI LHPs indicate that the design meets the LHP temperature control and CC control heater power requirements.
LHP Operating Temperature
Use Heat Exchanger and Separate Subcooler

- **Advantages**
  - The natural operating temperature will be closer to $T_{set}$ for heat loads between $Q_{Low}$ and $Q_{High}$.
  - The CC control heat power is reduced significantly.

- **Disadvantages**
  - Needs a separate subcooler.
  - Needs a longer liquid line, which imposes a higher frictional pressure drop.
GOES-R ABI Radiator/LHP Assembly System Architecture

Evaporator Assemblies (2)

Transport Lines

Heat Exchangers (2)

Sub-cooler Region (Condenser-like lines embedded in Panel)

Transport Lines

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LHP Operating Temperature Control
Use Pressure Regulator and Vapor Bypass

\[
\begin{align*}
Q_{\text{leak}} - Q_{\text{sub}} + Q_{\text{cc}} &= 0 \\
Q_{\text{cc}} &= Q_{\text{sub}} - Q_{\text{leak}}
\end{align*}
\]

- The pressure regulator and vapor bypass valve allow some vapor to flow to the reservoir when needed.
  - Re-distribution of LHP internal heat
- The required reservoir control heater power $Q_{\text{cc}}$ is reduced.
- Several variations of this approach.
  - Passive: no heater for bypass valve. A single set point temperature.
  - Active: bypass valve is controlled by an external heater.
LHP Operating Temperature Control
Use Pressure Regulator and Vapor Bypass

\[
Q_{\text{leak}} - Q_{\text{sub}} + Q_{\text{cc}} = 0
\]

\[
Q_{\text{cc}} = Q_{\text{sub}} - Q_{\text{leak}}
\]

- The pressure regulator and vapor bypass valve allow some vapor to flow to the reservoir when needed.
  - Re-distribution of LHP internal heat
- The required reservoir control heater power \( Q_{\text{cc}} \) is reduced.
- Several variations of this approach.
  - Passive: no heater for bypass valve. A single set point temperature.
  - Active: bypass valve is controlled by an external heater.
LHP Operating Temperature
Use Pressure Regulator and Vapor Bypass

- Advantages
  - Requires very little CC control heater power.
- Disadvantages
  - More complex design.
  - Calculation of flow rate through bypass valve is complex.
  - Additional heater and controller for the pressure regulator.
LHP Operating Temperature Control
Use Pressure Regulator and Vapor Bypass

• Passive bypass valve
  – Yamal 2000 spacecraft, launched in 2003
  – Payload temperature was controlled within ±2K.

• Active bypass valve
  – TerraSAR satellite
  – Ground tests demonstrated temperature control within ±0.5K for heat load of 5W to 15W and condenser sink temperature between 233K and 308K.
  – TerraSAR was launched in 2007. Thermal control system was functioning successfully.
LHP Operating Temperature
Use TEC

- **Advantages**
  - Can be used to heat or cool the CC
  - Changing the voltage polarity changes the mode of operation
  - Very efficient
- **Disadvantages**
  - More complex design
  - Additional mass
Schematic of ST 8 MLHP
Use TECs and Coupling Blocks for CC Temperature Control

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The loop operating temperature was controlled within ±0.5K by TECs regardless of changes in evaporator power and/or sink temperature, and regardless of which CC was being controlled.
LHP Operating Temperature Control
Use Secondary Evaporator

\[ Q_{cc} - Q_{sub} + Q_{cc} = 0 \]

\[ Q_{cc} = Q_{sub} - Q_{leak} \]

- The secondary evaporator forms an LHP within an LHP.
- The secondary loop cools the CC by drawing vapor out of the CC.
- Degenerates to the regular LHP when the secondary evaporator is not heated.
LHP Operating Temperature Control
Use Secondary Evaporator

- **Advantages**
  - Active cooling of the CC – can quickly reprime the loop
  - Especially useful for cryogenic LHP for start-up and parasitic heat control

- **Disadvantages**
  - Needs an additional evaporator and transport lines
  - Still needs CC control heater
NASA H2-CLHP POWER CYCLING

Date: 07/20/01

Note: TV chamber shroud was cooled by LN2

Temperature (K)

Power (Watts)

14:30 15:00 15:30 16:00 16:30 17:00 17:30 18:00 18:30 19:00 19:30 20:00 20:30

2nd Pump Power

Vapor Line (TC4)

Liquid Line (TC9)

Primary Pump (TC2)

2nd Condenser (TC15)

2nd Pump CC (TC13)

1st Pump CC (TC11)

Cold Finger (TC20)

2nd Pump CC (TC14)

Primary Pump Power

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LHP Start-up

- LHP Start-up is a complex phenomenon.

- The primary wick must be wetted prior to start-up.

- The loop start-up behavior depends on initial conditions inside the evaporator.
  - Vapor grooves on the outer surface of the primary wick
    - Liquid filled: superheat is required for nucleate boiling
    - Vapor presence: instant evaporation
  - Liquid core on the inner surface of the primary wick
    - Liquid filled: low heat leak
    - Vapor presence: high heat leak

- A minimum power is required for start-up under certain conditions.
Four Start-up Scenarios for LHP

• Vapor grooves
  – Liquid filled: superheat is required for nucleate boiling
  – Vapor presence: instant evaporation

• Liquid core
  – Liquid filled: low heat leak
  – Vapor presence: high heat leak
Vapor Presence in Vapor Grooves

• Situation 1
  – Vapor presence in vapor grooves
  – Core is liquid flooded; low heat leak
  – Instant liquid vaporization in grooves
  – Smooth start-up with no or small temperature overshoot during start-up transient

• Situation 2
  – Vapor presence in vapor grooves
  – Vapor presence in core; high heat leak
  – Instant liquid vaporization in grooves
  – Smooth start-up with possible large temperature overshoot during start-up transient
Worst Case Start-up – Situation 4

- **Situation 4**
  - Vapor grooves are flooded with liquid; superheat is required for nucleate boiling
  - Core contains vapor; high heat leak
  - The CC temperature rises along with the evaporator temperature
  - The required superheat may never be obtained before the maximum allowable temperature is reached.

![Diagram showing temperature changes](image-url)
Situation 3 – Choosing Between Two Evils

- **Situation 3**
  - Vapor grooves are flooded with liquid; superheat is required for nucleate boiling
  - Core is flooded with liquid; low heat leak
  - The CC temperature remains constant or rises slowly while the evaporator temperature is rising
  - The required superheat will eventually be reached.
- The current practice for LHP start-up is to flood the entire loop prior to start-up to guarantee the wick is wetted, and sustain the burden of potentially high superheat for nucleate boiling at start-up – “the lesser of the two evils”.

**Desired and Actual**
High and Low Power Start-up

• With high power to the evaporator, liquid in the vapor grooves can be vaporized quickly regardless of the initial two-phase status in the grooves and the evaporator core.
  – The required superheat, if any, can be achieved in a short time.
  – Within the short time, the total heat leak is small.

• With low power to the evaporator, start-up could be problematic.
  – Under situation 4, the required superheat for nucleate boiling may never be achieved.
  – After the loop starts, a steady state may not be established within the allowable temperature limit at low powers due to a high heat leak from evaporator to CC if the core contains vapor.
Some Examples of Start-up Tests

• Indication of the inception of loop start-up:
  – Sudden sharp increase of the vapor line temperature to the CC saturation temperature
  – Sudden sharp decrease of the liquid line temperature

• Successful start-up
  – The CC temperature approaches a SS
  – The vapor line temperature approaches a SS (same as or close to the CC temperature)
  – The evaporator temperature approaches a SS (slightly higher than the CC temperature)

• Results of some start-up tests under various conditions follow.
GLAS LHP Breadboard Start-up
(Evaporator core is liquid-filled)

Situation 3 start-up

GLAS LHP Start-Up
100 watts, No Controlling, Chiller@0°C, Radiator in Horizontal Position

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GLAS LHP Breadboard Start-up
(Vapor present in evaporator core)

Situation 4 start-up: 100W

GLAS LHP Start-Up
100 watts, No Controlling, Chiller@0°C, Radiator in Vertical Position

Graph showing temperature and power over time for different components:
- CompCham (TC2)
- Evaporator (TC10)
- VapLine (TC22)
- LiqLine (TC52)
- Cart1

Key events:
- Power spike at 10.0 hours
- Temperature changes in evaporator and comp cham
- Vap line and liq line indicate fluid movement

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GLAS LHP Breadboard Start-up
(Vapor present in evaporator core)

Situation 4 start-up: 20W
Enhancing the Start-up Success

• A small start-up heater is used to achieve the required superheat for nucleate boiling in a localized region to generate the first bubble in vapor grooves.
  – After vapor is present in grooves, liquid evaporation takes place instead of nucleate boiling, i.e. superheat is no longer required.
• Cool the CC using an active means (e.g. TEC).
LHP Shutdown

- Some instrument operation requires LHP to shutdown for a period of time.
- LHP can continue to pump fluid if the evaporator temperature is higher than the CC temperature.
- Requirements for LHP shutdown
  - No net heat load to evaporator
  - CC temperature is higher than evaporator temperature
    - Heating the CC is the only viable method

- When the CC temperature is higher than the evaporator temperature, fluid flow stops.
  - Loop will not restart as long as there is no net heat load to evaporator.
  - Loop may restart if the evaporator continues to receive net heat load and its temperature rises above the CC temperature.
- To guarantee that the payload stays above its minimum allowable temperature, the CC temperature control can be set slightly above that value during loop shutdown.
Analytical Modeling of LHP

• SINDA/Fluint can be used to model LHP operation.
  – CAPIL connector and CAPPMP macro to model wick
  – Phase suction option to model two-phase heat transfer
  – Tedious and time-consuming to build the detailed LHP model
  – Run time could be an issue

• Under NASA SBIR and the ST 8 Project, TTH Research Inc. has developed an LHP model specifically for the simulation LHP operation.
NASA LHP Analytical Model

- Developed by TTH Research, Inc. under NASA SBIR Project in 2002.
- The objective was to develop an analytical model to simulate LHP steady state and transient behaviors
  - based upon *physical laws* and verified by test data
  - efficient and stable solutions
  - easy to use by thermal analysts (non-experts)
  - accurate and detailed predictions for LHP researchers (experts)
  - Can be used as a stand-alone model for LHP design, or a subroutine to general thermal analyzer (e.g. SINDA/Fluint)
- Additional funding for modeling the secondary wick was provided by DOD and the ST8 project in 2005.
Modeling Approach

• Derive governing equations for each component and the overall loop based on mass, momentum and energy balance.
  – fluid movement based on pressure difference
  – improved heat leak model based on test data
  – two-phase correlations in condenser
  – database for fluid properties, wick performance characteristics

• Model Assumptions
  – One dimensional pipe flow
  – liquid and vapor at one temperature (saturation) inside the reservoir
  – track liquid level in CC at all times (including gravity effects)
  – Negligible amount of non-condensable gases

• Effects of gravity are included in the model.

*Compensation Chamber Fluid Distribution as a function of Gravity*
Nodal Map of LHP Analytical Model

Nodes 371-380 (Wall)
Fluid-to-Wall G171-G180
Nodes 1171-1180 (Fluid)

Nodes 261-270 (Wall)
Fluid-to-Wall G161-G170
Nodes 1161-1170 (Fluid)

Nodes 251-260 (Wall)
Fluid-to-Wall G151-G160
Nodes 1151-1160 (Fluid)

Nodes 341-350 (Wall)
Fluid-to-Wall G141-G150
Nodes 1141-1150 (Fluid)

Nodes 251-260 (Wall)
Fluid-to-Wall G51-G60

Nodes 1051-1060 (Fluid)
Nodes 201-220 (Wall)

Nodes 1021-1030 (Fluid)
Fluid-to-Wall G21-G30
Nodes 221-230 (Wall)

Nodes 1001-1020 (Fluid)
Fluid-to-Wall G1-G20
Nodes 201-220 (Wall)

Nodes 1061-1080 (Fluid)
Fluid-to-Wall G61-G80
Nodes 261-280 (Wall)

Nodes 1081-1100 (Fluid)
Fluid-to-Wall G81-G100
Nodes 281-300 (Wall)

Nodes 1101-1120 (Fluid)
Fluid-to-Wall G101-G120
Nodes 301-320 (Wall)

Nodes 1121-1140 (Fluid)
Fluid-to-Wall G121-G140
Nodes 321-340 (Wall)

Pump #1 Return Line
Node 1301
(Fluid in CC #1) (Vapor)

Condenser #1

Condenser #2

Condenser #3

Conditioner #4

Condenser #5

Pump #1 Return Line
Node 1306
Node 1301

Pump #2 Return Line
Node 1307
Node 1302

Pump #3 Return Line
Node 1308
Node 1303

Pump #4 Return Line
Node 1309
Node 1304

Pump #5 Return Line
Node 1310
Node 1305

Subcooler

Condenser #2

Condenser #3

Condenser #4

Condenser #5

Nodal Map of LHP Analytical Model

Introduction to LHP - Ku 2015 TFAWS
LHP Analytical Model Solution Scheme

Two-Step Predictor-Corrector

Thermal Analyzer (e.g. SINDA)

CALL LHP_IN

Thermal Analyzer (e.g. SINDA)

CALL LHP

END
LHP Analytical Model Input Data

- Vapor Line
  - O.D., wall thickness, length, material
- Liquid Line
  - O.D., wall thickness, length, material
- Condensers
  - No. of condensers
  - Condenser 1 O.D., wall thickness, length, material
  - Repeat for Condenser 2, Condenser 3, etc.
- Subcooler
  - O.D., wall thickness, length, material
- Evaporators
  - No. of evaporators
  - Evaporator 1
    - Vapor exit line: O.D., wall thickness, length, material
    - Liquid inlet line: O.D., wall thickness, length, material
    - Pump body O.D., length, material
    - Primary wick O.D., I.D., length, material, pore radius, permeability, porosity, thermal conductivity
    - Bayonet tube: O.D., I.D.
    - Vapor grooves: number of grooves, hydraulic diameter of each groove
    - Reservoir: O.D., I.D., length, material
    - Adverse elevation
    - Secondary wick: pore radius, permeability, cross sectional area, thermal conductivity, no. of vapor channels, hydraulic diameter of each vapor channel
    - Start-up initial condition (situation 1, 2, 3 or 4)
    - Superheat at start-up
      - Repeat for Evaporator 2, Evaporator 3, etc.
- Gravitational acceleration
- Working fluid
Model Capabilities

• LHP with up to 5 evaporators and up to 5 condensers
• Simulation of steady state or transient behavior
• Database for more than 40 working fluids
• Database for wick properties based on empirical test data
• Default values for input data
• Gravity effects included
• A FORTRAN subroutine to be used with any thermal analyzer (e.g. SINDA, TMG)
Model Limitations

• The analytical model can predict when system pressure drop exceeds capillary limit of primary wick. The model cannot simulate loop behavior thereafter.

• Model does not take into account effects of insufficient liquid in reservoir (undercharged LHP in 1-g)
Recent LHP Technology Developments

• Miniature LHP
  – 6.35 mm diameter evaporator

• A Single LHP with Multiple Evaporators and Multiple Condensers

• Hybrid CPL/LHP

• Cryogenic LHP
  – Nitrogen LHP: ~75K-100K
  – Neon LHP: ~28K-44K
  – Hydrogen LHP: ~20K-30K
  – Helium LHP: ~2.7K-4.4K
CEDTP Miniature Loop Heat Pipes

- Miniature LHPs under NASA CETDP program.
  - Breadboards built by Swales and Thermacore
Mini LHP for CCQ Flight Experiment

- Made by Russians
- Flown for CCQ Flight Experiment (2012)
• A single LHP with two evaporators and two condensers
• Miniature LHP
• TECs for reservoir temperature control
Cryogenic Loop Heat Pipe (CLHP)

• Nitrogen CLHP
• Hydrogen CLHP
CLHP for Large Area Cryocooling

- Delivered by TTH Research in 2007
- Manufactured by Thermacore, Inc.

- CLHP
  - all stainless steel construction
  - capillary pump: 1/4”OD x 1.5”L
  - wick: 1.2μm x 45% porosity
  - reservoir: 1/4”OD x 2.5”L
  - transport line: 1/16”OD x 63”L

- Evaporator Plate
  - copper 10” φ 48 in²

- Condenser Plate
  - copper 3” x 5.5” x 1”

- Hot reservoir
  - 1000 ml (not shown)
Other Advanced Topics Not Covered in This Course

• Temperature Oscillations in LHPs

• Temperature Hysteresis

• Effect of Secondary Wick on LHP Transient Operation

• Start-up and Re-start due to Reservoir Cold Shock

• Multiple LHPs Serving a Single Components (Swift ABT, GOES-R ABI, and GOES-R GLM)

• Gravity Effects
LHP Summary (1 of 3)

• Key to high heat transport of LHP
  – Metal wicks with very fine porous wick
  – *High thermal conductivity affects operating temperature*

• Key to robust LHP operation
  – Integral evaporator and CC design
  – Secondary wick connecting CC to evaporator: vapor tolerant

• Key to understanding LHP operation
  – CC saturation temperature governs the loop operating temperature
  – CC is plumbed in line with flow circulation
  – CC temperature itself affected by operating conditions
  – Thermodynamic constraints: $\Delta P$ is linked to $\Delta T$
  – CC volume and liquid inventory

• Key to determining CC saturation temperature
  – Net heat gain must be balanced by subcooling of returning liquid
  – Ambient temperature affects liquid subcooling
LHP Summary (2 of 3)

- Heat leak from evaporator to CC affects
  - Loop natural operating temperature
  - Overall system thermal conductance
  - Temperature hysteresis
- Heat leak from evaporator to CC is affected by
  - Wick thermal conductivity
  - Heat load to the evaporator
  - Two-phase status inside the evaporator core
- Liquid subcooling is affected by
  - Heat load to the evaporator
  - Temperature difference between sink and ambient
  - Parasitic heat gain/loss along the liquid line
- CC sizing and liquid inventory
  - Determined concurrently
  - Must satisfy cold start-up and hot operating conditions
  - Loop must not become liquid-filled at maximum non-operating temperature.
LHP Summary
3 of 3

- The thermodynamic constraint ($\Delta P$ versus $\Delta T$) affects
  - Normal operation
  - Start-up
  - Operation with presence of body force and/or NCGs
  - Operation of an LHP with multiple evaporators
  - Operation of multiple LHPs

- Operating temperature range
  - Never operate LHP near the freezing point except for rare extremely cold start-up transients
  - Never operate LHP near the critical point
Questions?