THERMAL & FLUIDS ANALYSIS WORKSHOP

GSFC· 2015

Introduction to Heat Pipes

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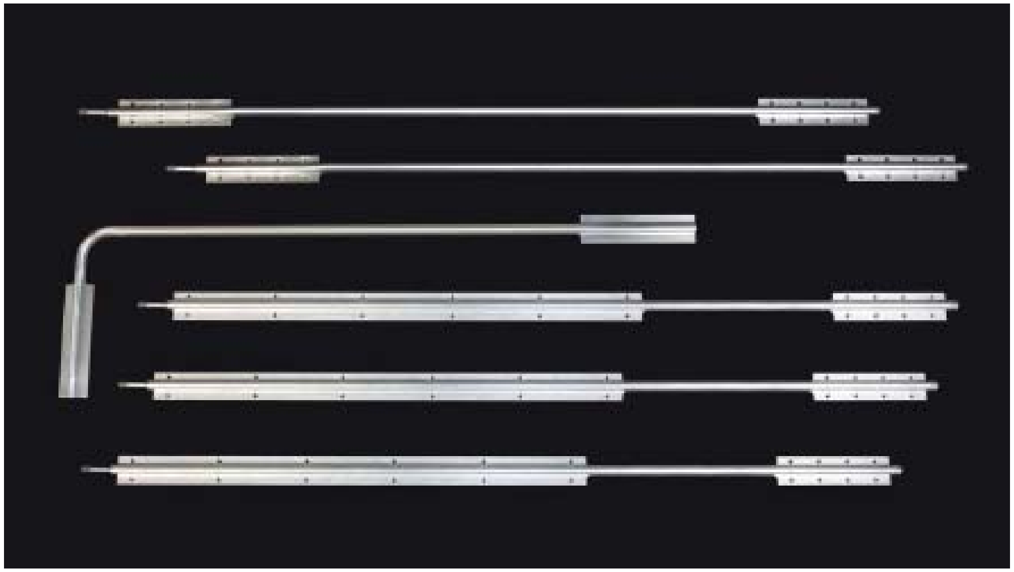
Outline

- Introduction
- Heat Pipe Operating Principles
  - Pressure Drops
  - Operating Temperature
- Functional Types of Heat Pipes
- Heat Pipe Operating Characteristics
- Heat Pipe Design and Selection
  - Design Considerations (mostly for Vendors)
  - Selecting Heat Pipes as Part of Thermal Control System and Modeling of Heat Pipes (for Thermal Analysts)
- Some Practical Considerations
- Some Examples of Flight Applications
- Other Types of Heat Pipes

Heat Pipes - Hardware

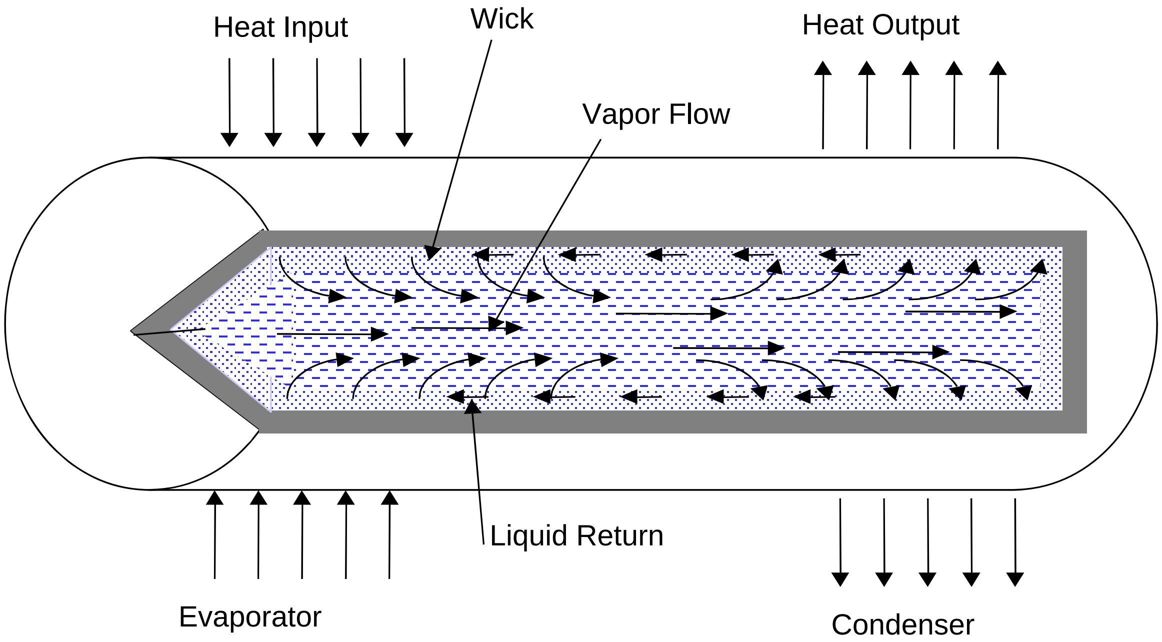


- Metal (aluminum) tube with grooves on the inner surface – cold extrusion
- Grooves are filled with the working fluid (water, ammonia, propylene, etc.)
- Flanges can be added on the outer surface for easy integration with instruments or radiators (The flange is an integral part of the extrusion)
- Various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

Introduction – Why Heat Pipes?

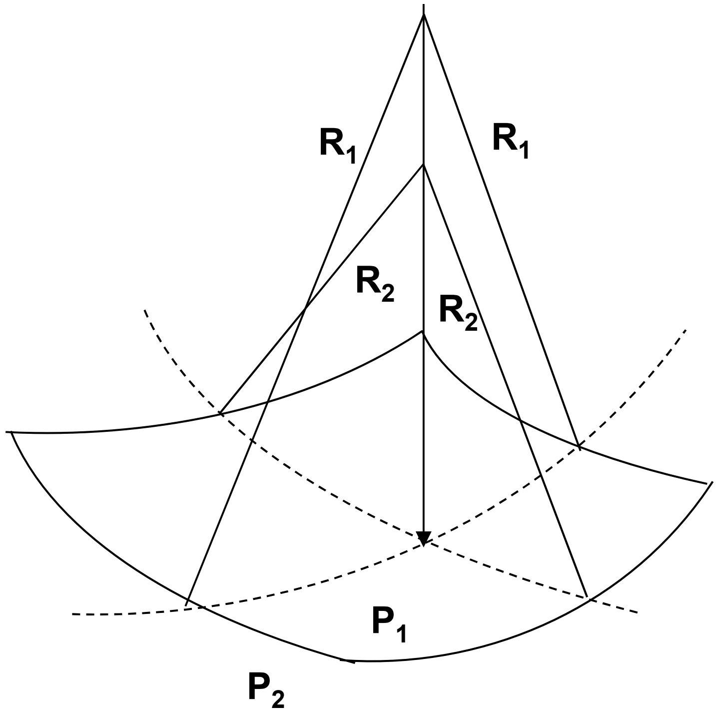
- Heat pipe is a capillary two-phase heat transfer device.
  - Transports heat from a heat source to a heat sink
  - Works as an isothermalizer
- Why two-phase thermal system?
  - Efficient heat transfer – boiling and condensation
  - Small temperature difference between the heat source and heat sink
- 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: one end (the evaporator) is attached to the heat source, and the opposite end (the condenser) to the heat sink. The middle section (the adiabatic section) is insulated.**
- **As liquid is vaporized at the evaporator, the vapor pressure builds up, forcing vapor to flow axially along the center core to the condenser .**
- **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 – no external pumping power is required; the waste heat provides the driving force for the fluid flow.**

Differential Pressure Across a Curved Surface

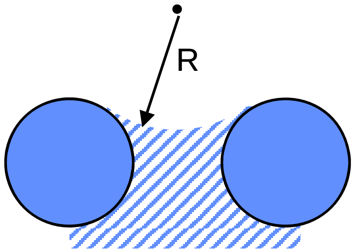


$\Delta P = P_1 - P_2 = \sigma\,(1/R_1 + 1/R_2)$

σ: 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.**

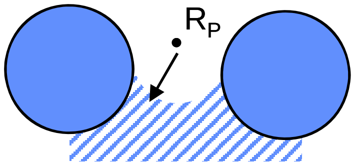


$\Delta P_{cap} = 2\sigma \cos\theta / R$

σ: Surface tension; R: Radius of curvature; θ: Contact Angle

- **The maximum capillary pressure**

$\Delta P_{cap,max} = 2\sigma \cos\theta / R_p$



$R \geq R_p$

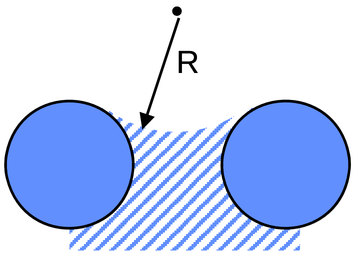
R_p : Radius of the pore

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.**

$$\Delta P_{tot} = \Delta P_{vap} + \Delta P_{liq} + \Delta P_{g}$$

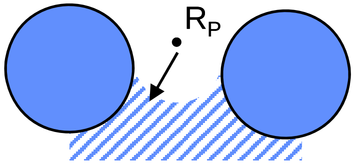
- **The meniscus will curve naturally so that the capillary pressure is equal to the total pressure drop.**



$$\Delta P_{cap} = \Delta P_{tot}$$

$$\Delta P_{cap} = 2\sigma \cos\theta / R \qquad (R \geq R_p)$$

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



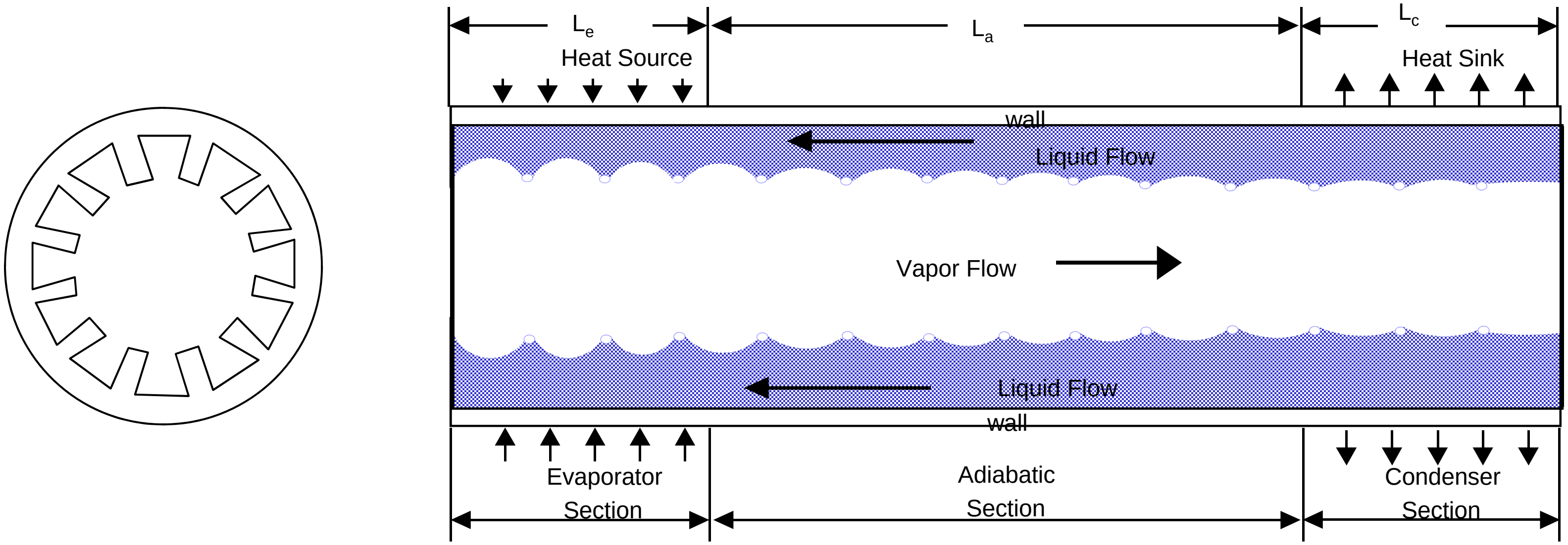
$$\Delta P_{cap,max} = 2\sigma \cos\theta / R_p$$

R_p : Radius of the pore

- **For normal operation of heat pipes:**

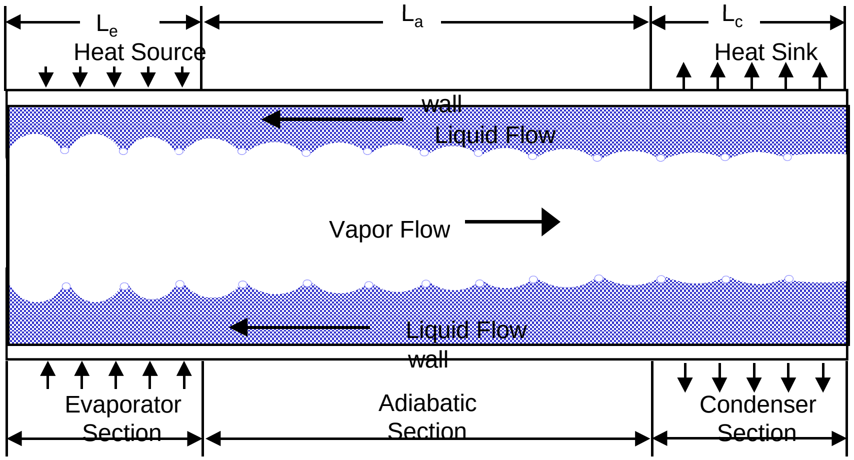
$$\Delta P_{tot} = \Delta P_{cap} \leq \Delta P_{cap,max}$$

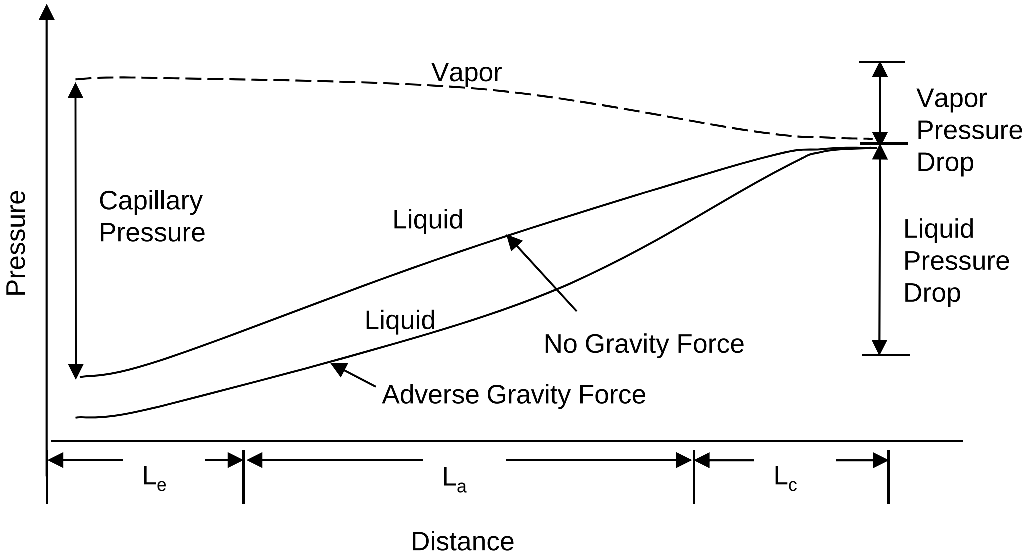
Pressure Differential at Liquid Vapor Interface



- The vapor pressure decreases as it flows from the evaporator to the condenser.
- The liquid pressure decreases as it flows from the condenser to the evaporator.
- At any cross section of the heat pipe, a pressure differential exists between the vapor and liquid phases. This delta pressure is sustained by the surface tension force developed at the liquid/vapor interface at the tip of each groove.
- The lowest delta pressure occurs at the very end of the condenser (zero). The highest delta pressure occurs at the very end of the evaporator.

Heat Pipes - Heat Transport Limit





b) Vapor and liquid pressure distributions

- **For proper heat pipe operation, the total pressure drop must not exceed its capillary pressure head .**

  $\Delta P_{tot} \le \Delta P_{cap,max}$

  $\Delta P_{tot} = \Delta P_{vap} + \Delta P_{liq} + \Delta P_g$

  $\Delta P_{cap,max} = \sigma \cos\theta / R_p$

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

- **Capillary pressure head:**

  $\Delta P_{cap} \propto 1/\ R_p$

- **Liquid pressure drop:**

  $\Delta P_{liq} \propto 1/\ R_p^2$

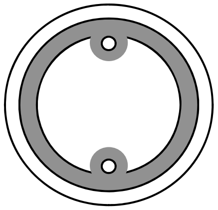
- **An optimal pore radius exists for maximum heat transport.**

- **Limited pumping head against gravity**

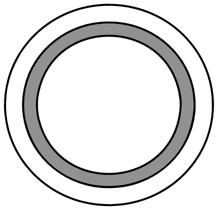
Some Wicks Used in Heat Pipes

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

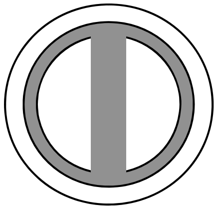
- Axial Grooves
  - Versatility
  - Design simplicity
  - Reliability
  - High heat transport
  - High thermal conductance
  - Broadly used in aerospace applications



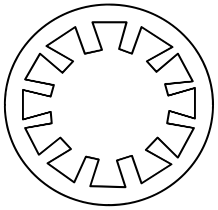
POWDER METAL WITH PEDESTAL ARTERY



CIRCUMFERENTIAL SCREEN WICK



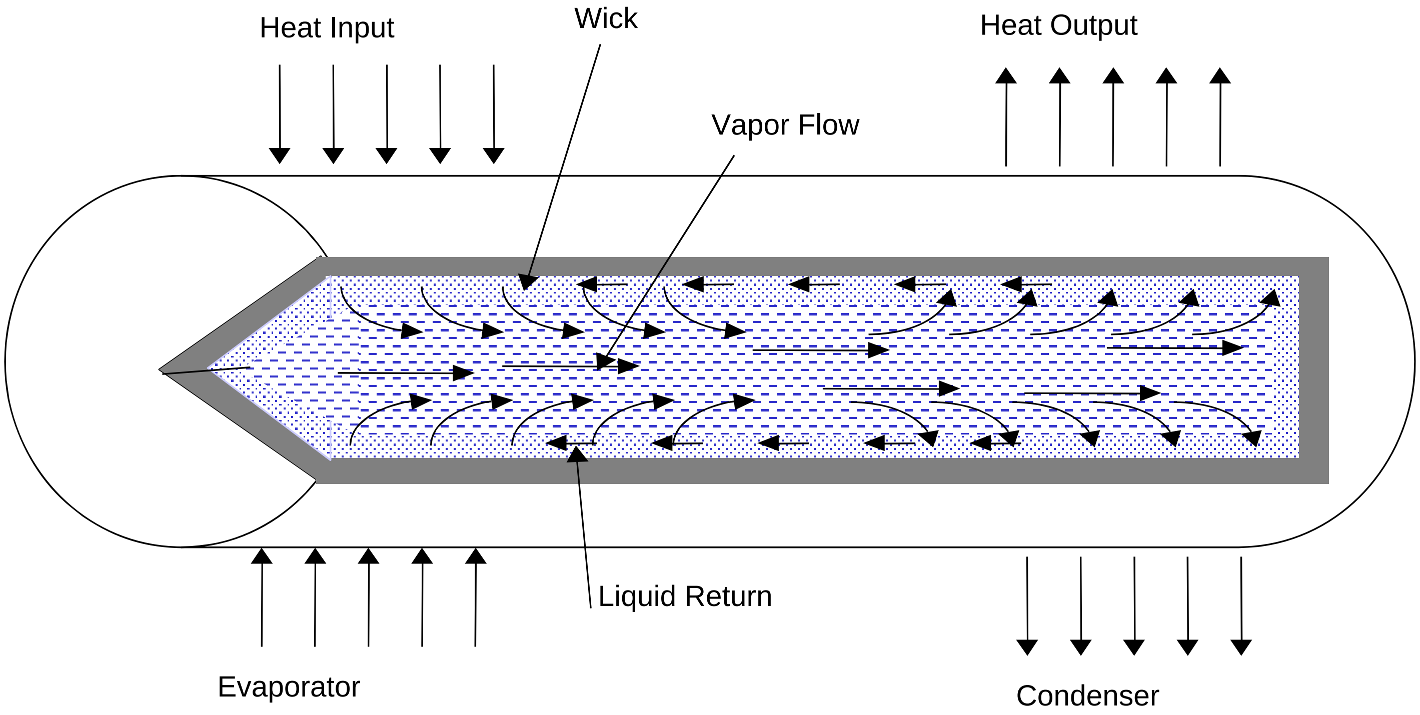
SLAB WICK



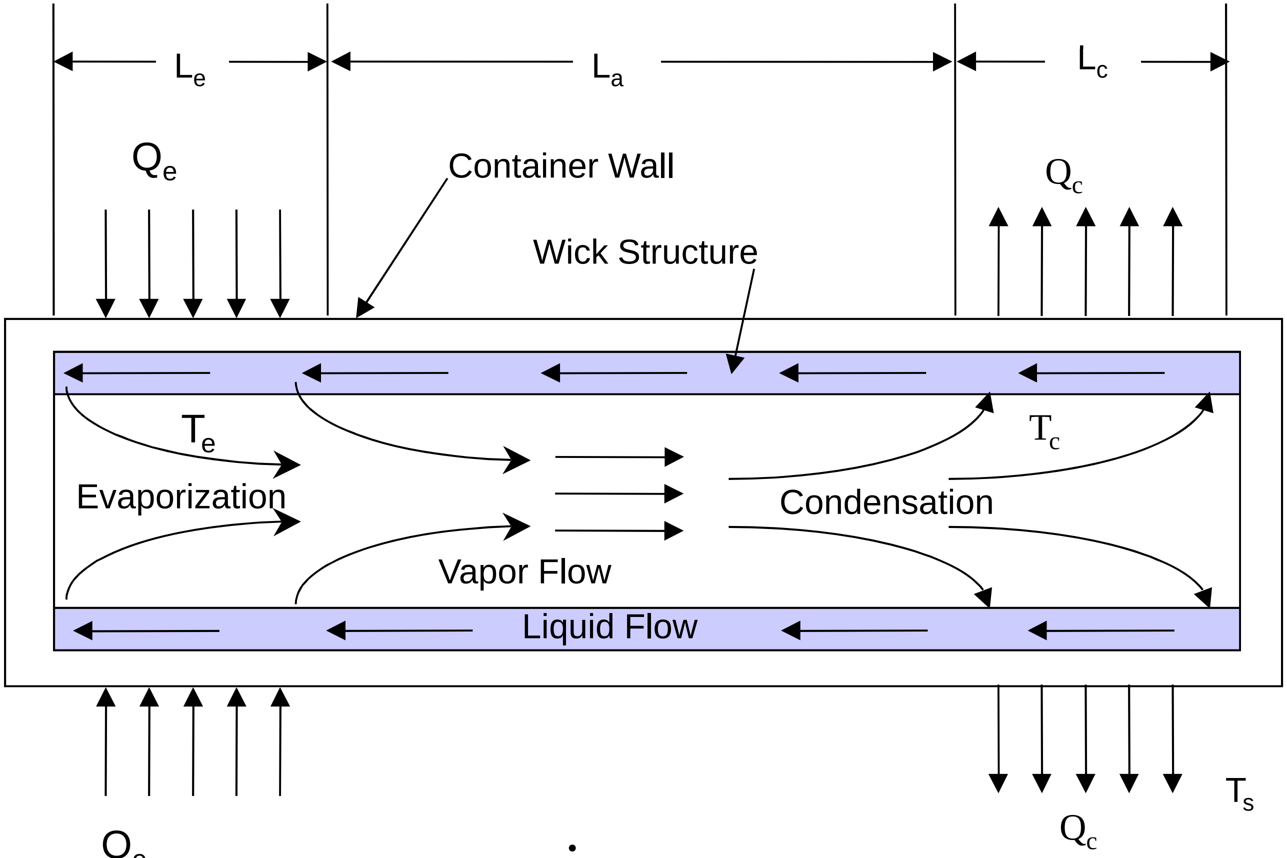
AXIAL GROOVES

Functional Types Of Heat Pipes

- **Three Basic Functional Types**
  - **Constant Conductance Heat Pipe (CCHP)**
  - **Variable Conductance Heat Pipe (VCHP)**
  - **Diode Heat Pipe**



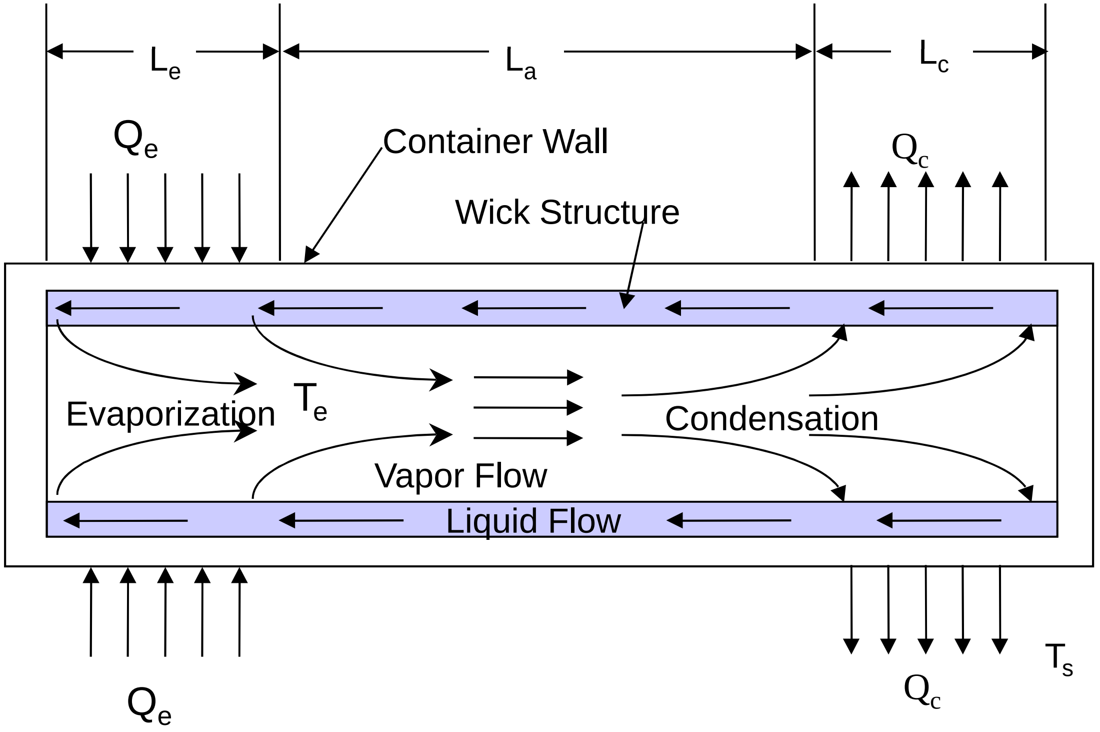
Energy Balance in Heat Pipe

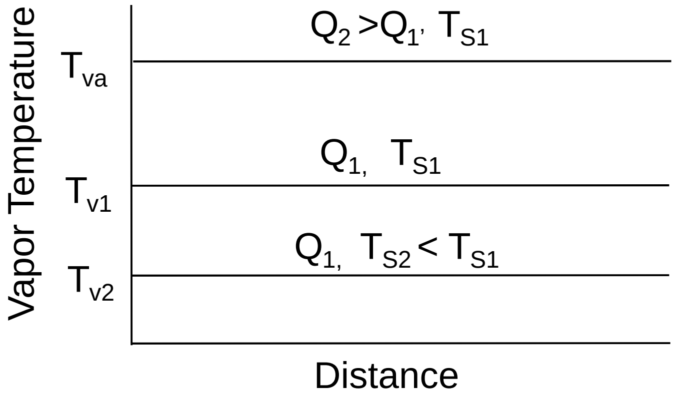


$Q_e = Q_c \equiv Q = \dot{m}\,\lambda$ $\qquad T_e \cong T_c \equiv T_v$

L_e = Evaporator length
L_a = Adiabatic length
L_c = Condenser length
$\dot{m}$ = Mass flow rate (liquid or vapor)
λ = Latent heat of vaporization

Thermal Characteristics of a CCHP





$Q = h(\pi D L_c)(T_V - T_s)$

L_c = constant

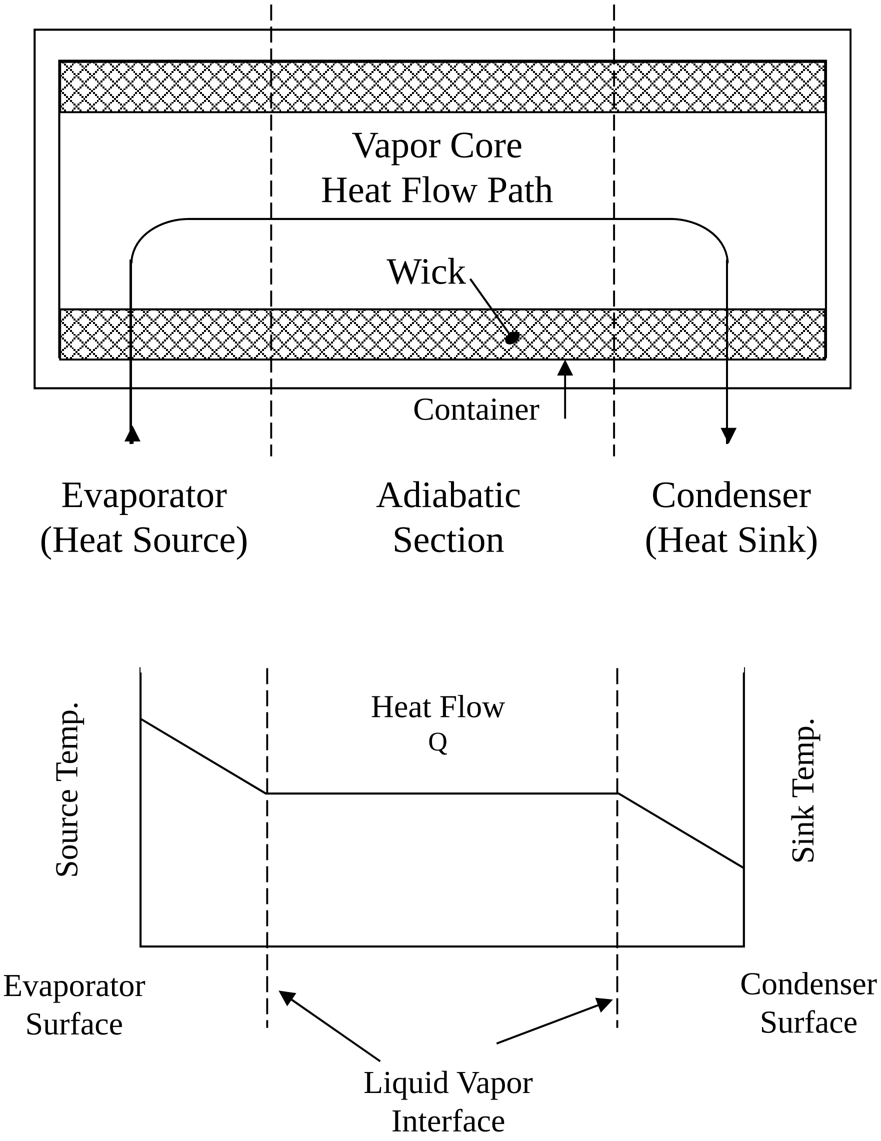
$h(\pi D L_c)$ = constant conductance

T_V varies with T_s and Q

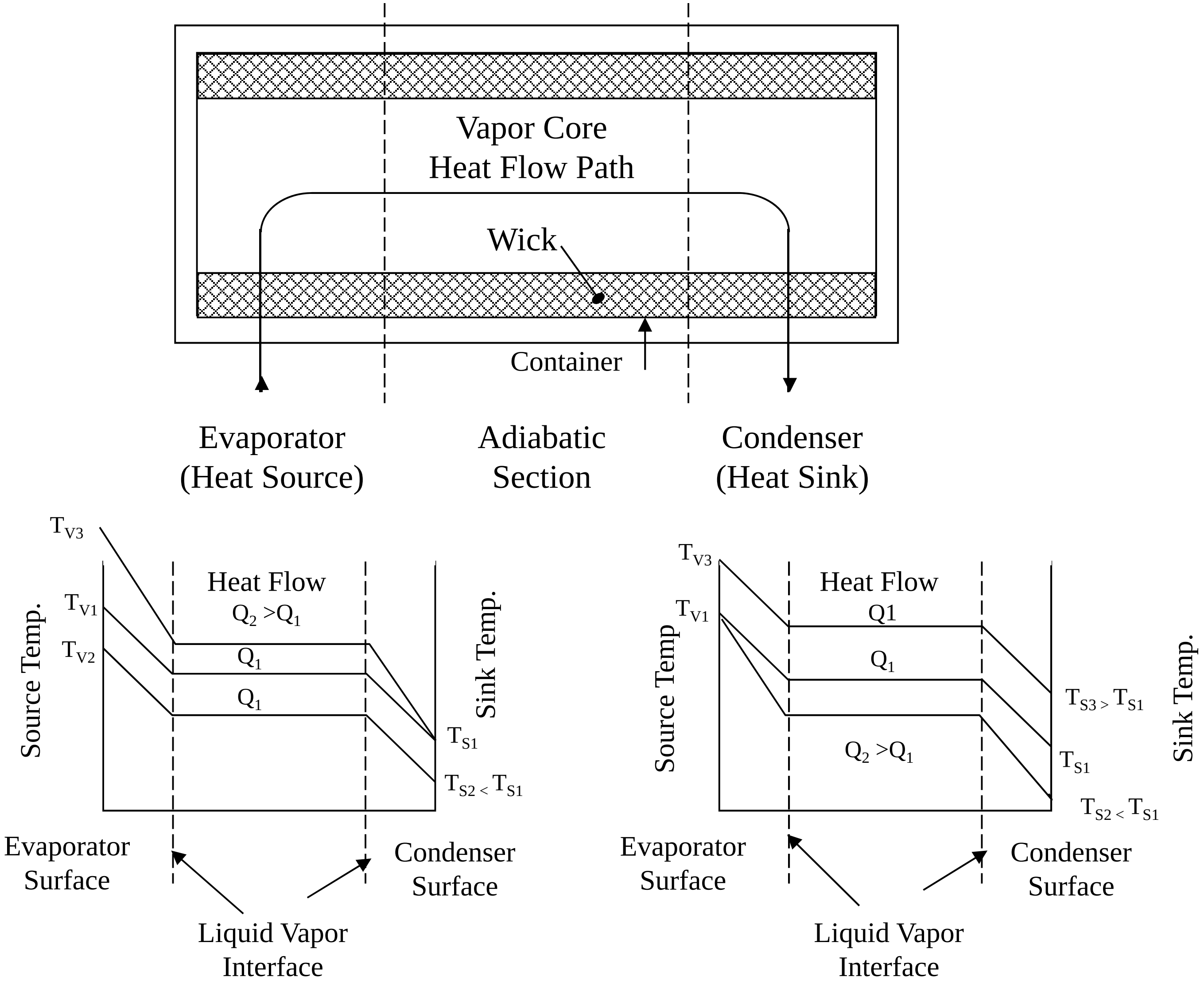
Temperature Gradient in a CCHP

- **The thermal conductance is very high for the fluid flow.**

- **The temperature difference from the heat source to the heat sink is dominated by the much smaller thermal conductance at the heat source/evaporator interface and the condenser/heat sink interface.**



Temperature Gradient in a CCHP



Governing Equations for CCHP Operation (1)

- First law of thermodynamics

$$Q_e = Q_c \equiv Q$$

- Second law of thermodynamics

$$T_e > T_c$$

- Capillary pressure capability

$$\Delta P_{cap,max} = 2\sigma \cos\theta / R_p$$

- Pressure balance

$$\Delta P_{cap,max} \geq \Delta P_{tot} = \Delta P_{vap} + \Delta P_{liq} + \Delta P_g$$

- Saturation states

$$T_e = f(P_e) \text{ and } T_c = f(P_c)$$

$$\Delta T = T_e - T_c = f(Q, T_c)$$

Governing Equations for CCHP Operation (2)

- Heat transfer in condenser zone

$$Q_c = Q = h_c(\pi D L_c)(T_c - T_s) \cong h_c(\pi D L_c)(T_v - T_s)$$

$$h_c(\pi D L_c) = \text{constant}$$

Q and T_s are independent variables

- Heat transfer in evaporator zone

$$Q_e = Q = h_e(\pi D L_e)(T_i - T_e) \cong h_e(\pi D L_e)(T_i - T_v)$$

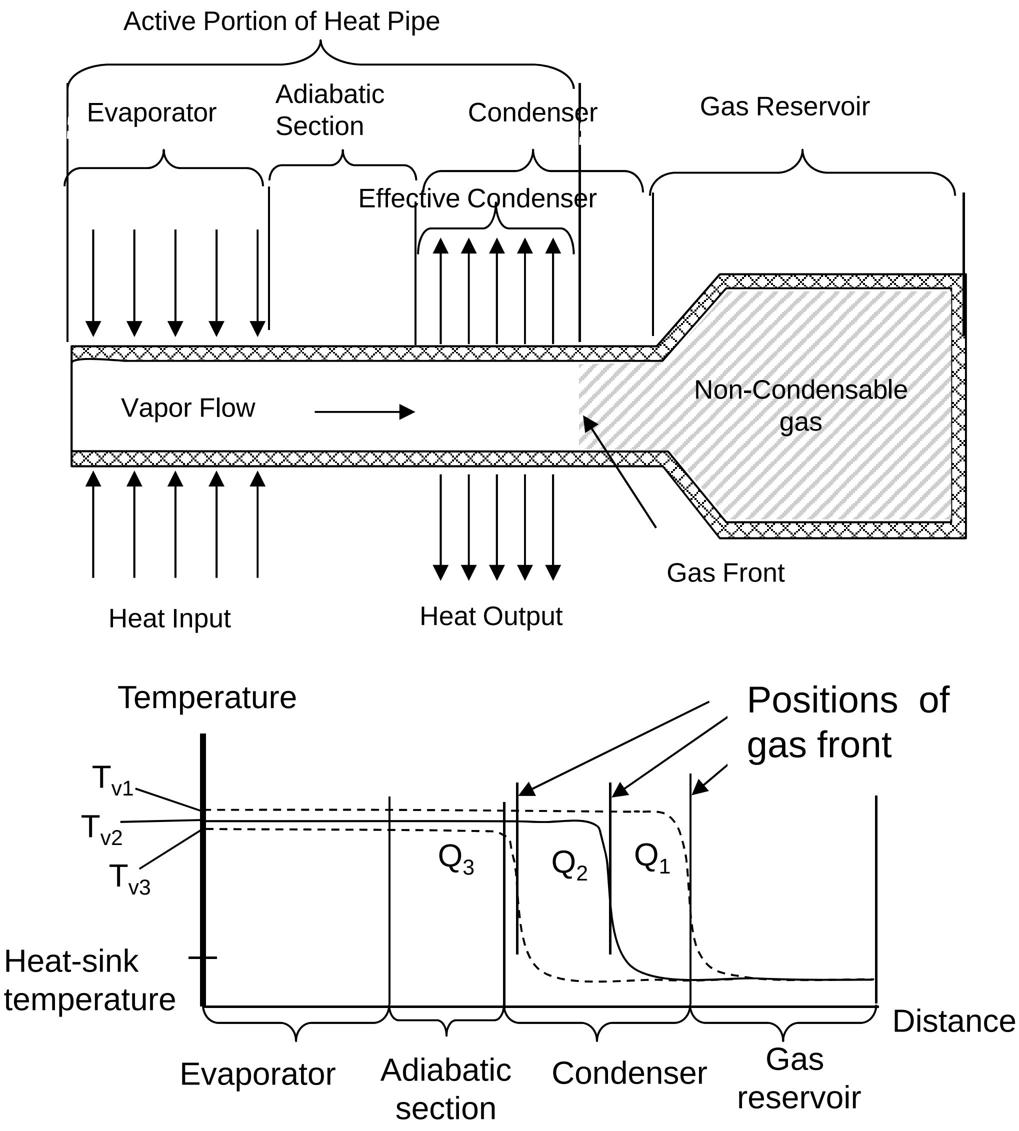
$$h_e(\pi D L_e) = \text{constant}$$

- Relationship between temperature differential and pressure differential

$$\Delta P_{vap} = P_e - P_c = f(Q, T_c)$$

$$\Delta T = T_e - T_c = f(\Delta P_{vap}) = f(Q, T_c)$$

Thermal Characteristics of a VCHP



$Q = h(\pi D L_c)(T_V - T_s)$

L_c varies with T_s and Q

so as to keep T_V constant

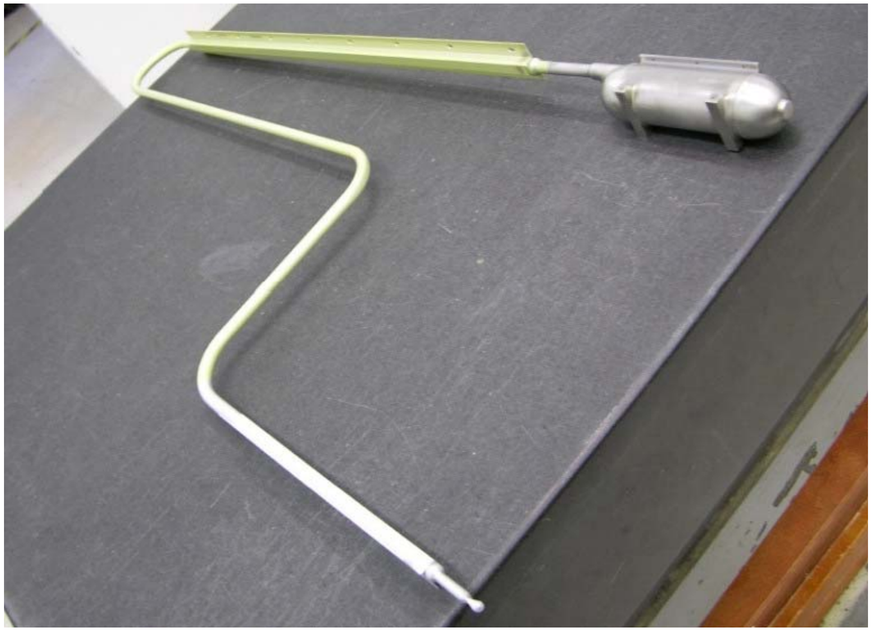
$h(\pi D L_c)$ = variable conductance

Reservoir size is a function of:

- **Range of heat load**
- **Range of sink temperature**
- **Temperature control requirement**

VCHPs

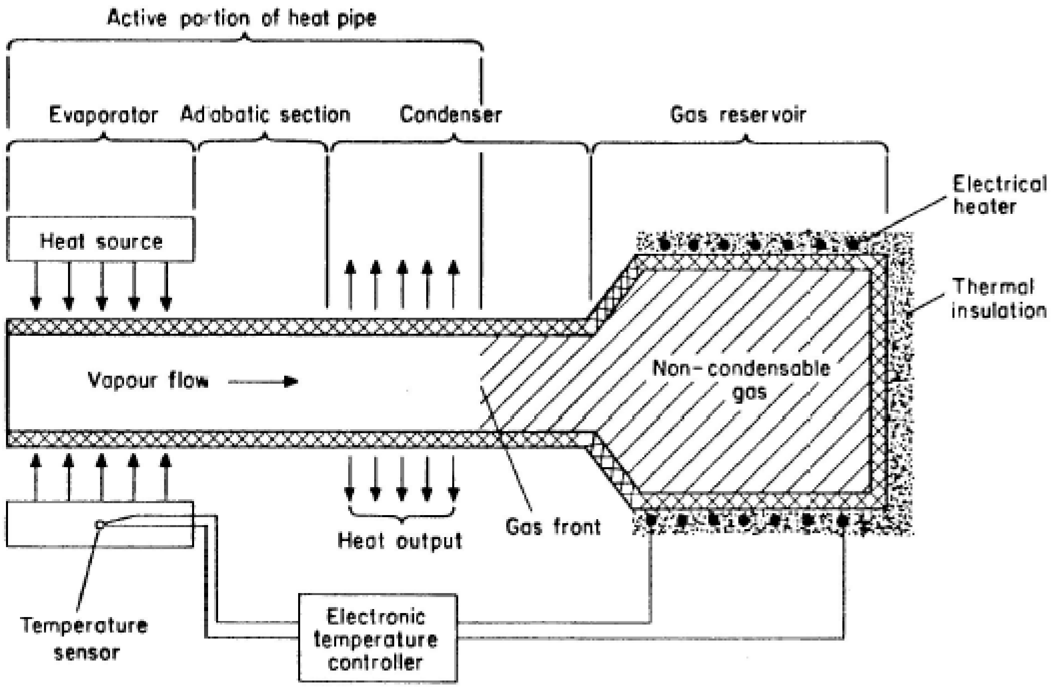
Typical VCHP



OCO-2 VCHPs

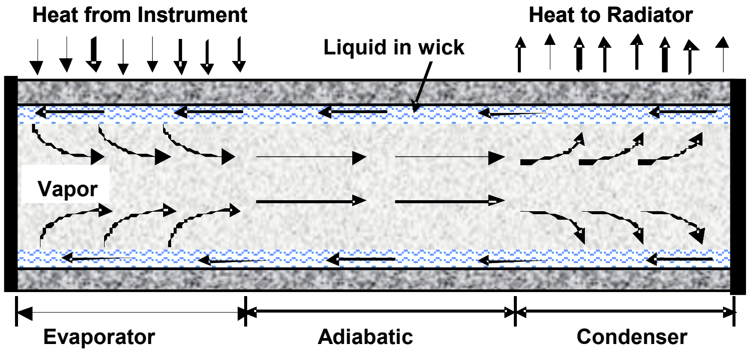
- Types of VCHPs
  - Feedback-controlled VCHP
  - Passive VCHP

Electrical Feedback-controlled VCHP

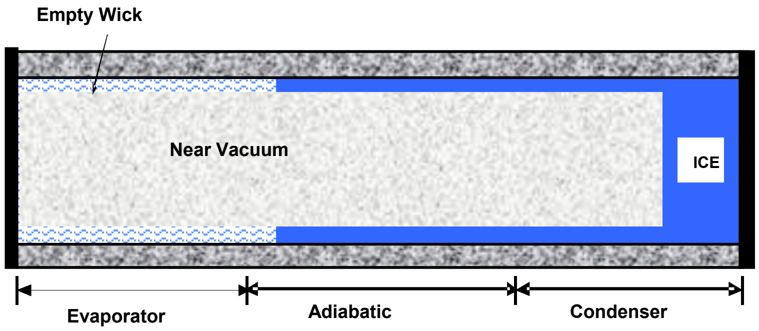


- **Typically maintain evaporator temperature control of ± 1-2 °C over widely varying evaporator powers and heat sink temperatures**
- **Roughly 1-2 W electrical power required for the reservoir heaters**

Passive VCHP - Gas-Charged Heat Pipe (GCHP)

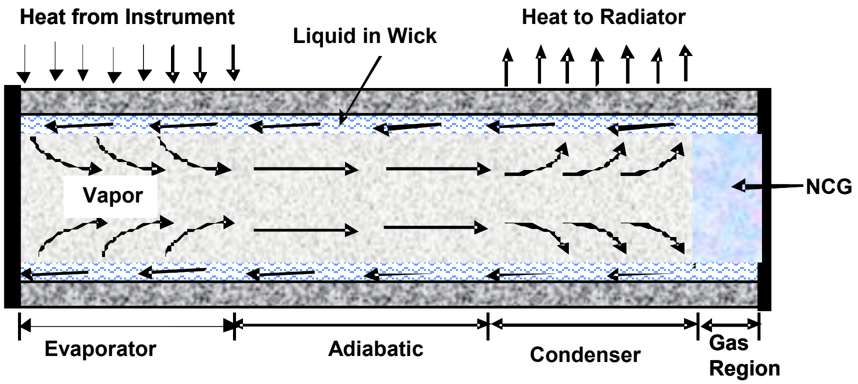


Normal Operation of a CCHP

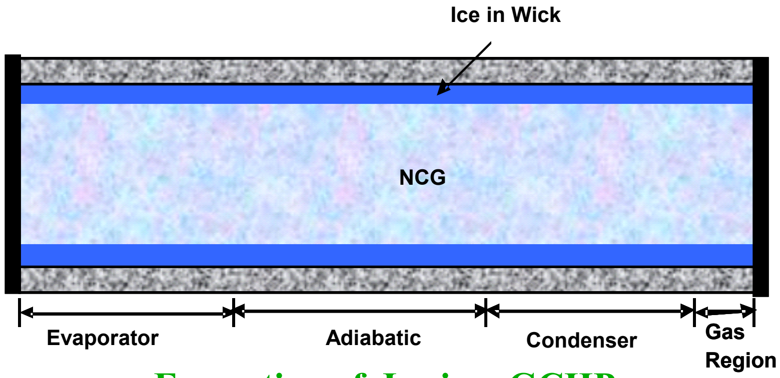


Formation of an Ice Plug in a CCHP

- Issues: formation of ice plug in the condenser and difficulty of re-start



Normal Operation of a GCHP



Formation of Ice in a GCHP

- NCG in GCHP: allows the heat pipe to freeze in a controlled fashion; no ice plug – no risk of pipe burst; helps re-start of the heat pipe.

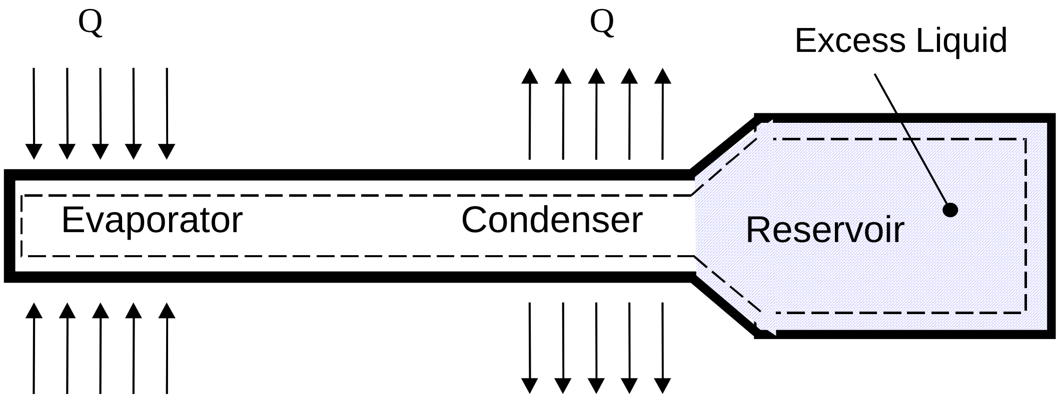
Diode Heat Pipes

- Diode heat pipes are designed to act like an electronic diode.

- Evaporator hotter than condenser
  - Heat flows from the evaporator to the condenser

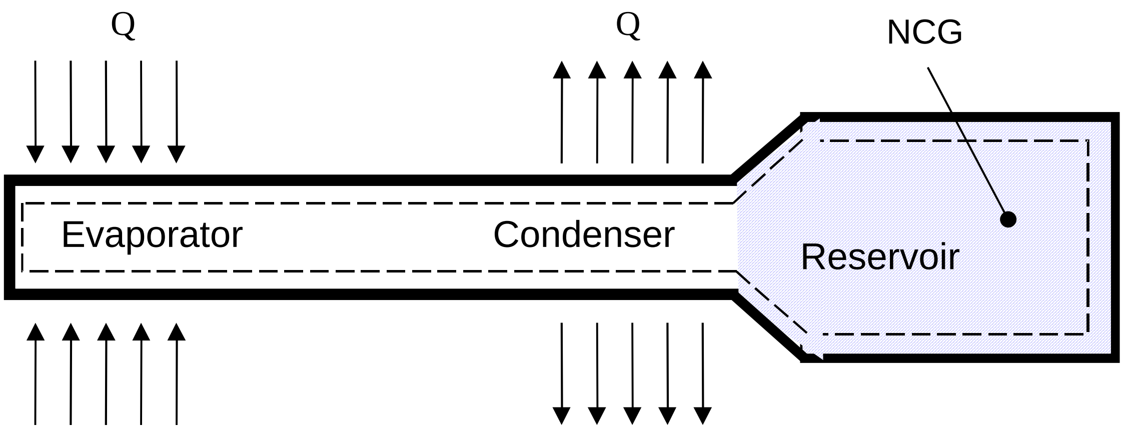
- Condenser hotter than evaporator
  - No heat flows from the condenser to the evaporator

Diode Heat Pipe – Excessive Liquid at Condenser End



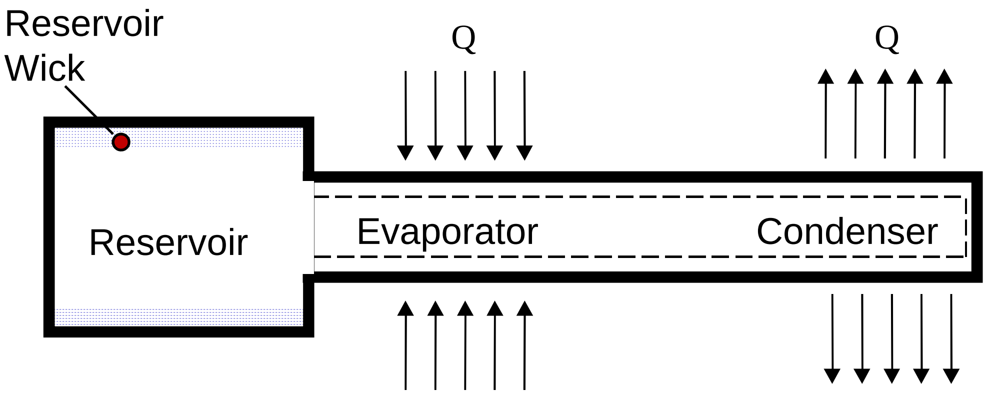
- **During normal operation, the diode heat pipe works as regular CCHP with excess liquid stored in the reservoir attached to the condenser.**
  - **Excess liquid may block part of the condenser depending on the thermal load and reservoir sink temperature.**
- **During reverse operation vapor flows in the opposite direction. Vapor condenses in the evaporator, eventually fills the entire evaporator section.**
  - **No heat can be dissipated to the evaporator.**

Gas Diode Heat Pipes – NCG at Condenser End



- During normal operation, the gas diode heat pipe works similarly to a VCHP.
  - Gas reservoir at the condenser end with NCG
  - NCG may blocks part of the condenser depending on the thermal load and reservoir sink temperature.
- During reverse operation vapor flows in the opposite direction
  - NCG moves to the opposite end of the heat pipe due to the change in pressure.
  - NCG blocks off what would be the condensing end, effectively shutting down the heat pipe.

Liquid Trap Diode Heat Pipes



- Reservoir at evaporator end of heat pipe contains wick.
  - Reservoir wick does not communicate with heat pipe wick.
- During normal operation the pipe works as a CCHP.
  - Liquid evaporates at hot end and condenses at cold end.
  - Liquid returns to hot end via heat pipe wick.
- During reverse direction, liquid evaporates at the hot end and condenses in the reservoir and becomes trapped.
  - Liquid cannot return to the hot end.
  - The pipe is shut down.
  - No heat dissipation to the regular evaporator.

Major Functions of Heat Pipes

- **Heat transfer**
- **Isothermalization**
- **Temperature control**
- **Heat flux transformation**
- **Thermal diode and switches**

Heat Pipe Operation

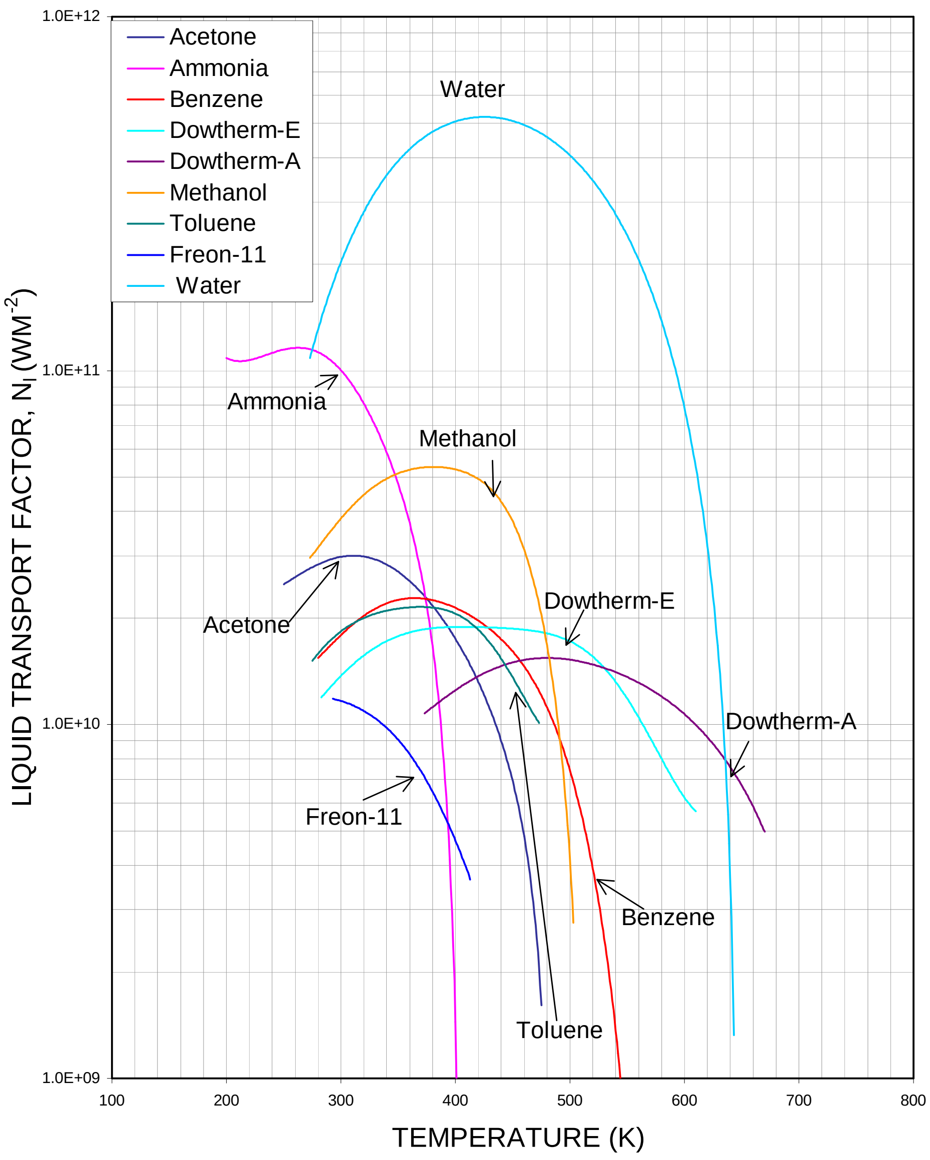
- **The heat pipe is an isothermalizer.**
  - **A single heat pipe can serve multiple heat sources and/or multiple heat sinks.**
  - **The vapor temperature is nearly isothermal.**
- **The heat pipe can be bent.**
  - **Small degradation in heat transport limit**
- **Although the heat pipe can transport hundreds of watts over many feet of distance, it has a very limited wicking capability, i.e. the total pressure drop it can sustain is small.**
  - **Example: no more than 0.5” adverse elevation using ammonia as the working fluid (< 100 Pa) in one-G environment.**
  - **Ground testing of a heat pipe requires that the heat pipe be placed horizontally with < 0.2” adverse elevation.**
- **When the heat pipe operates under a favorable elevation, liquid puddle may form at the evaporator end.**

Liquid Transport Factor vs Temperature

- **A convenient figure of merit is the liquid transport factor, N_l,**

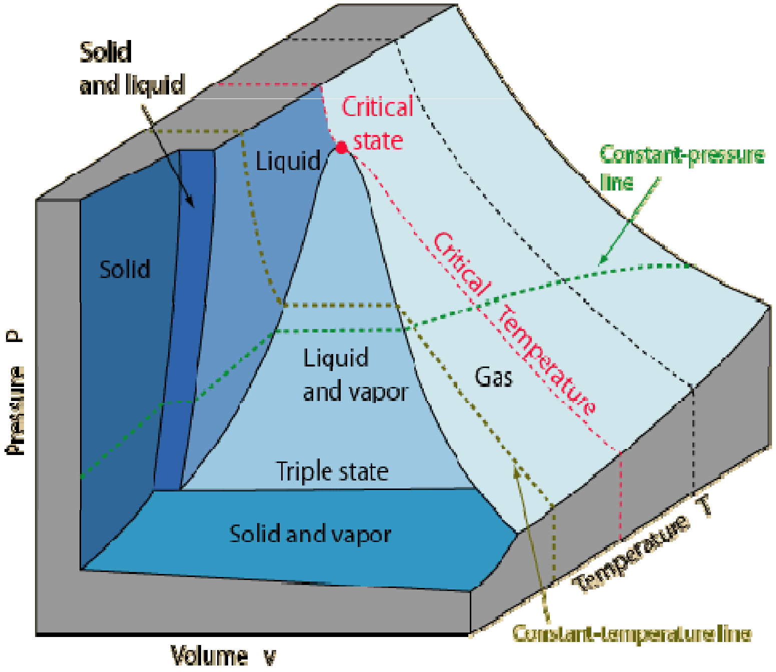
$$N_l = \lambda \sigma \rho_l / \mu_l$$

N_l = Latent Heat * Surface Tension * Liquid Density/ Liquid Viscosity



Heat Pipe Operation Near the Critical State

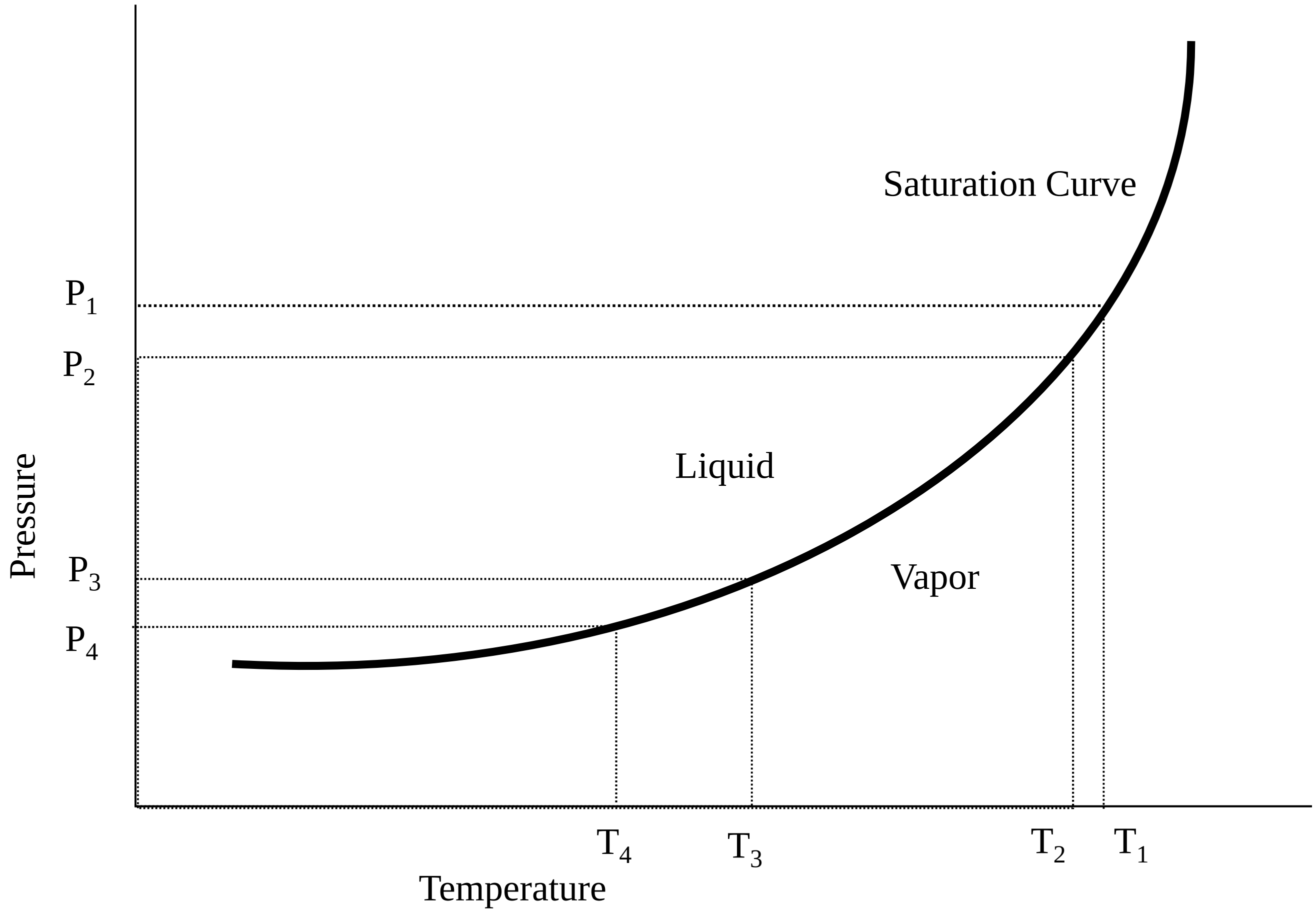
- Never operate a heat pipe near the critical state of the working fluid.
    - Diminishing liquid transport factor



A PvT surface for a substance which contracts on freezing

Heat Pipe Operation Near the Freeze Point

- **Move the HP operation away from the freezing point of the working fluid.**
  - **Non-isothermal**
  - **Low vapor pressure**

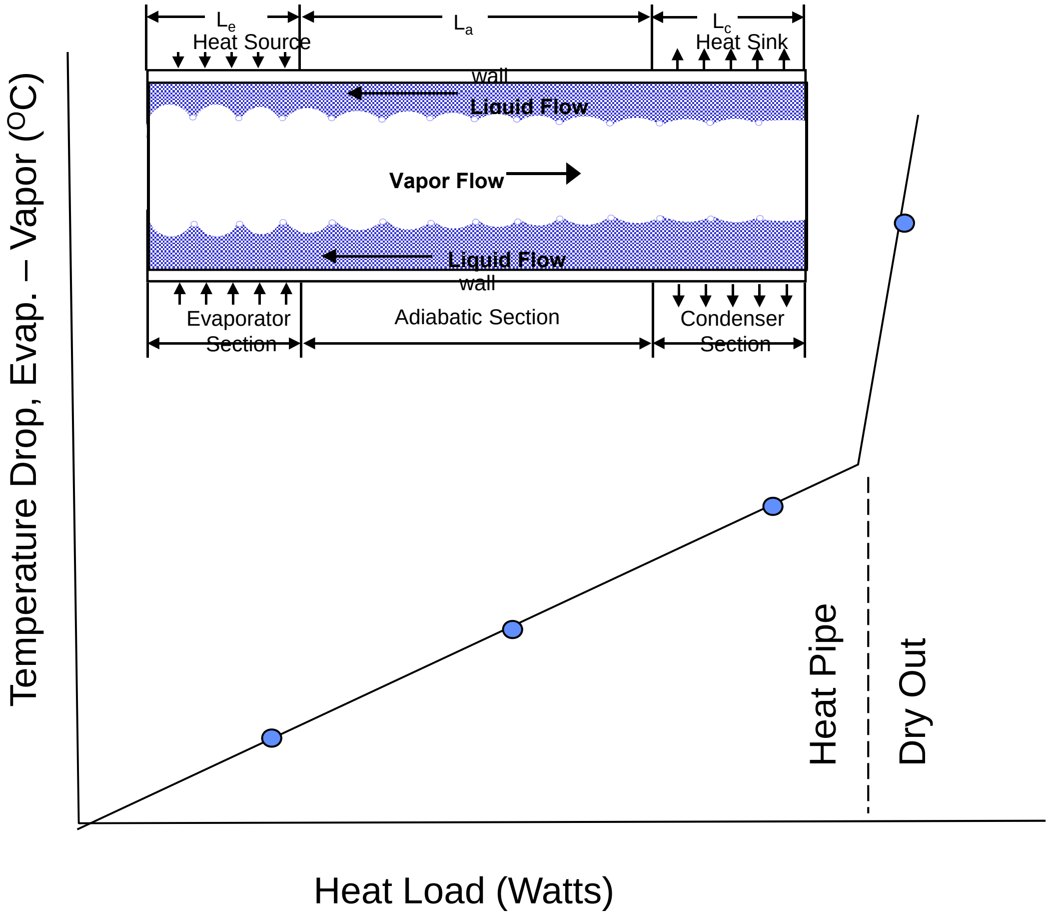


Heat Pipe Operating Limits

- Capillary Limit
  - Most common
- Vapor Pressure Limit
  - Operation near the frozen state
  - Rule of thumb: $(\Delta P_v / P_v) < 0.1$
- Entrainment Limit
  - High vapor velocity
- Boiling Limit
  - High heat flux
- Sonic Limit
  - Liquid metal heat pipes

Capillary Limit - Heat Pipe Dry-out Condition

- **The temperature difference between the end of the evaporator and the adiabatic section is usually plotted.**
- **Recovery from dry-out condition can be achieved by reducing the heat load.**



Heat Pipe Design Procedure

- **Determine the operating temperature range.**
- **Select the working fluid**
  - **Liquid transport factor**
  - **Never operate near the freezing temperature or the critical temperature of the working fluid.**
- **Select the container material.**
  - **Material compatibility**
  - **Structural strength**
- **Select the wick.**
  - **Material**
  - **Shape**
- **From the thermal requirement, determine the type of heat pipe.**
  - **CCHP, VCHP, Diode HP**
- **From the heat transport requirement, determine the heat pipe diameter and length, and number of heat pipes.**
  - **Temperature drop across the heat pipe**
  - **Temperature gradient requirement**
  - **Some computer models available**

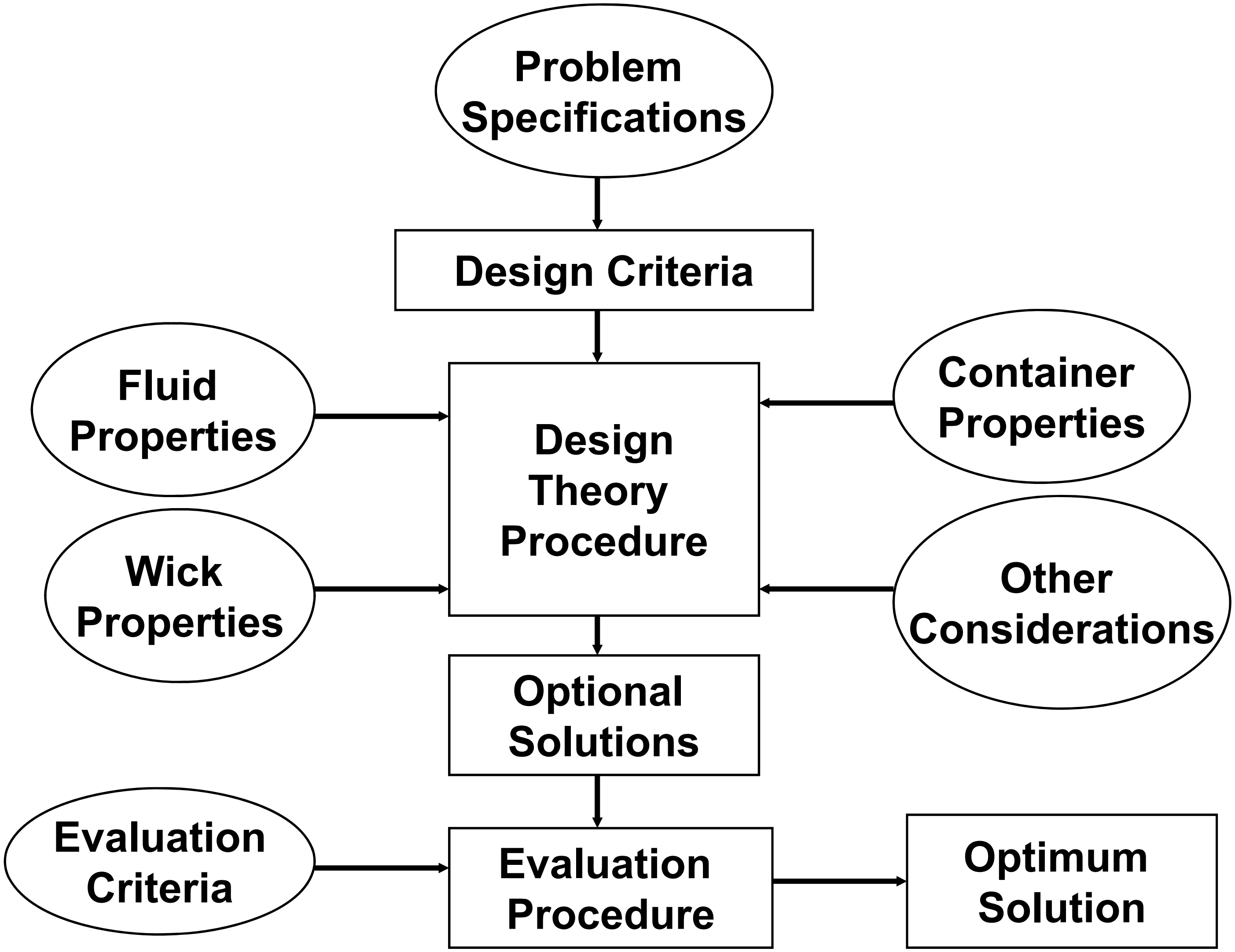
Heat Pipe Design Considerations (1)

- Heat pipe theory
- Physical, thermal, and mechanical constraints
- Material properties
- Application requirements
- Fabrication, processing, and testing limitations
- Reliability and safety

Heat Pipe Design Considerations (2)

- **Once the performance requirements and specifications are defined, the design and evaluation process can be initiated.**
- **Three Basic Consideration**
  - **Working fluid**
  - **Wick design**
  - **Container (envelope)**
- **Several options may exist.**
- **The final design usually represents an iteration among various design factors.**

Heat Pipe Design Procedure



Problem Specifications

Design Criteria

Fluid Properties

Wick Properties

Design Theory Procedure

Container Properties

Other Considerations

Optional Solutions

Evaluation Criteria

Evaluation Procedure

Optimum Solution

Problem Definition and Design Criteria (1)

Requirement	Impact on Design
Operating temperature range	Choice of working fluid; Pressure retention
Thermal load	Heat pipe diameter; No. of heat pipes; Wick design; Choice of working fluid
Transport length	Wick design
Temperature uniformity and overall ΔT	Wick design; Conductive path length trade-off; Heat pipe geometry
Physical requirements	Size, Weight, Structural strength and geometry
Acceptance and qualification testing	“one-G’ operation and “zero-G” correlation

Problem Definition and Design Criteria (2)

Requirement	Impact on Design
Ground testing	Orientation
Dynamic environment	Operation under accelerating field; Structural integrity
Thermal environment	Pressure retention under non-operating temperatures
Mechanical interfacing	Mounting provisions; Provision for thermal interfacing
Man Rating	Pressure vessel code; Fluid toxicity
Transient behavior	Choice of working fluid; Wick design; Variable conductance type
Reliability	Leak tightness; Material compatibility; Processing control; Redundancy

Working Fluid

- Variety of fluid possible - selection determined by applications: operating temperature, capacity, safety, etc.
- Must be able to exist as both vapor and liquid at the operating temperature.
  - Often best to select a fluid that has its normal boiling point near desired operating temperature.
- Use the liquid transport factor as the figure of merit.
- Purity of the working fluid is critical (99.999%).
  - Impurities reduce performance and may lead to undesirable NCG buildup.
- Must be compatible with other materials in the heat pipe.
- Operating pressure
- Wicking capability in body-force field
- Liquid thermal conductivity
- Vapor phase properties

Operating Temperature Ranges

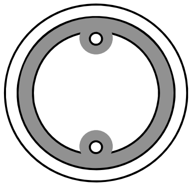
- Cryogenic
  - 0.1K to 150K
  - Elemental or simple organic compounds

- Low Temperature
  - 150K to 750K
  - Polar molecules or halocarbons

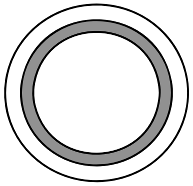
- High Temperature
  - 750K to 3000K
  - Liquid metals

Wick Material

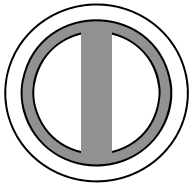
- Provides capillary pumping head.
- Provides porous media for liquid transport.
- Variety of design possibilities exist.
  - Axial groove (most common)
  - Screen
  - Sintered powder
  - Arteries
  - Composites
- Small uniform pore size is desirable.
  - Compromise with desire for high permeability



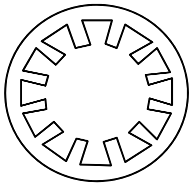
POWDER METAL WITH
PEDESTAL ARTERY



CIRCUMFERENTIAL
SCREEN WICK



SLAB WICK



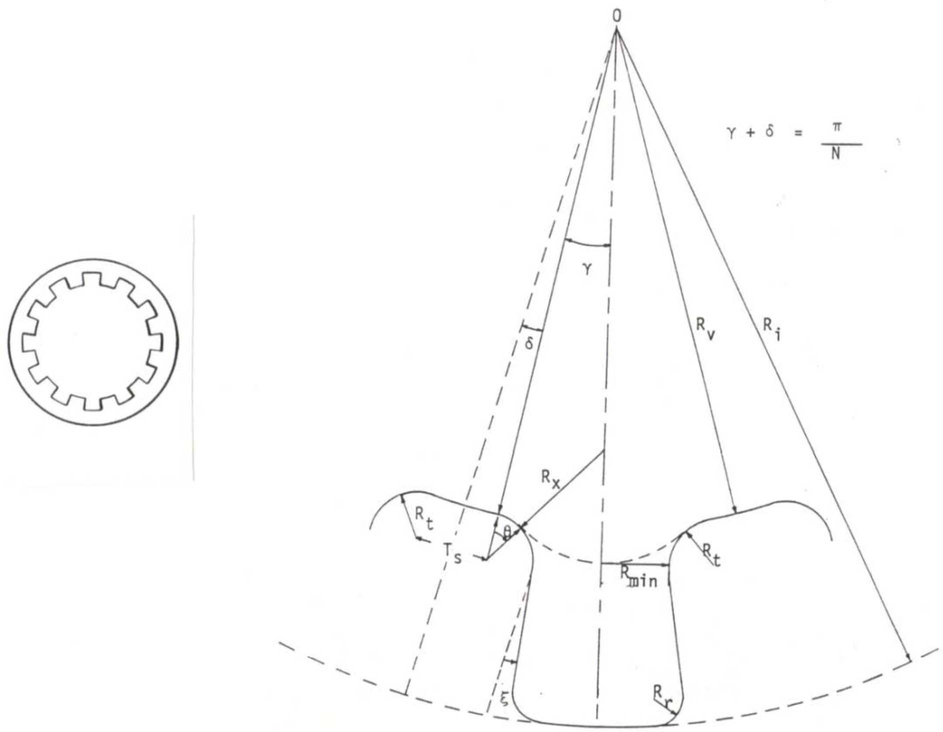
AXIAL GROOVES

Envelope Material

- **Typically a metal tube tightly sealed at both ends**
- **A variety of shapes, sizes, and configurations exist.**
- **Basic design considerations**
  - **Structure integrity and leak tight containment**
  - **Compatibility with working fluid and external environment**
  - **Internal size and geometry for liquid and vapor flow requirements**
  - **External interface with heat sources and sinks**
  - **Fabrication concerns**
  - **Heat transfer concerns**

Fluid Inventory

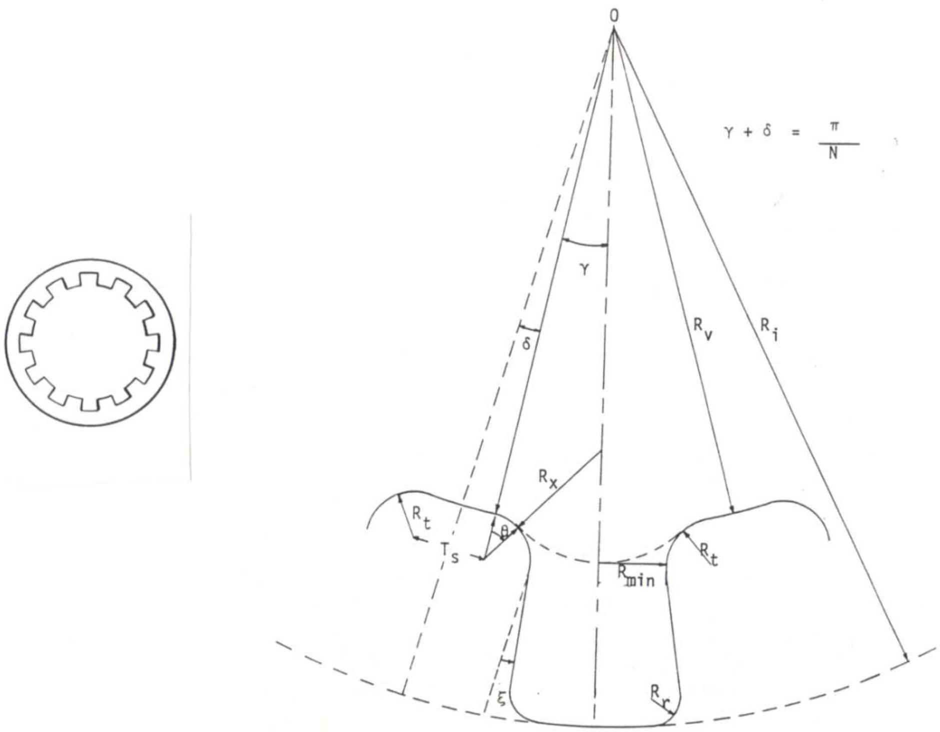
- Liquid charge must be sufficient to saturate the wick.
  - Performance degrades with improper charge.
  - Undercharge: reduced heat transport capability
  - Overcharge: liquid puddle in the condenser
- The optimal inventory will be determined based on operating conditions.



Fabrication/Testing

- **Cleaning and material compatibility are critical. Must develop and follow tight cleaning procedures.**
- **Proper level of fluid charge is important.**
- **Component and system level tests**
  - **In-process**
  - **Proof pressure**
  - **Burst**
  - **Leak**
  - **Performance - vary tilt to develop performance map**
- **Rigid requirements for space applications**
  - **MIL-STD1522A (USAF)**
  - **NSTS-1700.7B (NASA)**

Heat Pipe Design Tools

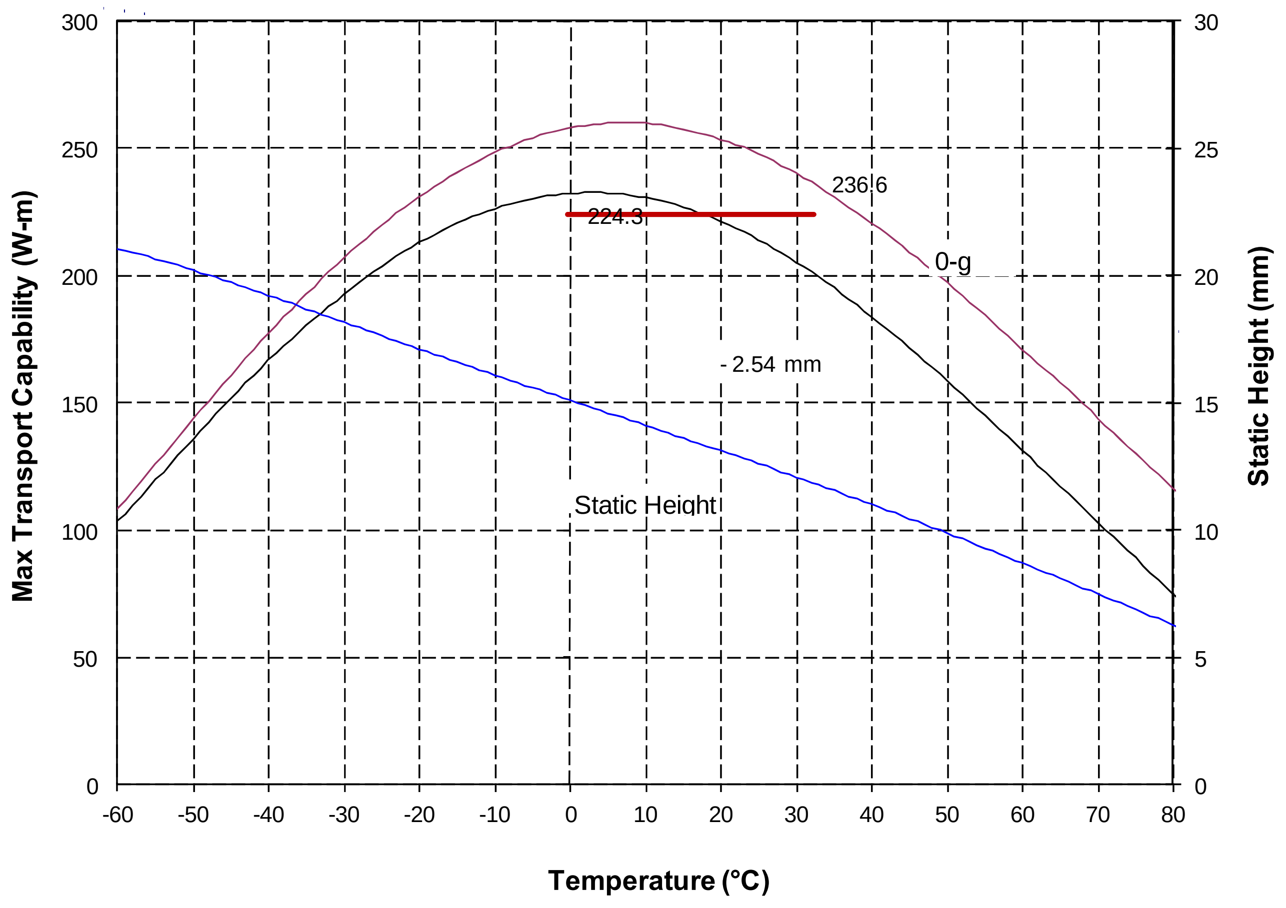


- **Each vendor has its own analytical design tools.**
- **Groove Analysis Program (GAP) software – good for axially grooved heat pipes**
  - **NASA-owned**
  - **Available for purchase through COSMOS**

Heat Pipe Selection – for Thermal Engineers (1)

- First and foremost: determine the operating temperature range.
- Select the working fluid.
- Select the wick and container material.
    - Material compatibility
- Obtain performance curves for various heat pipes from vendors.

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

Heat Pipe Selection – for Thermal Engineers (2)

- From the thermal requirements, determine the type of heat pipe.
  - CCHP, VCHP, Diode HP
- From the heat transport requirement, determine the heat pipe diameter and length, and number of heat pipes.
  - Overall temperature drop from heat source to heat sink
  - Temperature gradient requirement
  - Temperature uniformity requirement
  - Physical constraints – diameter and shape of heat pipes
  - Mass constraints
  - Design margins
  - Cost
- Ground test requirement at the instrument and spacecraft level

Other Practical Considerations

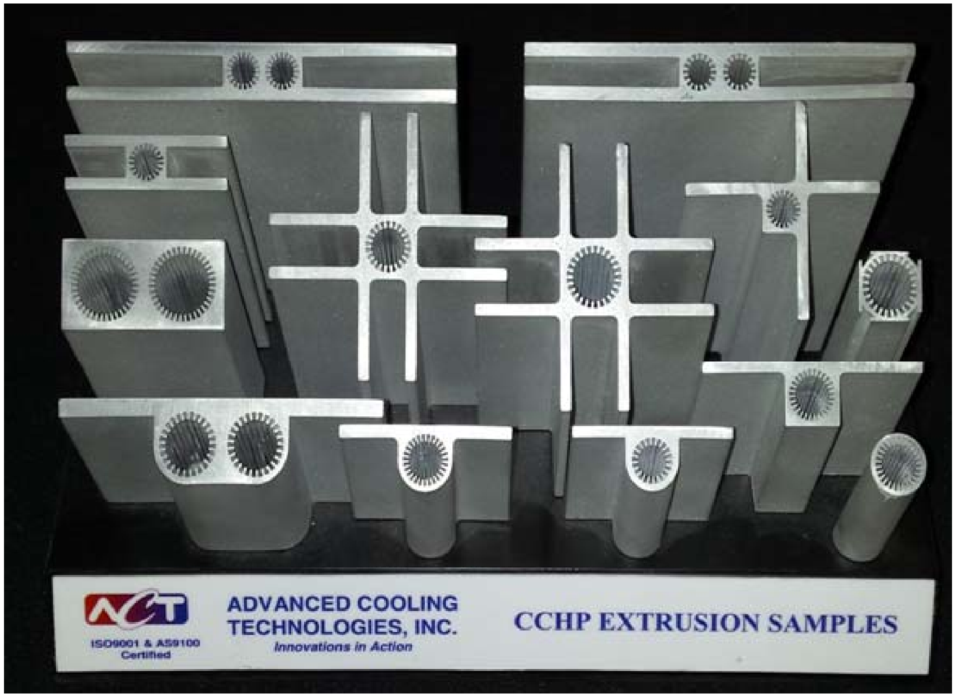
- 3-dimensional heat pipes
- Dual-bore heat pipes
- Ground testing of heat pipes in reflux mode

3-Dimensional Heat Pipes

- **3-D heat pipes cannot be tested in one-G for its performance verification.**
- **For design qualifications, an equivalent 2-D heat pipe can be made with same number of bends, same degree of bend for each bend, and same segment lengths, and test for its performance.**
- **For acceptance test, the 3-D pipes may be tested in segments.**
  - **Adequate for axially-grooved heat pipes which have uniform grooves.**
  - **Inadequate for slab wick heat pipes.**

Dual Bore Heat Pipes

- Some reasons to use dual bore heat pipes
  - for redundancy
  - to reduce heat flux and temperature gradient between the heat source and the heat pipe
  - HP can serve as structural member
- For qualification test, each bore is charged and tested separately.
- For acceptance test, both pipes are tested together – cannot tell whether one of them fails.
- For charging, one bore is charged first, then the other.
- Performance such as the heat transport, heat flux, thermal conductance, liquid slug and NCG can only be done for both heat pipes on the "average" basis.
- Dual bore heat pipes are more difficult to bend.



Ground Testing of Heat Pipes in Reflux Mode

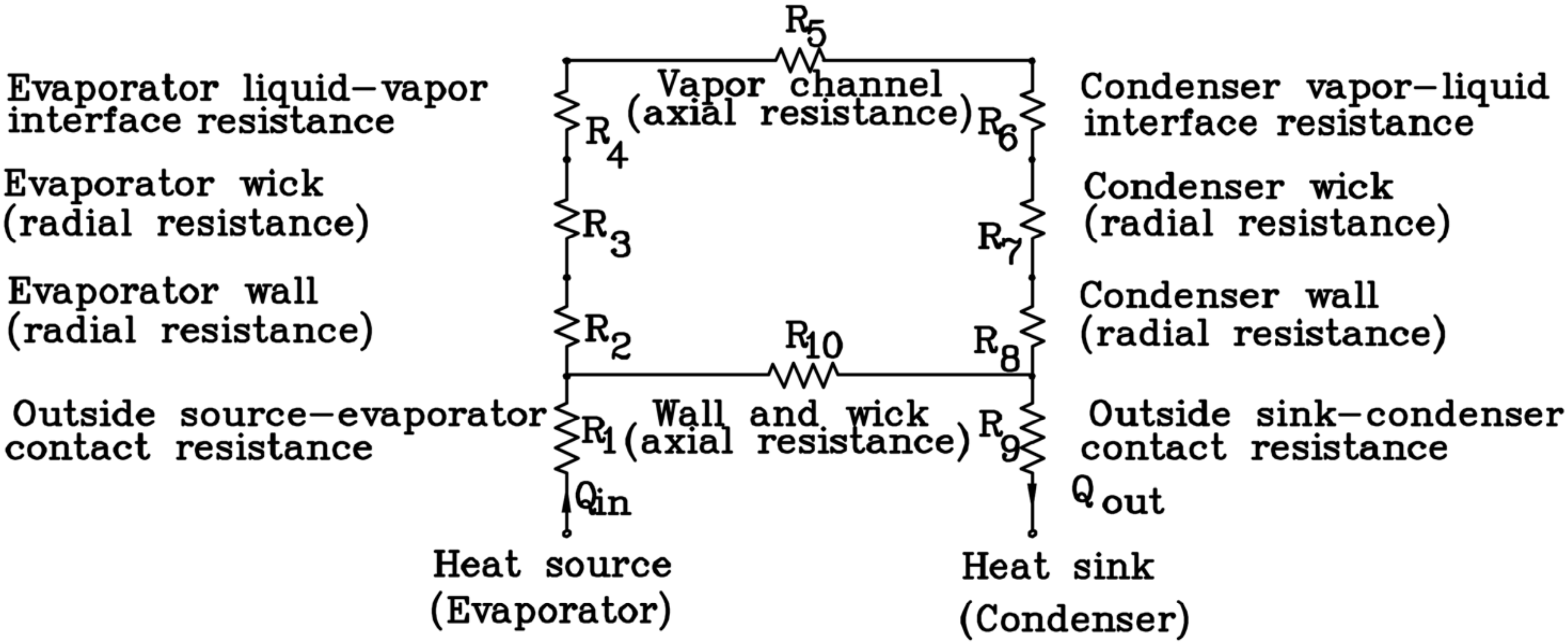
- **It may be necessary to test the heat pipe in a reflux mode during instrument and/or spacecraft level test.**

- **Liquid puddle will form at the evaporator which is below the condenser.**

- **Liquid may not boil to generate vapor unless a superheat is exceeded at the evaporator.**

- **To facilitate the ground testing, some concentrated heater can be attached to the evaporator to create a high heat flux, which initiates liquid boiling.**

Detailed Thermal Resistance Model of Heat Pipe



Heat Pipe Modeling Using SINDA/FLUINT

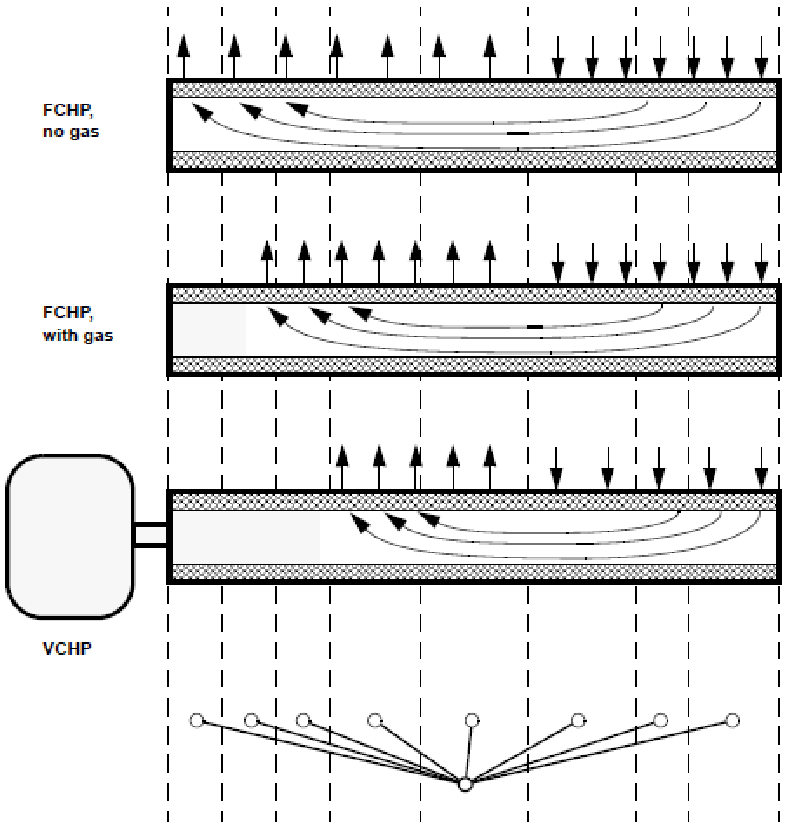


Figure 7-2 Heat Pipe Variations and Typical Network Diagram

- NOT an HP design tool – e.g. groove dimensions, VCHP reservoir sizing.
- Appropriate for most TCS design and analysis
- Very important: read the manual for capabilities/limitations.

Heat Pipe Modeling Using SINDA/FLUINT

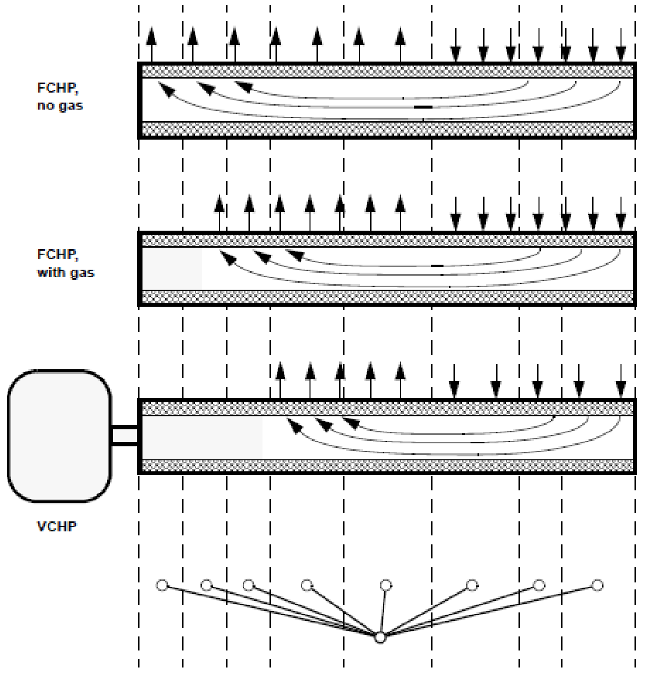
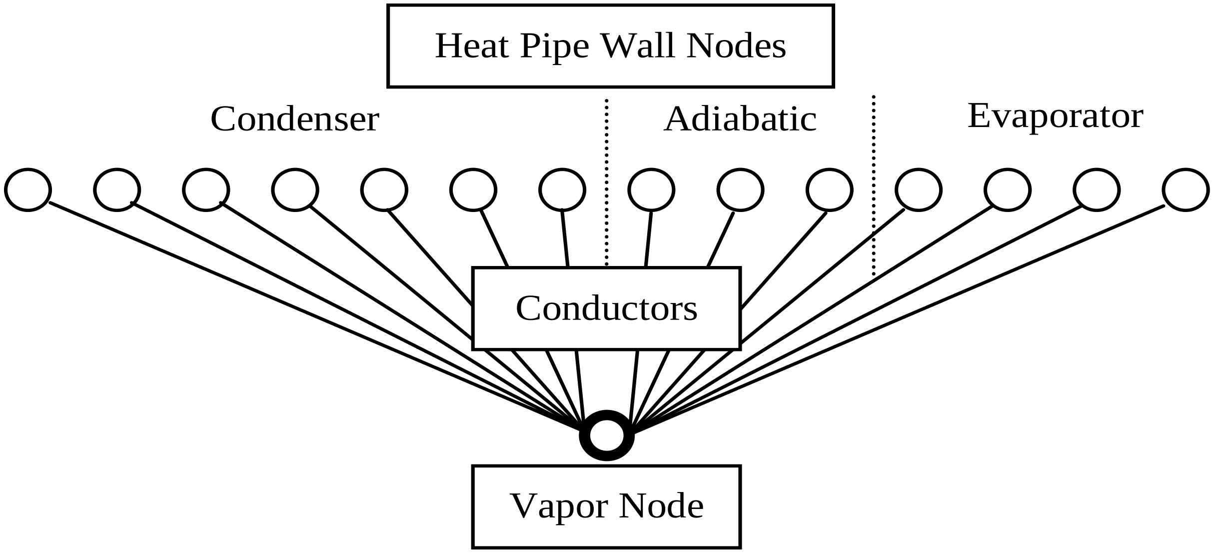


Figure 7-2 Heat Pipe Variations and Typical Network Diagram

- **Uses subroutines HEATPIPE and HEATPIPE2.**
- **Simulates CCHP, gas-charged CCHP, gas-charged VCHP.**
- **The vapor is assumed to be a uniform temperature (i.e. single node).**
- **The vapor node must be an arithmetic node.**
- **Make certain all units are consistent.**
- **Called from Variables 1 block**

VCHP Modeling – Node/Conductor Network



- Modeling a VCHP in SINDA begins as a basic node-conductor network
- Conductors are initialized for each heat pipe wall node to the vapor node and can be adjusted depending on the gas front location
- To simulate NCG located in a particular node in the condenser the conductor for that wall node to the vapor node is set to zero or a percentage of the original value if partially blocked

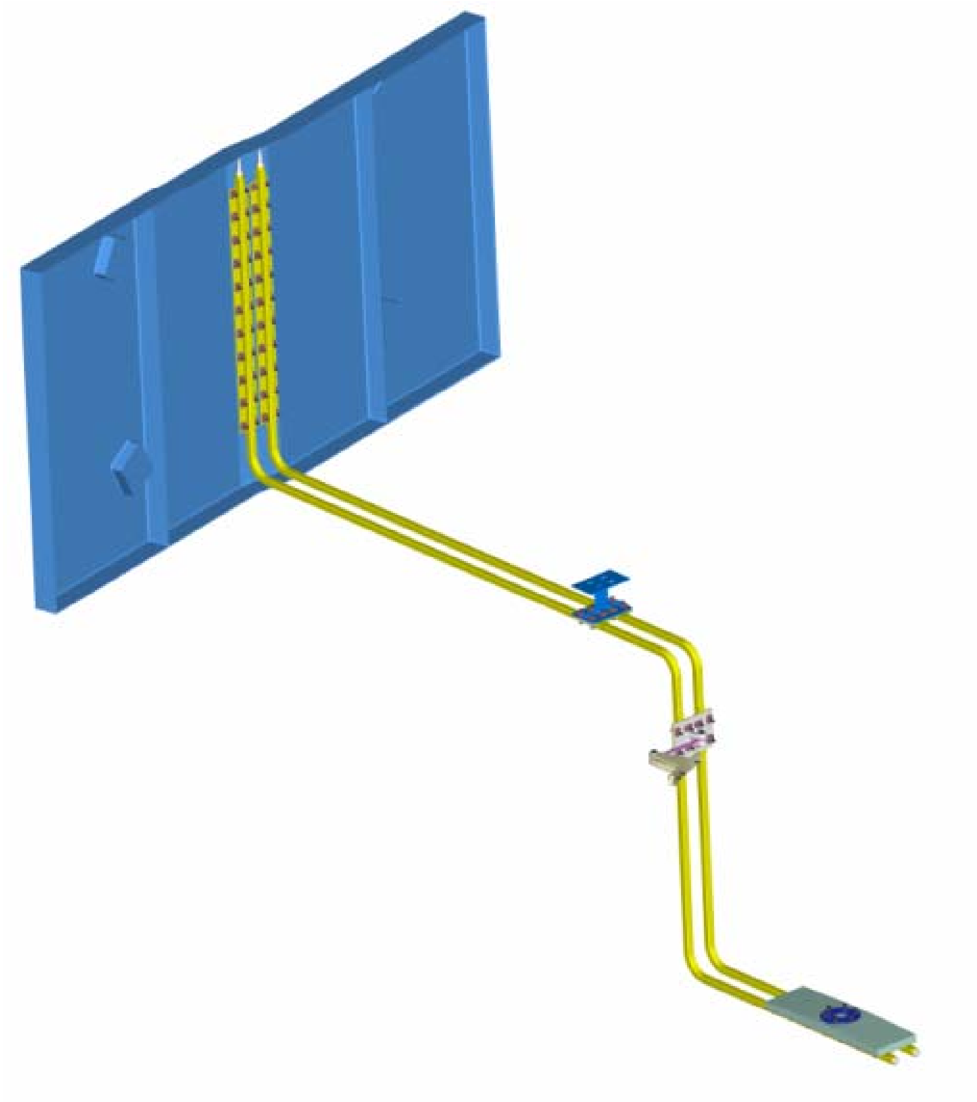
Flight Heat Pipes

- **Ammonia HPs**
  - **Most prevalent**
  - **Too many to list**
- **Water HPs**
  - **NRL WindSat (launched 2003)**
- **Butane HPs**
  - **MESSENGER- Diode HP (2004 - 2011)**
- **Ethane HPs**
  - **LDEF (1984-1990)**
  - **Swift XRT (launched 2004)**
  - **LDCM TIRS (launched 2013)**
- **Oxygen HPs (flight experiment)**
  - **CCHP on STS-62 (1994)**
  - **Flexible diode HP on CRYOHD experiment on STS-94 (1997)**
- **Nitrogen HPs (flight experiment)**
  - **CCHP on STS-62 (1994)**
- **Methane HPs (flight experiment)**
  - **Flexible diode HP on CRYOHD experiment on STS-94 (1997)**

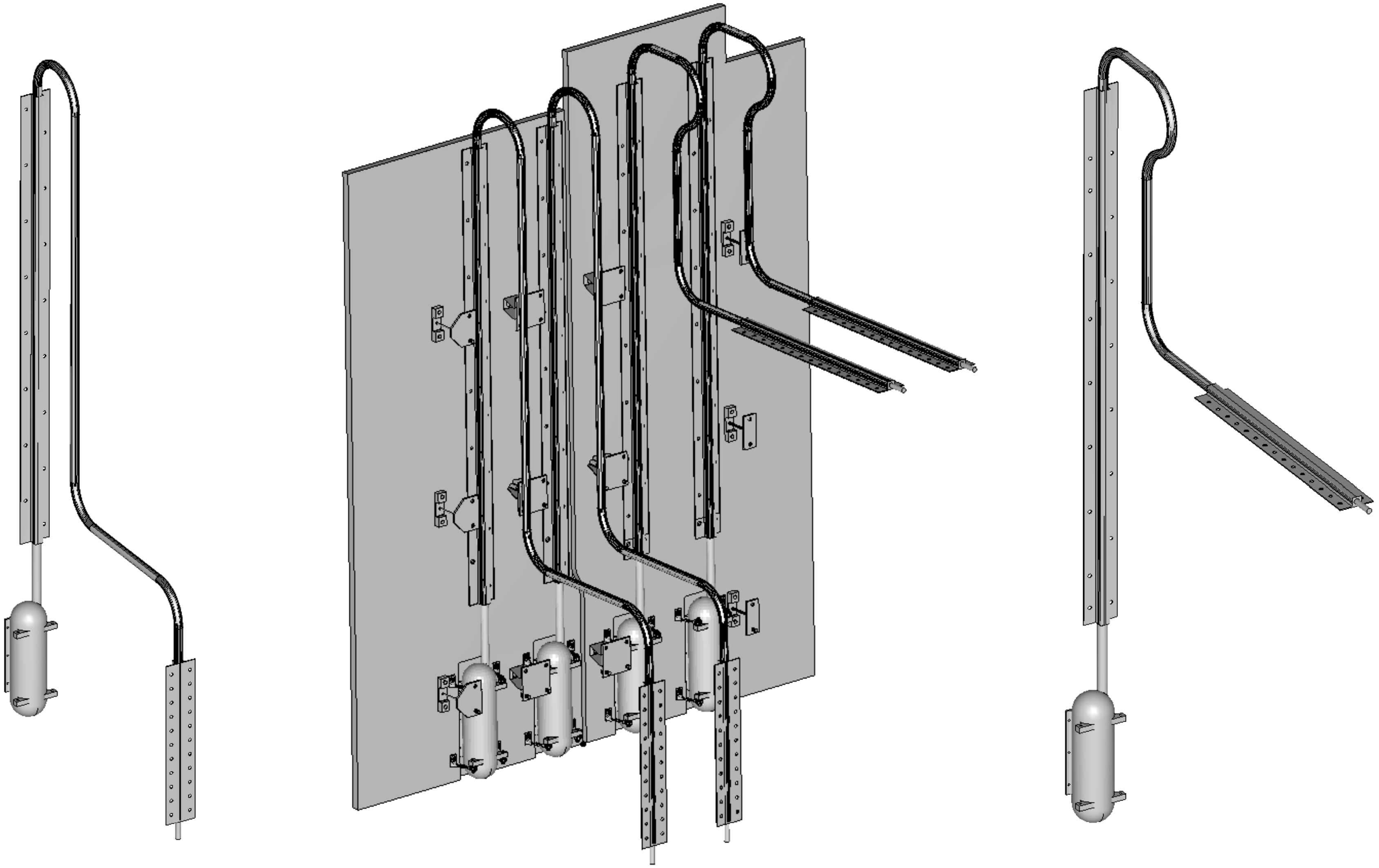
Triple Point and Critical Temperature of Some fluids

Fluid	Freezing Temperature (K)	Critical Temperature (K)
Ammonia	195.4	405.5
Butane	134.6	425.1
Ethane	89.9	305.3
Helium	2.2	5.2
Hydrogen	13.8	33.2
Methanol	175.6	512.6
Methane	90.7	190.8
Neon	24.6	44.4
Nitrogen	63.2	126.2
Oxygen	54.4	154.6
Pentane	143.5	469.8
Propylene	88	365.6
Water	273.1	647

Swift XRT Ethane Heat Pipes

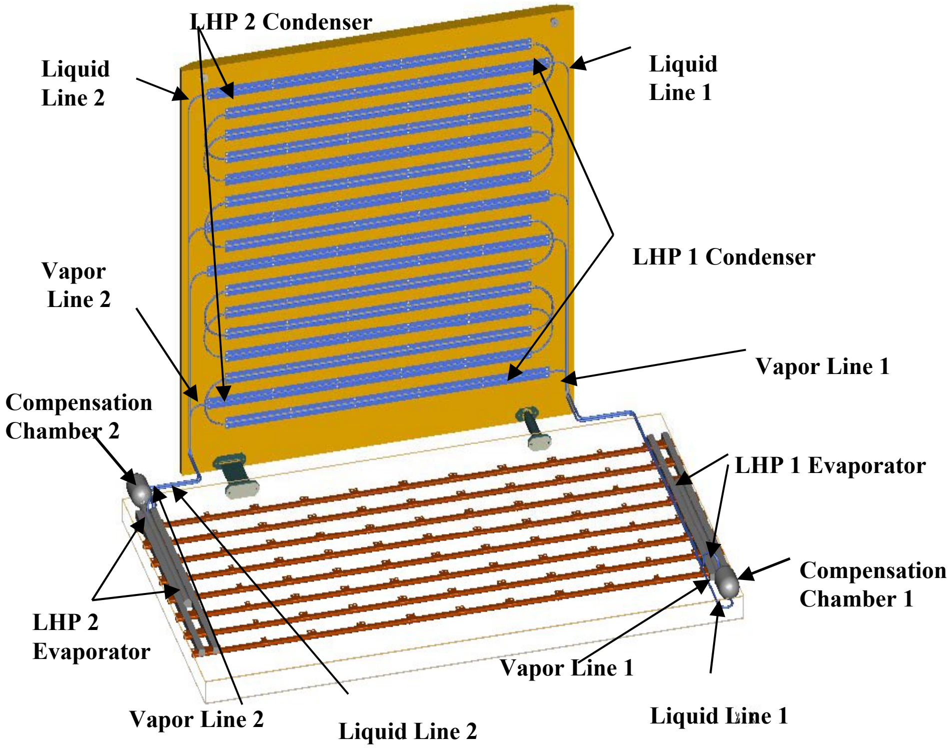


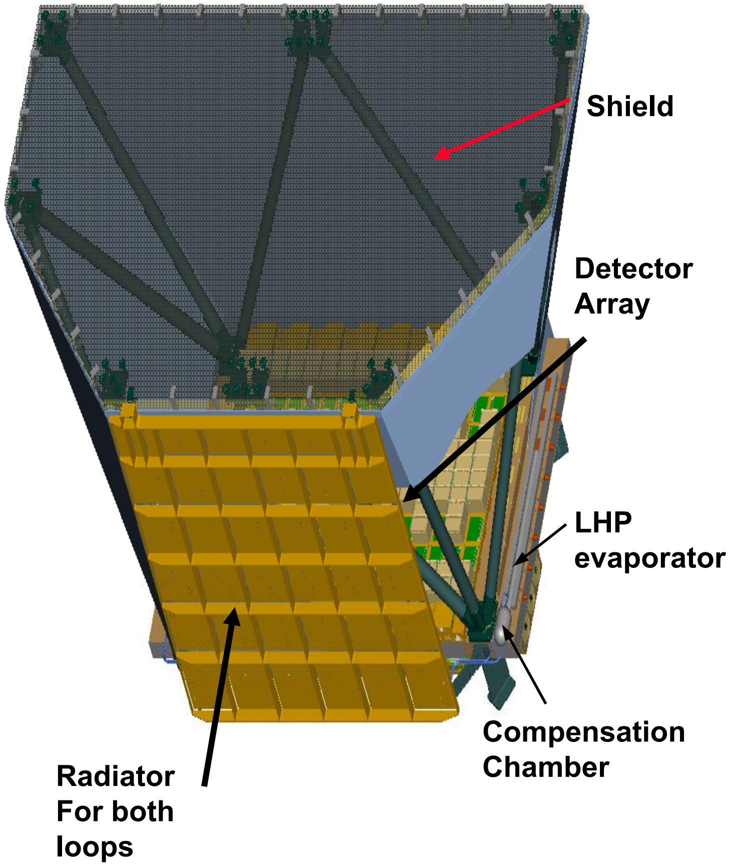
Orbiting Carbon Observatory – 2 (OCO-2) VCHP



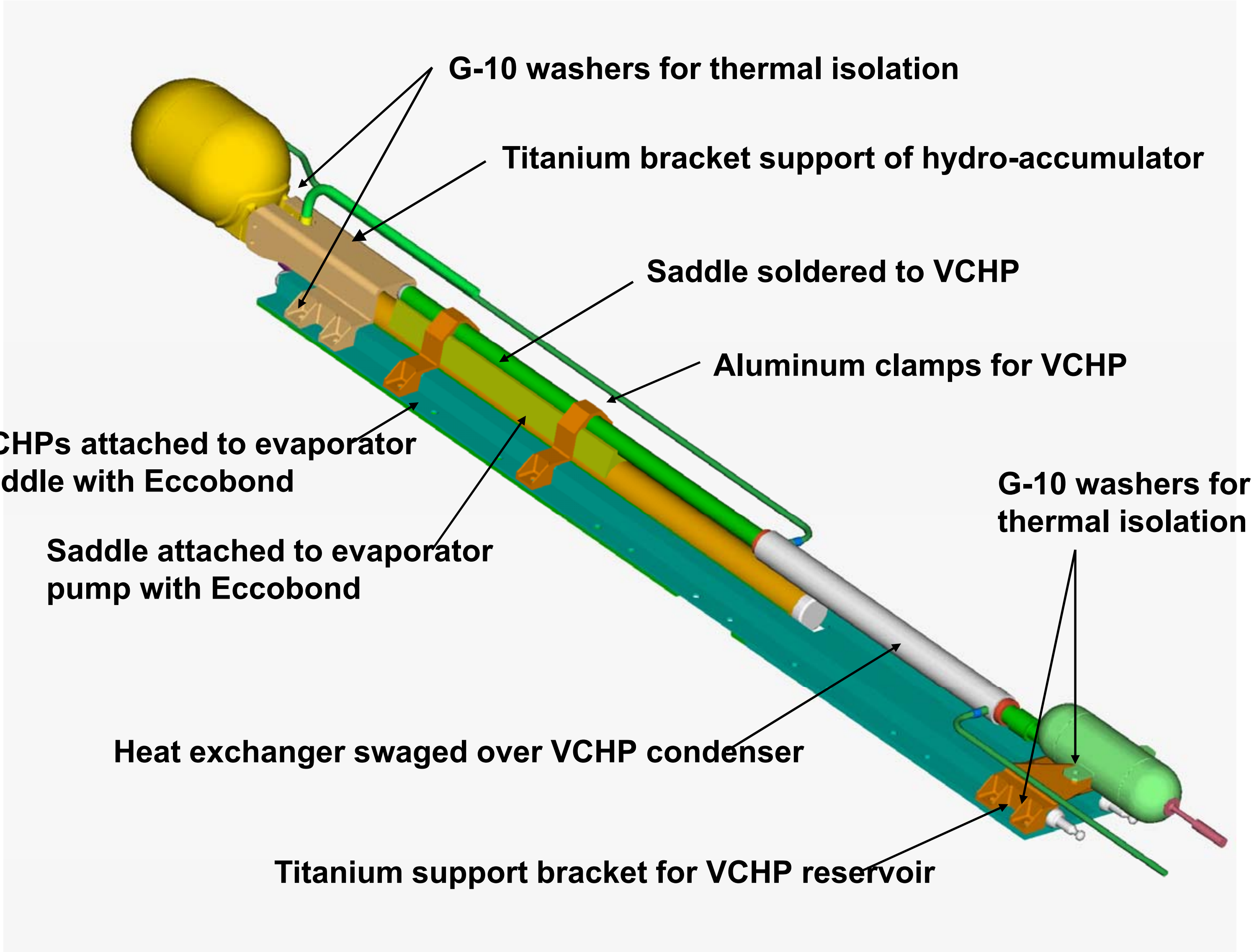
CCHPs/VCHPs/LHPs on SWIFT ABT

- 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 System – VCHP and LHP Evaporator



G-10 washers for thermal isolation

Titanium bracket support of hydro-accumulator

Saddle soldered to VCHP

Aluminum clamps for VCHP

CCHPs attached to evaporator saddle with Eccobond

G-10 washers for thermal isolation

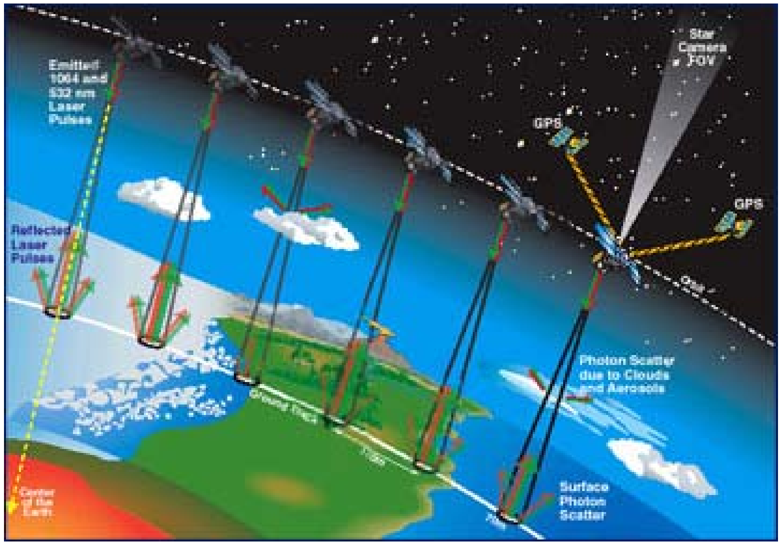
Saddle attached to evaporator pump with Eccobond

Heat exchanger swaged over VCHP condenser

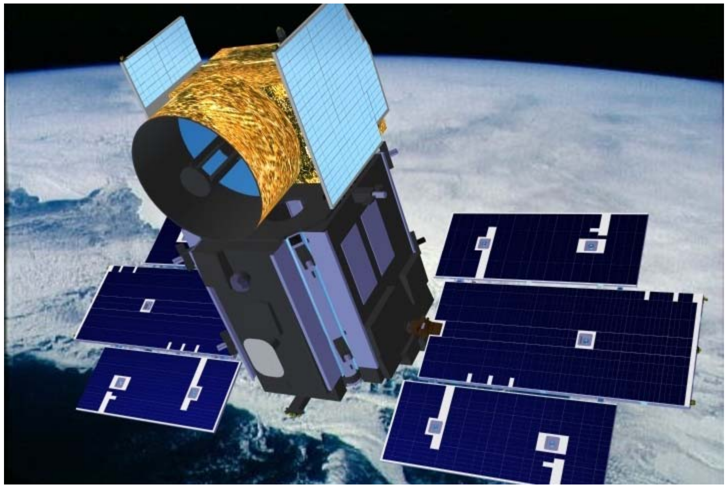
Titanium support bracket for VCHP reservoir

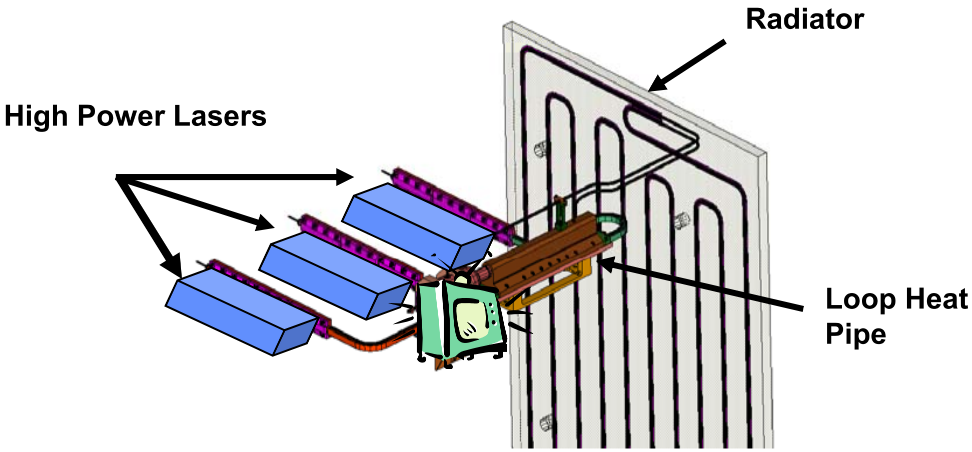
Swift BAT VCHPs and LHPs

HPs/LHPs on ICESat GLAS



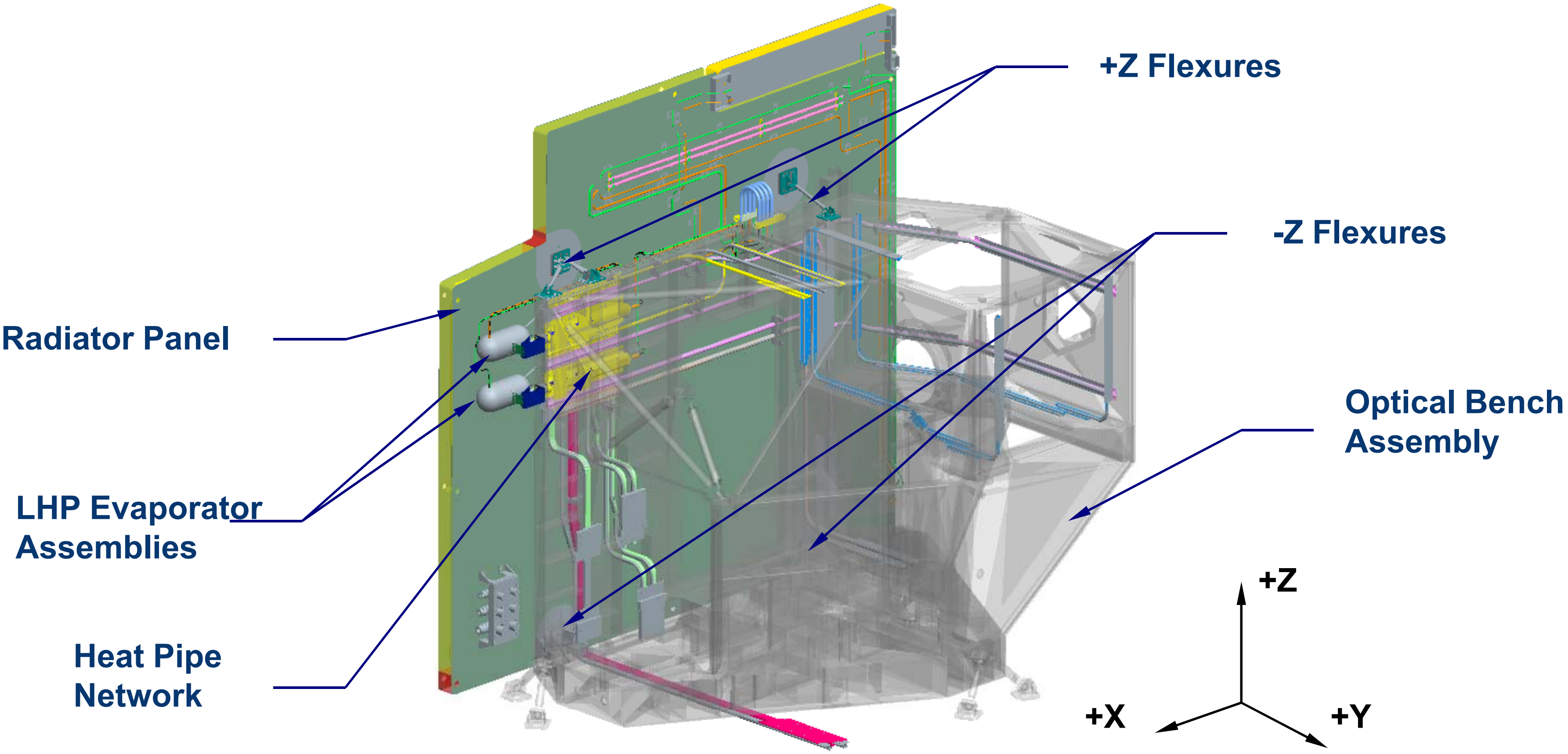
- GLAS has high powered lasers to measure polar ice thickness
- First known application of a two-phase loop to a laser
- 2 LHPs; Laser altimeter and power electronics
  - Propylene LHPs
- Launched January, 2003
- Both LHPs successfully turned on
- Very tight temperature control ~ 0.2 °C





GOES-R ABI HPs/LHPs Assembly

- Radiator LHP Assembly contains two parallel redundant LHPs, a shared radiator, heaters, thermostats, thermistors, and an electrical harness assembly.
- Evaporator Assemblies mount to Heat Pipe Network on Optical Bench



+Z Flexures

-Z Flexures

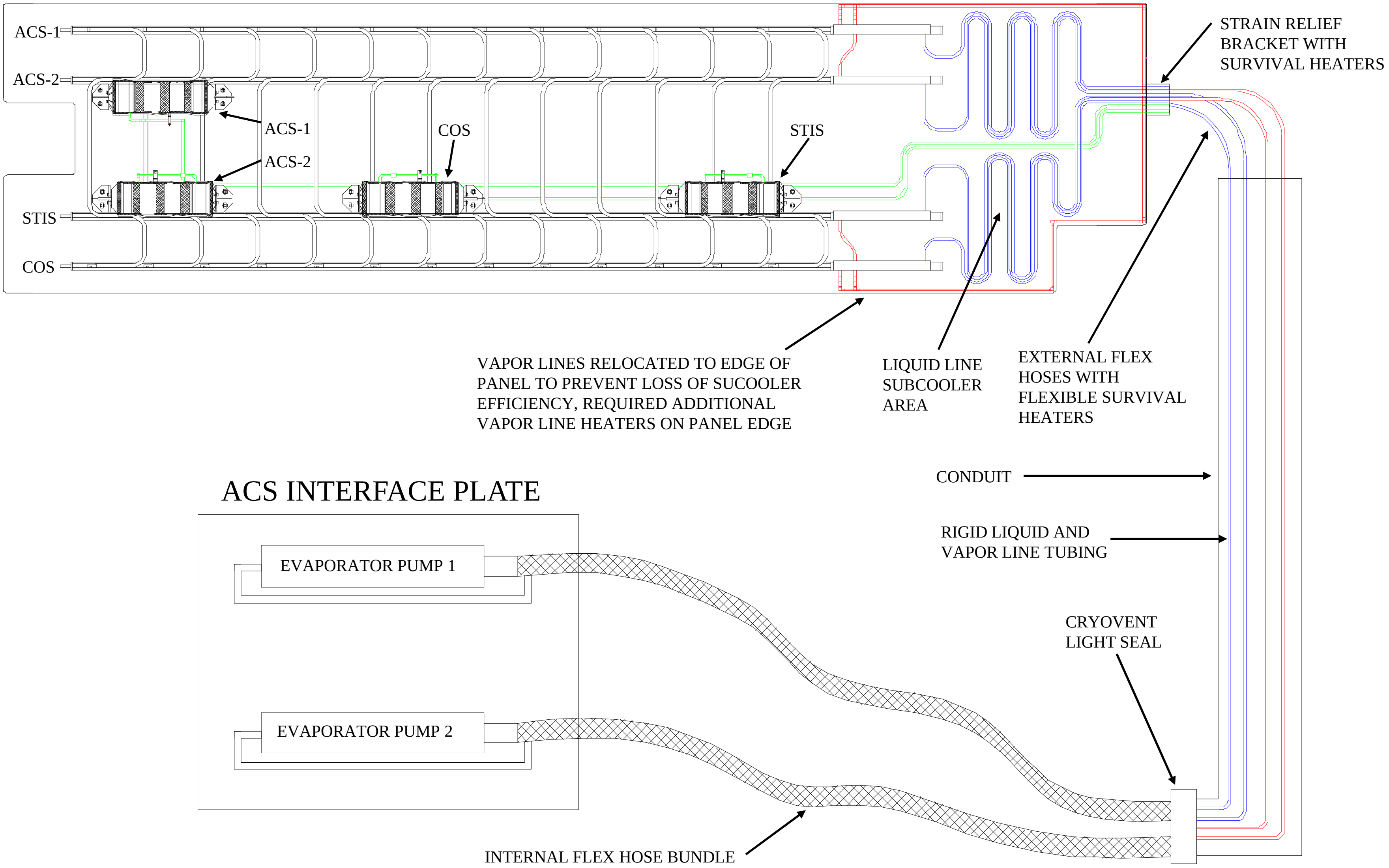
Radiator Panel

Optical Bench Assembly

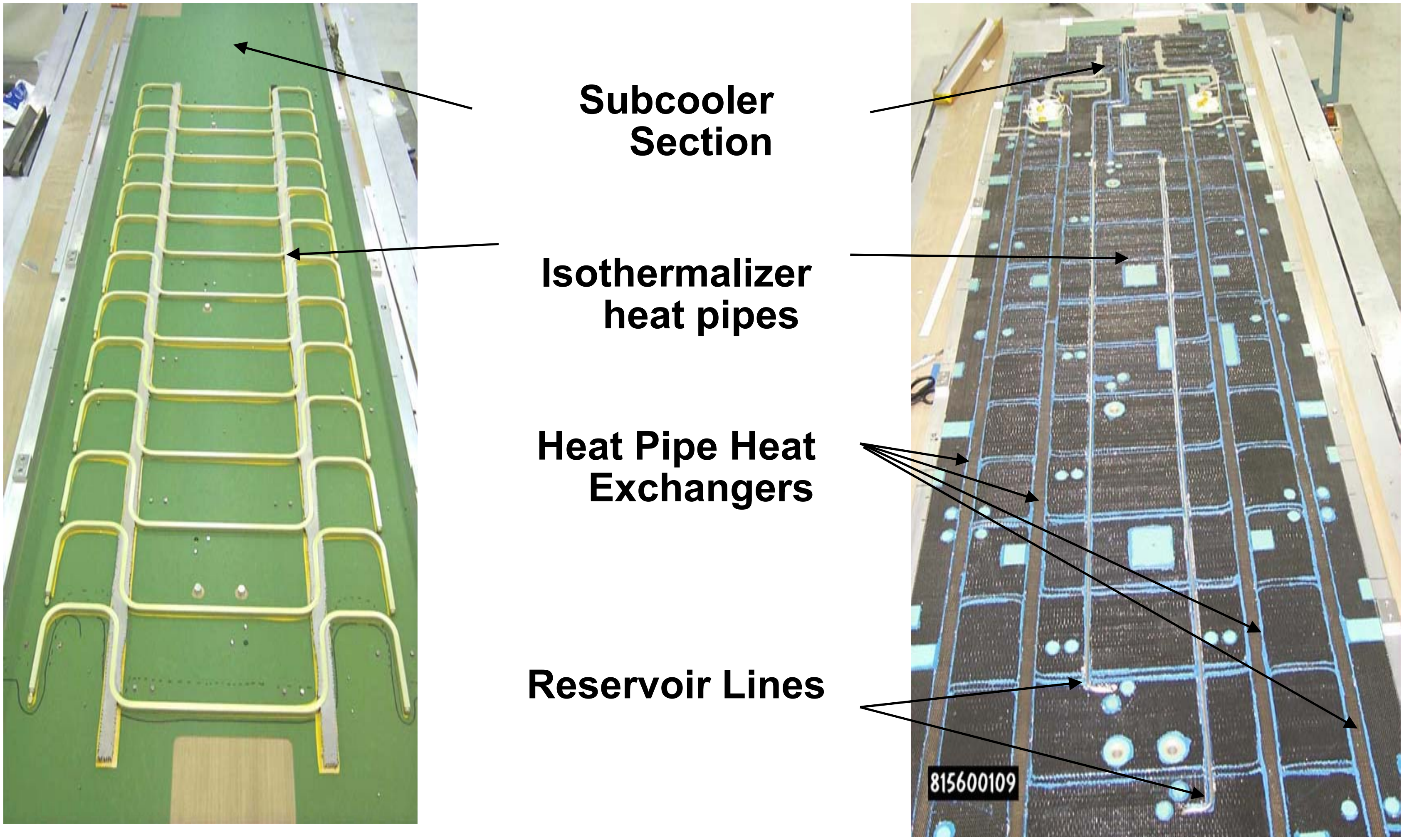
LHP Evaporator Assemblies

Heat Pipe Network

HST ACS CPLs and ASCS Radiator Design



HST CPL/HP Radiator Assembly



Subcooler Section

Isothermalizer heat pipes

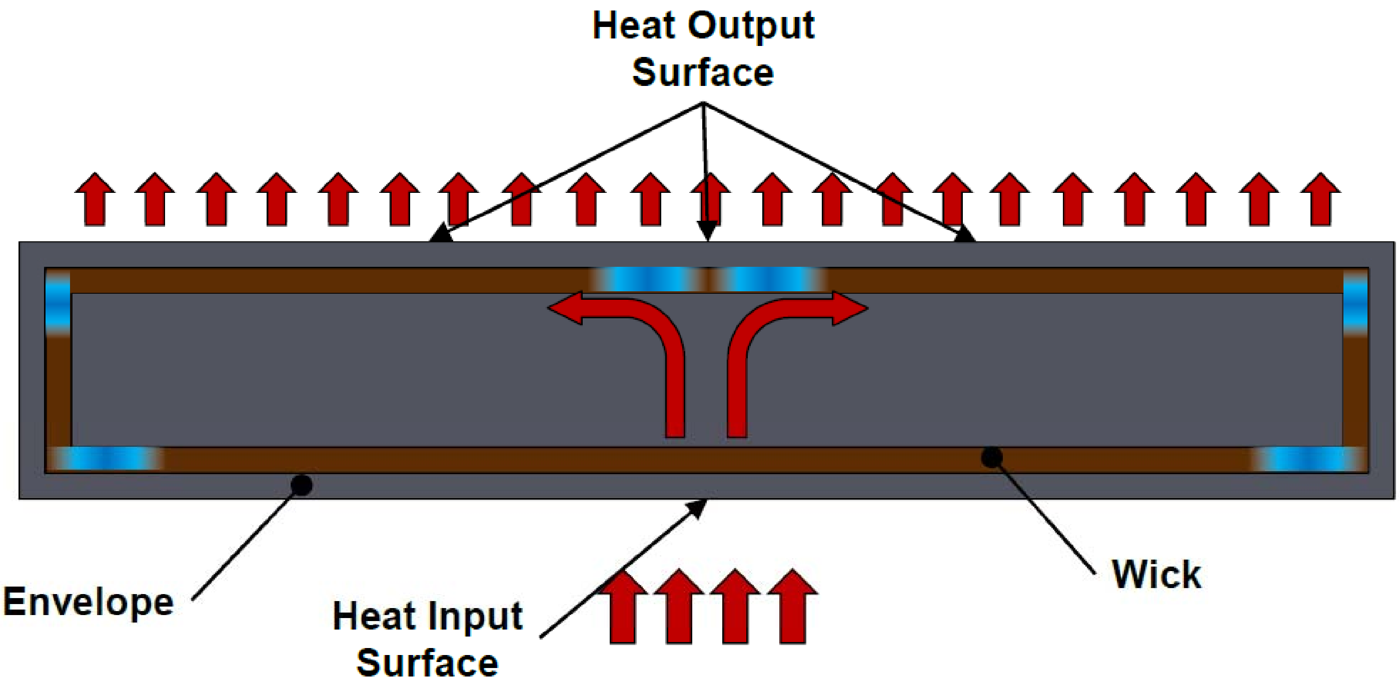
Heat Pipe Heat Exchangers

Reservoir Lines

Other Types of Heat Pipes

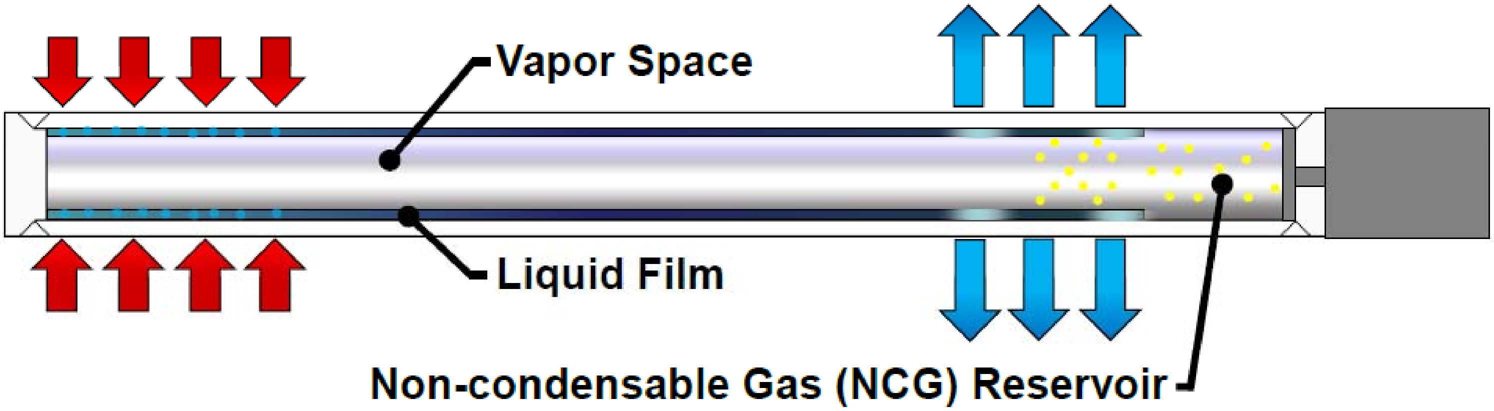
- **Vapor Chamber**
- **Pressure Controlled VCHP**
- **Two-Phase Closed Thermosyphon**
- **Rotating Heat Pipe**
- **Oscillating Heat Pipe**

Vapor Chamber



- **Vapor chambers are planar heat pipes for heat spreading and/or isothermalizing**

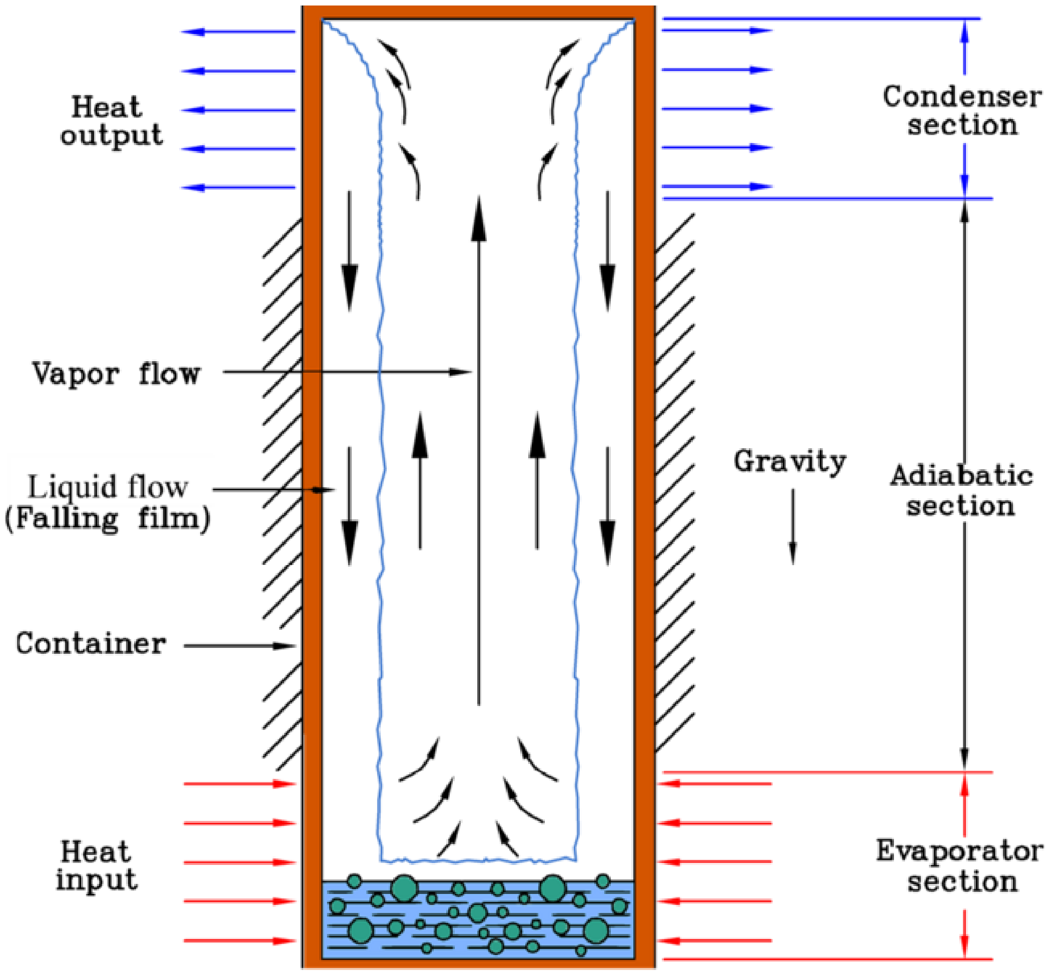
Pressure Controlled VCHP



- **Vary reservoir volume or amount of gas**
  - **Actuator drives bellows to modulate the reservoir volume**
  - **Pump/vacuum pump adds/removes gas**
- **Used for precise temperature control**

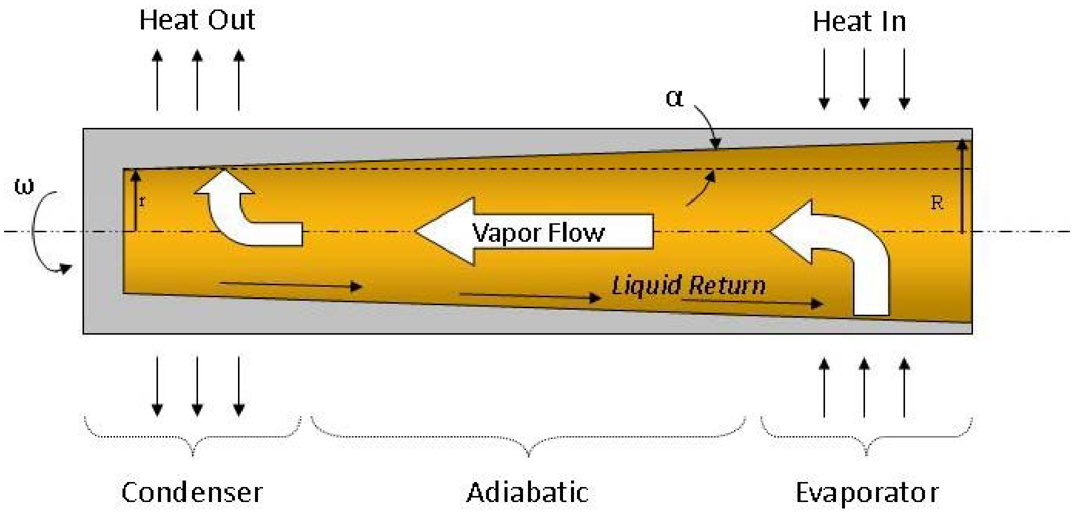
**** Anderson, W.G, et al., "Pressure Controlled Heat Pipe Applications," 16th International Heat Pipe conference, Lyon, France, May 20-24, 2014**

Two-Phase Closed Thermosyphons



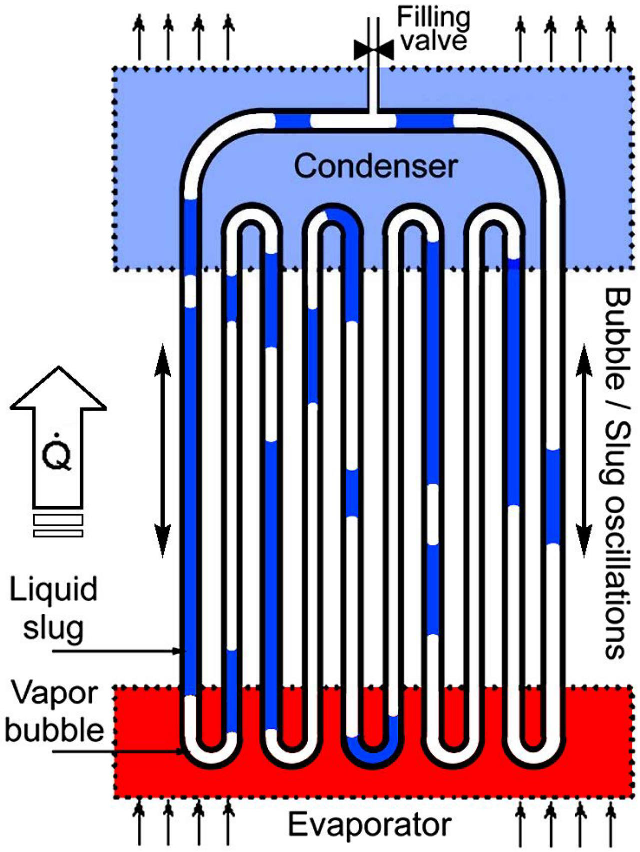
- A gravity-assisted wickless heat pipe
- The condenser section is located above the evaporator so that the condensate is returned by gravity.
- The entrainment limit is more profound.
- The operation is sensitive to the working fluid fill volume.

Rotating Heat Pipe



- A rotating heat pipe uses centrifugal forces to move the condensate from the condenser to the evaporator
- The inside of the heat pipe is a conical frustum, with the evaporator inside diameter (I.D.) larger than the condenser I.D.
- A portion of the centrifugal force is directed along the heat pipe wall, due to the slight taper ($R\omega^2 \sin\alpha$).

Oscillating Heat Pipes



- **A capillary tube (with no wick structure) bent into many turns and partially filled with a working fluid**
- **When the temperature difference between evaporator and condenser exceeds a certain threshold, the gas bubbles and liquid plugs begin to oscillate spontaneously back and forth.**

Questions?