Adaptable Single Active Loop Thermal Control System (TCS) for Future Space Missions

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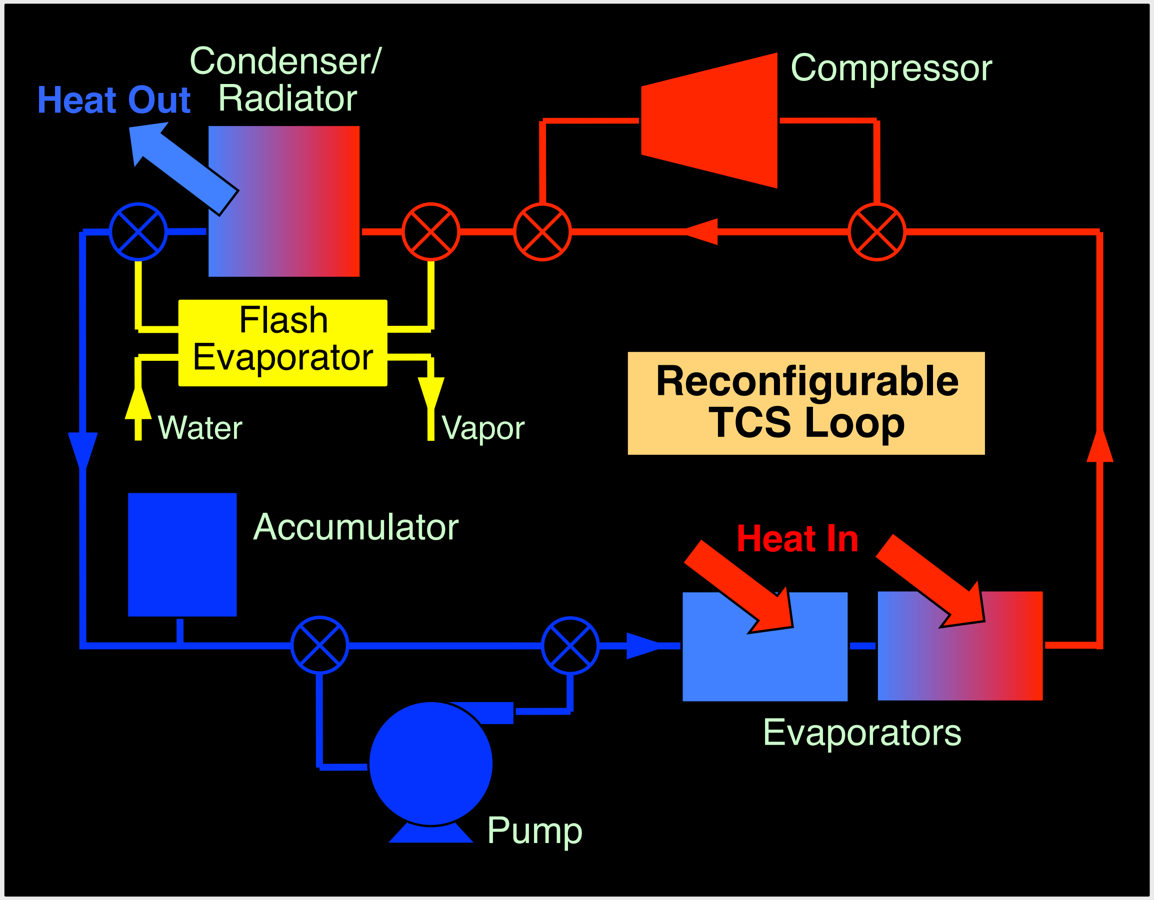
Research Objectives



Develop Adaptable Single-Loop Thermal Control System (ASL-TCS) that can tackle widely varying heat loads of different space missions and both cold and warm environments while improving system performance, reducing weight and volume, and ensuring reliable operation irrespective of gravity

Thermal Requirement for Different Missions

Thermal loads and effective sink temperatures for different missions based on Orion Multi-Purpose Crew Vehicle (MPCV)

	Launch to LEO	TLC, TNEOC, TMC	LLO	LSO	NEO	MSO	LMO
Thermal Load	1.2 kW	1 kW	5 kW	6.25 kW	TBD	6.25 kW	5 kW
Effective Sink Temperature	-93 to -66°C (180 to 207K)	-198°C (75 K)	-213 to 17°C (60 to 290 K)	-56 to -34°C (217 to 239K)	TBD	-123 to -23°C (150 to 250K)	22°C (295 K)

LEO: Low Earth Orbit
LLO: Low Lunar Orbit
TLC: Trans Lunar Coast
TNEOC: Trans Near Earth Objects Coast
TMC: Trans Mars Coast

LSO: Lunar Surface Operation
NEO: Near-Earth Object
MSO: Mars Surface Operation
LMO: Low Mars Orbit

LLO and LMO associated with heat sink temperatures that exceed lowest minimum fluid temperature of 2°C at inlet to cabin HX, therefore requiring heat pump mode

Requirements for Heat Pump Mode

$T_{cabinHX,in}$ = 2°C: prevent frost formation on evaporator surfaces
T_{evap} = 5°C: evaporation temperature
Condenser pinch temp. = 5°C maintain adequate condenser performance
LLO: T_{sink} = 17°C, $T_{cond,out}$ = 22°C
LMO: T_{sink} = 22°C, $T_{cond,out}$ = 27°C
Max T_{lift} = 80°C when T_{evap} = 5°C (60°C for R404a with T_{crit} = 72.07°C)
$Q_{cabinHX}$ = 0.75 kW
$Q_{avionicsHX}$ = 0 – 5.5 kW

Pressure:
Max pressure = P_{sat} at $T_{cond,,sat}$ = T_{evap} (= 5°C) + T_{lift} (= 80°C)
Min pressure = P_{sat} at $T_{cabinHX,in}$ = 2°C

Radiator Area: $A_{radiator,s} = A_{vapor} + A_{sat} + A_{liquid}$, $T_{cond,sat} = T_{evap} + T_{lift}$

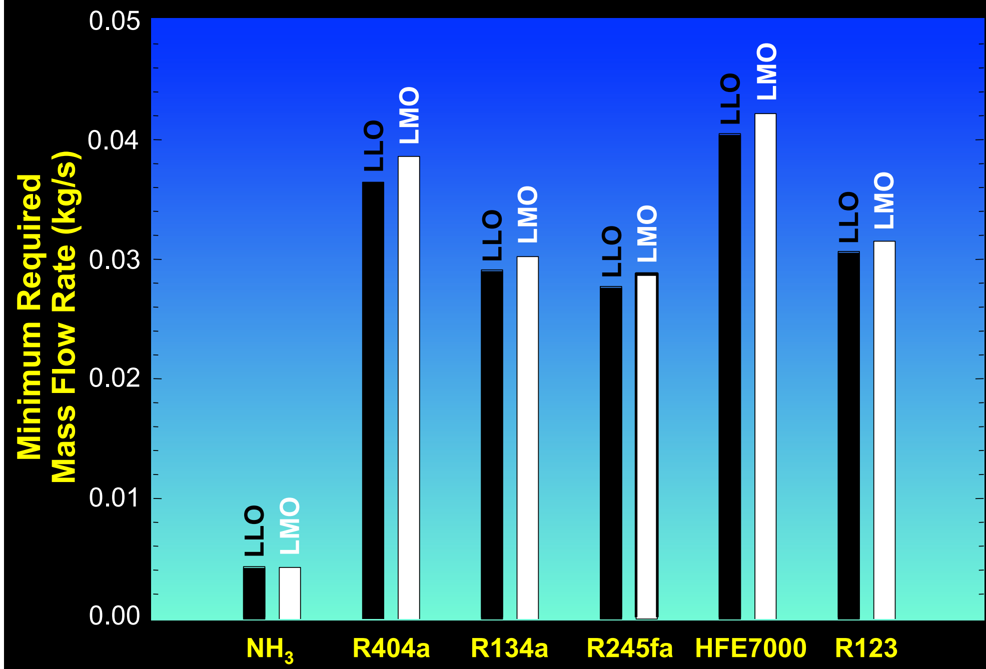
$$A_{vapor} = \frac{\dot{m}_{hp}\, c_{p,f}\left(T_{cond,in} - T_{cond,sat}\right)}{\varepsilon\,\sigma\left\{\left(\frac{T_{cond,in}+T_{cond,sat}}{2}\right)^4 - T_{sink}^4\right\}} \;,\; A_{sat} = \frac{\dot{m}_{hp}\, h_{fg}}{\varepsilon\,\sigma\left\{T_{cond,sat}^{\;4} - T_{sink}^4\right\}} \;,\; A_{liquid} = \frac{\dot{m}_{hp}\, c_{p,f}\left(T_{cond,sat} - T_{cond,out}\right)}{\varepsilon\,\sigma\left\{\left(\frac{T_{cond,sat}+T_{cond,out}}{2}\right)^4 - T_{sink}^4\right\}}$$

Coefficient of Performance: $COP = \frac{Q_{cabinHX} + Q_{avionicsHX}}{W_{comp}/\eta_{comp}}$, $\eta_{comp} = 85\%$

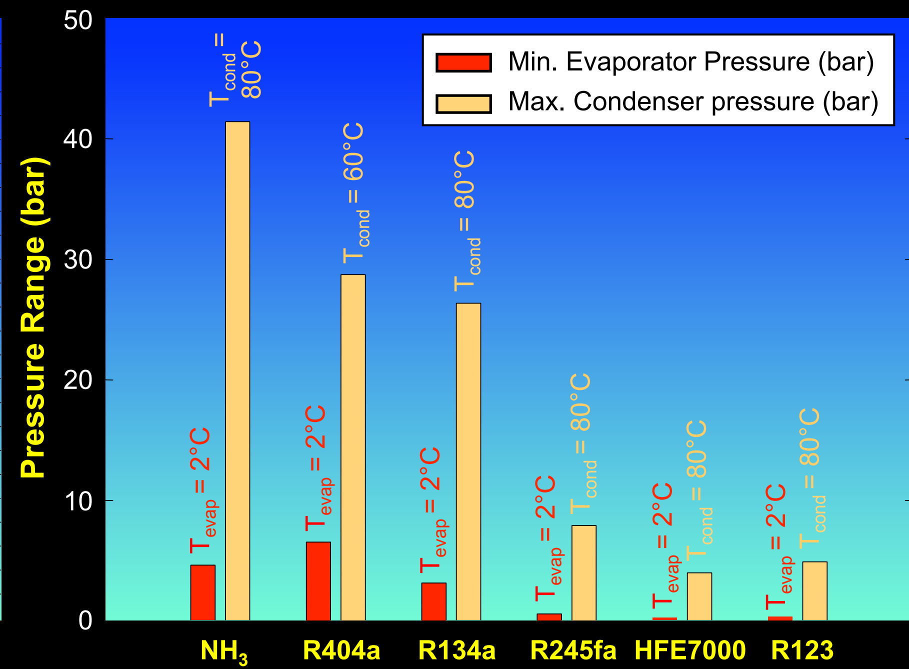
$$W_{comp} = \int_{P_{avionicsHX,out}}^{P_{cond,in}} V\,dP = \dot{m}_{hp}\left(h_{cond,in} - h_{avionicsHX,out}\right)$$

Requirements for Heat Pump Mode

Mass Flow Rate



Maximum and Minimum Pressure



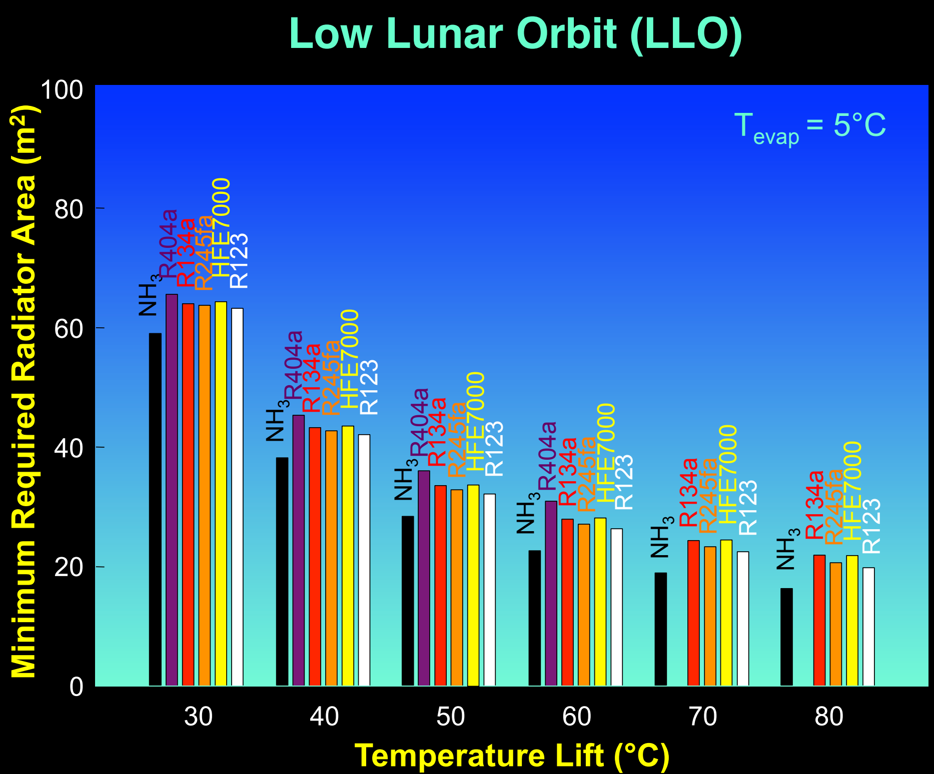
Mass Flow Rate:

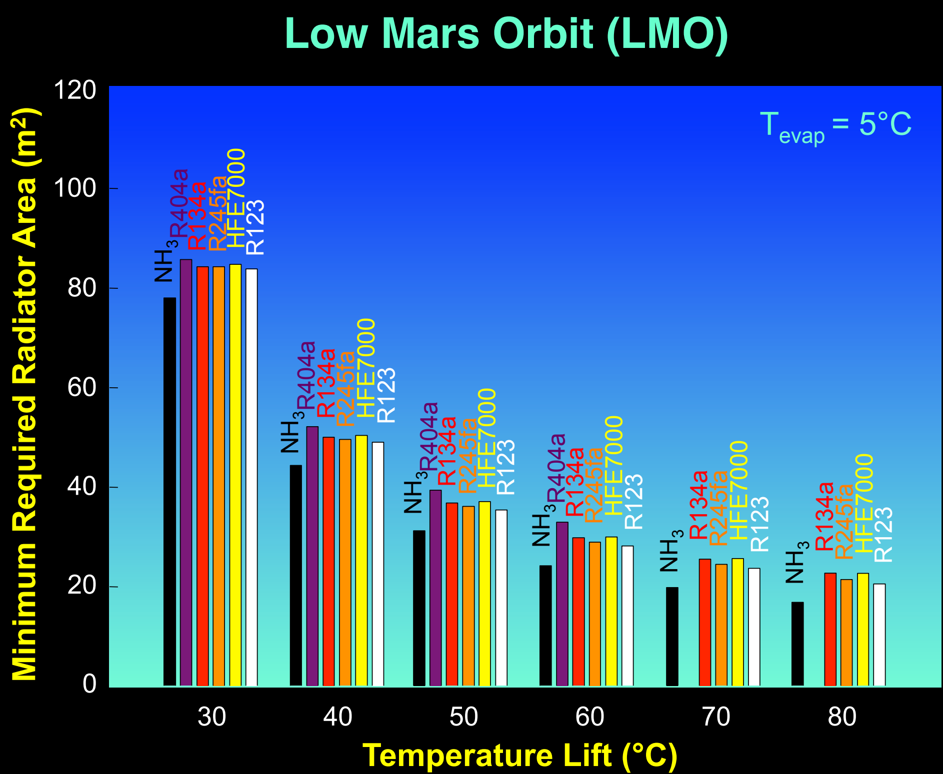
- LLO: Lower $T_{cond,out}$, lower enthalpy at inlet to cabin HX, higher evaporator enthalpy rise, lower mass flow rate
- NH_3 requires lowest flow rate

Pressure:

- Max pressure highest for NH_3, lowest for HFE7000

Required Radiator Area for Heat Pump Mode



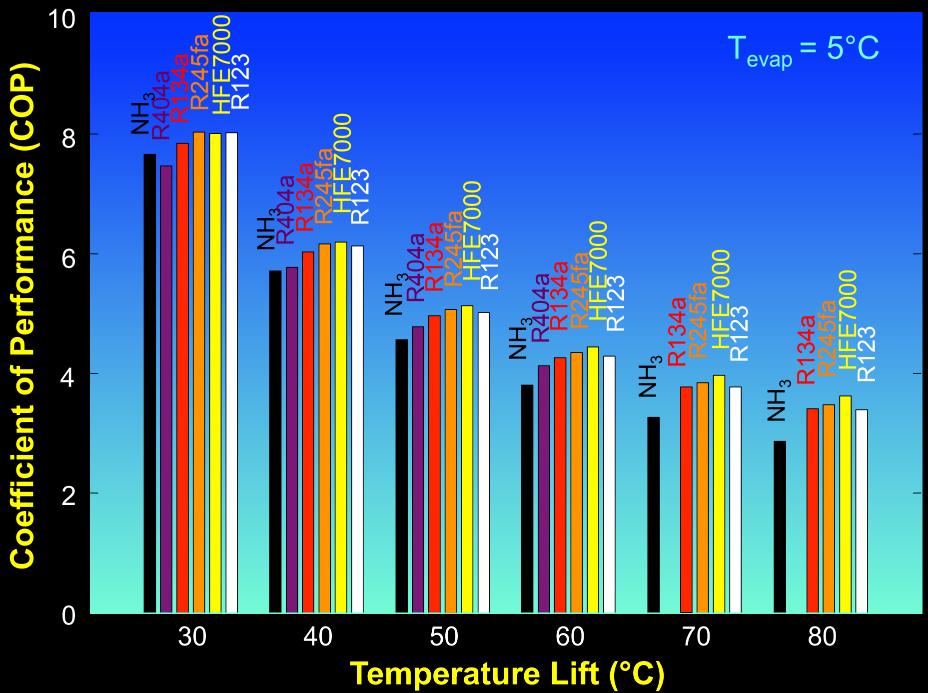


Mass Flow Rate:

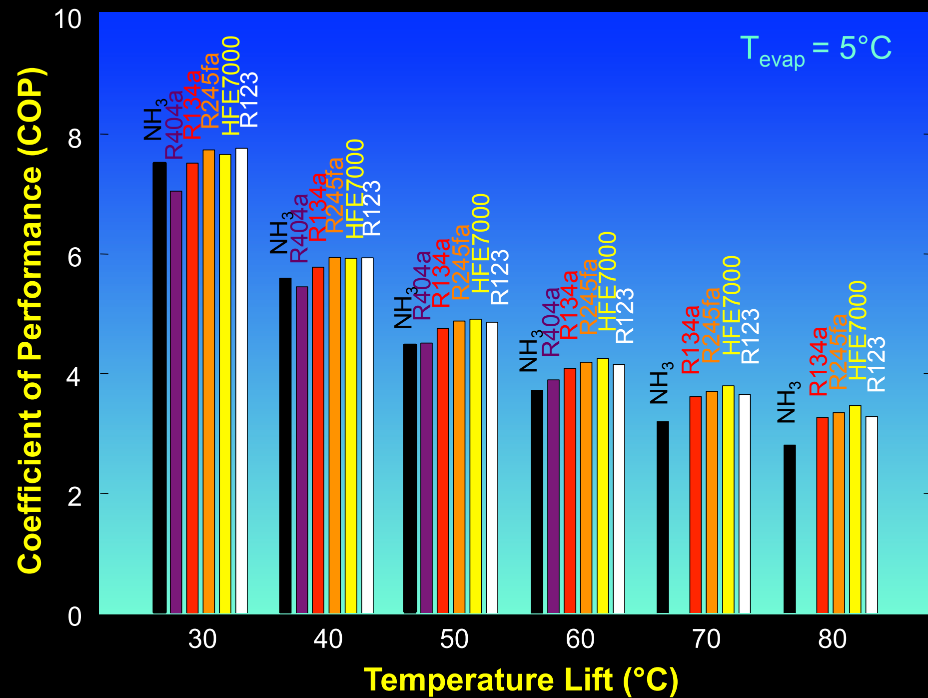
- Area decreases with increasing T_{lift}
- NH_3 requires smallest area but area differences among fluids are small

Coefficient of Performance (COP) for Heat Pump Mode

Low Lunar Orbit (LLO)



Low Mars Orbit (LMO)



COP Trends

- Decreases with increasing T_{lift} because of higher compressor work
- Higher for LLO because of lower evaporator inlet enthalpy
- Fairly equal for different fluids

Fluid Selection

1. **Chlorofluorocarbons (CFCs)**
   - Consist of chlorine, fluorine and carbon
   - Ex: R11, R12, R113, R114 and R115
   - High ozone depletion potential (ODP)
   - Already banned
2. **Hydrochlorofluorocarbons (HCFCs)**
   - Consist of hydrogen, chlorine, fluorine and carbon
   - Ex: R22, R123, R124 and R142b
   - Small but finite ODP
   - Being gradually phased out
3. **Hydrofluorocarbons (HFCs)**
   - Consist of hydrogen, fluorine and carbon
   - Ex: R404a, R134a, R245fa, HFE7000
   - Zero ODP; low global warming potential (GWP)
   - Currently preferred refrigerants

Toxicity Rating:

Class A: no evidence of toxicity below 400 ppm

Class B: evidence of toxicity below 400 ppm

Flammability Rating:

Class 1: no flame propagation in open air

Class 2: may propagate flame under certain co nditions in open air

Class 3: highly flammable

	Type	Rating	Critical Pressure (MPa)	Critical Temperature (°C)
Ammonia	-	B2	11.33	132.25
R404a	HFC	A1	3.73	72.12
R134a	HFC	A1	4.06	101.06
R245fa	HFC	B1	3.65	154.01
HFE7000	HFC	A1	2.48	165.00
R123	HCFC	B1	3.66	183.68

Comparison of Fluid Performances

NH_3: Requires smallest flow rate but highest condenser pressure; exhibits toxicity and flammability

R404a: An HFC that requires high condenser pressure; exhibits no toxicity or flammability, zero ODP and low GWP

R134a : An HFC that provides compromise between reducing flow rate and reducing pressure; exhibits no toxicity or flammability, zero ODP and low GWP

R245fa: An HFC that provides compromise between reducing flow rate and reducing pressure; exhibits no flammability, zero ODP and low GWP, but some toxicity

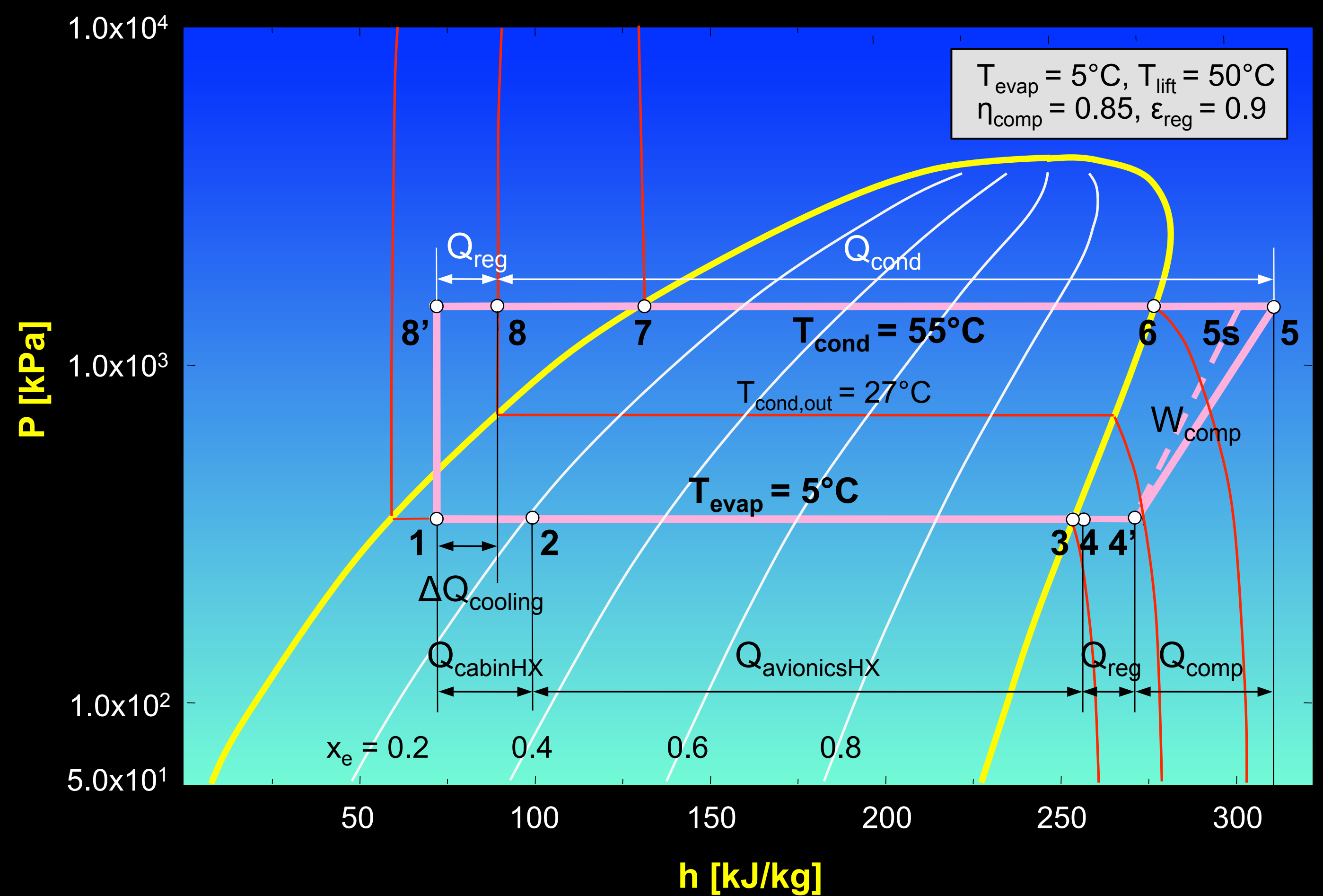
HFE7000: An HFC that requires low condenser pressure but high flow rate; exhibits no toxicity or flammability, zero ODP and low GWP; used as replacement to R123

R123: An HCFC that requires low condenser pressure but high flow rate; exhibits no toxicity or flammability but some ODP

No significant differences among fluids in terms of radiator area or COP

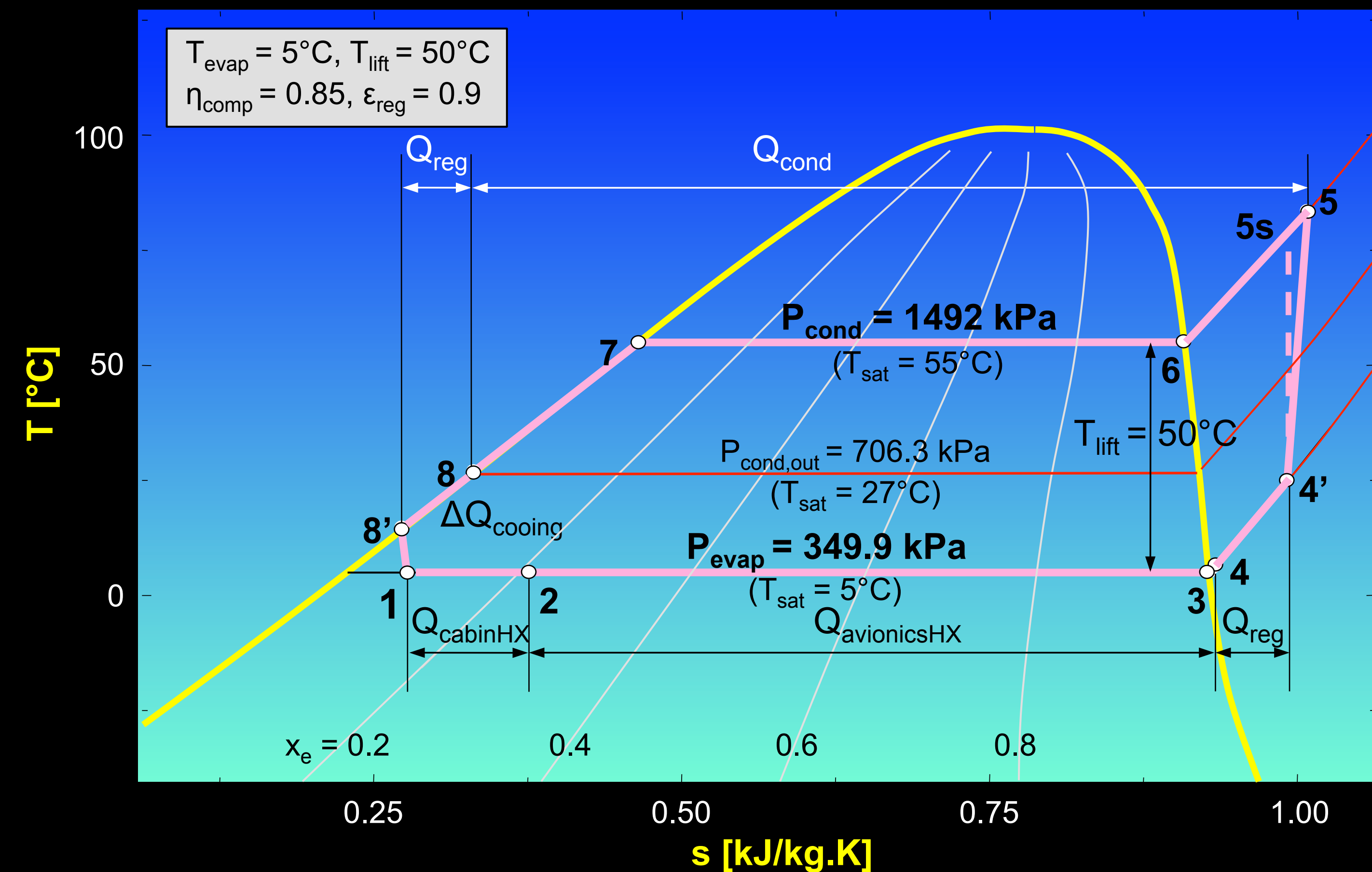
Preferred Coolant: R134a (1,1,1,2-Tetrafluoroethane, CH_2FCF_3)

p-h Diagram for Heat Pump with LLSL-HX for Low Mars Orbit (LMO) using R134a



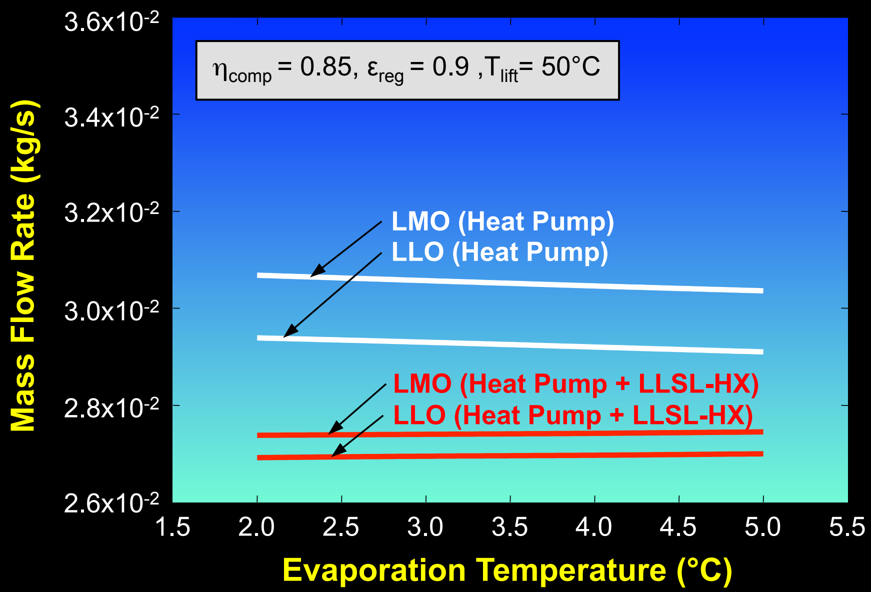
- LLSL-HX used high temperature of subcooled liquid exiting condenser to further superheat vapor before entering compressor
- Compared to basic heat pump: 8 to 8' and 4 to 4'

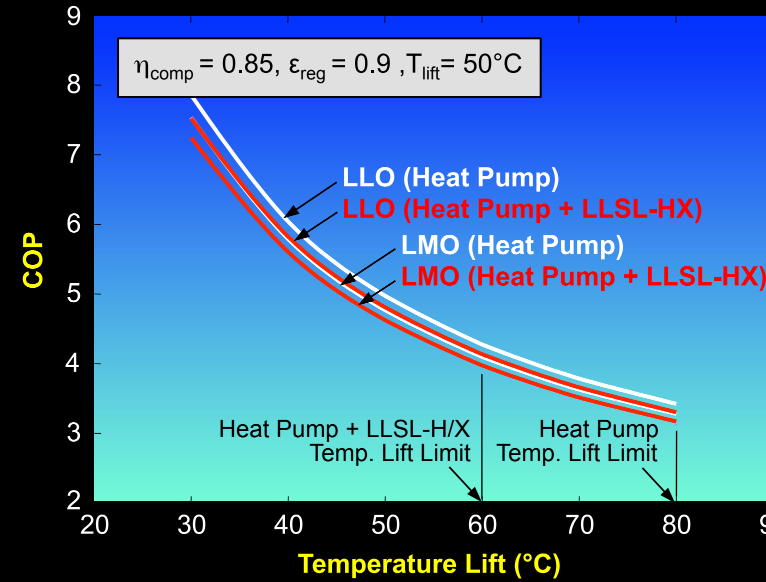
T-S Diagram for Heat Pump with LLSL-HX for Low Mars Orbit (LMO) using R134a

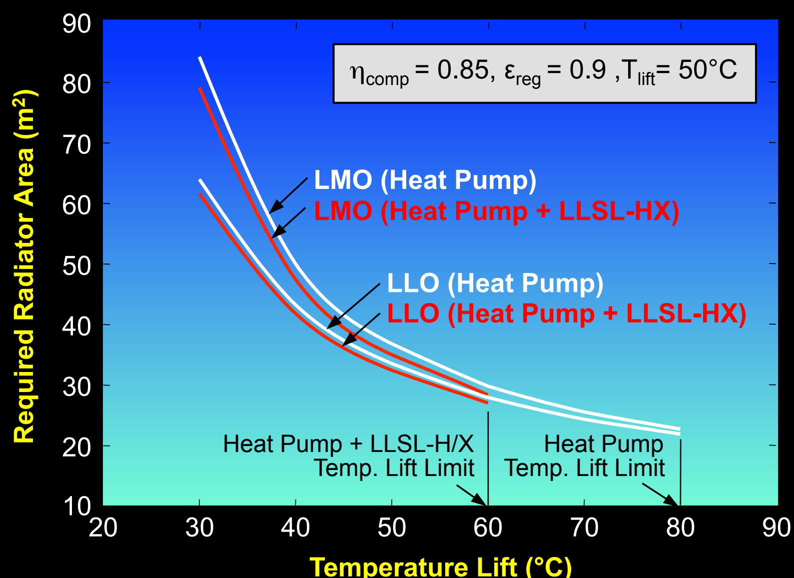


$$COP' = \frac{\left(Q_{cabinHX} + Q_{avionicsHX}\right) + \Delta Q_{cooling}}{W_{comp} + \Delta W_{comp}} = \left[\frac{1 + \left\{ \dfrac{\Delta Q_{cooling}}{Q_{cabinHX} + Q_{avionicsHX}} \right\}}{\left\{ 1 + \dfrac{\Delta W_{comp}}{W_{comp}} \right\}} \right] COP$$

Heat Pump with LLSL-HX versus Basic Heat Pump Mode for R134a







Low Lunar Orbit (LLO)
Low Mars Orbit (LMO)

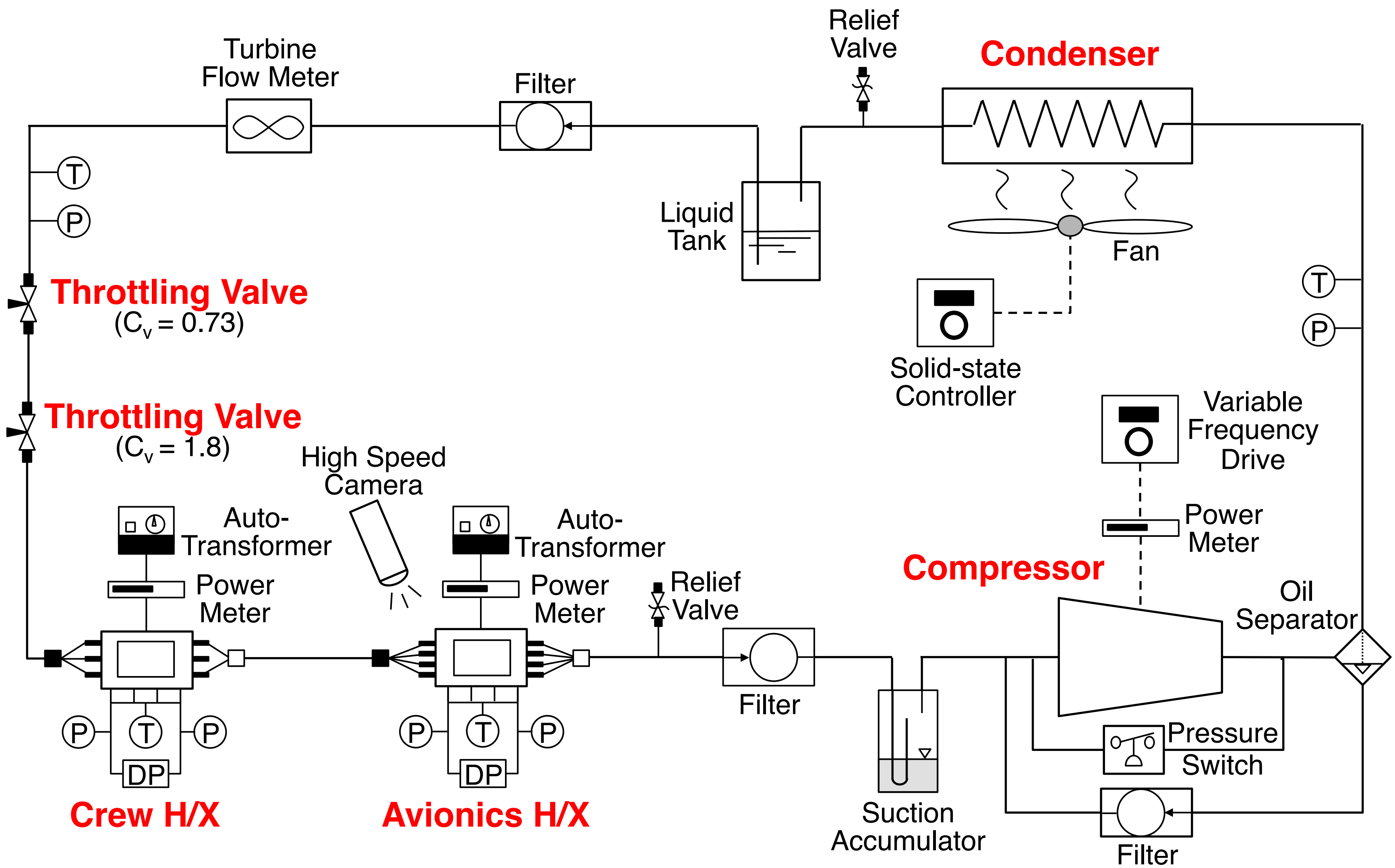
Mass Flow Rate: appreciable reduction with LLSL-HX

COP: some degradation with LLSL-HX

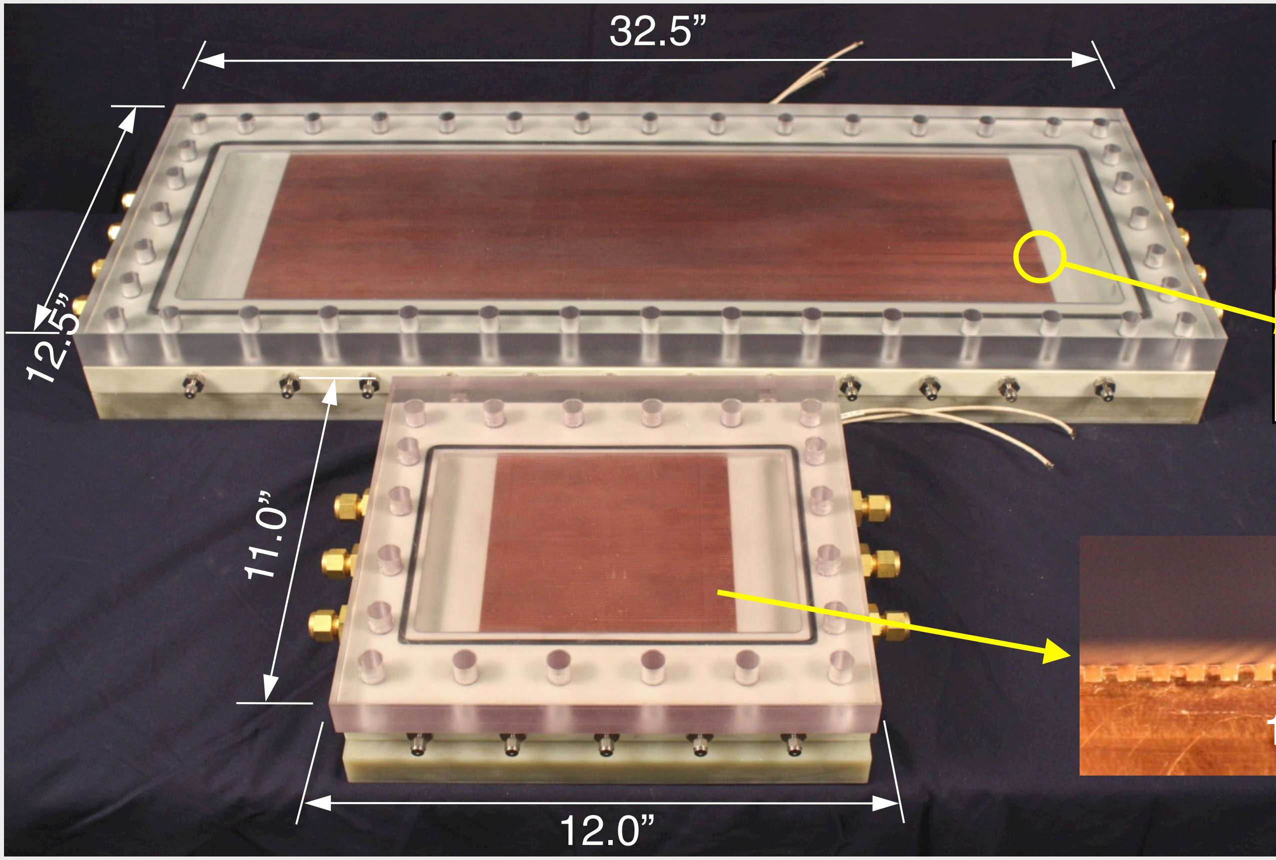
Radiator Area: some improvement with LLSL-HX

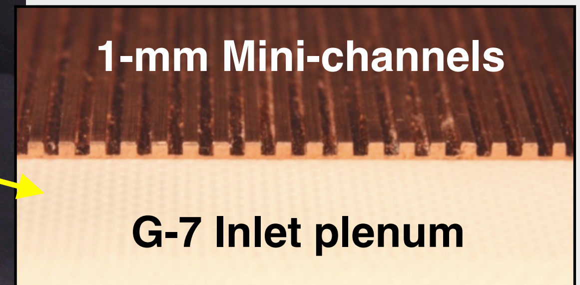
ASGSR 2015 | Boiling and Two-Phase Flow Laboratory (BTPFL) | November 2015

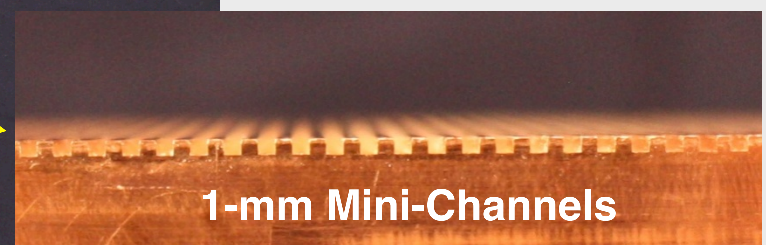
Heat Pump Test Loop



Avionics H/X & Cabin HX

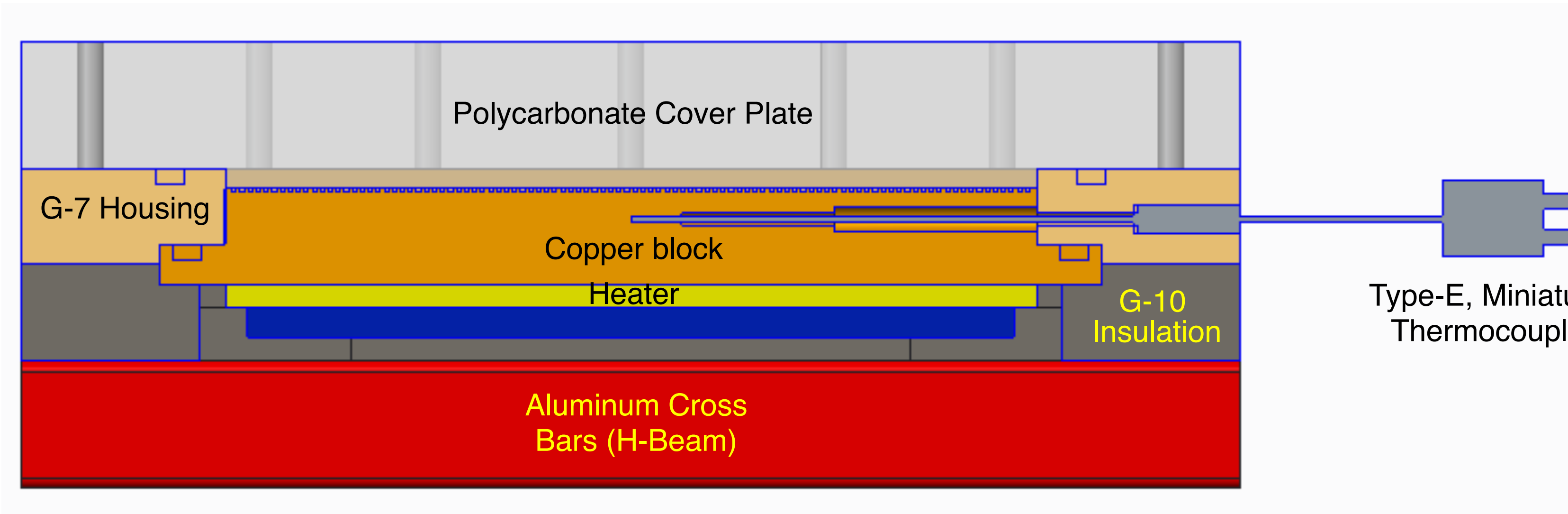


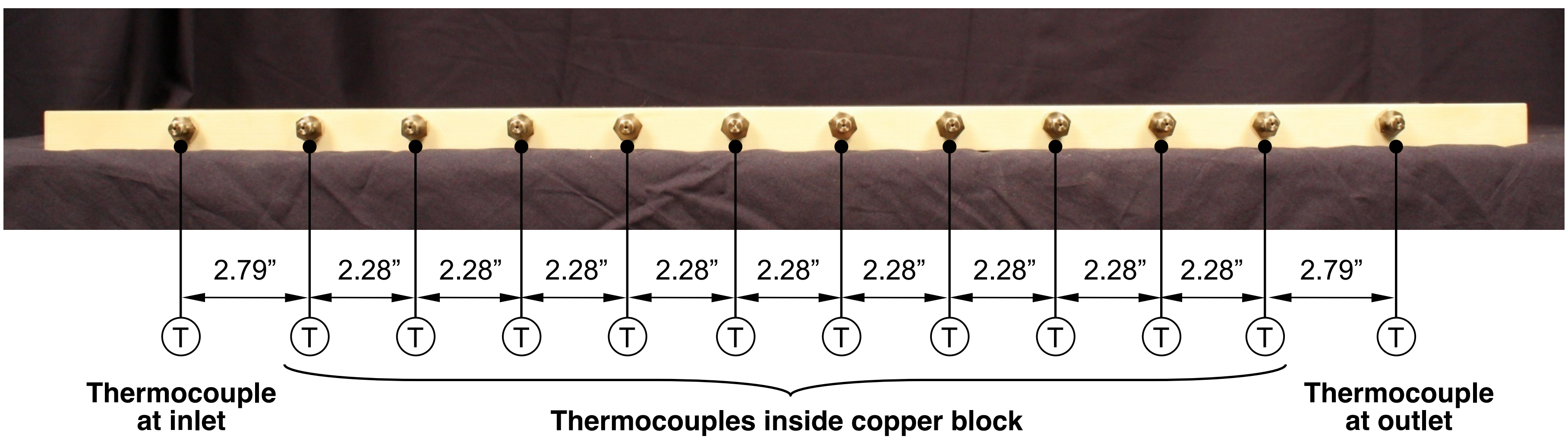




	Max. Heat Load, Q (kW)	Max. Heat Flux, q” (W/cm^2)	Overall Dimensions	Number of Mini-Channels	Expected Pressure Drop (by correlation)
Cabin HX	0.75 kW	3.13	Length : 152.4 mm (6“) Width : 152.4 mm (6“)	75	1.26 psi
Avionics HX	5.5 kW (LSO/MSO)	4.58	Length: 609.6 mm (24“) Width: 203.2 mm (8“)	100	6.34 psi

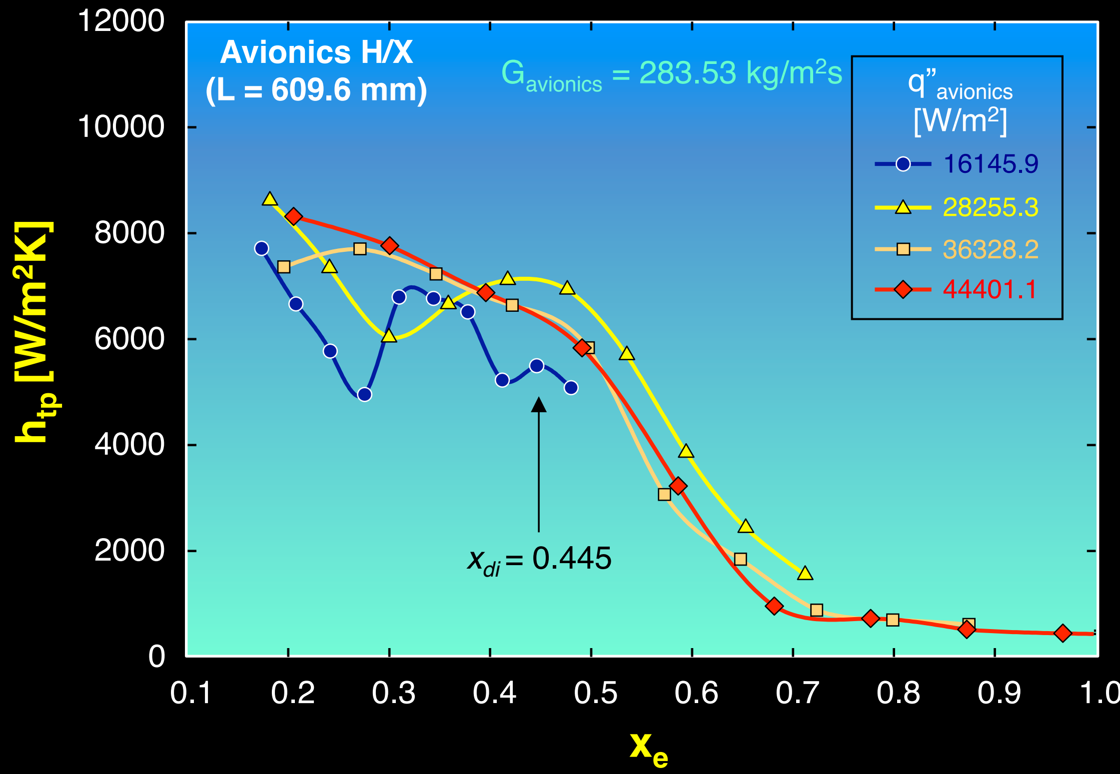
Avionics HX: Cross Section and Temperature Measurements



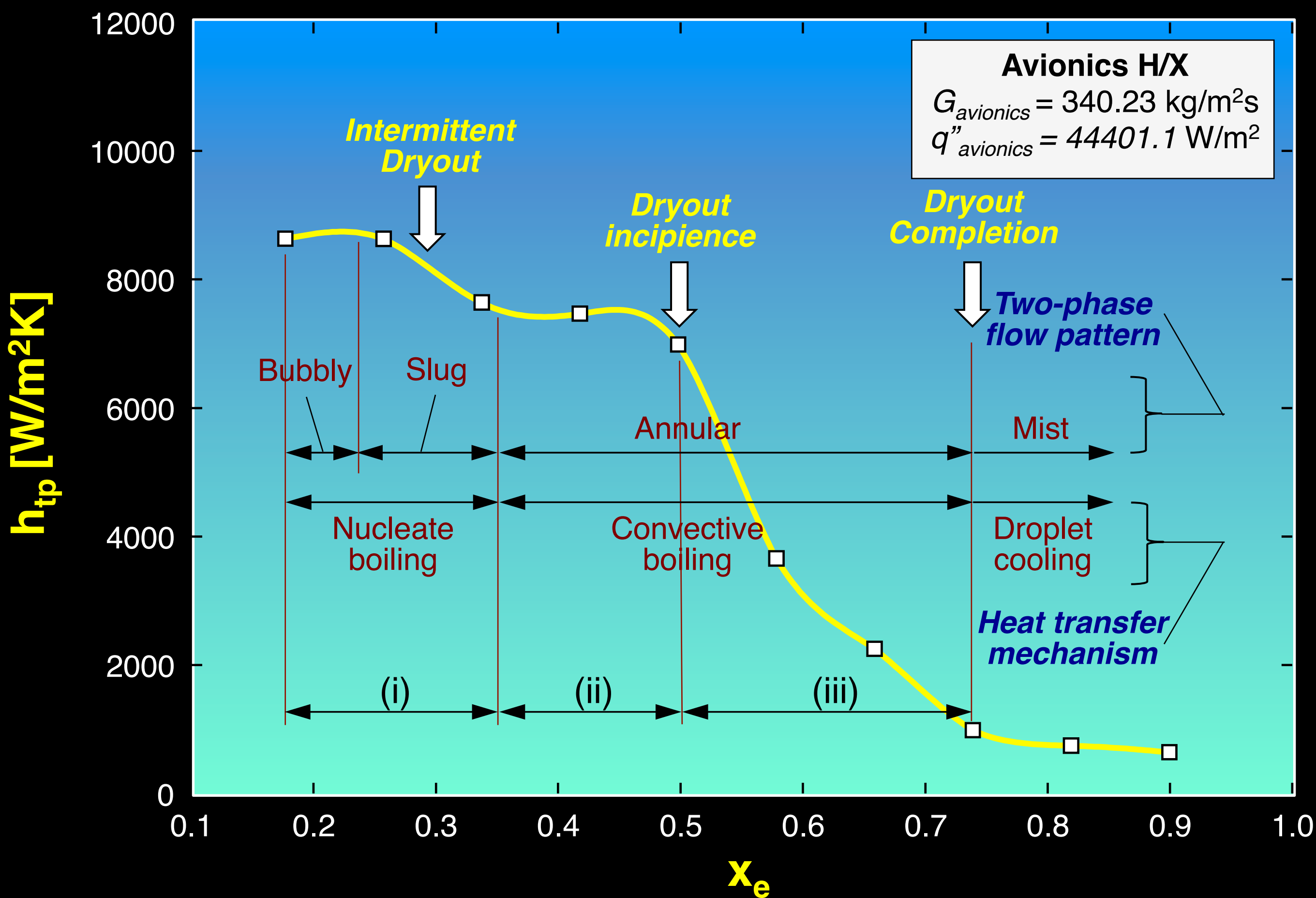


Heat Transfer Characteristics and Dryout Effects

Avionics H/X: Heat Flux Effects

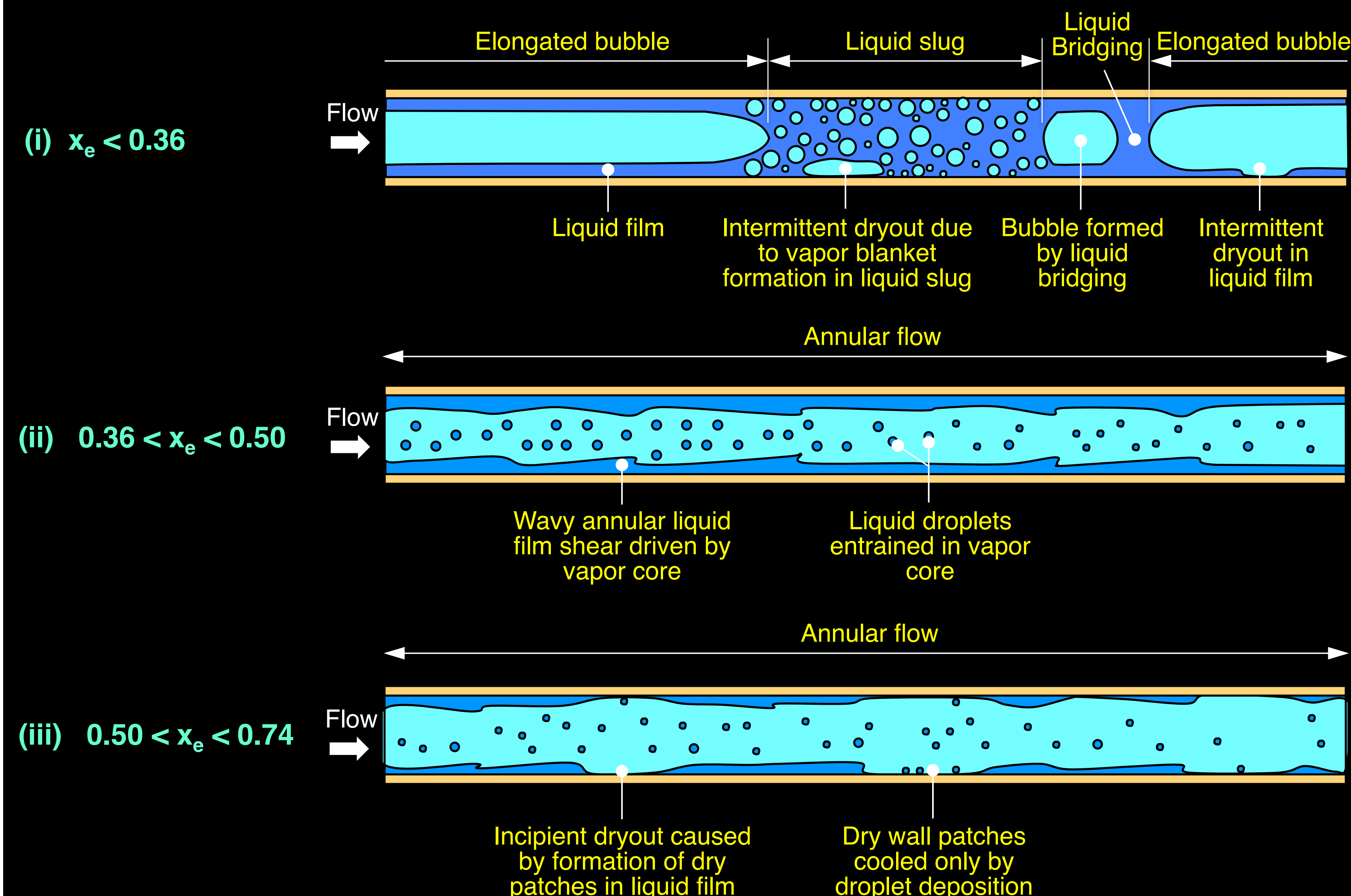


Avionics H/X: Two-Phase Flow Patterns and Heat Transfer Mechanisms



- **Intermittent Dryout:** mostly in liquid film surrounding elongated slug flow bubble or due to vapor blanket formation within the liquid slug
- **Incipient Dryout:** dry wall patches in annular film
- **Dryout Completion:** annular flow replaced by mist flow, with cooling provided only by droplet deposition

Avionics H/X: Two-Phase Flow Patterns and Heat Transfer Mechanisms



Macro-channel:

Chen (1966)

Liu & Winterton (1961)

Mini/Micro-channel:

Lazarek & Black (1982)

Tran et al. (1996)

Kandlikar (2004)

Lee & Mudawar (2005)

Bertsch et al. (2009)

Kim & Mudawar (2014)

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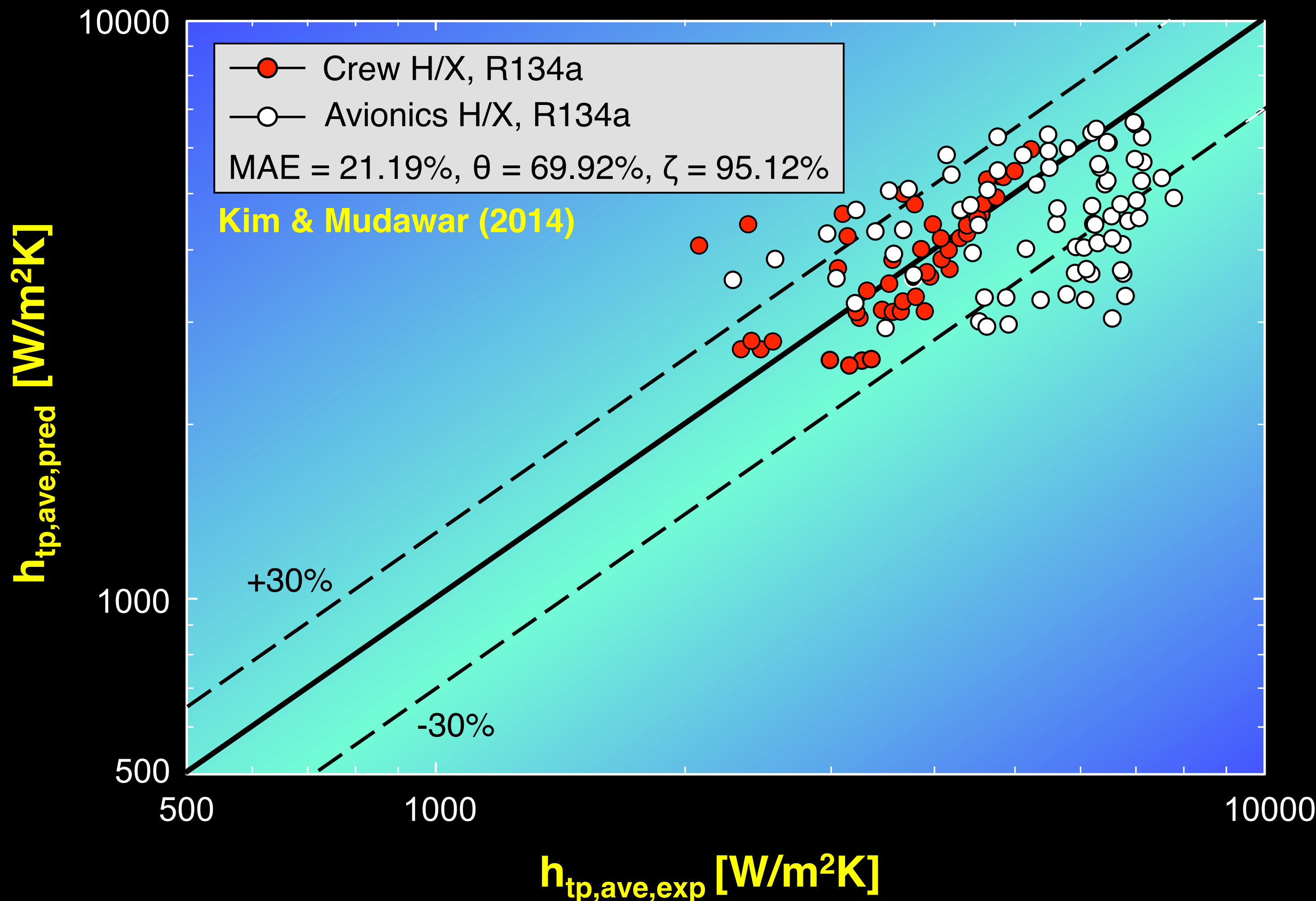
Comparison of Present Average Two-Phase Heat Transfer Coefficient with Predictions of Universal Methodology



Universal Predictive Methodology for Saturated Flow Boiling Heat Transfer in Small Diameter Tubes

Consolidated database:
10,805 saturated boiling heat transfer coefficient data points from 37 sources

- Working fluid:
  FC72, R11, R113, R123, R1234yf, R1234ze, R134a, R152a, R22, R236fa, R245fa, R32, R404A, R407C, R410A, R417A, CO_2, water

- Hydraulic diameter:
  $0.19 < D_h < 6.5$ mm

- Mass velocity:
  $19 < G < 1608$ kg/m^{2}s

- Liquid-only Reynolds number:
  $57 < Re_{fo} < 49{,}820$

- Flow quality:
  $0 < x < 1$

- Reduced pressure:
  $0.005 < P_R < 0.69$

Kim & Mudawar, *Int. J. Heat Mass Transfer* 64 (2013) 1239-1256

$$\boxed{h_{tp} = \left(h_{nb}^2 + h_{cb}^2\right)^{0.5}}$$

For nucleate boiling dominant regime :

$$h_{nb} = \left[2345\left(Bo\frac{P_H}{P_F}\right)^{0.70} P_R^{\,0.38}\left(1-x_e\right)^{-0.51}\right]\left(0.023\,Re_f^{0.8}\,Pr_f^{0.4}\,\frac{k_f}{D_h}\right)$$

For convective boiling dominant regime :

$$h_{cb} = \left[5.2\left(Bo\frac{P_H}{P_F}\right)^{0.08} We_{fo}^{\,-0.54} + 3.5\left(\frac{1}{X_{tt}}\right)^{0.94}\left(\frac{\rho_g}{\rho_f}\right)^{0.25}\right] \times\left(0.023\,Re_f^{0.8}\,Pr_f^{0.4}\,\frac{k_f}{D_h}\right)$$

where $Bo = \dfrac{q''_H}{G\,h_{fg}}$, $P_R = \dfrac{P}{P_{crit}}$, $Re_f = \dfrac{G\left(1-x_e\right)D_h}{\mu_f}$

$$We_{fo} = \frac{G^2 D_h}{\rho_f\,\sigma}\ , \qquad X_{tt} = \left(\frac{\mu_f}{\mu_g}\right)^{0.1}\left(\frac{1-x_e}{x_e}\right)^{0.9}\left(\frac{\rho_g}{\rho_f}\right)^{0.5}$$

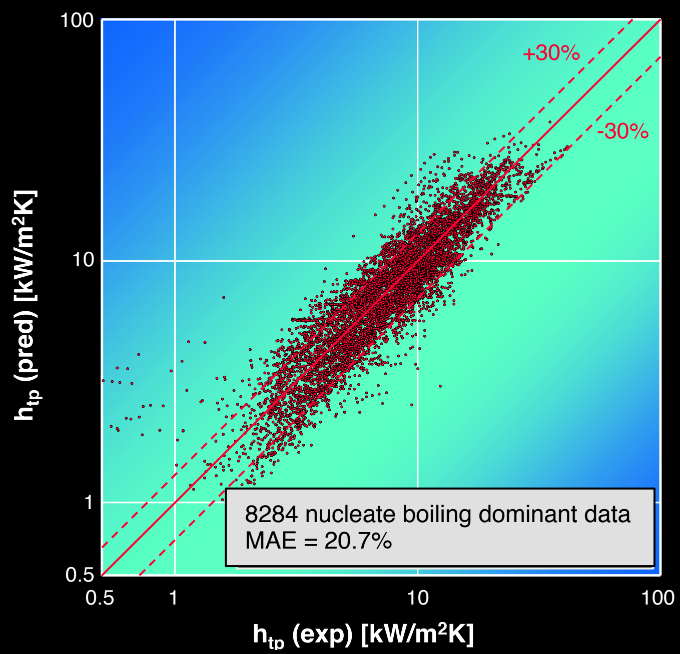
q''_H: effective heat flux averaged over heated perimeter of channel

P_H: heated perimeter of channel

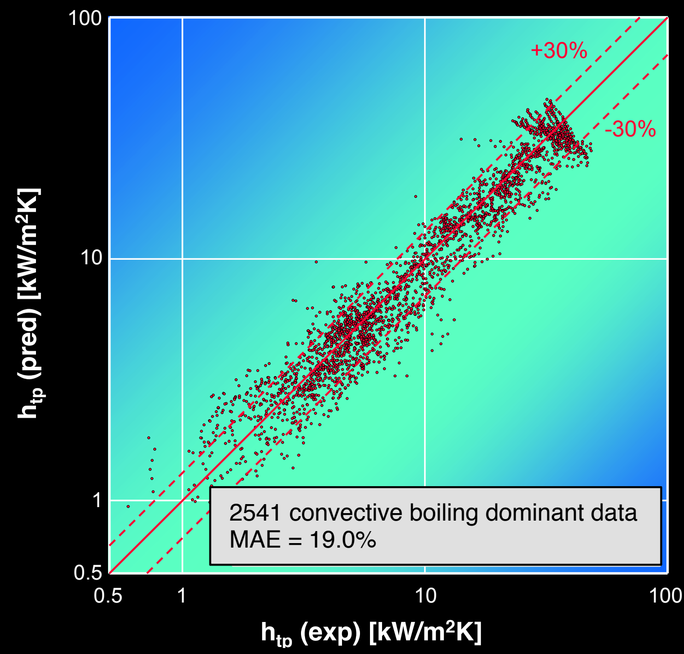
P_F: wetted perimeter of channel

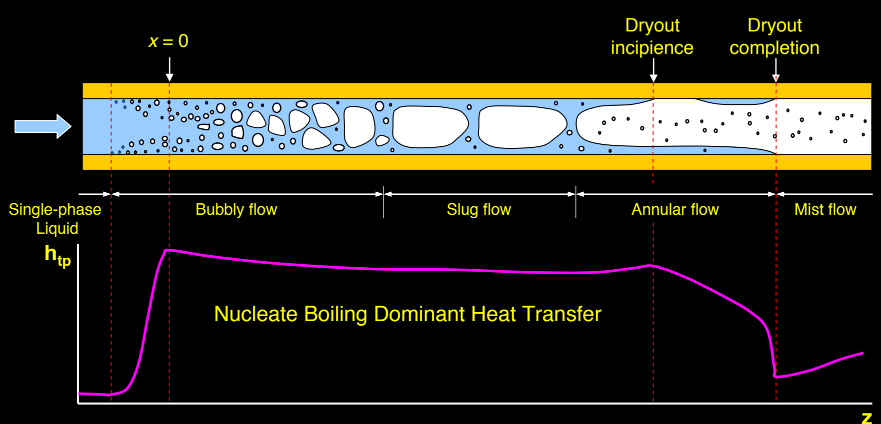
Universal Predictive Methodology for Saturated Flow Boiling Heat Transfer in Small Diameter Tubes

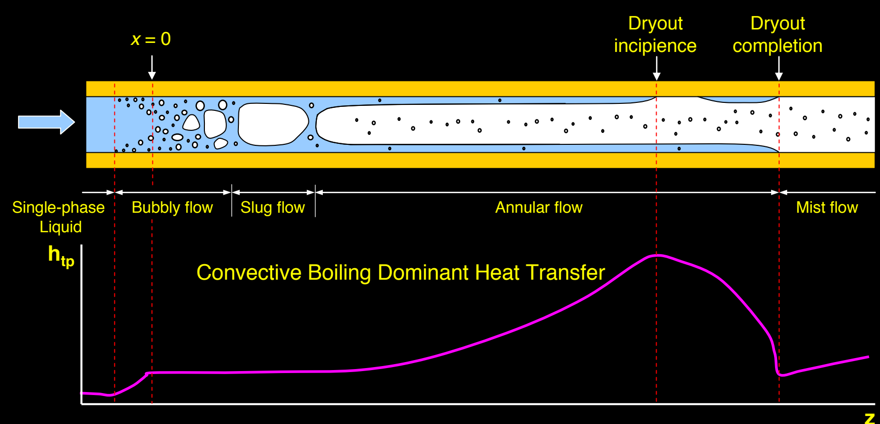
Nucleate Boiling Dominant Data



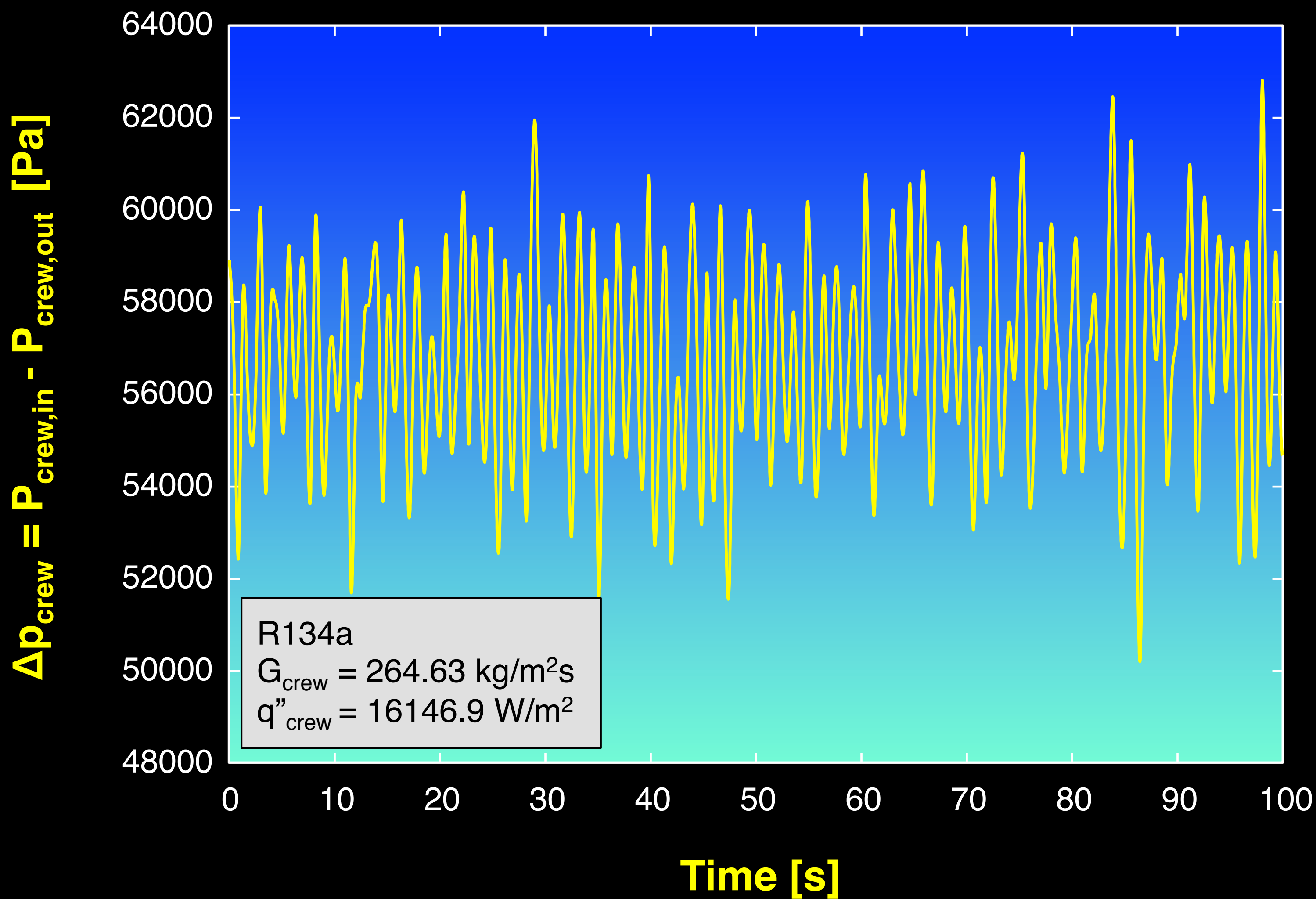
Convective Boiling Dominant Data





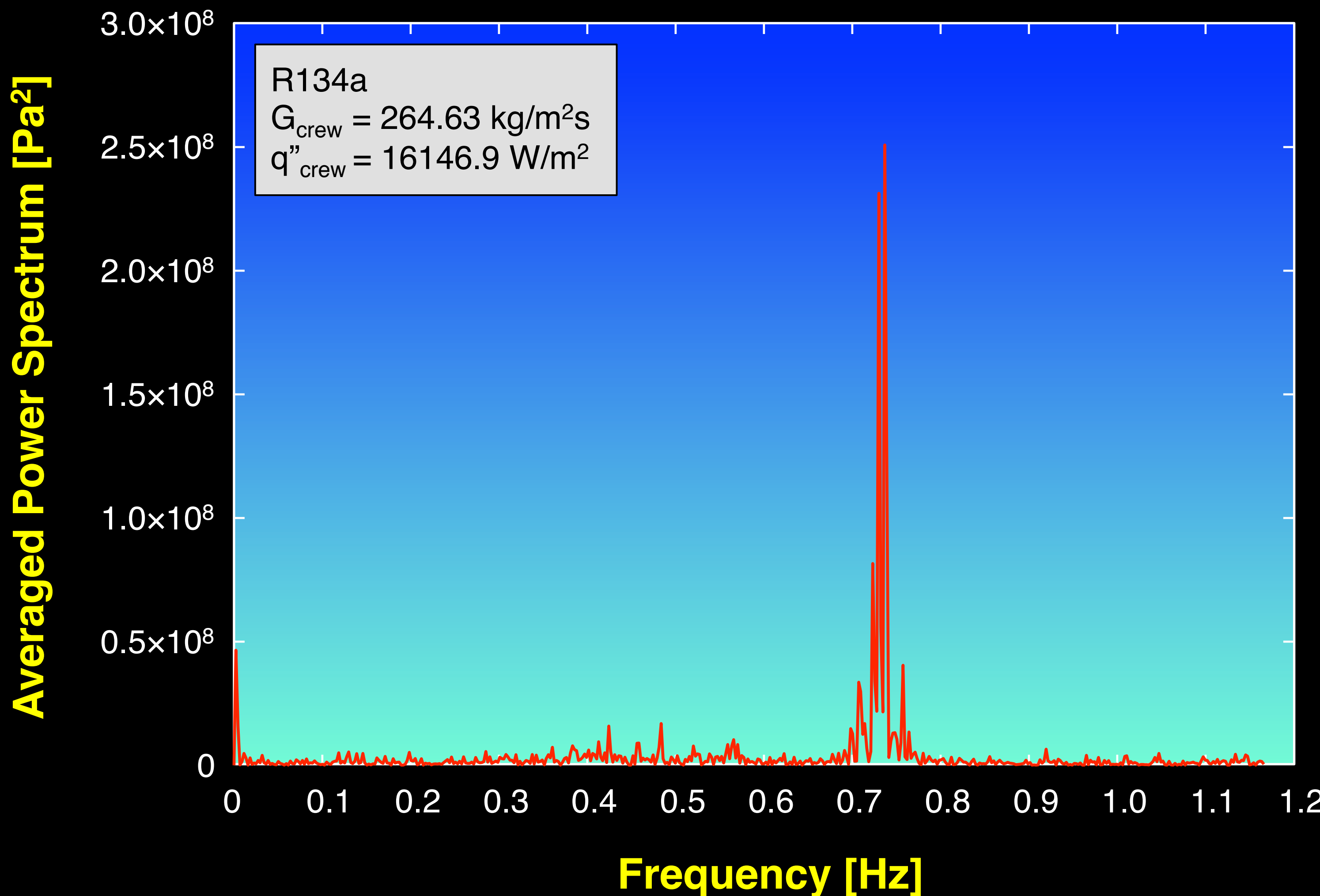


Pressure Drop Oscillations in Crew H/X



Parallel channel instability: Small amplitude, high frequency pressure drop oscillations (4,000 - 10,000 Pa over period of 1.33 s)

Pressure Drop Oscillations in Crew H/X



Discrete Fourier transform: pressure drop response in frequency domain (power spectrum peak of 0.74 Hz (~ 1.33 sec)