



Heat Pipes for Space Applications

Part 1: Axially Grooved Heat Pipes





Outline

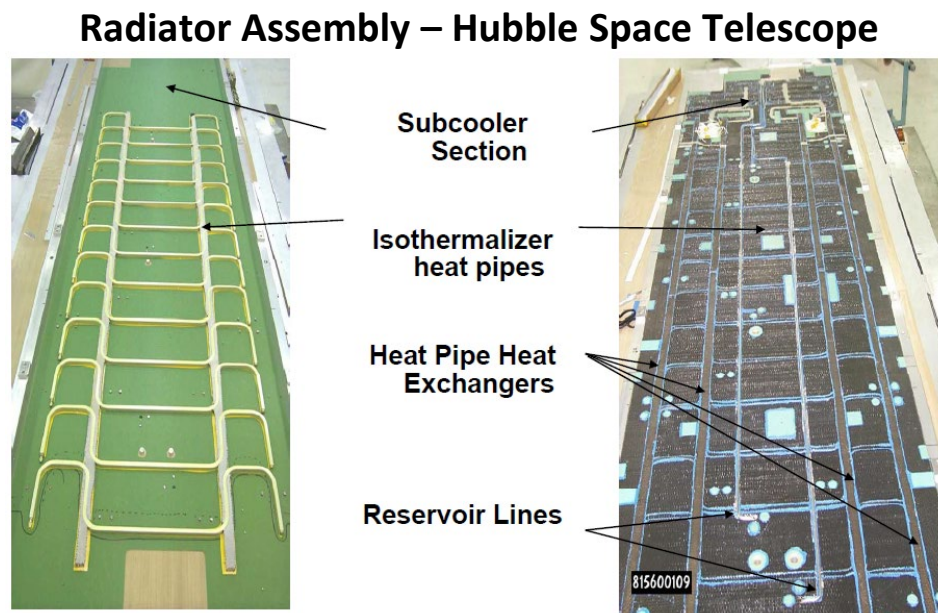
- Introduction
- Heat pipe definitions
- Heat pipe characteristics
 - Physical
 - Operational
 - Performance
- Design considerations
- Summary





Introduction

- Heat pipes are frequently used in space for thermal management.
 - Spacecraft radiators may have dozens of embedded heat pipes.



- Heat pipe is a heat transfer device which is capable of transporting:
 - high rates: up to several kilowatts
 - over long distances: up to several meters
 - with small temperature difference: on the order of several degrees.





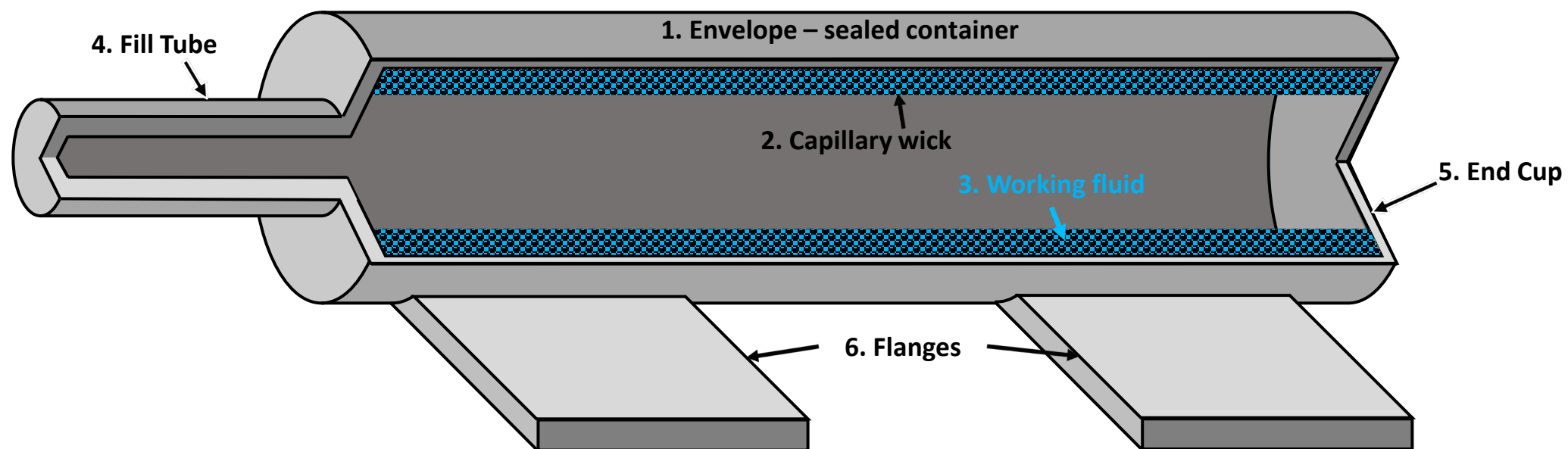
Heat Pipe Definitions

- T. P. Cotter, “Theory of Heat Pipes,” 1965
 - *A heat pipe is a self-contained structure which achieves very high thermal conductance by means of two-phase fluid flow with capillary circulation.*
- S. W. Chi, “Heat Pipe Theory and Practice, A Sourcebook,” 1976
 - *The heat pipe, a device for transmitting heat from one location to another over a small temperature gradient, ...*
- P. D. Dunn and D. A. Reay, “Heat Pipes,” 1994
 - *The heat pipe is a device of very high thermal conductance.*
- B. Zohuri, “Heat pipe Design and Technology,” 2016
 - *Heat pipes are two-phase flow heat transfer devices where a process of liquid to vapor and vice versa circulates between evaporator and condenser with high effective thermal conductivity.*



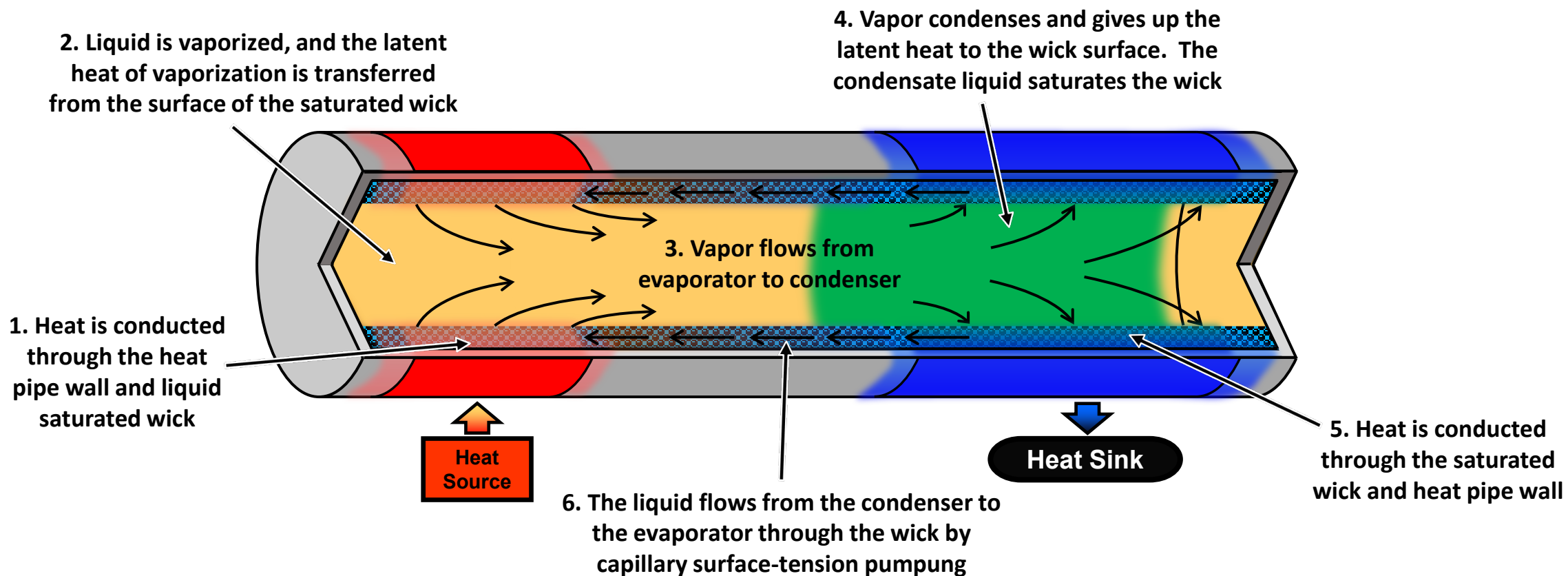


Heat Pipe Elements





Heat Pipe Operation



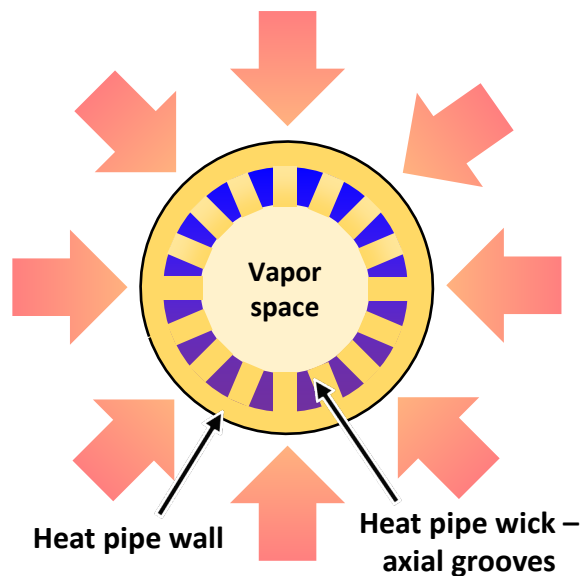
The primary driving force that causes a heat pipe to operate is an externally applied heat load to the evaporator and a heat removal from the condenser.



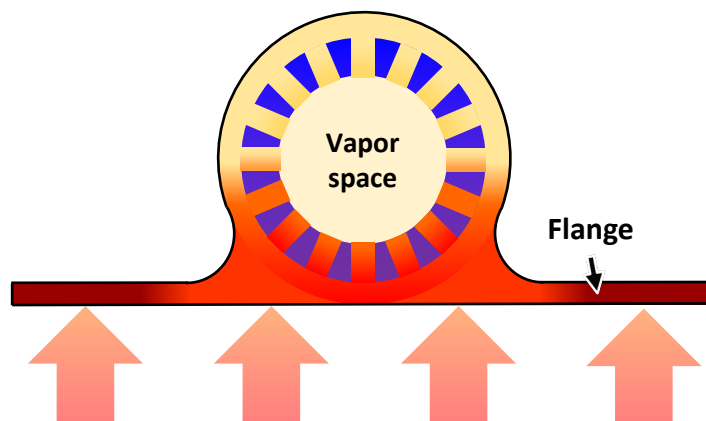


Heat Transfer in the Evaporator

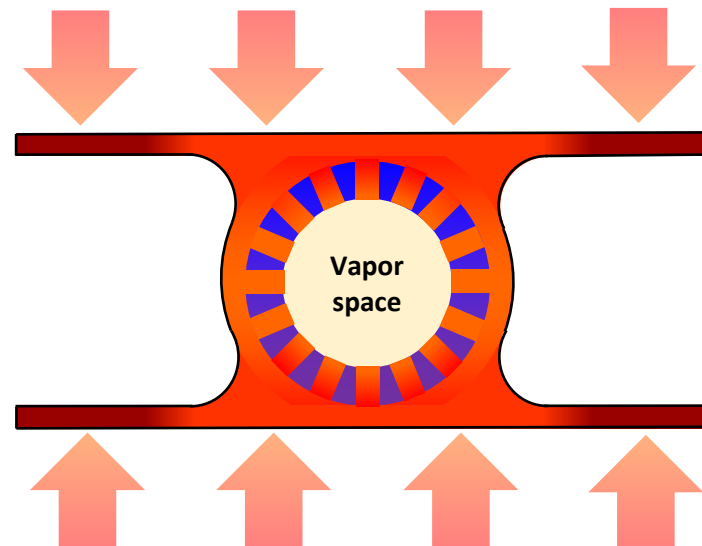
1. Uniform Heat Load



2. One-Sided Heat Load



3. Two-Sided Heat Load

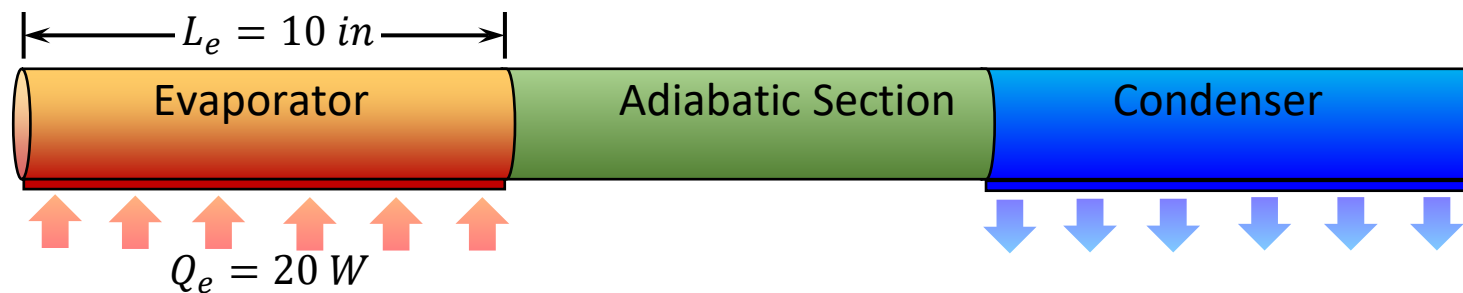
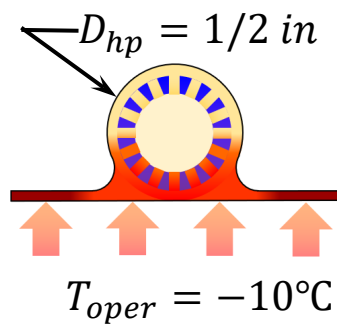


Space applications primarily deal with one-sided and two-sided heat load cases





One-Sided Heat Load



Calculating the evaporator temperature drop

1. Find the evaporator conductance per unit length at the operating temperature

$$D_{hp} = 0.5 \text{ in}, \quad T_{oper} = -10^\circ\text{C} \rightarrow C_{e1} = 2.95 \frac{\text{W}}{\text{in } ^\circ\text{C}}$$

2. Calculate the evaporator heat load per unit length.

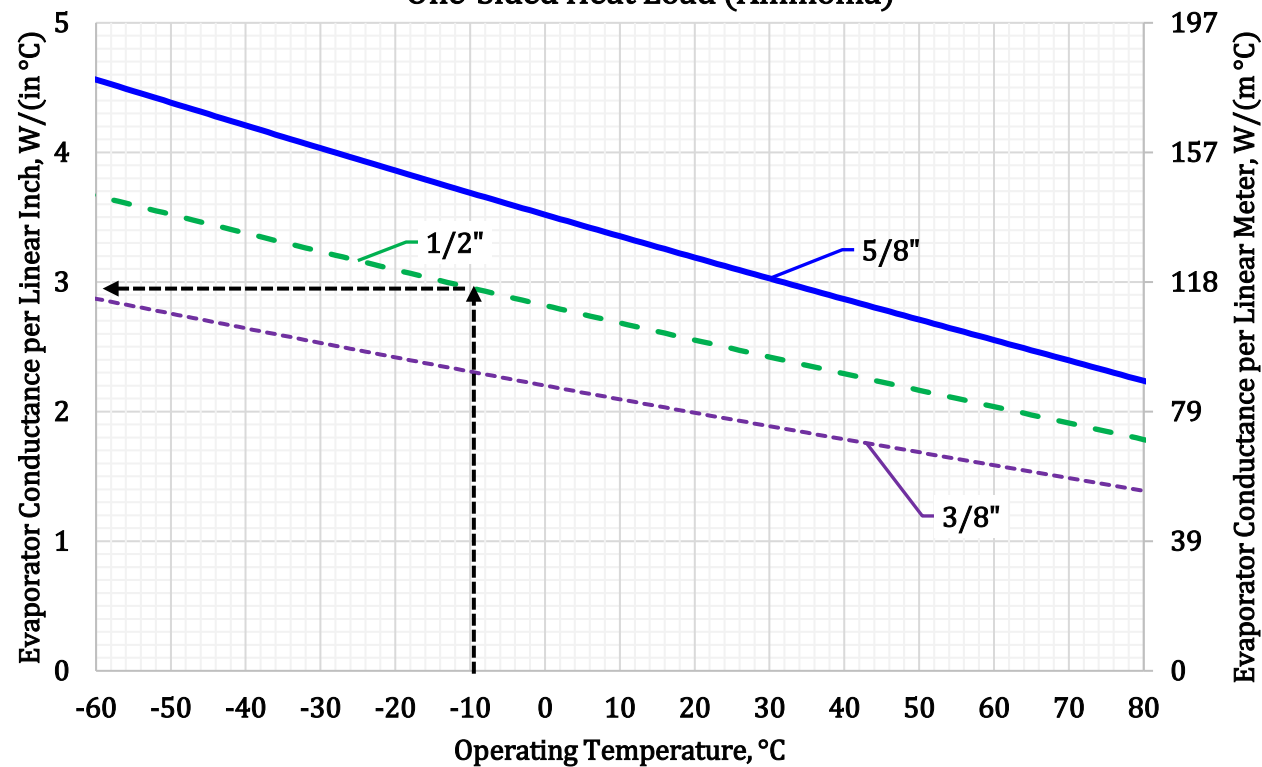
$$Q_e = 20 \text{ W}, \quad L_e = 10 \text{ in}, \quad q'_e = \frac{Q_e}{L_e} = 2 \frac{\text{W}}{\text{in}}$$

3. Calculate the evaporator temperature drop.

$$\Delta T_{e-1side} = \frac{q'_e}{C_{e1}} = \frac{2 \text{ W/in}}{2.95 \text{ W/(in } ^\circ\text{C)}} \approx 0.7^\circ\text{C}$$

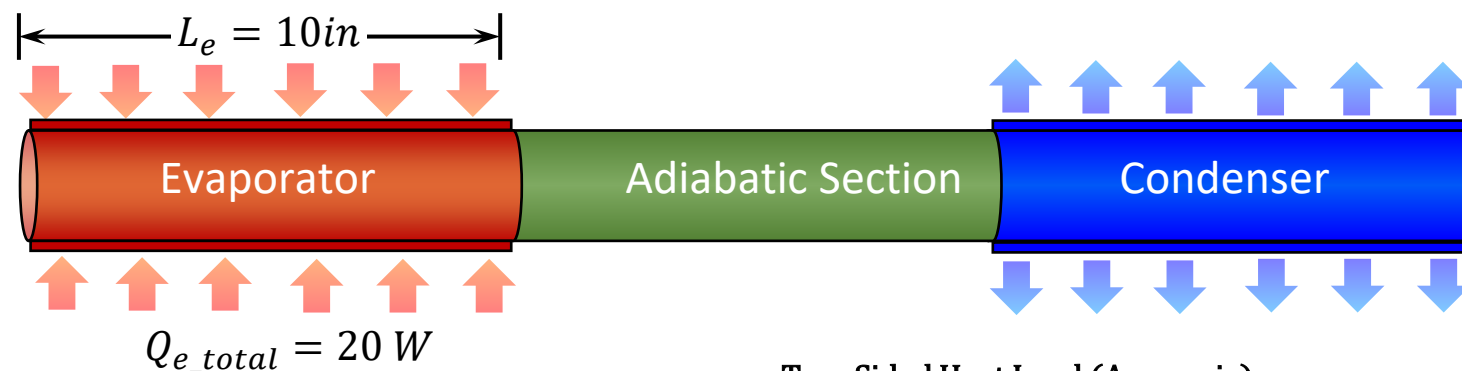
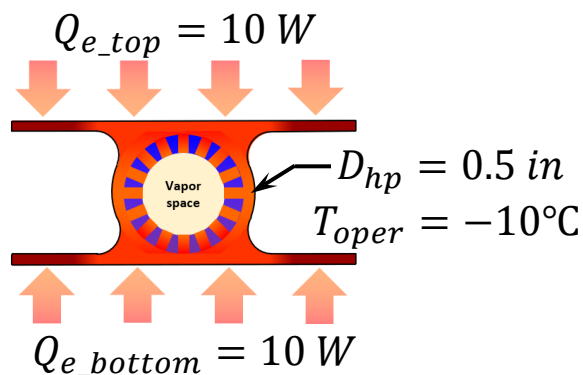
4. Thus, the temperature difference between the heat loaded surface and vapor space is about 0.7°C

One-Sided Heat Load (Ammonia)





Two-Sided Heat Load



Calculating the evaporator temperature drop

1. Find the evaporator conductance per unit length at the operating temperature

$$D_{hp} = 0.5\text{ in}, \quad T_{oper} = -10^\circ\text{C} \rightarrow C_{e2} = 5 \frac{\text{W}}{\text{in } ^\circ\text{C}}$$

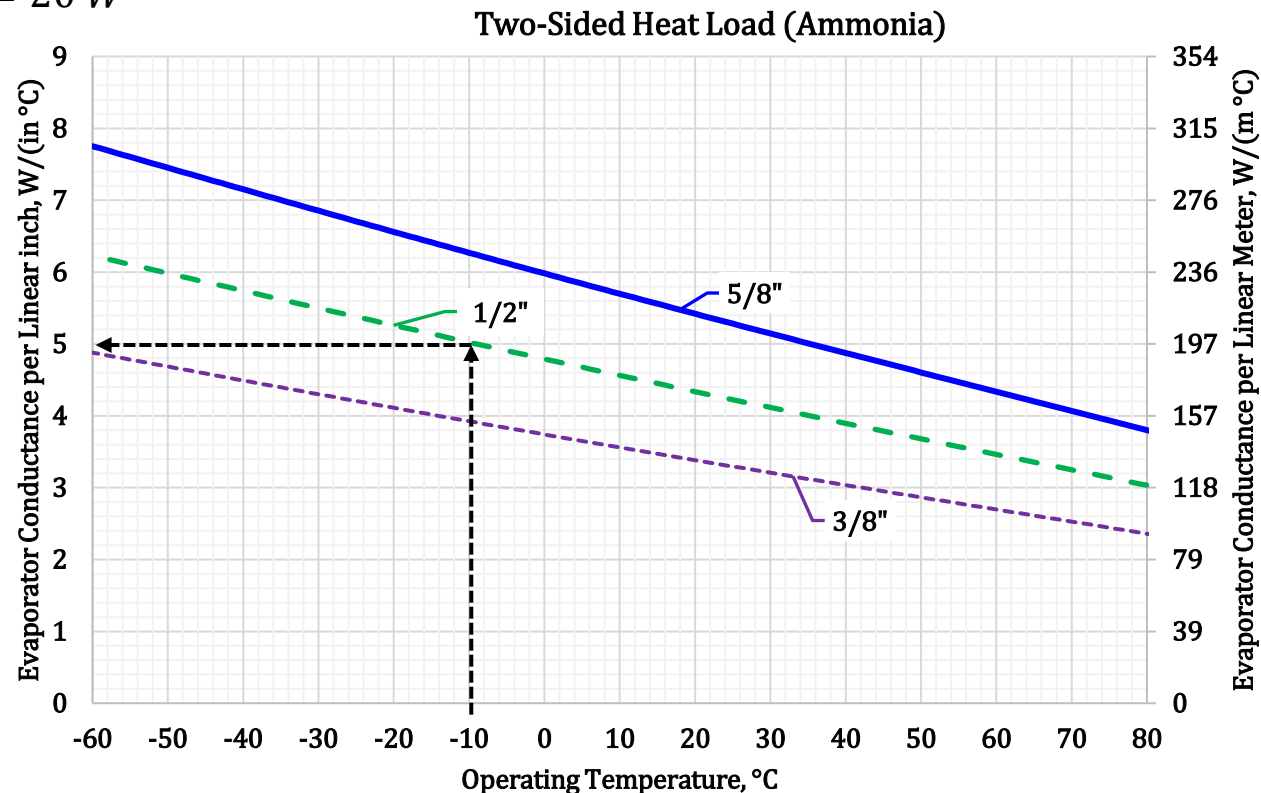
2. Calculate the evaporator heat load per unit length.

$$Q_e = 20\text{ W}, \quad L_e = 10\text{ in}, \quad q'_e = \frac{Q_e}{L_e} = 2 \frac{\text{W}}{\text{in}}$$

3. Calculate the evaporator temperature drop.

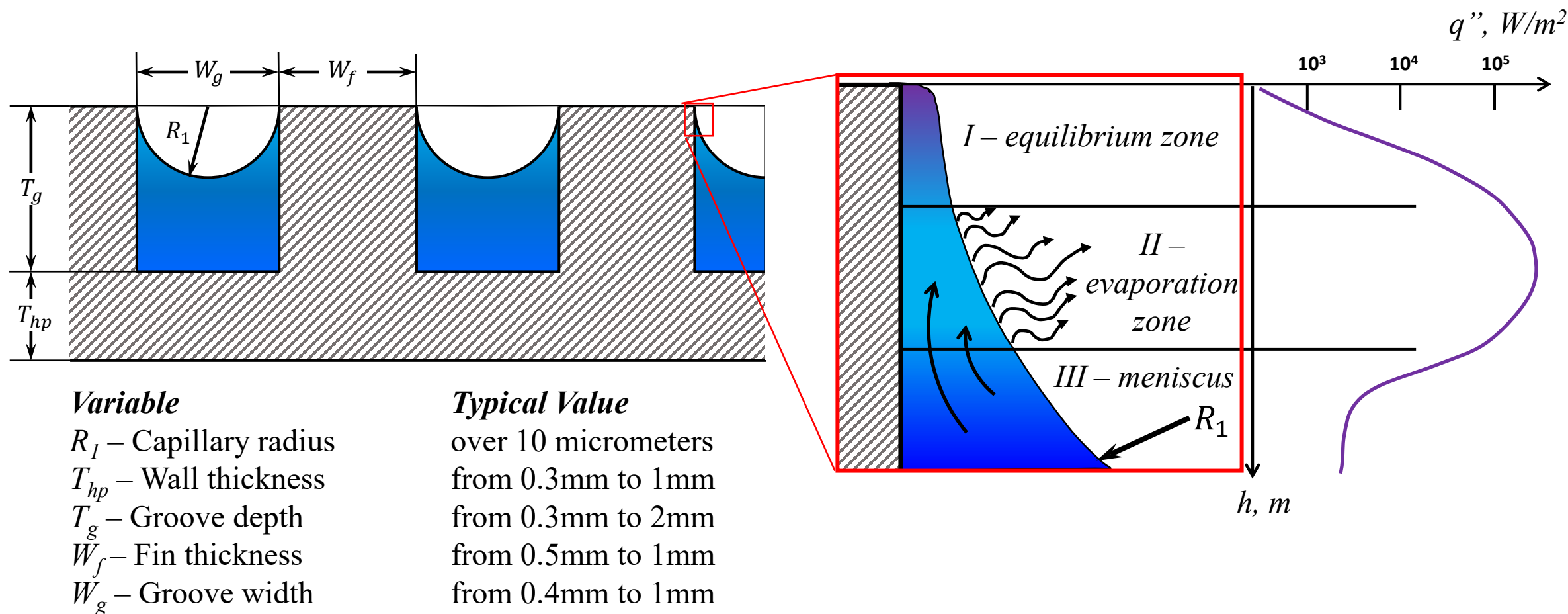
$$\Delta T_{e-1side} = \frac{q'_e}{C_{e2}} = \frac{2\text{ W/in}}{5\text{ W/(in } ^\circ\text{C)}} = 0.4^\circ\text{C}$$

4. Thus, the temperature difference between the heat loaded surface and vapor space is less than 0.5°C





Evaporation Process

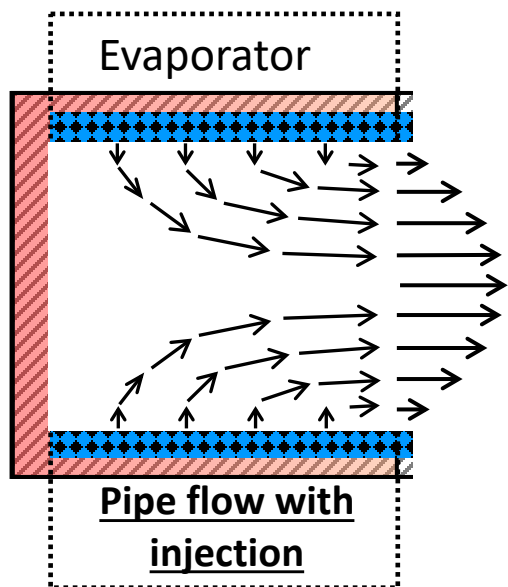


For ammonia heat pipes the effective heat transfer coefficient in the evaporator ranges from 2,000 W/(m² · K) to 6,000 W/(m² · K). A value of $h_{evap} = 4,000 \text{ W/(m}^2 \cdot \text{K)}$ is recommended for preliminary assessments.





Vapor Flow in the Evaporator

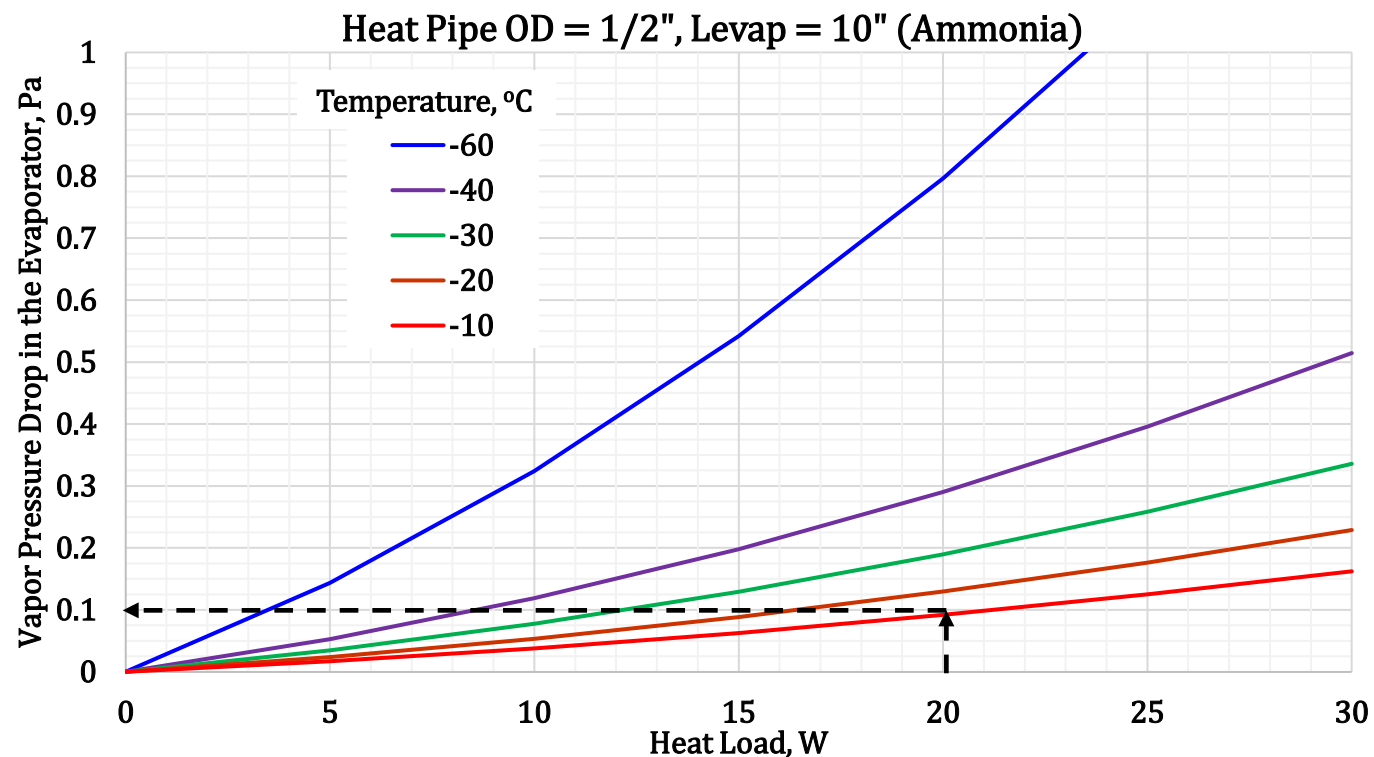


Pressure gradient to
accelerate vapor to
the axial velocity v

Pressure gradient to
overcome frictional drag
forces at the wick surface

$$\Delta P_{ve} = \Delta P_{ve}^{inertial} + \Delta P_{ve}^{viscous} = \rho v^2 + \frac{8\mu_v \dot{m}}{\rho \pi R_{vs}^4} \frac{L_e}{2}$$

- Typically the pressure drop of the vapor flow in the evaporator is very small.
- Example: Heat load, $Q = 20 \text{ W}$
Heat pipe diameter, $D_{hp} = 0.5 \text{ in}$
Evaporator length, $L_e = 10 \text{ in}$
Operating temperature, $T_{oper} = -10^\circ\text{C}$
 $\Delta P_{ve} = 0.1 \text{ Pa}$
- The inertial component of the pressure drop can be partially recovered in the condenser section when vapor flow decelerates.





Vapor Flow in the Adiabatic Section

Turbulent ($Re > 2100$)

$$\Delta P_{va} = \frac{2}{R_{vs}} f \frac{1}{2} \rho v^2 L_a$$

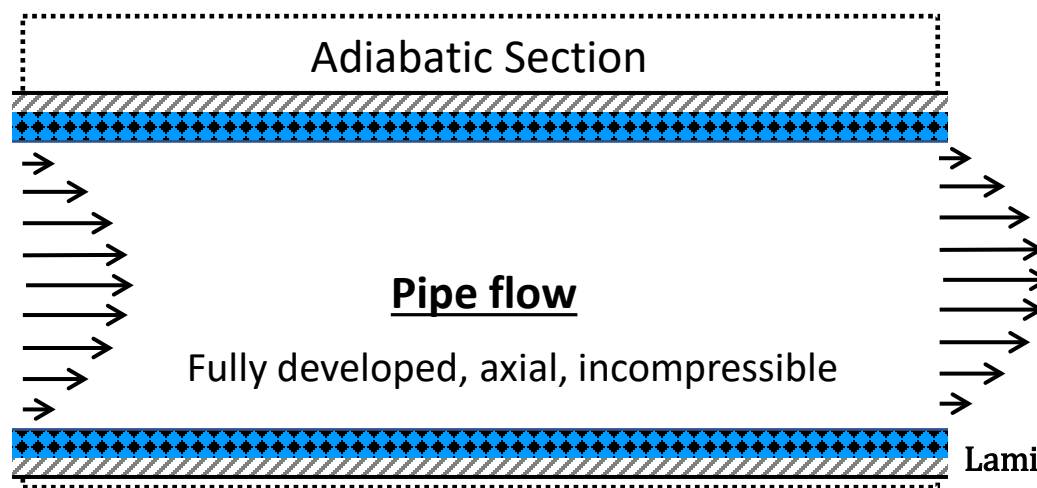
where $f = \frac{0.0791}{Re^{1/4}}$

- In most space applications the vapor flow is laminar.

- Example: *Heat load, $Q = 20(W)$*
Heat pipe diameter, $D_{hp} = 0.5(in)$
Adiabatic section length, $L_a = 30(in)$
Operating temperature, $T_{oper} = -10(^{\circ}C)$

- From the plot: $\frac{\Delta P_{va}}{QL_a} = 0.0006 \frac{Pa}{W in}$

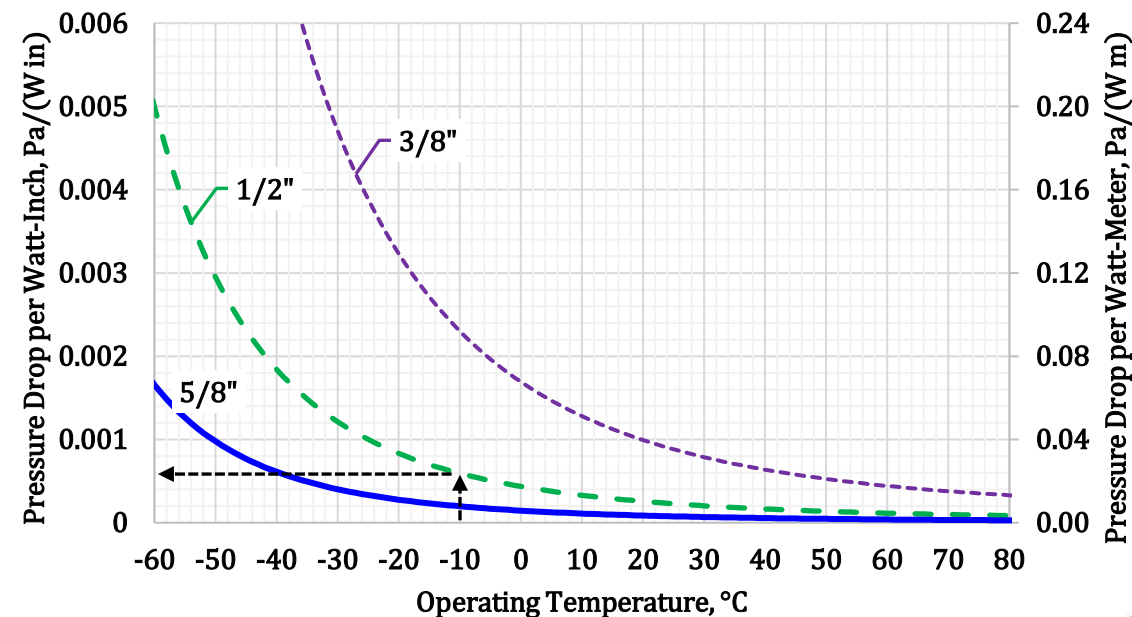
- Thus, $\Delta P_{va} = 0.0006 \frac{Pa}{W in} \cdot 30 in \cdot 20W = 0.36Pa$



Laminar ($Re < 2100$)

$$\frac{\Delta P_{va}}{QL_a} = \frac{8\mu_v}{\rho_v \pi H_{fg} R_{vs}^4}$$

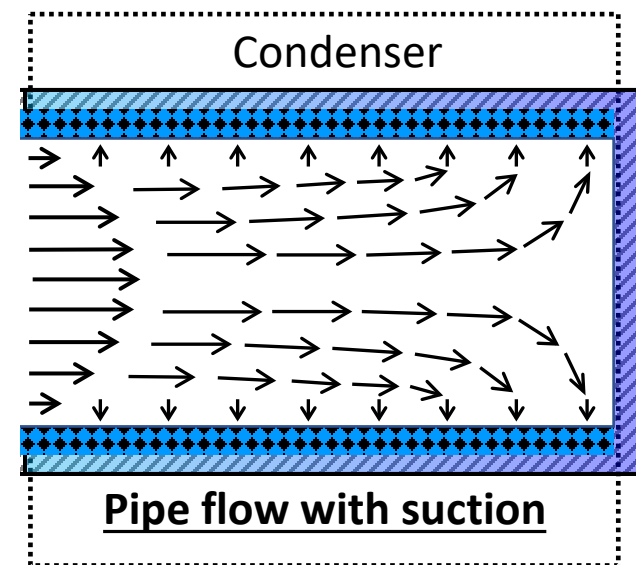
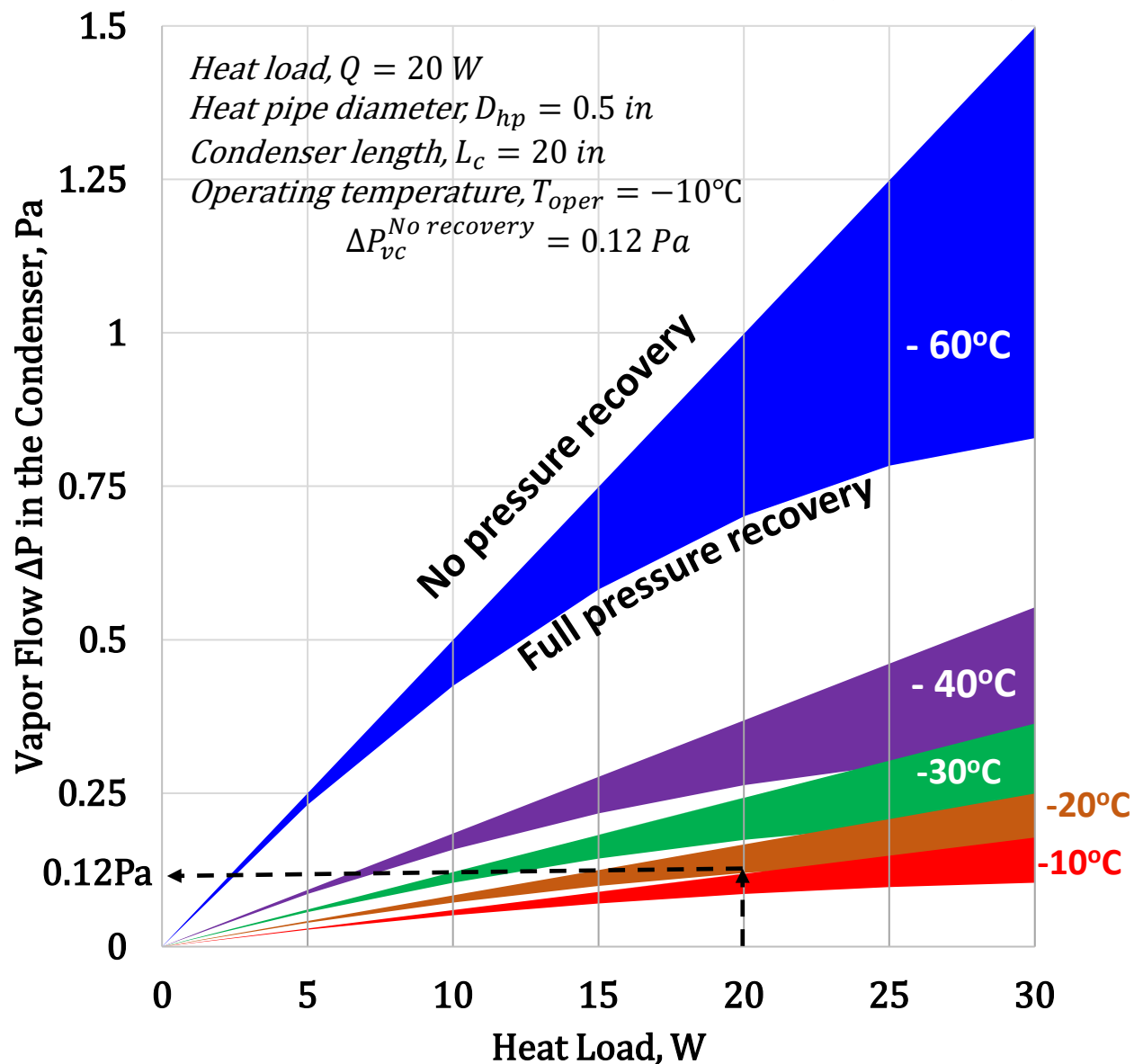
Laminar Vapor Flow in the Adiabatic Section (Ammonia)





Vapor Flow in the Condenser

Heat Pipe OD = 1/2", L_{cond} = 20" (Ammonia)



Pressure gradient
to deccelerate
vapor stream.

Pressure gradient to
overcome frictional drag
forces at the wick surface

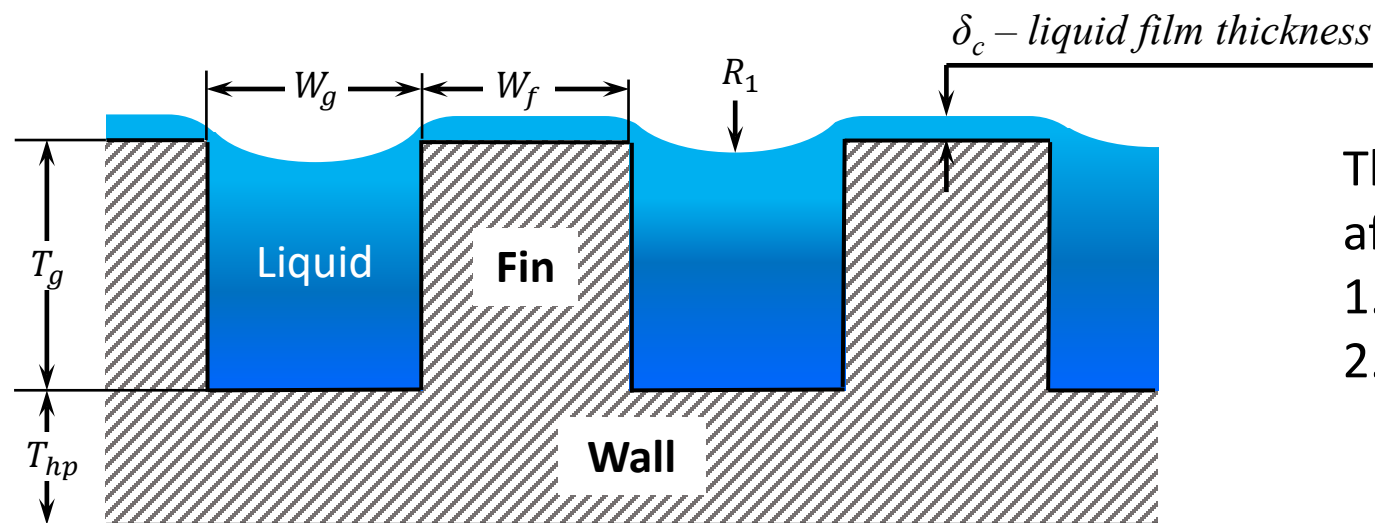
$$\Delta P_{vc} = \Delta P_{vc}^{inertial} + \Delta P_{vc}^{viscous} = -\rho v^2 + \frac{8\mu_v \dot{m} L_c}{\rho \pi R_{vs}^4 2}$$

Negative –
decceleration





Condensation Process



Variable

R_1 – Capillary radius

T_{hp} – Wall thickness

T_g – Groove depth

W_f – Fin thickness

W_g – Groove width

δ_c – Liquid film thickness

Typical Value

order of centimeters

from 0.3mm to 1mm

from 0.3mm to 2mm

from 0.5mm to 1mm

from 0.4mm to 1mm

from 5 mkm to 30 mkm

The heat transfer coefficient in the condenser affected by the following parameters:

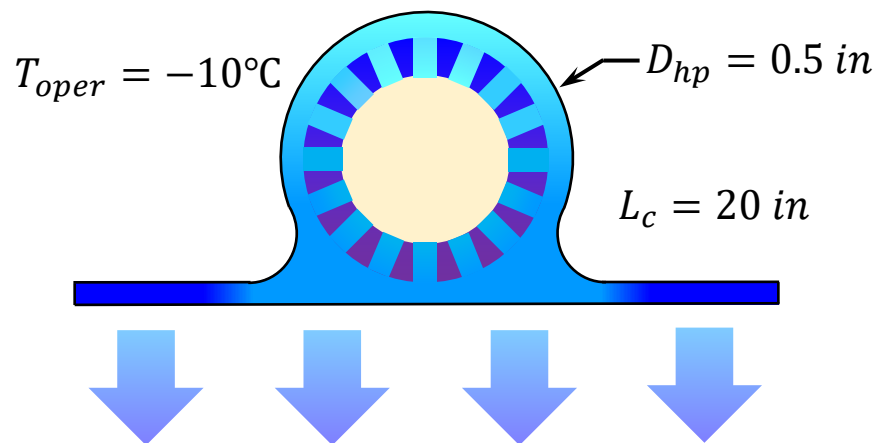
1. Liquid film thickness, δ_c
2. Fluid properties, such as:
 - a) Latent heat
 - b) Liquid density
 - c) Liquid viscosity
 - d) Surface tension
3. Groove geometry
4. Heat flux
5. Presence of non-condensable gases

For ammonia heat pipes the effective heat transfer coefficient in the condenser ranges from 2,000 W/(m² · K) to 20,000 W/(m² · K). A value of $h_{cond} = 8,000 \text{ W/(m}^2 \cdot \text{K)}$ is recommended for preliminary assessments.





Heat Transfer in the Condenser



Calculating the condenser temperature drop

1. Find the condenser conductance per unit length at the operating temperature

$$D_{hp} = 0.5 \text{ in}, \quad T_{oper} = -10^\circ\text{C} \rightarrow C_c = 7 \frac{W}{\text{in } ^\circ\text{C}}$$

2. Calculate the condenser heat load per unit length.

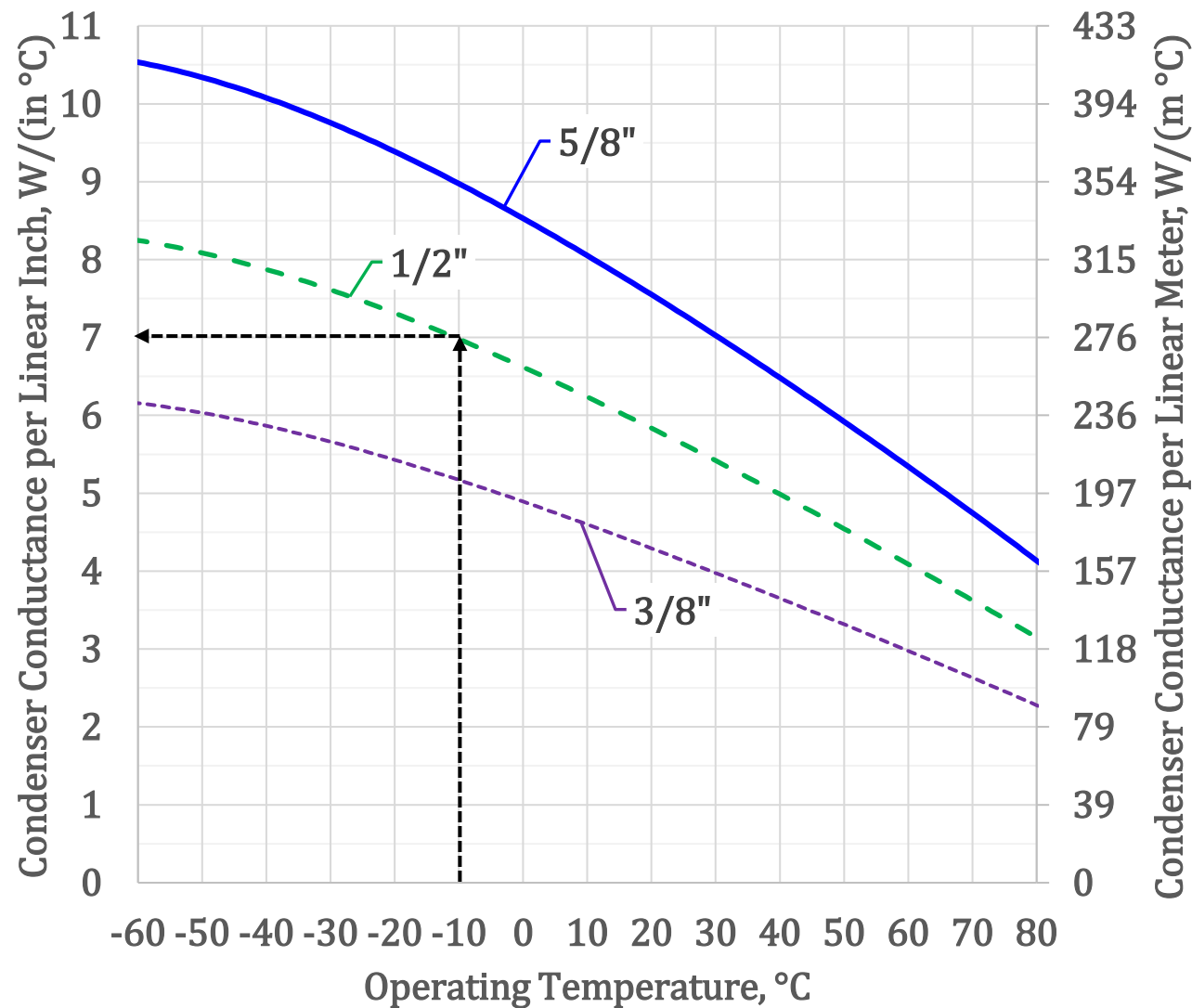
$$Q_c = 20 \text{ W}, \quad L_c = 20 \text{ in}, \quad q'_1 = \frac{Q_c}{L_c} = 1 \frac{W}{\text{in}}$$

3. Calculate the condenser temperature drop.

$$\Delta T_{c-1side} = \frac{q'_1}{C_c} = \frac{1}{7} \approx 0.143^\circ\text{C}$$

4. Thus, the temperature difference between the vapor space and the heat rejection surface is about 0.14°C

One-Sided Heat Rejection (Ammonia)





Liquid Flow in the Grooves

- The liquid in the grooves flows back to the evaporator by capillary pumping.
- The flow is laminar.

Calculating the Liquid Pressure Drop

Heat load, $Q = 20\text{ W}$

Heat pipe diameter, $D_{hp} = 0.5\text{ in}$

Heat pipe length, $L_{hp} = 60\text{ in}$

Operating temperature, $T_{oper} = -10^\circ\text{C}$

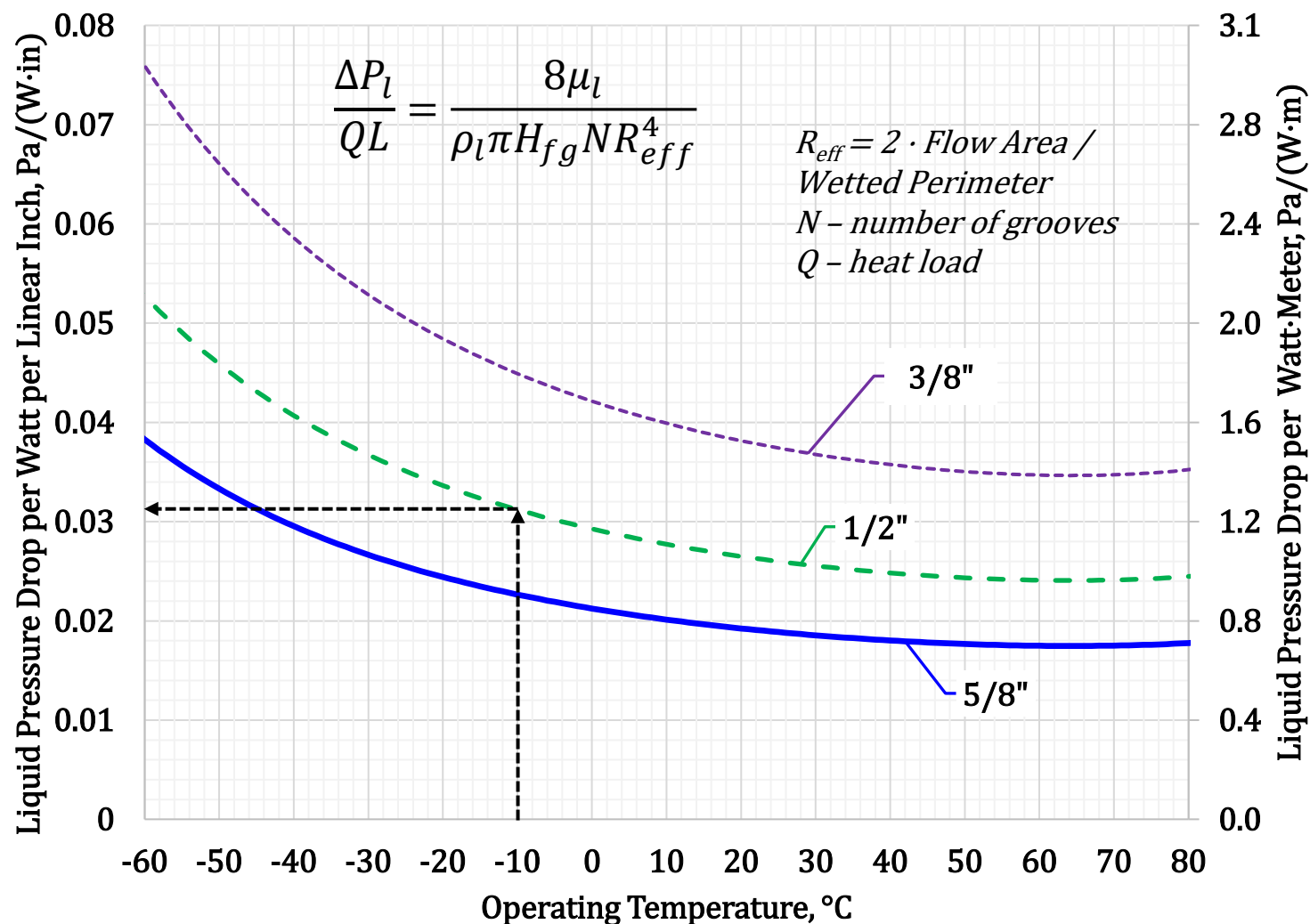
- Find the liquid pressure drop per watt per unit length at the operating temperature for selected heat pipe diameter

$$\frac{\Delta P_l}{QL} = 0.032 \frac{\text{Pa}}{\text{W in}}$$

- Calculate the liquid pressure drop

$$\Delta P_l = 0.032 \frac{\text{Pa}}{\text{W in}} \cdot 60\text{ in} \cdot 20\text{ W} = 38.4\text{ Pa}$$

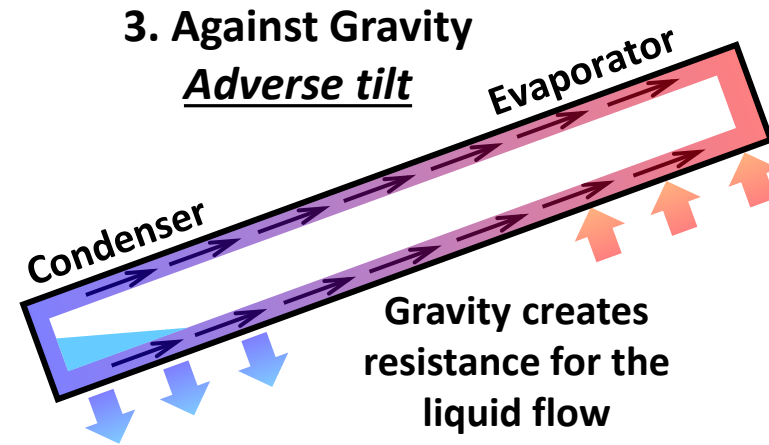
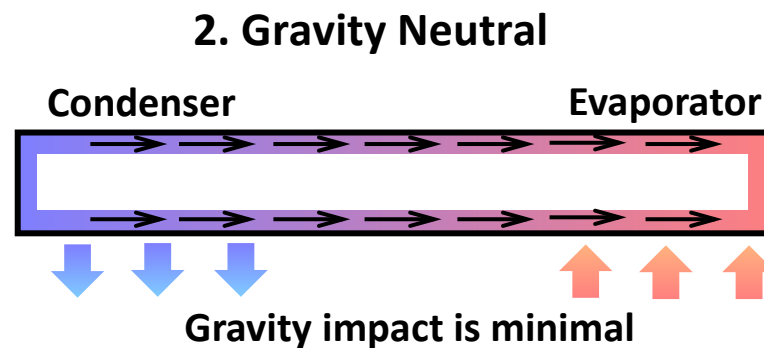
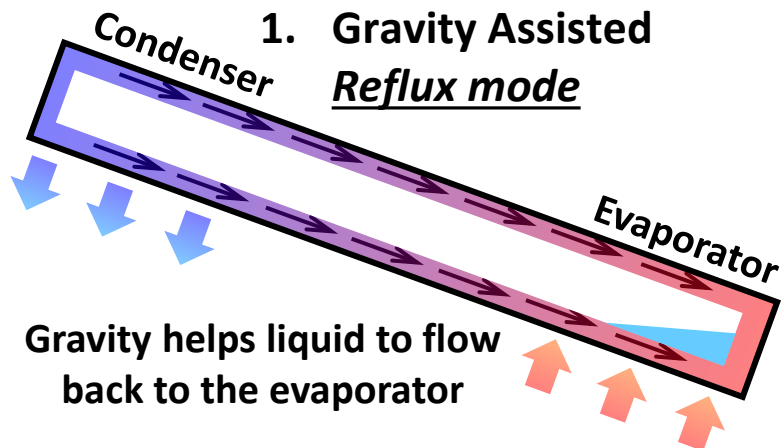
Liquid Pressure Drop (Ammonia)





Gravitational Impact

Axial groove heat pipe operation is affected by gravity



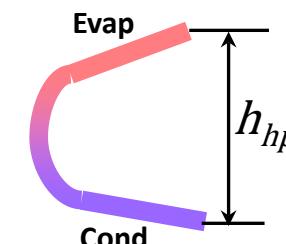
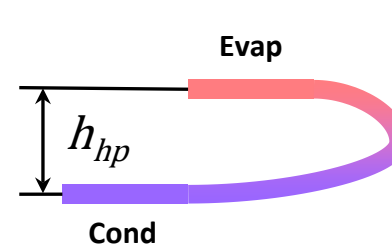
The pressure difference due to hydrostatic head of the liquid is equal to:

$$\Delta P_g = \rho_l g h_{hp} - \text{general formula}$$

where ρ_l - the liquid density

g - the gravity acceleration

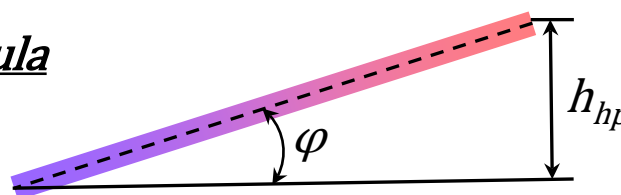
h_{hp} - the height difference between heat pipe ends



$$\Delta P_g = \rho_l g L_{hp} \sin \varphi - \text{straight heat pipe formula}$$

where L_{hp} - the heat pipe length

φ - the heat pipe tilt angle





Pressure Balance in the Heat Pipe

- The total pressure drop in a heat pipe is a sum of three components:
 1. Pressure drop in the vapor flow from the evaporator to the condenser, ΔP_v
 2. Pressure drop in the liquid flow to return liquid back to the evaporator, ΔP_l
 3. The gravitational head, ΔP_g
- The maximum capillary pumping head $(\Delta P_c)_{max}$ must be greater than the total pressure drop in the heat pipe.

$$(\Delta P_c)_{max} \geq \Delta P_v + \Delta P_l + \Delta P_g$$

- If this condition is not met, a dry out will occur in the evaporator and heat pipe operation will be ceased.





Capillary Limit

The capillary limit (wicking limit) is achieved when:

$$(\Delta P_c)_{max} = \Delta P_v + \Delta P_l + \Delta P_g$$

Example:

Heat load, $Q = 20 \text{ W}$

Heat pipe diameter, $D_{hp} = 0.5 \text{ in}$

Heat pipe length, $L_{hp} = 60 \text{ in}$

Evaporator length, $L_e = 10 \text{ in}$

Condenser length, $L_c = 20 \text{ in}$

Operating temperature, $T_{oper} = -10^\circ\text{C}$

Find heat transport capacity from the capillary limit plot:

$$Q_{max_0-g} L_{eff} \approx 4,200 \text{ W}\cdot\text{in}$$

Effective length:

$$L_{eff} = L_{hp} - (L_e + L_c)/2 = 45 \text{ in}$$

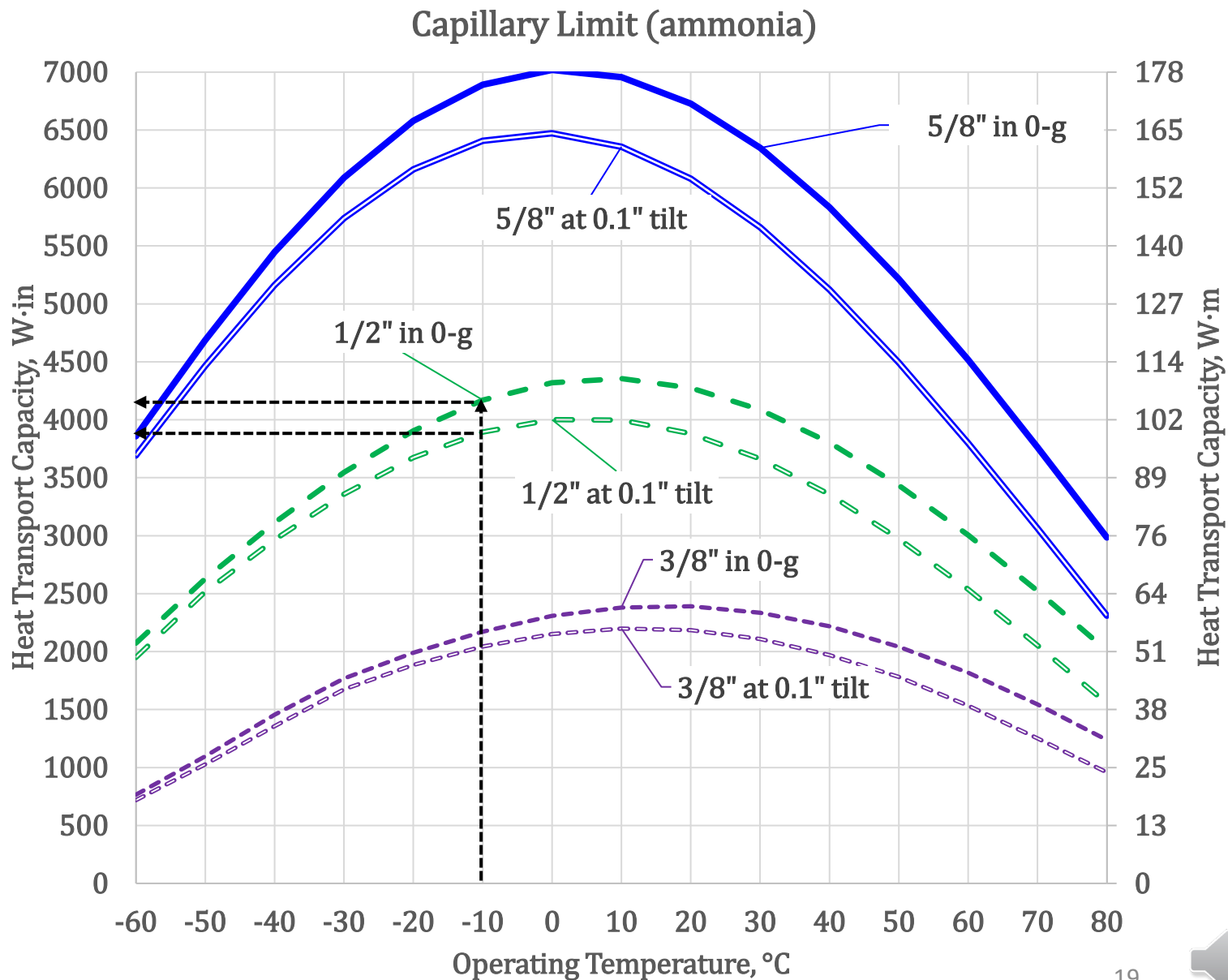
Thus, the capillary limit in zero-g is equal to:

$$Q_{max_0-g} = (Q_{max} L_{eff}) / L_{eff} \approx 93 \text{ W}$$

Typically ground testing performed with 0.1" adverse tilt.

$$Q_{max_0.1"} L_{eff} \approx 3,800 \text{ W}\cdot\text{in}$$

$$Q_{max_0.1"} \approx 84 \text{ W}$$





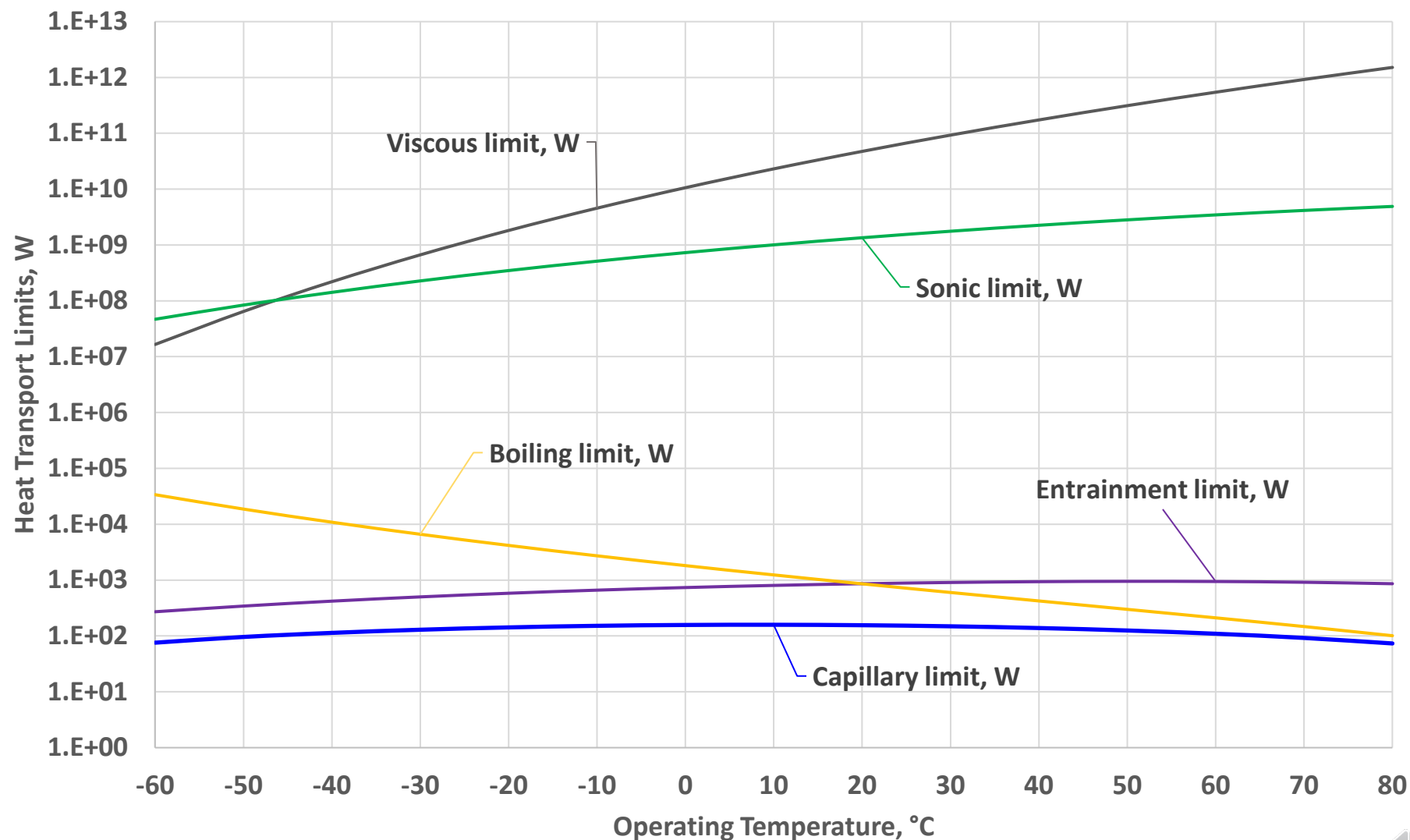
Heat Transport Limits

Heat transport limits:

- Capillary limit
- Sonic limit
- Boiling limit
- Entrainment limit
- Low pressure limit (Viscous limit)

The heat transport in most cases is limited by capillary pumping pressure.

Transport Limits for an Ammonia HP (OD = 1/2", Le = 10", Lc = 20", Lhp = 60")





Maximum Heat Flux

The maximum heat flux or the maximum heat load per unit length is affected by:

1. Heat pipe orientation in 1G.
2. Evaporator length.
 - Lengths of the adiabatic section and condenser also affect the maximum heat flux, but to a lesser extent.
3. Heat pipe size (outside diameter).
4. Operating temperature.
5. Internal geometry.
6. Fluid charge.

The values in this table are recommended as a starting point for zero-g case.

Parameter	Heat Pipe OD, in		
	3/8	1/2	5/8
Max heat load per linear inch (1-sided heat load), W/in	10	13	16
Max heat load per linear inch (2-sided heat load), W/in	13	17	23





When to Consider Heat Pipes?

1. Transport heat from one location to another.

- When solid conductors cannot meet your requirements.
- Example: a spacecraft instrument generates 5W of heat and it is located one meter from the radiator panel.

2. Provide heat spreading for high heat flux applications.

- Without heat spreading the surface/component would be damaged (melted).
- Example: leading edge of the reentry vehicle.

3. Create isothermal condition.

- Temperature uniformity provides substantial benefits.
- Example: radiator panel size can be reduced when its temperature is uniform

In many applications heat pipes are used for more than one purpose listed above.





When a Heat Pipe is NOT the Best Choice

- Short heat transport distance
 - less than 1 inch (< 25 mm)
- Solid aluminum or copper (pyrolytic graphite in some cases) “will do the job” or meet all requirements, such as:
 - Thermal conductance
 - Weight and size
 - Price
 - Delivery
- Other factors could lead to an alternative solution. For example:
 - High radiation dose
 - HP performance degrades from radiation exposure.
 - Freezing of the working fluid could be a problem.
 - High temperature survival can be a problem too due to excessive internal pressure
 - Wide operating temperature range
 - Operating temperature range for each fluid is narrower than saturation temperature range (from freezing to critical temperature)





Summary

- Heat pipes are well suited for many space applications.
- Their benefits include:
 - Passive operation and selfregulating
 - Simple construction
 - No moving solid parts
 - Excellent thermal performance
- This presentation helps assessing a heat pipe suitability for a given space application.
- Contact Sergey Semenov (Sergey.Y.Semenov@nasa.gov) with heat pipe questions.

