Heat Pipes for Space Applications

Part 1: Axially Grooved Heat Pipes

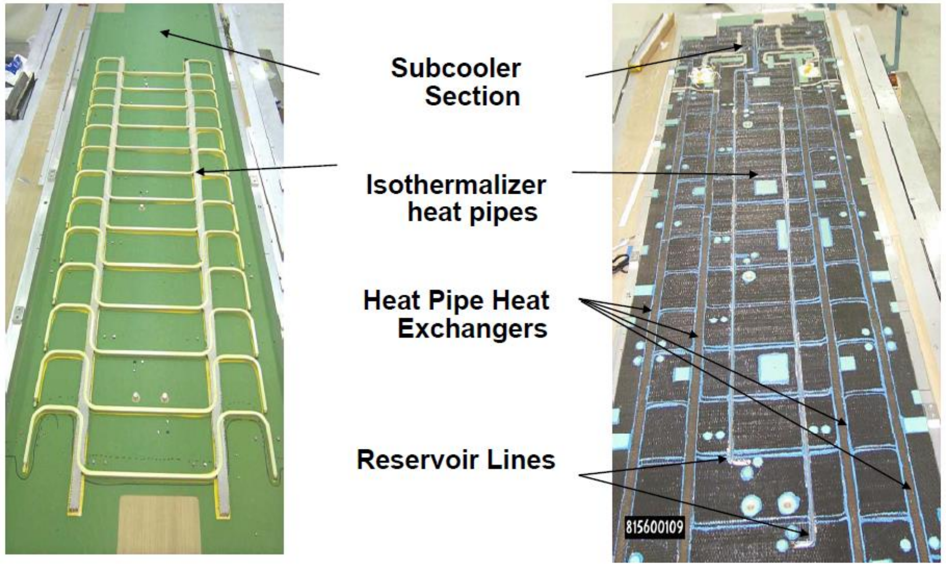
Outline

- 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.

Radiator Assembly – Hubble Space Telescope

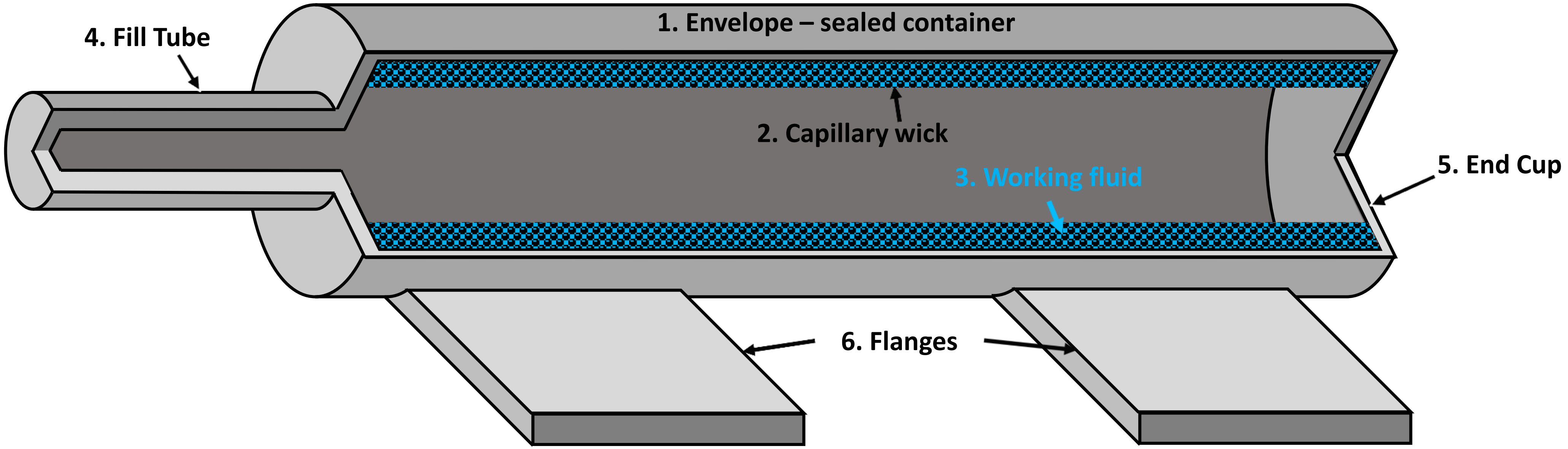


- Heat pipe is a heat transfer device which is capable of transporting:
  - high rates: up to several kilowatts
  - over long distances: up to several meters
  - with small temperature difference: on the order of several degrees.

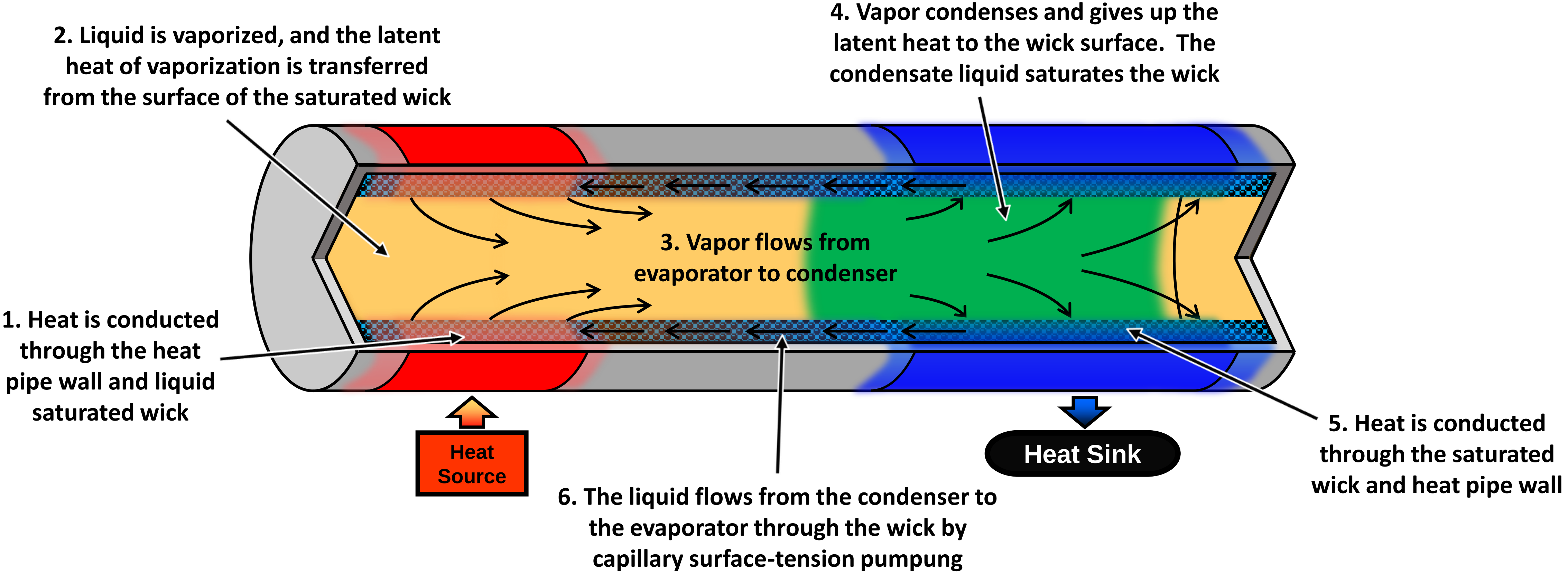
Heat Pipe Definitions

- 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



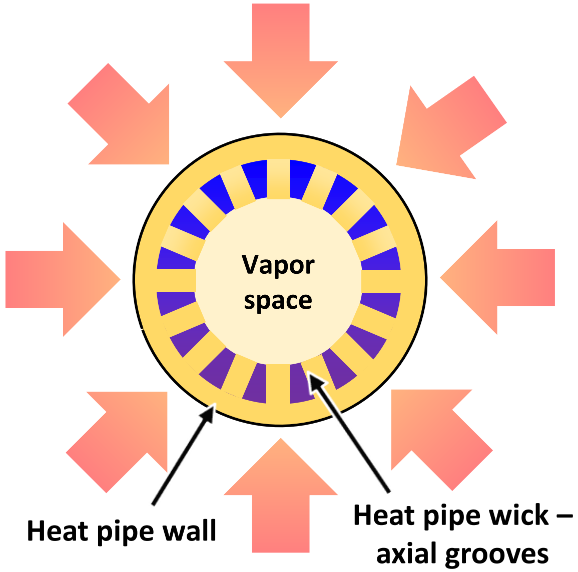
Heat Pipe Operation



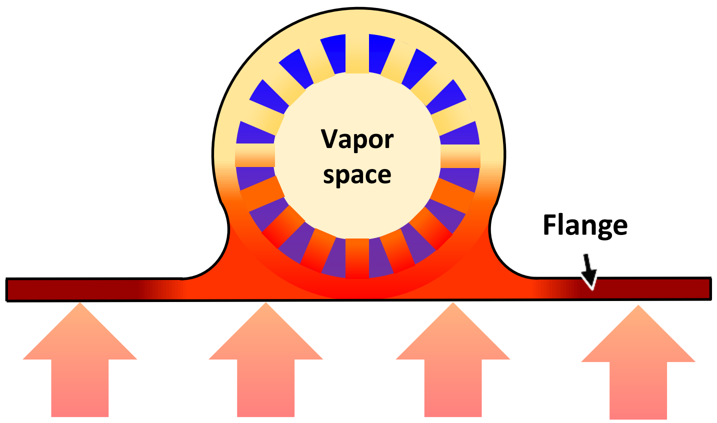
The primary <u>driving force</u> that causes a heat pipe to operate is an externally applied <u>heat load to the evaporator and a heat removal from the condenser</u>.

Heat Transfer in the Evaporator

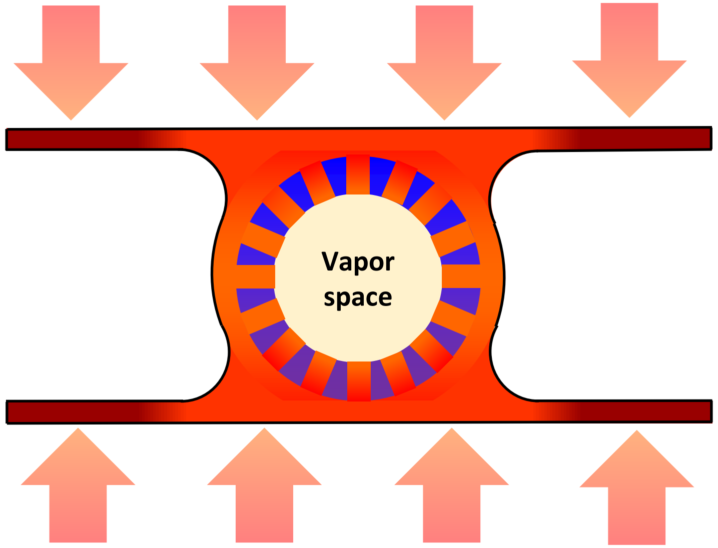
1. Uniform Heat Load



2. One-Sided Heat Load

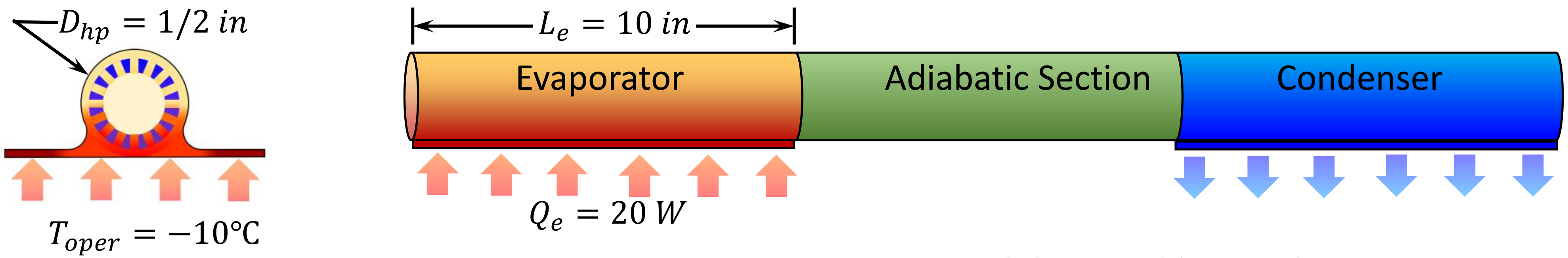


3. Two-Sided Heat Load



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

$$D_{hp} = 0.5\ in, \qquad T_{oper} = -10°C \rightarrow C_{e1} = 2.95 \frac{W}{in\ °C}$$

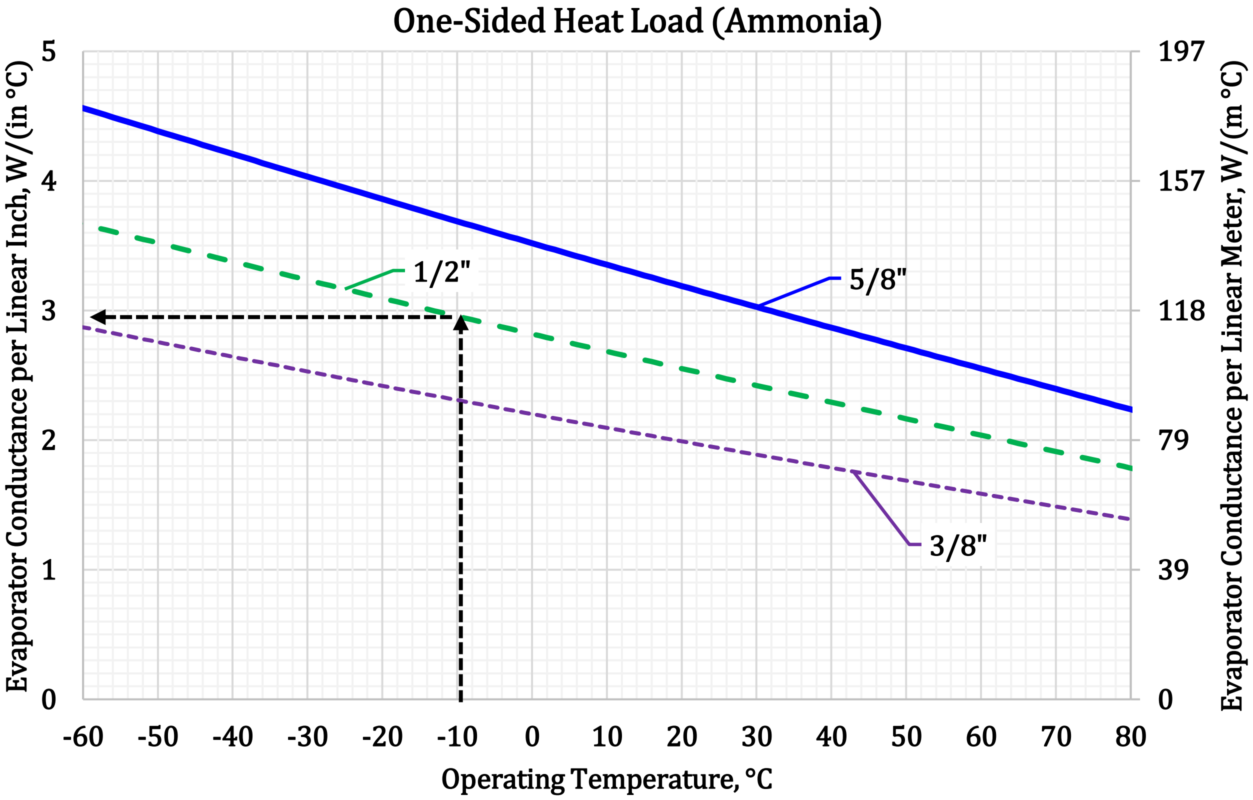
2. Calculate the evaporator heat load per unit length.

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

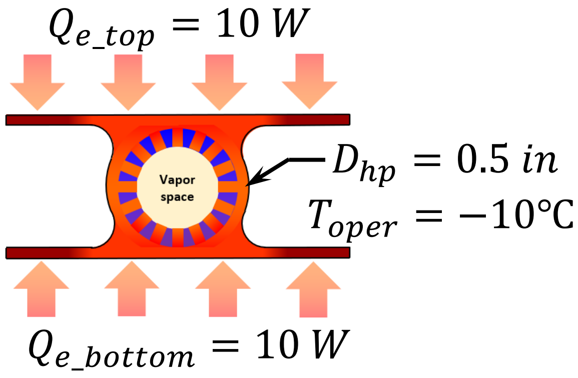
3. Calculate the evaporator temperature drop.

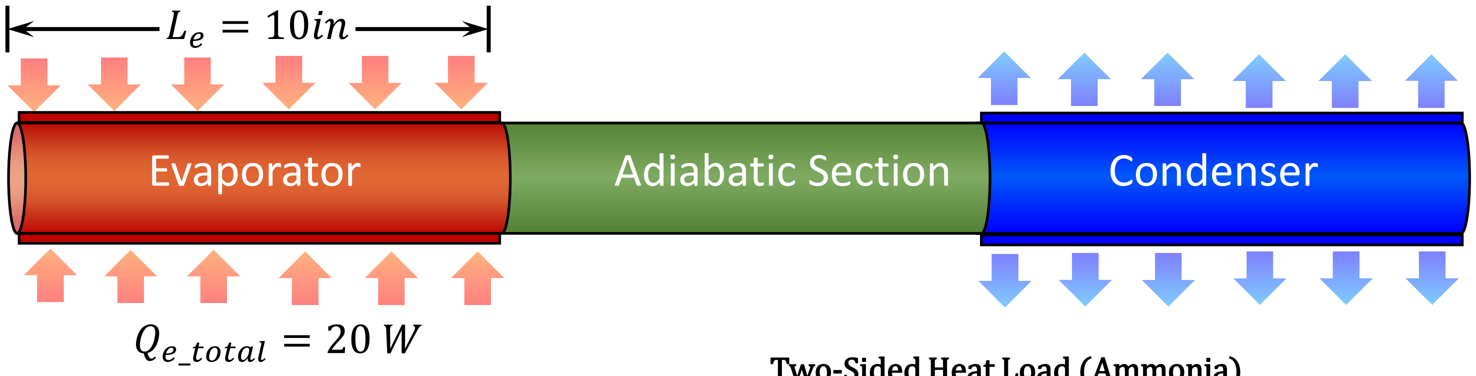
$$\Delta T_{e-1side} = \frac{q'_e}{C_{e1}} = \frac{2\ W/in}{2.95\ W/(in\ °C)} \approx 0.7°C$$

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



Two-Sided Heat Load





Calculating the evaporator temperature drop

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

$$D_{hp} = 0.5\ in, \qquad T_{oper} = -10°C \rightarrow C_{e2} = 5\frac{W}{in\ °C}$$

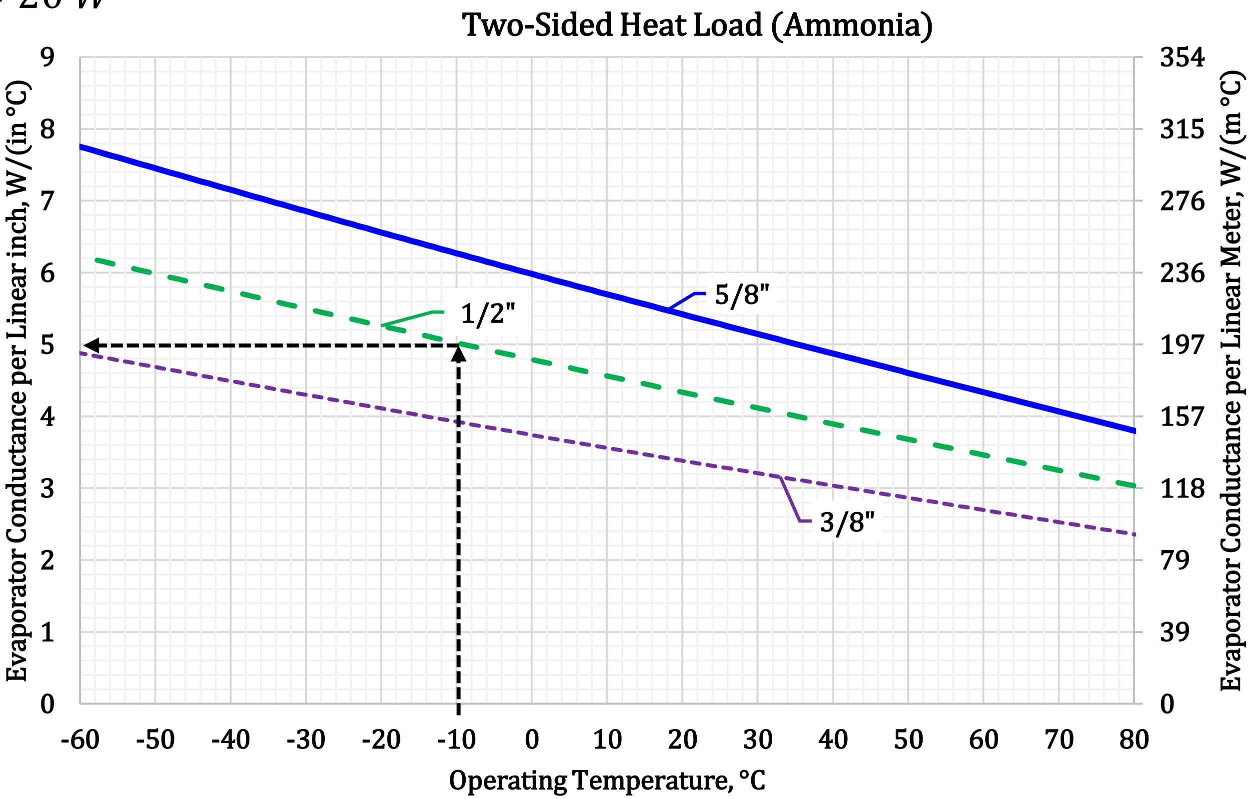
2. Calculate the evaporator heat load per unit length.

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

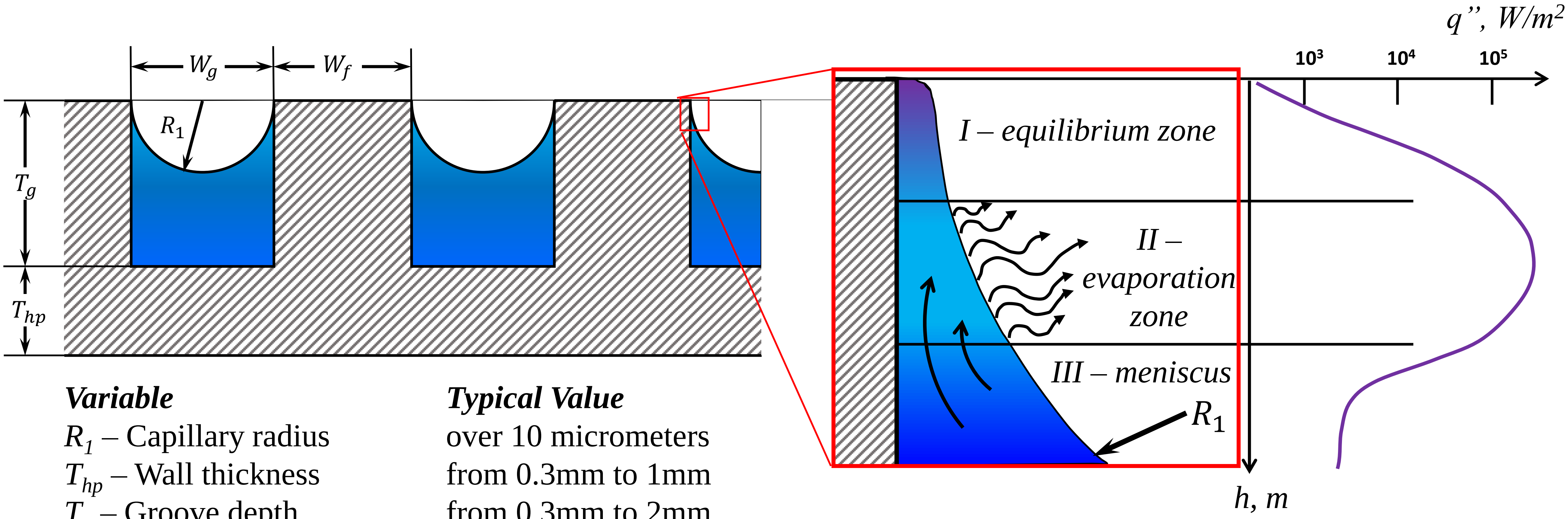
3. Calculate the evaporator temperature drop.

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

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



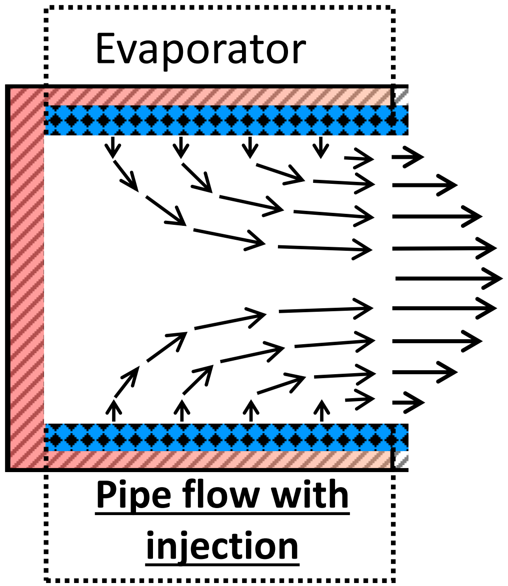
Evaporation Process



Variable	*Typical Value*
R_1 – Capillary radius	over 10 micrometers
T_{hp} – Wall thickness	from 0.3mm to 1mm
T_g – Groove depth	from 0.3mm to 2mm
W_f – Fin thickness	from 0.5mm to 1mm
W_g – Groove width	from 0.4mm to 1mm

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 W/(m² · K)** is recommended for preliminary assessments.

Vapor Flow in the Evaporator

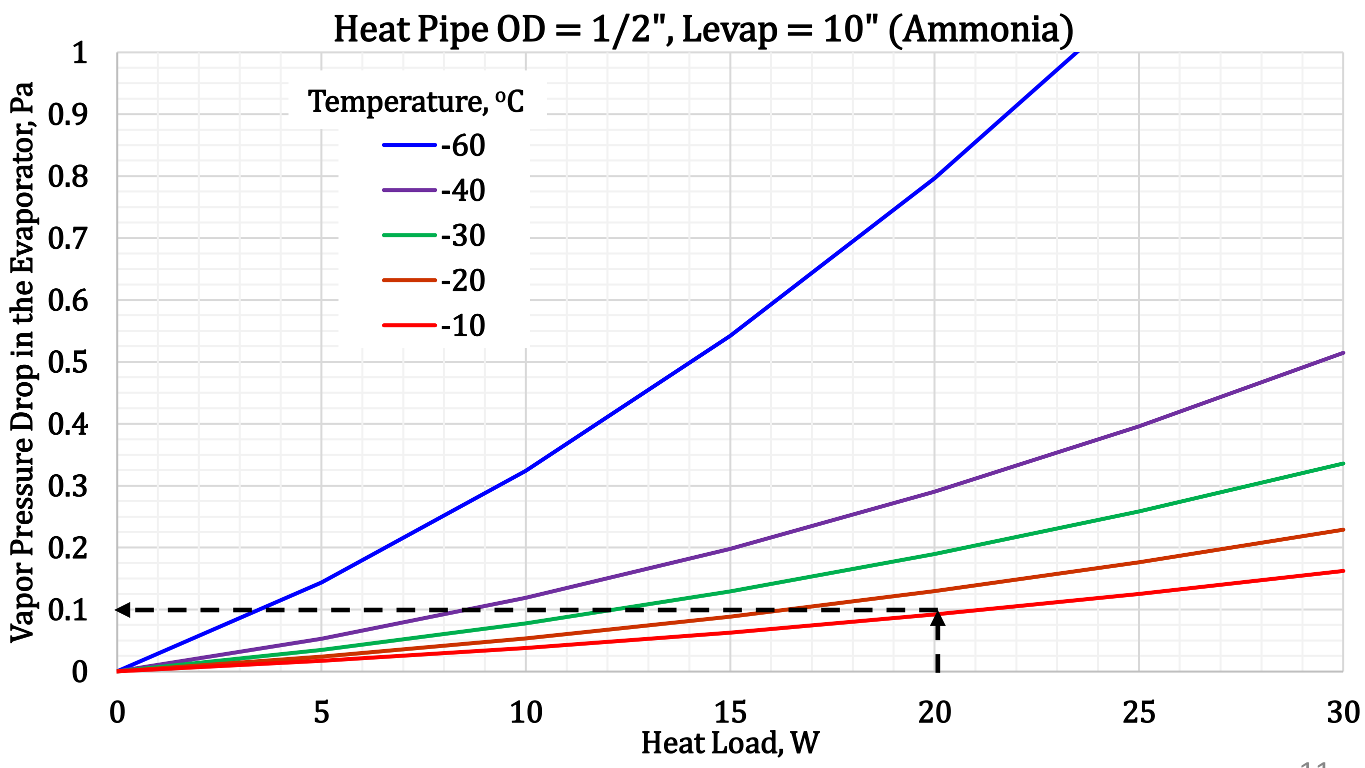


- Typically the pressure drop of the vapor flow in the evaporator is very small.
- Example: $Heat\ load, Q = 20\ W$
  $Heat\ pipe\ diameter, D_{hp} = 0.5\ in$
  $Evaporator\ length, L_e = 10\ in$
  $Operating\ temperature, T_{oper} = -10°C$
  $\Delta P_{ve} = 0.1 Pa$
- The inertial component of the pressure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

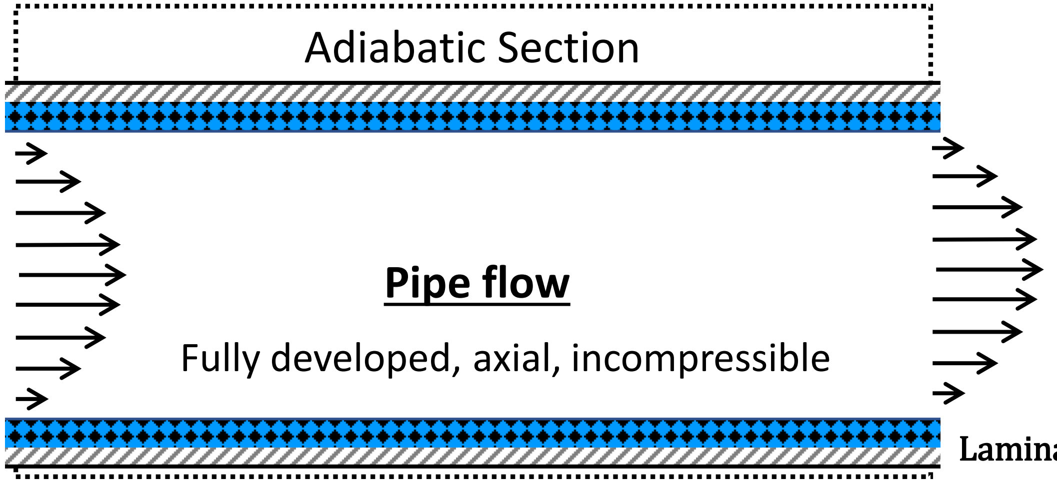
Pressure gradient to accelerate vapor to the axial velocity v

Pressure gradient to overcome frictional drag forces at the wick surface

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



Vapor Flow in the Adiabatic Section



Turbulent (Re > 2100)

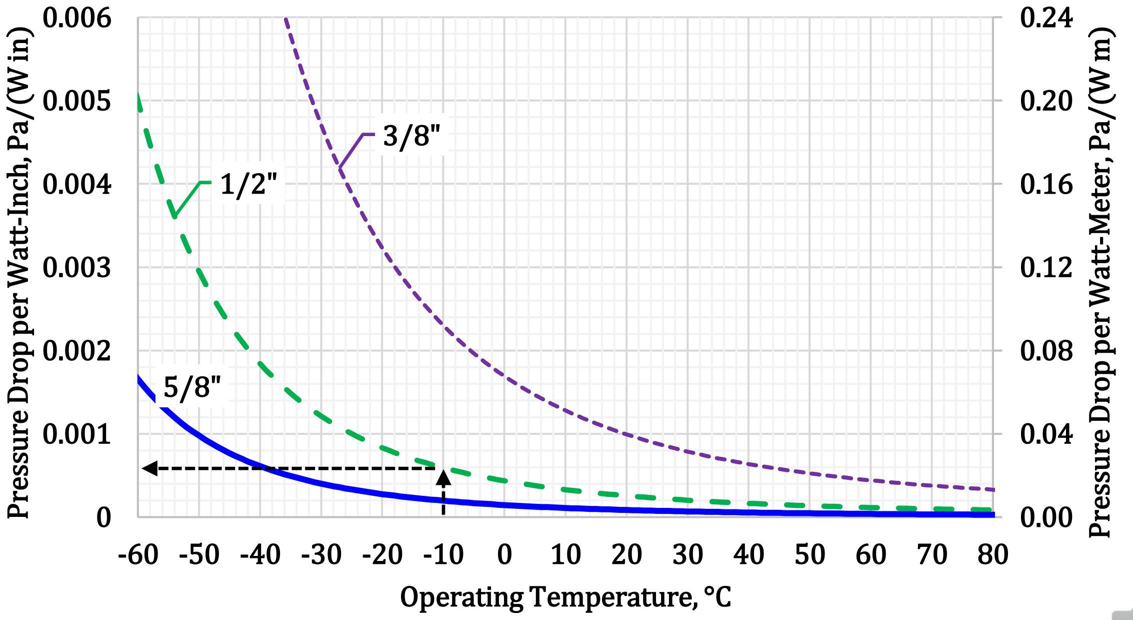
$$\Delta P_{va} = \frac{2}{R_{vs}} f \frac{1}{2} \rho v^2 L_a$$

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

Laminar (Re < 2100)

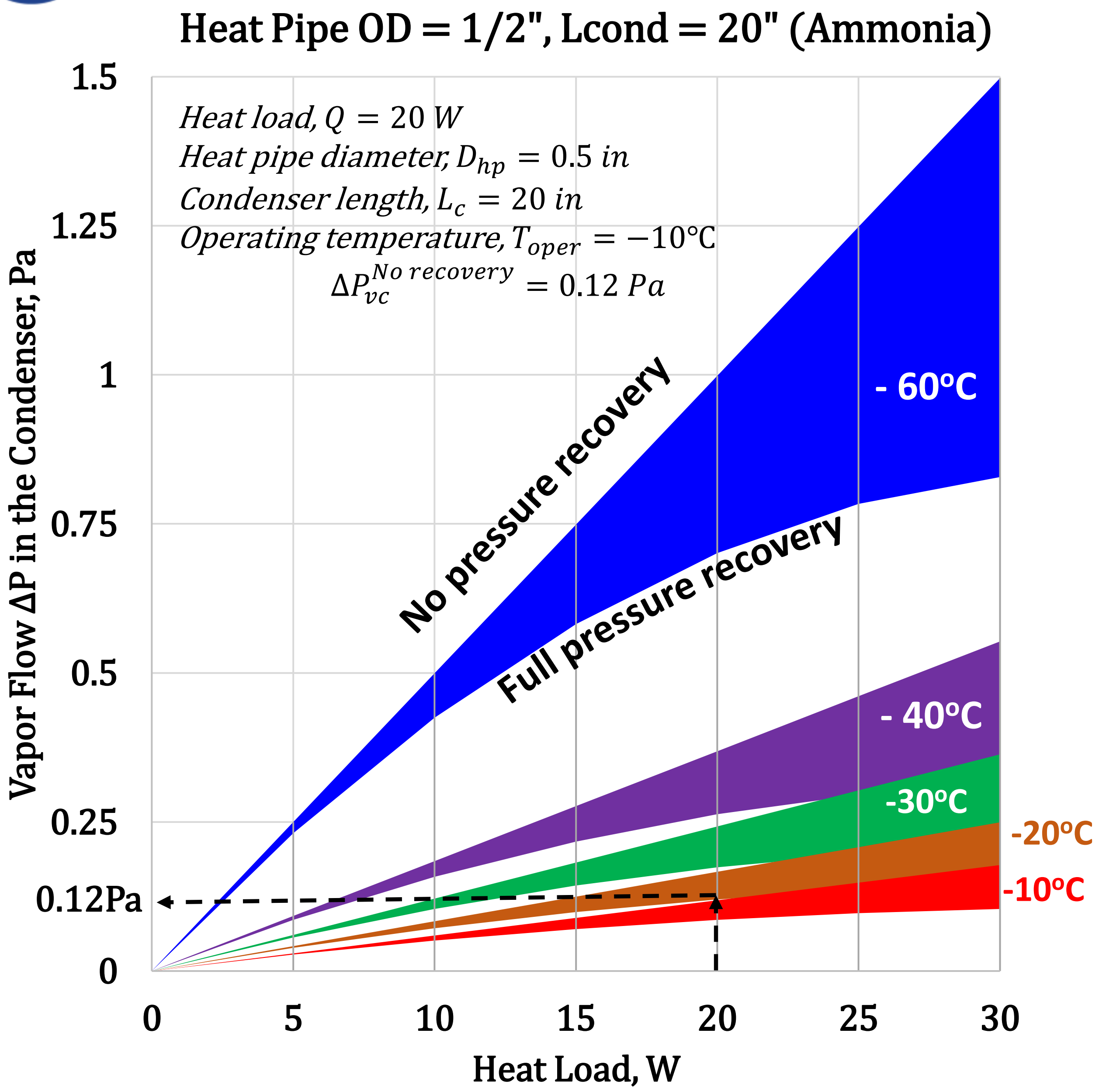
$$\frac{\Delta P_{va}}{Q L_a} = \frac{8\mu_v}{\rho_v \pi H_{fg} R_{vs}^4}$$

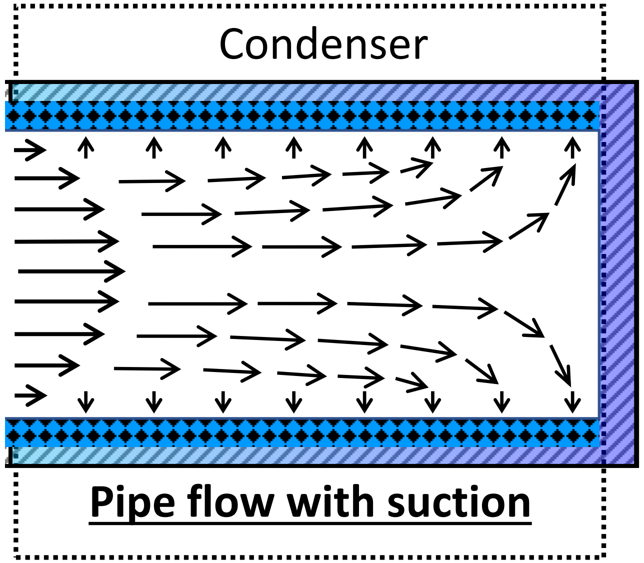
Laminar Vapor Flow in the Adiabatic Section (Ammonia)



- 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, $T_{oper} = -10(°C)$
- From the plot: $\frac{\Delta P_{va}}{Q L_a} = 0.0006 \frac{Pa}{W\ in}$
- Thus, $\Delta P_{va} = 0.0006 \frac{Pa}{W\ in} \cdot 30\ in \cdot 20W = 0.36 Pa$

Vapor Flow in the Condenser





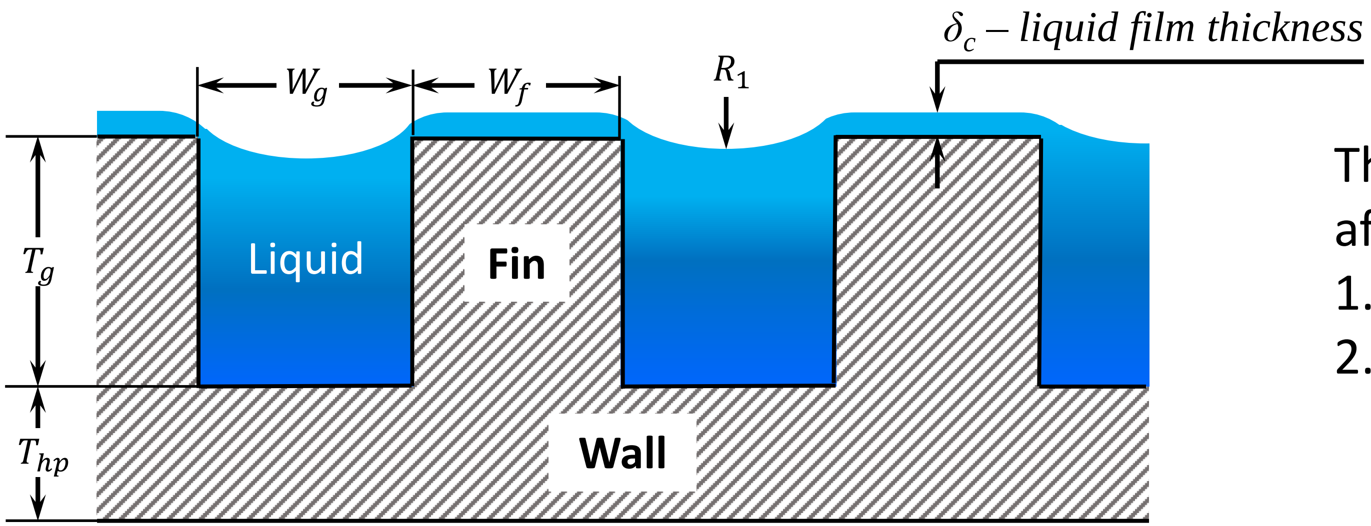
Pressure gradient to decccelerate vapor stream.

Pressure gradient to overcome frictional drag forces at the wick surface

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

Negative – decceleration

Condensation Process



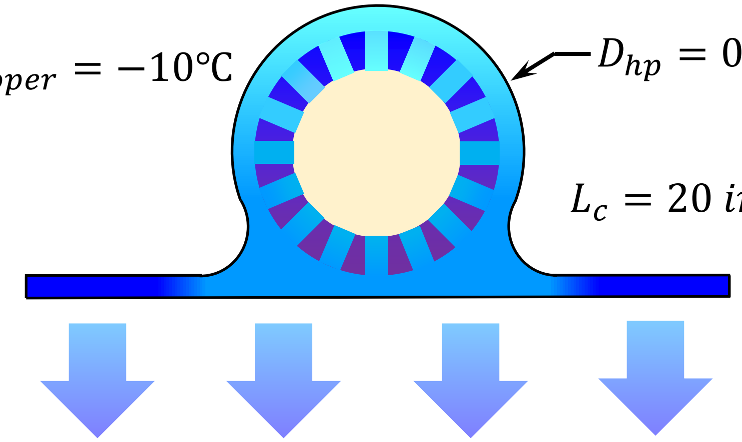
Variable	***Typical Value***
R_1 – Capillary radius	order of centimeters
T_{hp} – Wall thickness	from 0.3mm to 1mm
T_g – Groove depth	from 0.3mm to 2mm
W_f – Fin thickness	from 0.5mm to 1mm
W_g – Groove width	from 0.4mm to 1mm
δ_c – Liquid film thickness	from 5 mkm to 30 mkm

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

1. Liquid film thickness, δ_c
2. Fluid properies, 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 $W/(m^2 \cdot K)$ to 20,000 $W/(m^2 \cdot K)$.
A value of $h_{cond} = 8{,}000\ W/(m^2 \cdot K)$ 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

$$D_{hp} = 0.5\ in, \qquad T_{oper} = -10°C \rightarrow\ C_c = 7\frac{W}{in\ °C}$$

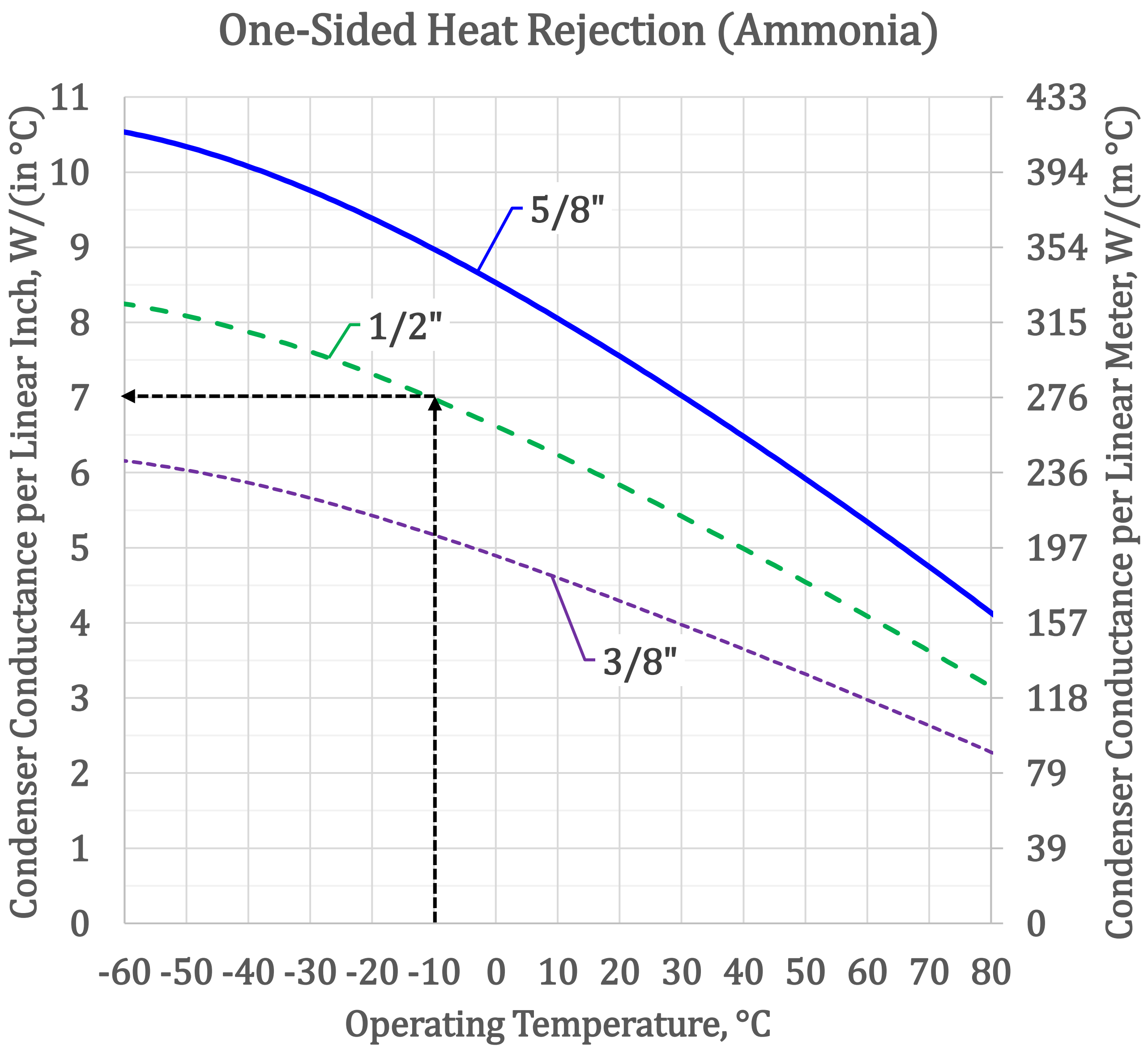
2. Calculate the condenser heat load per unit length.

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

3. Calculate the condenser temperature drop.

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

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



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

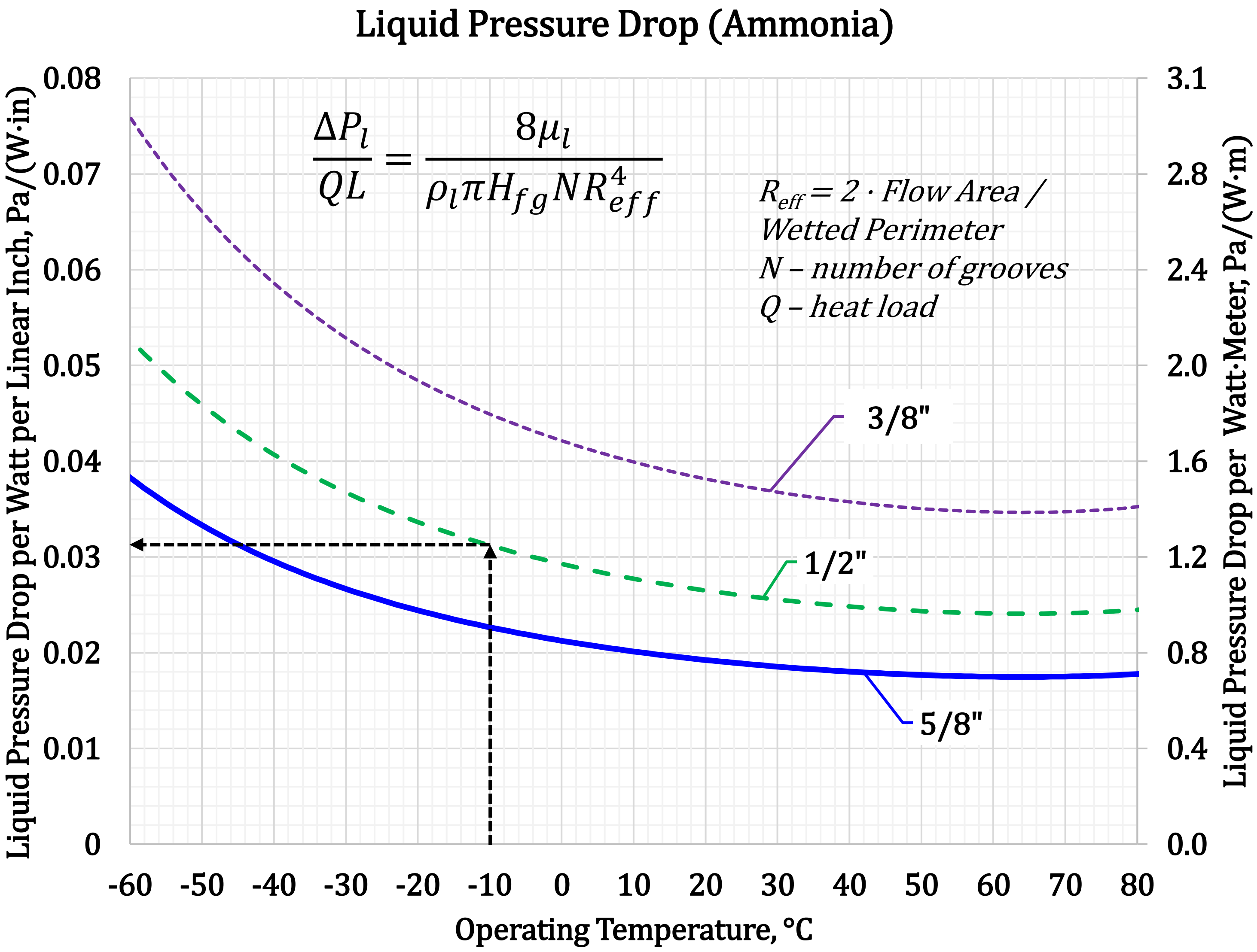
$Heat\ load, Q = 20\ W$
$Heat\ pipe\ diameter, D_{hp} = 0.5\ in$
$Heat\ pipe\ length, L_{hp} = 60\ in$
$Operating\ temperature, T_{oper} = -10°C$

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

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

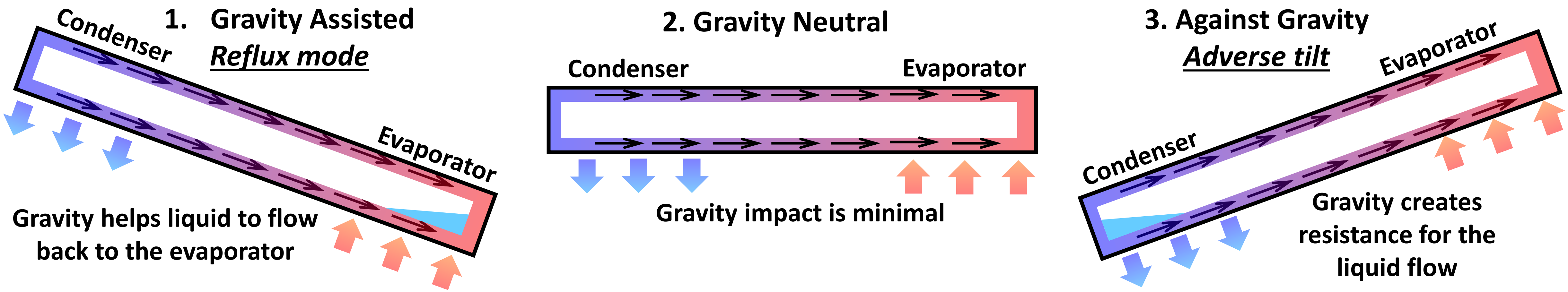
2. Calculate the liquid pressure drop

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



Gravitational Impact

Axial groove heat pipe operation is affected by gravity



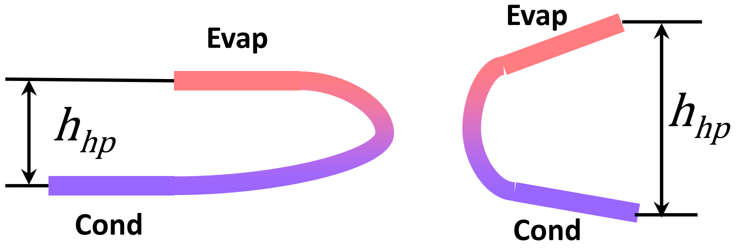
The pressure difference due to hydrostatic head of the liquid is equal to:

$\Delta P_g = \rho_l g\, h_{hp}$ – ***general formula***

where ρ_l – *the liquid density*

g – *the gravity acceleration*

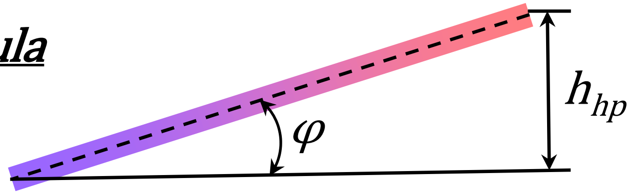
h_{hp} – *the height difference between heat pipe ends*



$\Delta P_g = \rho_l g\, L_{hp} \sin\varphi$ – ***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, $Q = 20\ W$
Heat pipe diameter, $D_{hp} = 0.5\ in$
Heat pipe length, $L_{hp} = 60\ in$
Evaporator length, $L_e = 10\ in$
Condenser length, $L_c = 20\ in$
Operating temperature, $Toper = -10°C$

Find heat transport capacity from the capillary limit plot:

$$Q_{max\_0\text{-}g} L_{eff} \approx 4{,}200\ W\cdot in$$

Effective length:

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

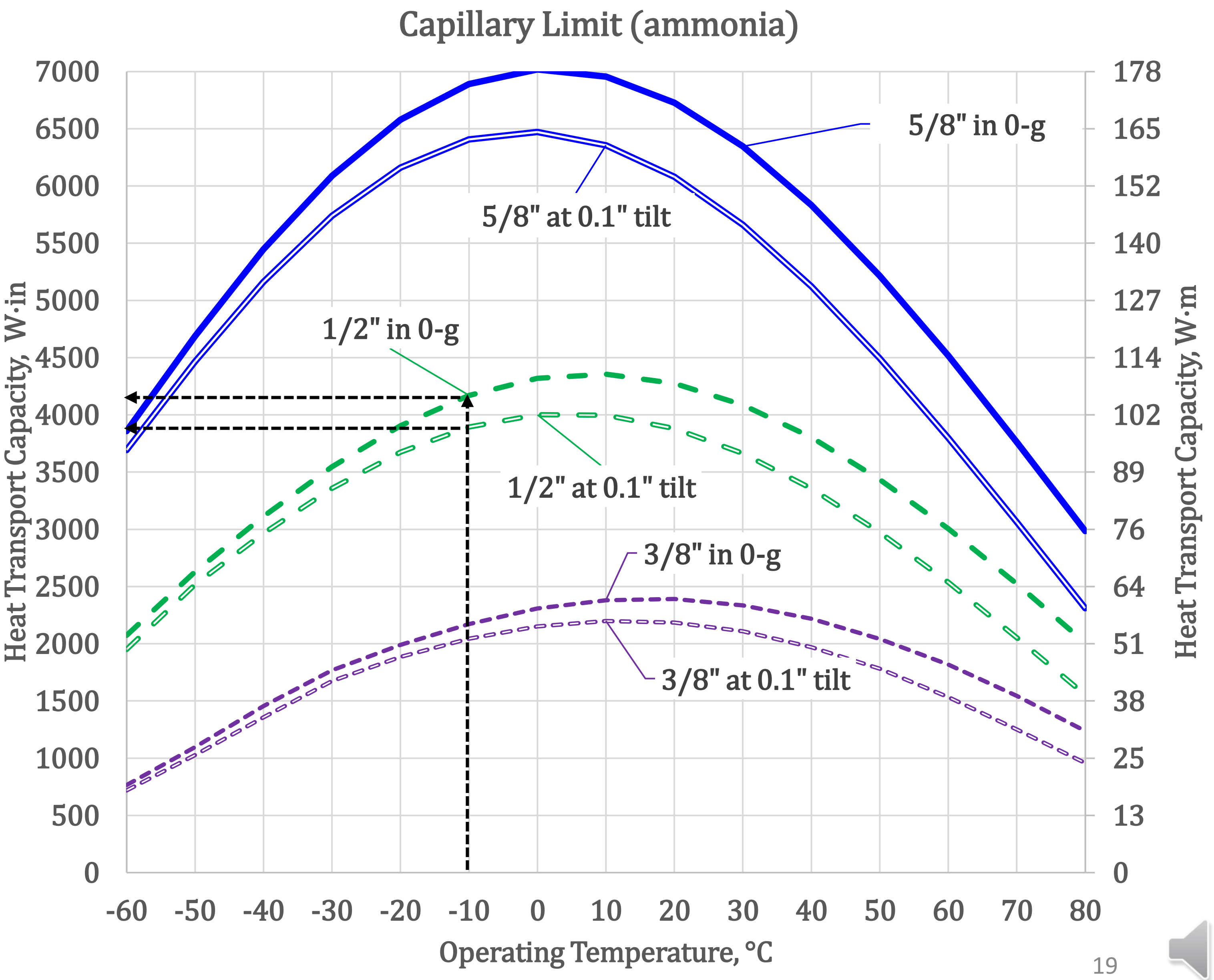
Thus, the capillary limit in zero-g is equal to:

$$Q_{max\_0\text{-}g} = (Q_{max} L_{eff})/L_{eff} \approx 93\ W$$

Typically ground testing performed with 0.1" adverse tilt.

$$Q_{max\_0.1"} L_{eff} \approx 3{,}800\ W\cdot in$$

$$Q_{max\_0.1"} \approx 84\ W$$

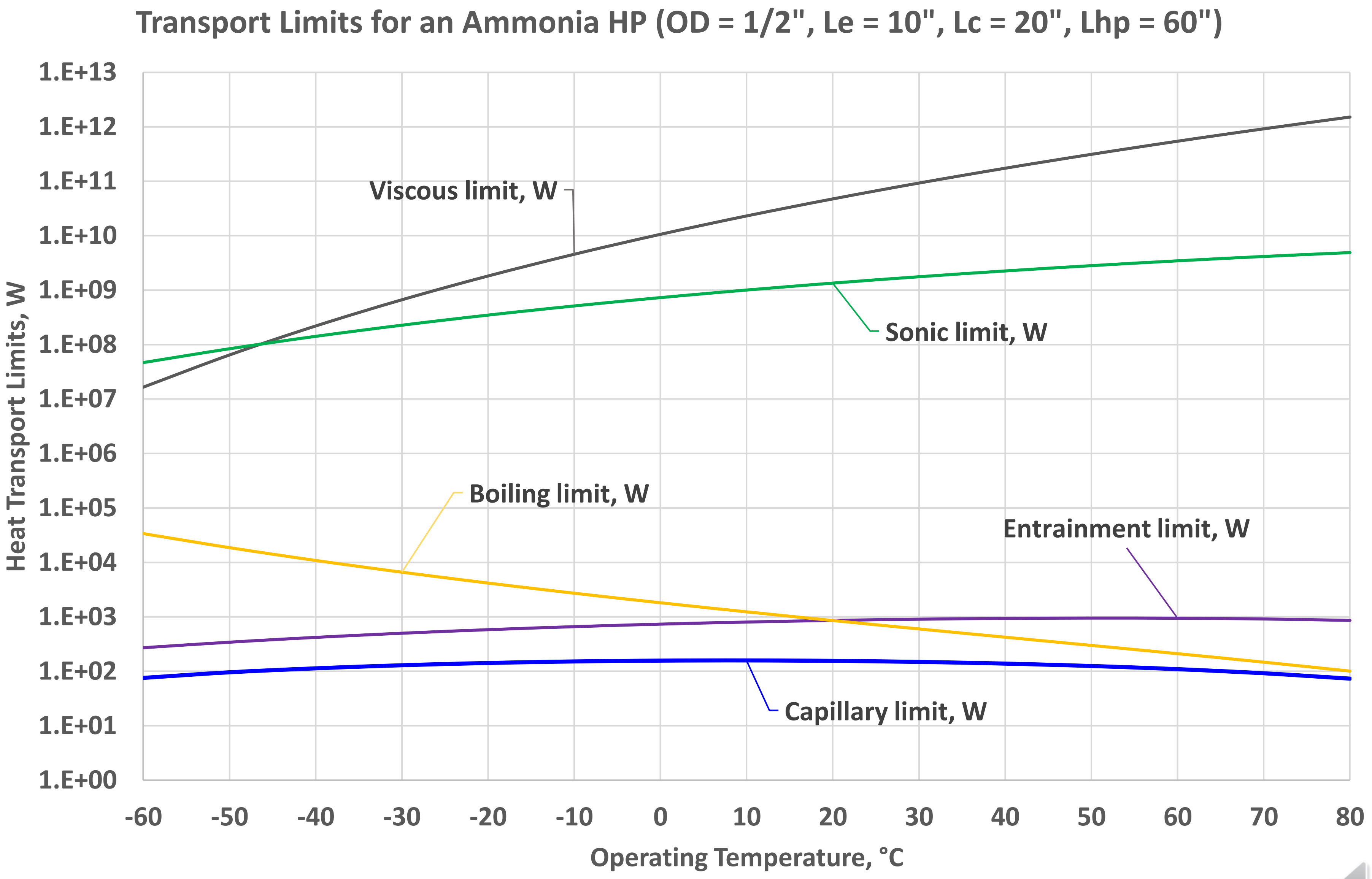


Heat Transport Limits

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.



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.