Capillary Two-Phase Thermal Devices for Space Applications

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Outline

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• Heat Pipe Operating Principles
  – Pressure Drops
  – Operating Temperature
• Heat Pipe Operating Characteristics
• Loop Heat Pipe Operating Principles
  – Pressure Drops
  – Operating Temperature
• Loop Heat Pipe Operating Characteristics
• Examples of Space Applications
Heat Pipes - Hardware

- Metal (aluminum) tube with grooves on the inner surface – cold extrusion
- Grooves are filled with the working fluid (water, ammonia, propylene, etc.)
- Flanges can be added on the outer surface for easy integration with instruments or radiators (The flange is an integral part of the extrusion)
- Various diameters, lengths, and groove sizes

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Some Wicks Used in Heat Pipes

- Many HP hardware variations exist.
  - Size
  - Length
  - Shape
  - Wick material
  - Wick construction
  - Working fluid

- Axial Grooves
  - Design simplicity
  - Reliability
  - High heat transport
  - High thermal conductance
  - Versatility
  - Broadly used in aerospace applications

POWDER METAL WITH PEDESTAL ARTERY
CIRCUMFERENTIAL SCREEN WICK
SLAB WICK
AXIAL GROOVES
Introduction – Why Heat Pipes?

• Heat pipe is a capillary two-phase heat transfer device.
  – Transports heat from a heat source to a heat sink
  – Works as an isothermalizer

• Why two-phase thermal system?
  – Efficient heat transfer – boiling and condensation
  – Small temperature difference between the heat source and heat sink

• Why capillary two-phase system?
  – Passive – no external pumping power
  – Self regulating – no flow control devices
  – No moving parts – vibration free
Heat Pipes – Operating Principles

- Typical use of heat pipe: transports heat from one end (evaporator) to the other (condenser).
- Vapor flows from the evaporator to the condenser along the center core.
- Vapor condenses at the condenser. Liquid is drawn back to the evaporator by the capillary force along the grooves.
- The pressure difference between the vapor and liquid phases is sustained by the surface tension force of the fluid.
- Passive – Waste heat provides the driving force for the fluid flow; no external pumping power.
Differential Pressure Across a Curved Surface

\[ \Delta P = P_1 - P_2 = \sigma \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \]

\( \sigma \): Surface tension; \( R_1 \) and \( R_2 \): Radii of curvature
Pressure Differential Across a Meniscus

- A meniscus will be formed at the liquid/vapor interface, and a capillary pressure is developed.

\[ \Delta P_{\text{cap}} = 2\sigma \cos \theta / R \]

\(\sigma\): Surface tension; \(R\): Radius of curvature; \(\theta\): Contact Angle

- The maximum capillary pressure

\[ \Delta P_{\text{cap,max}} = 2\sigma \cos \theta / R_p \]

\(R \geq R_p\)

\(R_p\): Radius of the pore
Pressure Balance in Heat Pipes

- The fluid flow will induce a frictional pressure drop. The total pressure drop over the length of the heat pipe is the sum of individual pressure drops.

\[ \Delta P_{\text{tot}} = \Delta P_{\text{vap}} + \Delta P_{\text{liq}} + \Delta P_{g} \]

- The meniscus will curve naturally so that the capillary pressure is equal to the total pressure drop.

\[ \Delta P_{\text{cap}} = \Delta P_{\text{tot}} \]

\[ \Delta P_{\text{cap}} = 2\sigma \cos \theta / R \quad (R \geq R_p) \]

- The flow will stop when the capillary limit is exceeded.

\[ \Delta P_{\text{cap,max}} = 2\sigma \cos \theta / R_p \]

\[ R_p : \text{Radius of the pore} \]

- For normal operation of heat pipes:

\[ \Delta P_{\text{tot}} = \Delta P_{\text{cap}} \leq \Delta P_{\text{cap,max}} \]
Pressure Differential at Liquid Vapor Interface

![Diagram of pressure differential at liquid vapor interface](image)

- **Le**: Heat Source
- **La**: Liquid Flow
- **Lc**: Heat Sink
- **Wall**: Vapor Flow
- **Evaporator Section**: Liquid Flow
- **Adiabatic Section**: Vapor Flow
- **Condenser Section**: Liquid Flow
Heat Pipes – Pressure Drops

- Vapor pressure drop diagram
- Liquid pressure drop diagram
- Pressure drop due to gravity head
- Pressure differential between vapor and liquid - sustained by capillary force
- The highest pressure differential occurs at the very end of the evaporator.
- Pressure drops depend on heat load and transport distance.

b) Vapor and liquid pressure distributions
Heat Pipes - Heat Transport Limit

- The total pressure drop must not exceed its capillary pressure head.
  \[ \Delta P_{\text{tot}} = \Delta P_{\text{vap}} + \Delta P_{\text{liq}} + \Delta P_g \]
  \[ \Delta P_{\text{cap, max}} = \sigma \cos \theta / R_p \]
  \[ \Delta P_{\text{tot}} \leq \Delta P_{\text{cap, max}} \]

- 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 pumping head against gravity
Functional Types Of Heat Pipes

- Three Basic Functional Types
  - Constant Conductance Heat Pipe (CCHP)
  - Variable Conductance Heat Pipe (VCHP)
  - Diode Heat Pipe
Energy Balance in Heat Pipe

\[ Q_e = Q_c \equiv Q = \dot{m} \lambda \]
\[ T_e \approx T_c \equiv T_v \]

- \( Q_e \) = Evaporator length
- \( Q_c \) = Adiabatic length
- \( L_c \) = Condenser length
- \( \dot{m} \) = Mass flow rate (liquid or vapor)
- \( \lambda \) = Latent heat of vaporization

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Thermal Characteristics of a CCHP

\[ Q = h(\pi DL_c)(T_v - T_s) \]

\( L_c = \text{constant} \)

\( h(\pi DL_c) = \text{constant conductance} \)

\( T_v \) varies with \( T_s \) and \( Q \)

\( Q_2 > Q_1, \ T_{S1} \)

\( Q_1, \ T_{S1} \)

\( Q_1, \ T_{S2} < T_{S1} \)

Vapor Temperature

Distance

\( T_{va} \)

\( T_{v1} \)

\( T_{v2} \)
Thermal Characteristics of a VCHP

\[ Q = h(\pi DL_c)(T_V - T_s) \]

L_c varies with T_s and Q so as to keep T_v constant
\[ h(\pi DL_c) = \text{variable conductance} \]

Reservoir size is a function of:
- Range of heat load
- Range of sink temperature
- Temperature control requirement
VCHPs

Typical VCHP

- Types of VCHPs
  - Feedback-controlled VCHP
  - Passive VCHP

OCO-2 VCHPs
A convenient figure of merit is the liquid transport factor, $N_l$,

$$N_l = \frac{\lambda \sigma \rho}{\mu_l}$$

$N_l$ = Latent Heat * Surface Tension * Liquid Density/ Liquid Viscosity
Heat Pipe Performance Curve for Given Heat Pipe Design and Working Fluid (Usually Provided by the Vendor)

TRANSPORT CAPABILITY VS. TEMPERATURE
DIE 16692, Single Sided Heat Pipe, Ammonia Fluid

Max Transport Capability (W/m)

Temperature (°C)

Static Height (mm)

-254 mm

-2.54 mm

0 g

Static Height

224.8

236.6
Heat Pipes - Heat Transport Limit

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

- 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

b) Vapor and liquid pressure distributions
• Wicks are present only in the evaporator, and wick pores can be made small.
• Smooth tubes can be sized independently 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.
Variable Conductance Capillary Pumped Loop

- 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
- Can accommodate multiple evaporators and condensers in a single loop.
• **Main design features**
  - The reservoir forms an integral part of the evaporator assembly.
  - A primary wick with fine pore sizes provides the pumping force.
  - A secondary wick connects the reservoir and evaporator, supplying liquid.
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
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:

\[
\Delta P_{\text{tot}} = \Delta P_{\text{groove}} + \Delta P_{\text{vap}} + \Delta P_{\text{cond}} + \Delta P_{\text{liq}} + \Delta P_{\text{wick}} + \Delta P_{g}
\] (1)

The capillary pressure rise across the wick meniscus:

\[
\Delta P_{\text{cap}} = 2\sigma \cos \theta /R
\] (2)

The maximum capillary pressure rise that the wick can sustain:

\[
\Delta P_{\text{cap, max}} = 2\sigma \cos \theta /r_p
\] (3)

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

The meniscus will adjust it radius of curvature so that the capillary pressure rise matches the total pressure drop which is a function of the operating condition:

\[
\Delta P_{\text{cap}} = \Delta P_{\text{tot}}
\] (4)

The following relation must be satisfied at all times for proper LHP operation:

\[
\Delta P_{\text{tot}} \leq \Delta P_{\text{cap, max}}
\] (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.
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
  - Heat exchange between CC and ambient
- As the operating condition changes, the CC temperature will change during the transient, but eventually reaches a new steady temperature.

\[ Q_{cc} - Q_{sub} - Q_{leak} + Q_{RA} = 0 \]
LHP Natural Operating Temperature
No Active Control of CC Temperature

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

\[ Q_{\text{leak}} = G_{E,cc} \left( T_E - T_{cc} \right) \]

\[ Q_{\text{sub}} = \dot{m} C_p \left( T_{cc} - T_{in} \right) \]

- 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.
LHP Operating Temperature
CC Temperature Controlled at $T_{set}$

$Q_{cc} = Q_{sc} - Q_{L}$

$Q_{L} - Q_{sc} + Q_{cc} = 0$

- **CC** is cold biased, and electrical heaters are commonly used to maintain $T_{cc}$ at $T_{set}$.
- $Q_{cc}$ varies with $Q_{sc}$, which in turns varies with evaporator power, condenser sink temperature, ambient temperature and number of coupling blocks.
- 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)
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
  1/13/2003 to 8/14/2010

- **SWIFT, 2 LHPs**
  Launched Nov 2004

- **GOES N-Q, 5 LHPs each**
  Launched 2006
CPL and LHP Flight Applications – NASA Spacecraft

- 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.
Swift XRT Ethane Heat Pipes
Orbiting Carbon Observatory–2 (OCO-2) VCHPs
Terra CPLs

- Over 16 years of successful on-orbit operations

• Terra launched 12/1999

• Two-phase loops (CPLs) are on SWIR, TIR and MOPPIT instruments
• On the second day after launch, the first CPL system in a flight mission was started successfully.
• All 3 CPLs continue to demonstrate reliable, stable thermal control for their instruments
• SWIR set temperature reset three times
• Nominal operations continue
Terra - Temperature Reset with Stable Control for the ASTER-SWIR Instrument

- July of 2001 - ASTER-SWIR cryo-coolers getting too hot.
- CPL loop temperature was reduced by 4.5 °C in 3 steps

Reservoir and Instrument Interface temperatures change as commanded and then remain constant

Radiator and various line temperatures adjust according to new set points
CPL on HST/SM-3B
STS-108, Feb/2002

CPL was added to HST Aft Shroud on SM-3B

Astronauts fed CPL evaporator through bottom of shroud, attached it to cryo-cooler, and attached new radiator to handrails.

CPL removes ~ 400 W heat from NICMOS cryocooler which allows the NICMOS sensor to be reactivated.

Tight temperature control
HST ACS CPLs and ASCS Radiator Design

- ACS INTERFACE PLATE
  - EVAPORATOR PUMP 1
  - EVAPORATOR PUMP 2

- STRAIN RELIEF BRACKET WITH SURVIVAL HEATERS
- LIQUID LINE SUBCOOLER AREA
- VAPOR LINES RELOCATED TO EDGE OF PANEL TO PREVENT LOSS OF SUCCOOLER EFFICIENCY, REQUIRED ADDITIONAL VAPOR LINE HEATERS ON PANEL EDGE
- EXTERNAL FLEX HOSES WITH FLEXIBLE SURVIVAL HEATERS
- RIGID LIQUID AND VAPOR LINE TUBING
- CRYOVENT LIGHT SEAL
- CONDUIT
- INTERNAL FLEX HOSE BUNDLE
- STISCOS
- ACS
- STIS
- COS
- ACS-1
- ACS-2

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HST CPL/HP Radiator Assembly

Subcooler Section

Isothermalizer heat pipes

Heat Pipe Heat Exchangers

Reservoir Lines
The loop was fully charged and integrated with the radiator on the ground, and was installed to the HST by the astronaut.
HST NICMOS Temperatures

NICMOS Inlet/Outlet Neon Temperatures

- Weighted Avg of Inlet & Outlet (Control Point)
- NICMOS Inlet
- NICMOS Outlet

Key Events:
- NICMOS Safed
- Warm HST Attitudes
- Surge Completed Ramp Compressor Speed to 7300 rps
- Warm HST Attitudes
- 70K Setpoint On Neon Gas Achieved
Tropospheric Emission Spectrometer (TES)

- 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 Instrument Loop Heat Pipe Layout

SIGNAL CHAIN/ LASER HEAD ASSEMBLY
LHP EVAPORATOR

MECHANICAL COOLER B
LHP EVAPORATOR

MECHANICAL COOLER A
LHP EVAPORATOR

IEM LHP EVAPORATOR

MECHANICAL COOLER ELECTRONICS LHP EVAPORATOR

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EOS-Aura TES Components Thermal Performance

![Graph showing temperature variation over time for Cryocooler Electronics and Cryocooler Compressor.](image)

Date of Year

Temperature, K

- Cryocooler Electronics
- Power Boards
- Cryocooler Compressor
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
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

GLAS CLHP Transient Data 02/20/03 (Laser Turn-on, Turn off warmup heaters, all components powered)
CCHPs/VCHPs/LHPs on SWIFT ABT

- Burst Alert Telescope, a gamma ray detector array, is one of three instruments on Swift
- Launched: 20 November, 2004
- Detector array has 8 CCHPs for isothermalization and transfer of 253 W to dual, redundant, LHPs located on each side
Swift BAT VCHPs and LHPs
• 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.
HPs and LHPs on IceSat-2 ATLAS LTCS

Subcooler

Radiator with embedded condenser lines

LHP evaporator and CC

CCHP

Lasers

Vapor Line

Evaporator

Reservoir

Liquid Line
GOES-R Spacecraft Layout

- Z
(earth)

GPS ANT
STAR TRACKERS
X-BAND ANT
GLM
ABI
OMNI/BICONE ANT
SAR ANT
L/S-BAND ANT
UHF ANT
L-BAND GRB ANT
SGPS
SUN SENSORS
EXIS
SEB
SUVI
EHIS (hidden)
MPS-LO
MPS-HI
MAGNETOMETER
SOLAR ARRAY

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GOES-R ABI HPs/LHPs Assembly

Radiator Panel
LHP Evaporator Assemblies
Heat Pipe Network

+Z Flexures
-Z Flexures
Optical Bench Assembly

+X
+Y
+Z
GOES-R ABI HPs/LHPs Assembly
GOES-R GLM LHPs

- SR filter (Third)
- SB filter (Second)
- NB filter (First)
- Interface to S/C cold plate
- Evaporator
- Reservoir
- Condenser
- CCD Assembly

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GOES-R GLM LHP Flight Hardware
Questions?