Results and lessons from cryogenic phase change experiments with LH2 and LCH4

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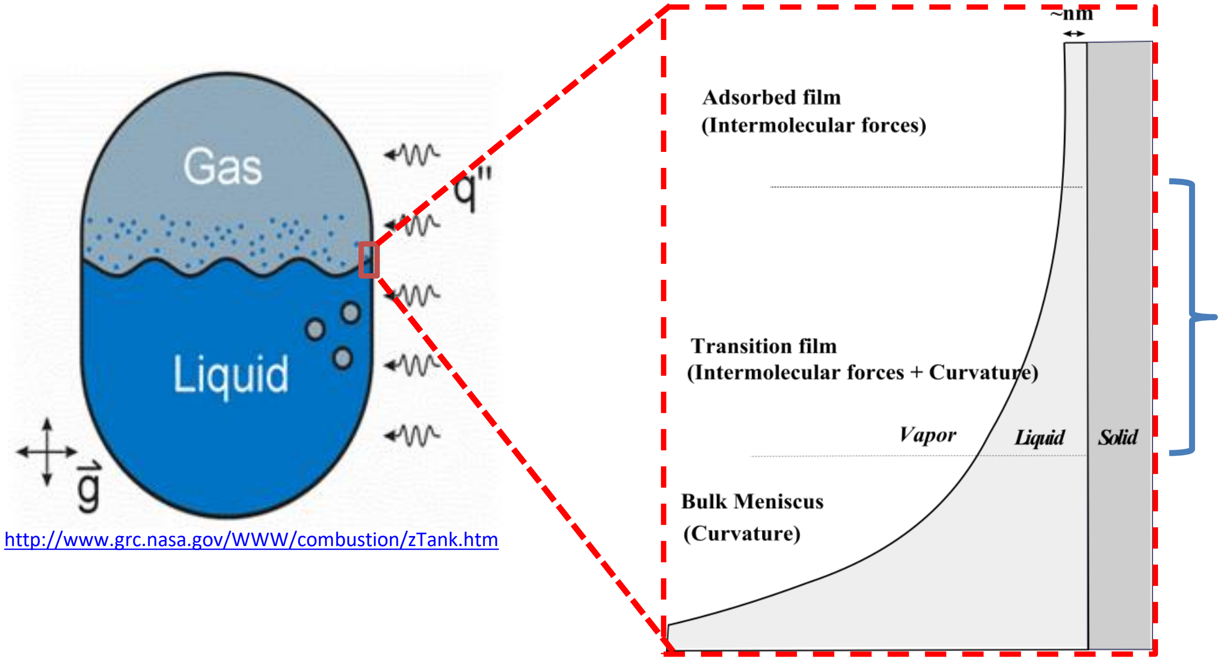
Thermal and Fluids Analysis Workshop, 2023

Motivation

Specific microgravity key challenge areas:

1) Evaporation and condensation processes
2) Liquid/ullage interface dynamics
3) Long term predictions of propellant behavior



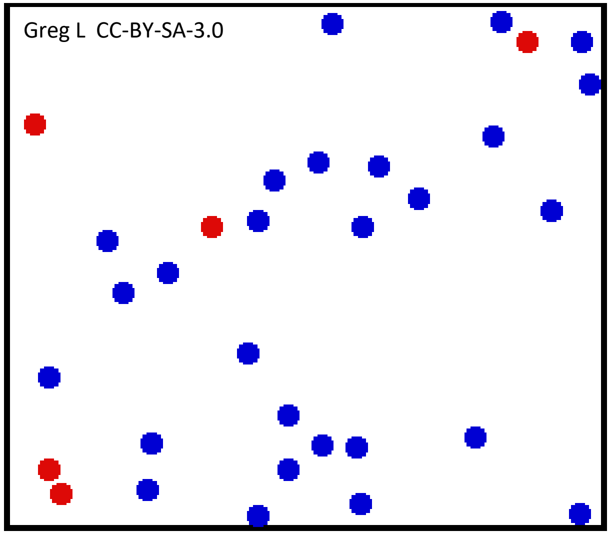
http://www.grc.nasa.gov/WWW/combustion/zTank.htm

Maximum evaporation flux

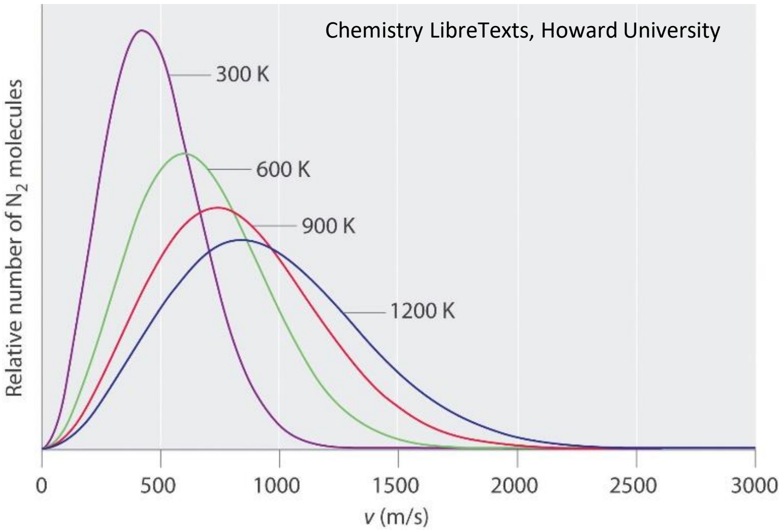
Dynamics of the liquid-gas interface is largely unknown

Current modeling of evaporation involves using kinetic theory expressions that requires accommodation coefficient(s).

Kinetic Theory



Greg L CC-BY-SA-3.0



Chemistry LibreTexts, Howard University

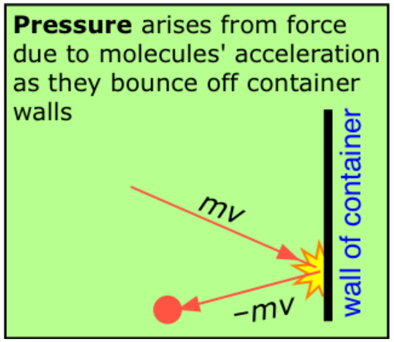
$$f_m = n\left(\frac{m}{2k\pi T}\right)^{\frac{3}{2}} \exp\left(-\frac{m}{2kT}(c_x^2 + c_y^2 + c_z^2)\right)$$

Maxwell Boltzmann distribution

c_i : Velocity of the molecules
k : Boltzmann constant
T : Temperature
m : Mass of molecule
n : Density number

Assumptions

- Equilibrium
- Molecules are in constant random motion
- Elastic collisions
- Translational effects only
- Quantum mechanical effects neglected



Pressure arises from force due to molecules' acceleration as they bounce off container walls

Kinetic Theory Of Phase Change

Hertz (1882)

- Measured evaporation of Mercury
- Determined maximum rate of evaporation from Kinetic theory

Knudsen (1915)

- Measured rate always lower than Kinetic theory rate
- Evaporation and Condensation Coefficients

Schrage (1953)

- Modified Maxwellian distribution

Maxwellian Distribution

$$J = \sqrt{\frac{m}{2\pi k_B}}\left(\frac{P_{sat}(T_L)}{\sqrt{T_L}} - \frac{P_v}{\sqrt{T_v}}\right)$$

Hertz-Knudsen equation

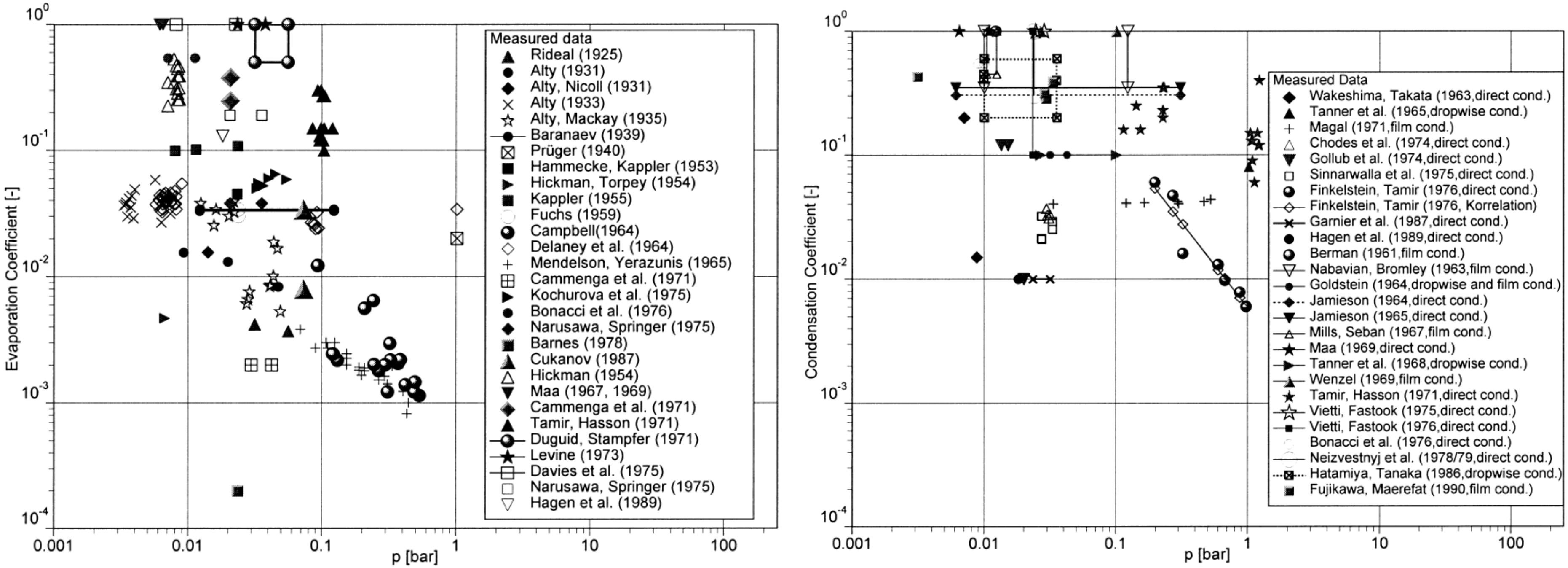
Maxwellian Distribution with drift velocity

$$J = \frac{2}{2-\alpha_c}\sqrt{\frac{m}{2\pi k_B}}\left(\alpha_e \frac{P_{sat}(T_L)}{\sqrt{T_L}} - \alpha_c \frac{P_v}{\sqrt{T_v}}\right)$$

Hertz-Knudsen-Schrage Equation

Phase Change Coefficient(s)

- 80+ years of measurements yields ***3+ orders of magnitude difference***
- Variations due to wall material, geometry, contact angle?



Evaporation/Condensation coefficients for water

Marek and Straub. *Int. J. Heat Mass Trans* (2001).

No measurements for **cryogenic fluids**

PLANAR INTERFACES ONLY!

What if the interface is not planar?

$$J = \frac{2\alpha}{2-\alpha}\sqrt{\frac{m}{2\pi k_B}}\left(\frac{P_{Li}}{\sqrt{T_{Li}}} - \frac{P_{vi}}{\sqrt{T_v}}\right)$$

Burrows (1957,1960,1965)

- α = *f* (Area ratio, shape factor)
- Shape factor is yet another tuning parameter
- Empirical fit to experimental data

Bryson et al (1972,1974)

- α = *f* (Area ratio, shape factor, radius)
- Empirical fit to experimental data

Kaplon (1986)

- Claims Burrows' fit to be inaccurate
- Proposes a new fit

Wayner et al (1976,1991)

- Local interfacial thermodynamics

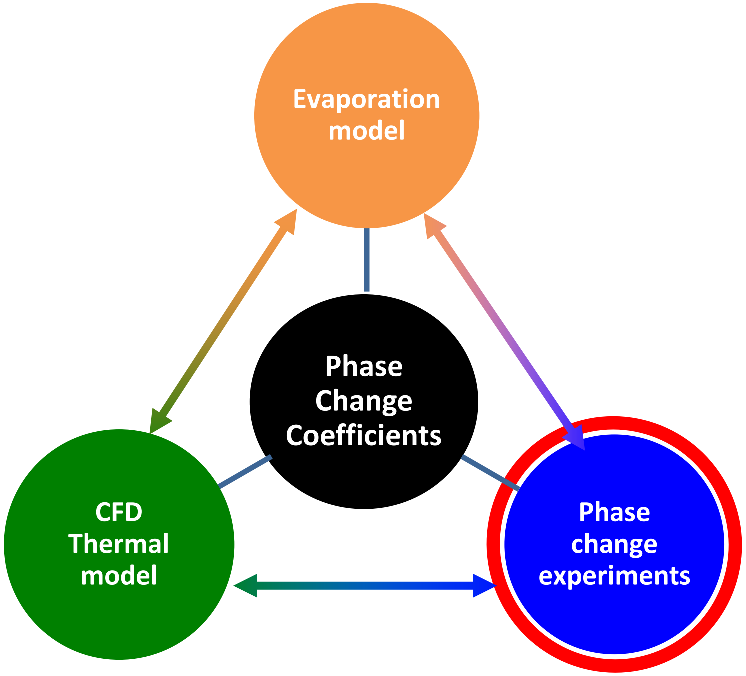
$$J = \frac{2\alpha}{2-\alpha}\sqrt{\frac{M}{2\pi R T_{Li}}}\left[\frac{P_v M h_{fg}}{R T_v T_{Li}}(T_{Li} - T_v) + \frac{P_v V_l}{R T_{Li}}(\Pi + \sigma K)\right]$$

Disjoining Pressure

Curvature

Tune **coefficients** and/or **interfacial thermodynamics**?

Fudge factors *Physics*

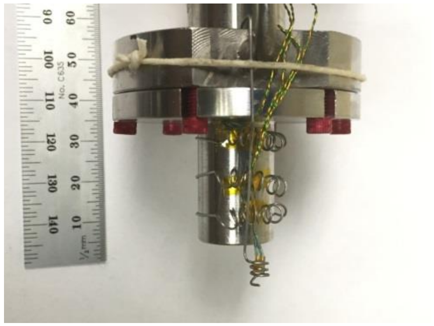


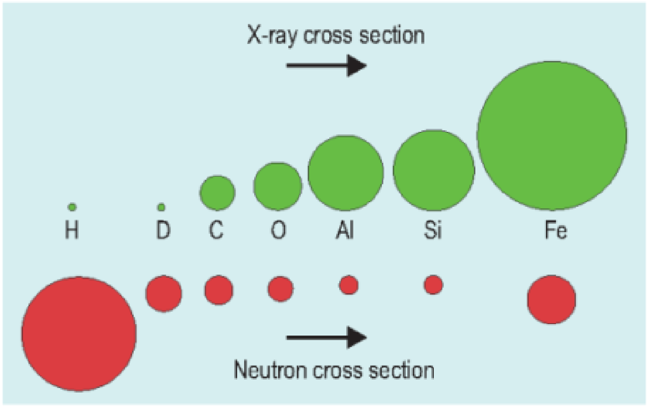
Phase Change Experiments

Visualization of cryo phase change

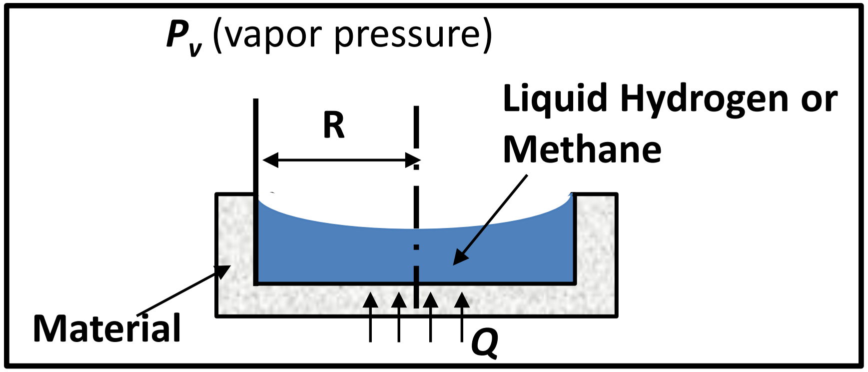
How do you determine location of fluid inside an opaque metal container?

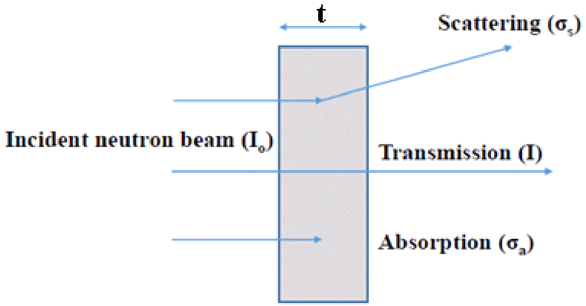
Neutron Imaging!





http://www.ncnr.nist.gov/AnnualReport/FY2003_html/RH2/

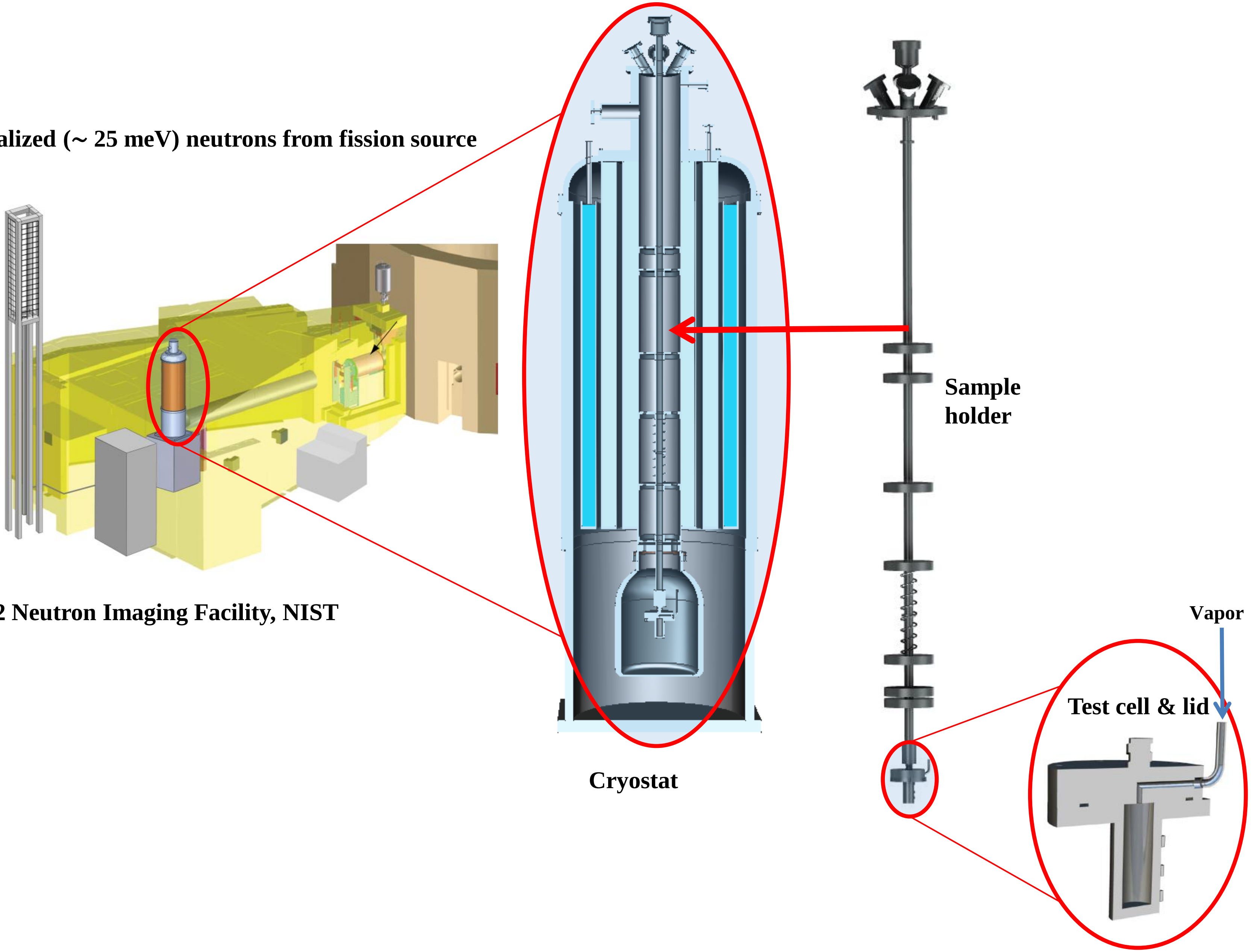




$$I = I_0 e^{-\mu t}$$

Beer-Lambert Law

Experimental setup



Thermalized (~ 25 meV) neutrons from fission source

BT2 Neutron Imaging Facility, NIST

Cryostat

Sample holder

Test cell & lid

Vapor

Bellur et al., *Cryogenics* (2016).

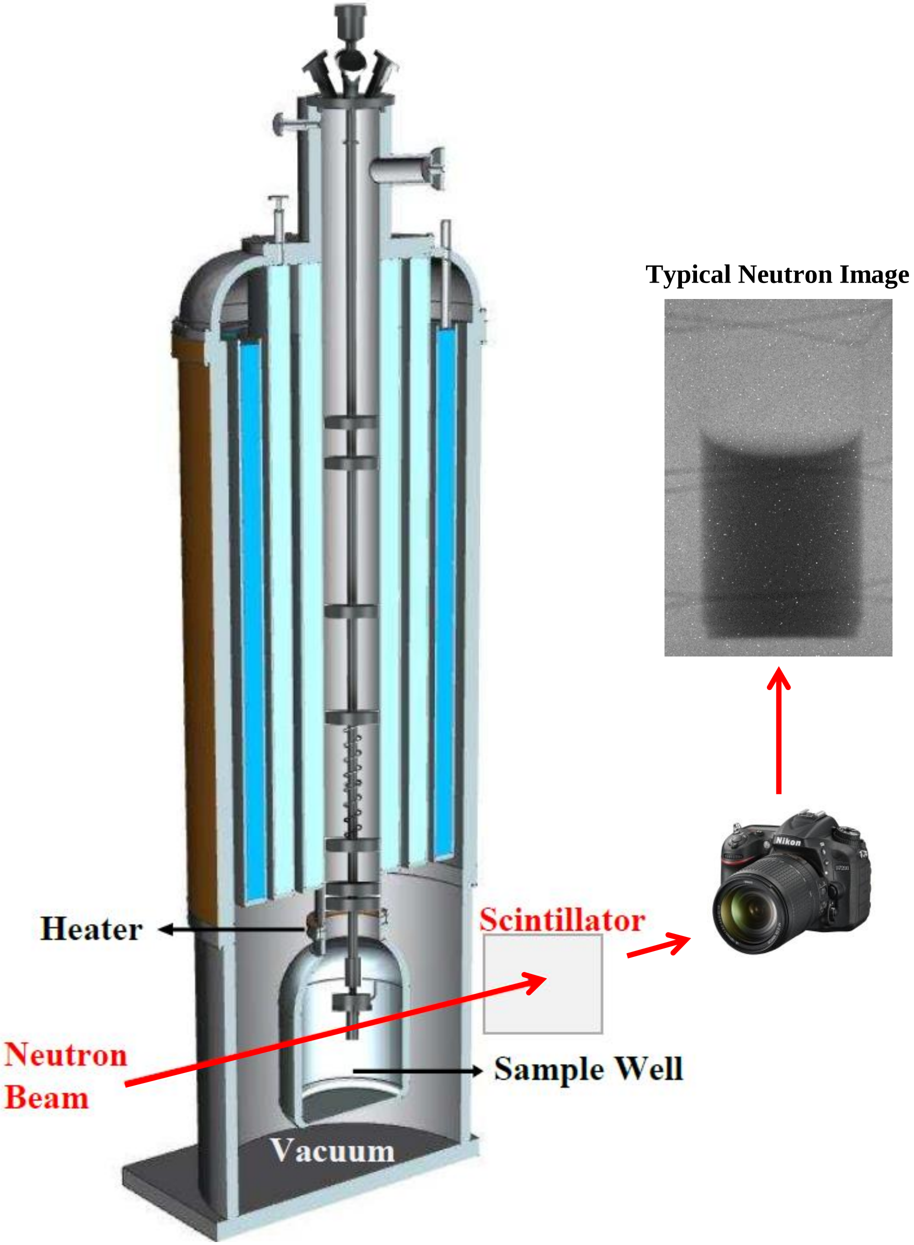
Imaging setup

Scintillator: **7.6 mg/cm^2, 20 μm Gadoxysulfide screen**

Optics: **Andor NEO sCMOS camera, 6.5 μm pixel pitch; Nikon lens with PK13 extension tube**

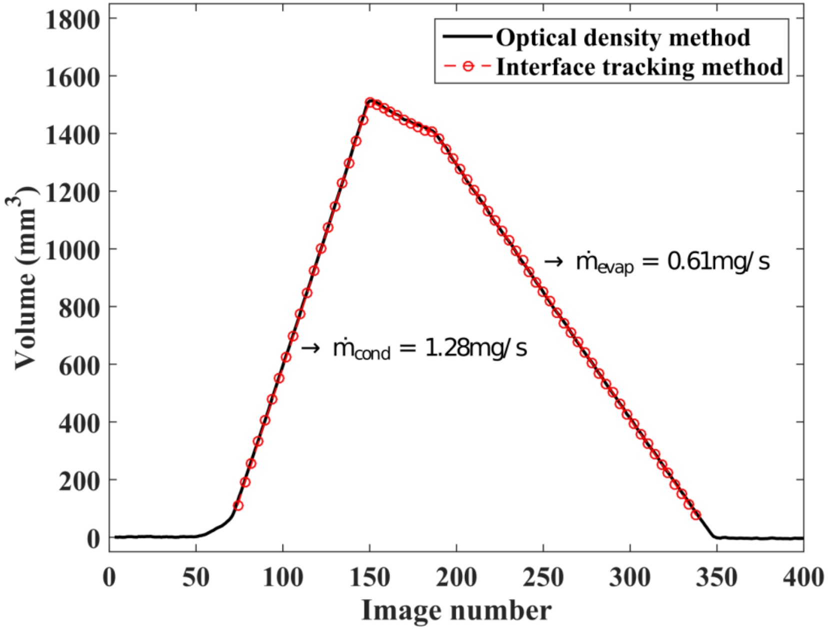
Images: **16 bit FITS format**

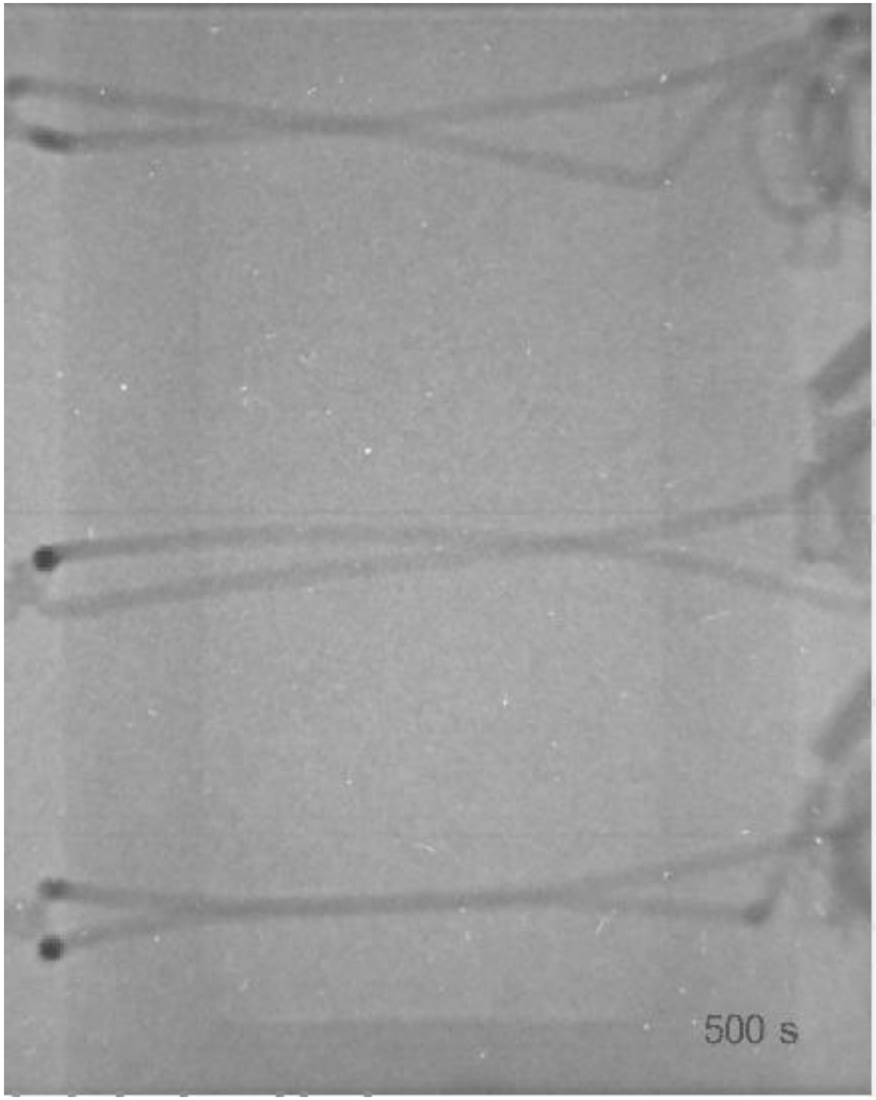
Resolutions: **14 μm spatial**
10 s temporal



Condensation and Evaporation of liquid H2- 10 mm AL 6061

Saturation → 21K
Condensation < Tsat
Evaporation > Tsat

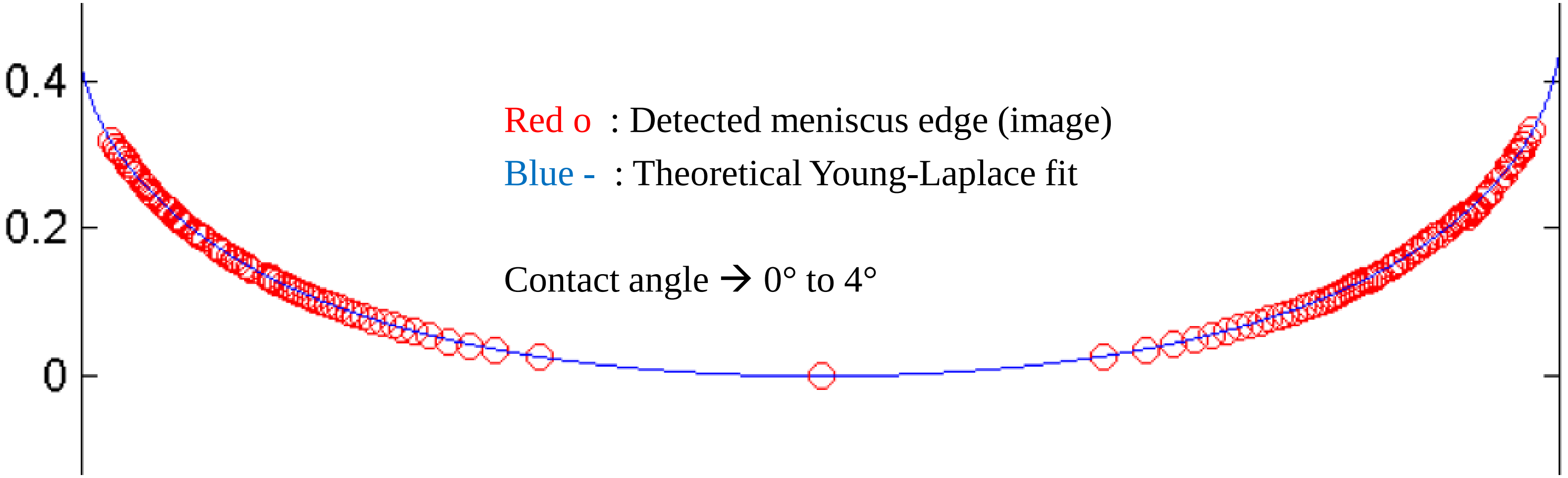




Bellur et al. *J. Flow Vis. Image Process.* (2016).
Bellur et al., *Journal of Heat Transfer* (2015).

Interface Curvature

14 µm spatial resolution
10 s temporal resolution



Red o : Detected meniscus edge (image)

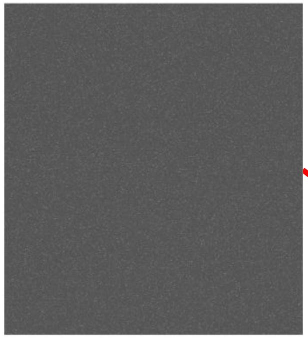
Blue - : Theoretical Young-Laplace fit

Contact angle → 0° to 4°

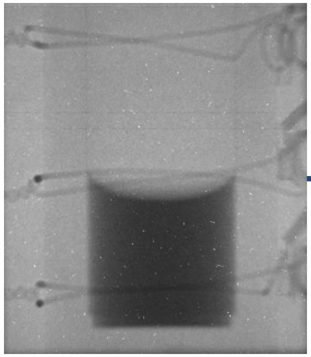
Are cryogenic fluids perfectly wetting? Contact angle → 0 °?

Bellur et al., *Journal of Heat Transfer* (2016).

Optical Density Image Transformation

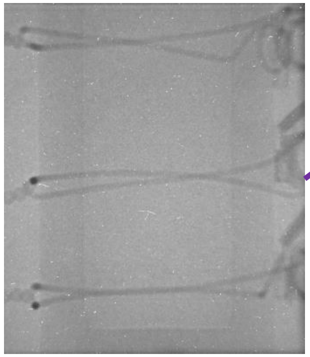


Background Image
Beam Off (I_{back})

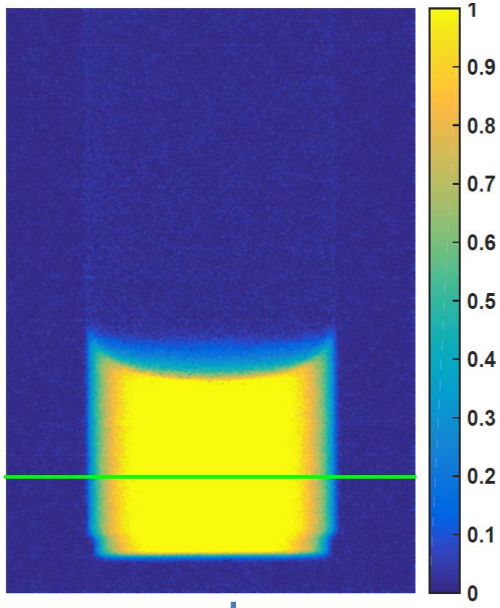


Neutron Image (I)

$$\boxed{OD = -ln\left(\frac{I - I_{back}}{I_0 - I_{back}}\right)}$$



Reference Image
empty cell (I_0)



Beer-Lambert Law

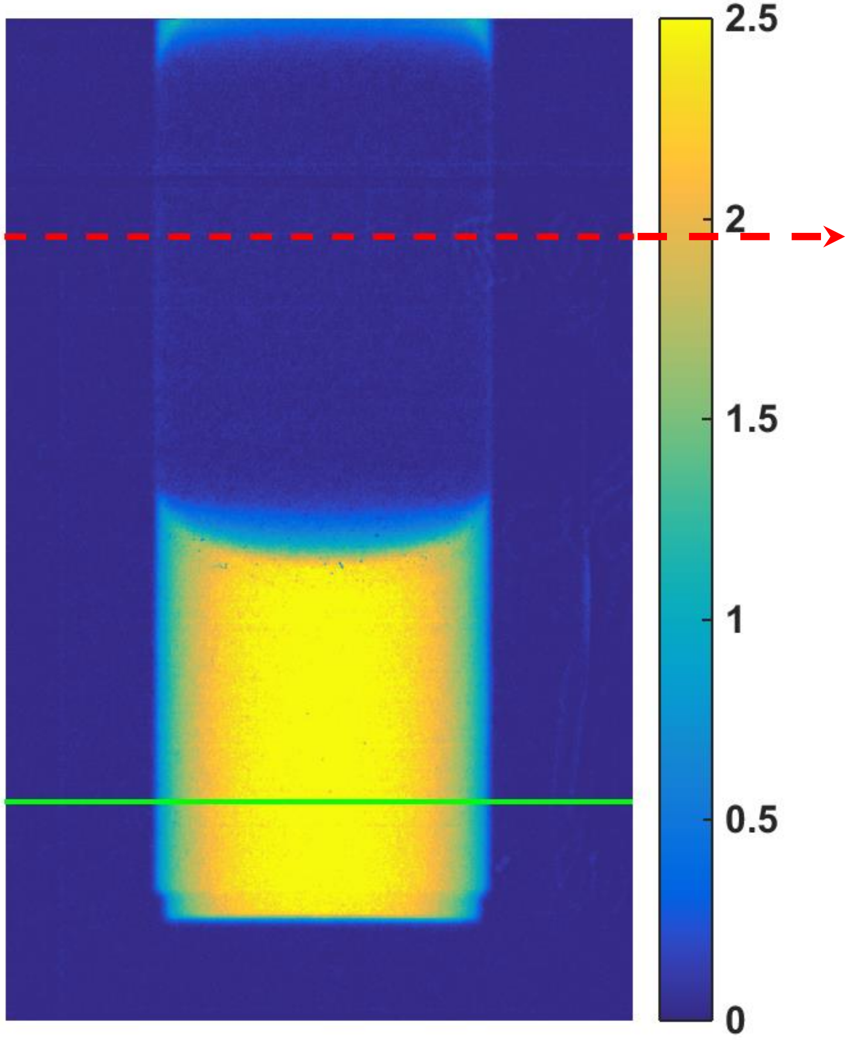
$$\boxed{OD = \mu t + \beta t^2}$$

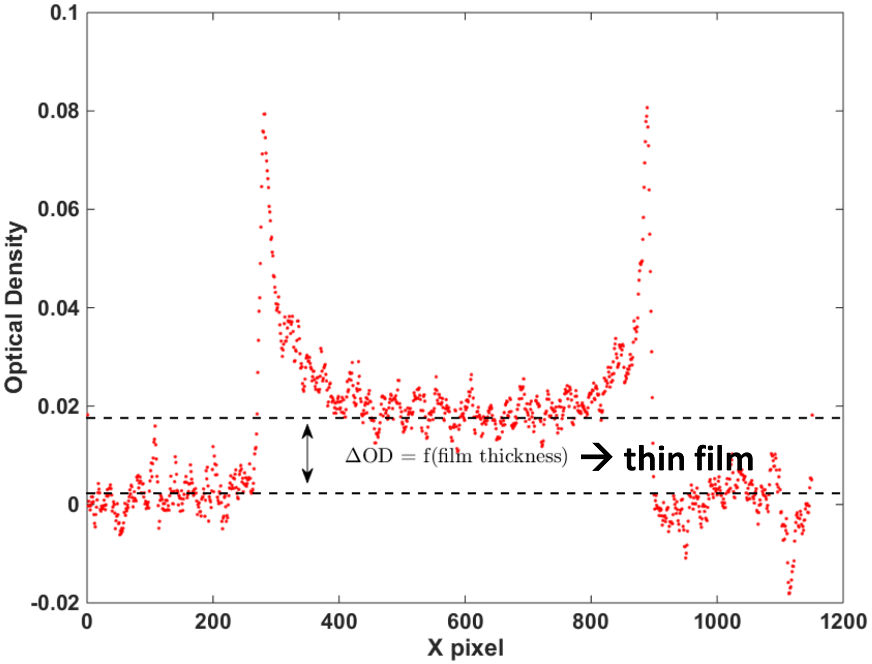
Fluid Thickness (t)

β : beam hardening correction factor

Bellur et al., *Journal of Heat Transfer* (2016).

Film Thickness Measurement





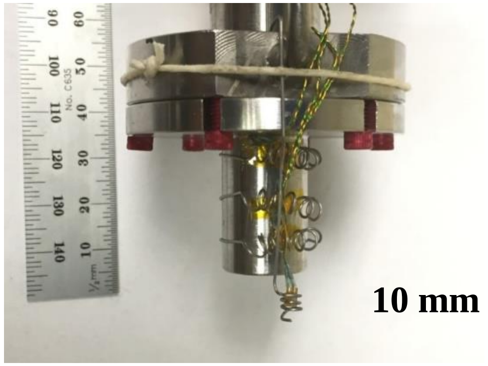
Film thicknesses as low as ***3 μm*** can be measured even though pixel size is ***14 μm***.

LH_2 and LCH_4 are perfectly wetting to both Al 6061 and SS316L

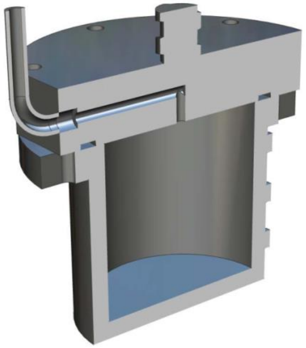
Summary of tests conducted

		Pressure (psia)	Saturation Temperature (K)	Condensation Sub-cool (K)	Evaporation Super-heat (K)
Conical cell	*Run 1*	17.9	21.0	20.8/20.6	22/23
	Run 2	17.9	21.0	19	25
	Run 3	13.8	19.9	19	21/22
	Run 4	13.8	19.9	18.5	25
	Run 5	28.6	23.0	22.7/22.5	N/A
	Run 6	20.6	21.6	N/A	22.5
	Run 7	25.4	22.5	21.5	N/A
	Run 8	25.4	22.5	N/A	28
10mm SS	*Run 1*	17.9	21.0	19.9	22
	Run 2	13.8	19.9	18.8	21
	Run 3	28.6	23.0	21.9	23.5
	Run 4	28.6	23.0	22.5	24/25/27
	Run 5	28.6	23.0	22.5	28
30mm AL	*Run 1*	17.9	21.0	20/20.7	22/24/25
10mm AL	*Run 1*	17.9	21.0	19	23
	Run 2	13.8	19.9	17	22
	Run 3	28.6	23.0	20	26
	Run 4	28.6	23.0	20.5	26

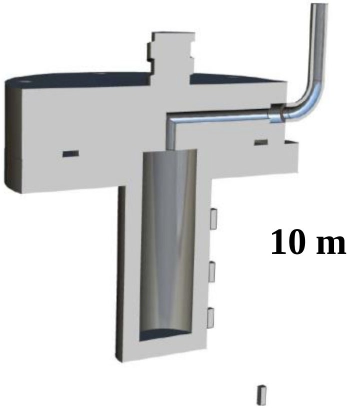
		Temperature (K)	Saturation Pressure (psia)	Condensation pressure (psia)	Evaporation pressure (psia)
10 mm Al	*Run 1*	121.0	30.0	30.2	Could not be held constant
	Run 2	115.4	20.0	20.4	17.6
	Run 3	111.9	15.0	15.7	12.7
	Run 4	116.8	22.0	22.5	20.2
	Run 5	121.0	30.0	31.2	27.1
	Run 6	114.2	18.0	18.6	17



10 mm SS 316

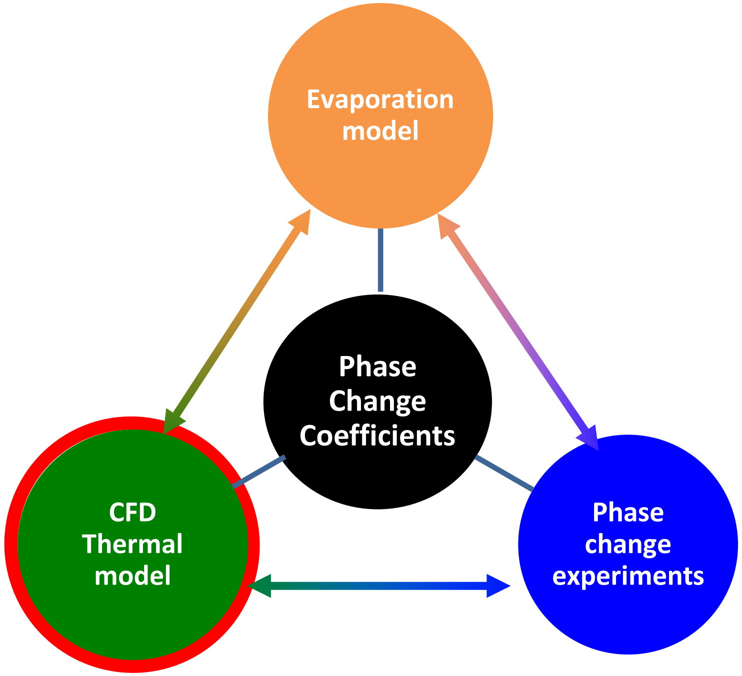


30 mm AL 6061



10 mm AL 6061

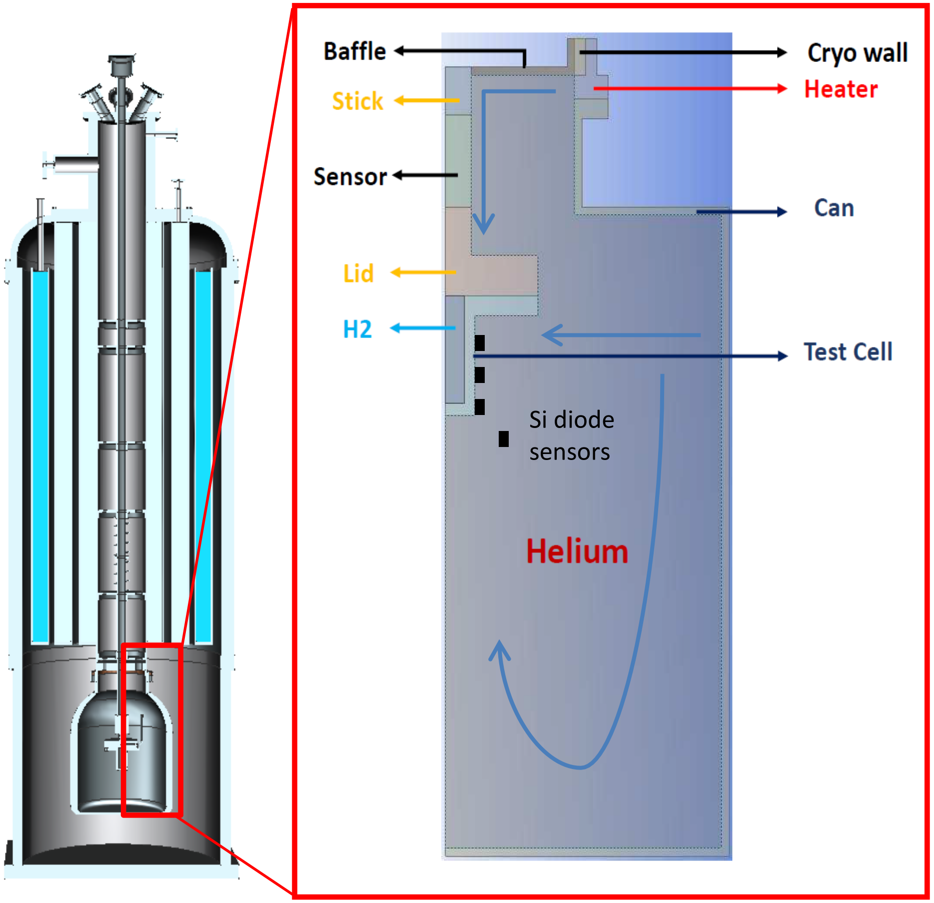
Bellur et al., *Cryogenics* (2022).
Bellur et al., *Data-In-Brief* (2022).



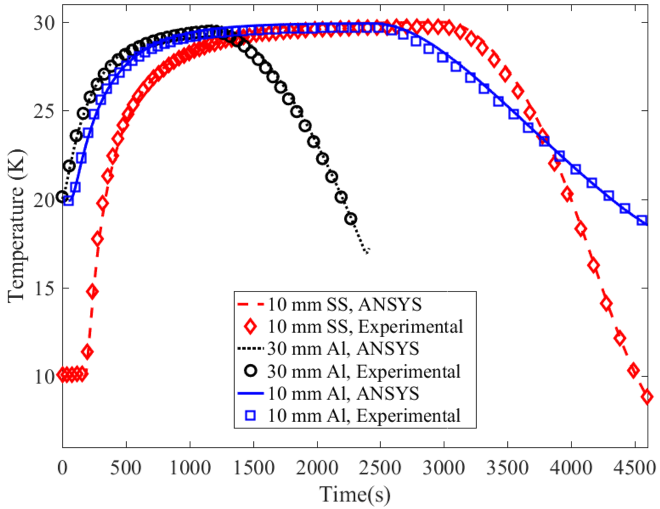
CFD Thermal Model

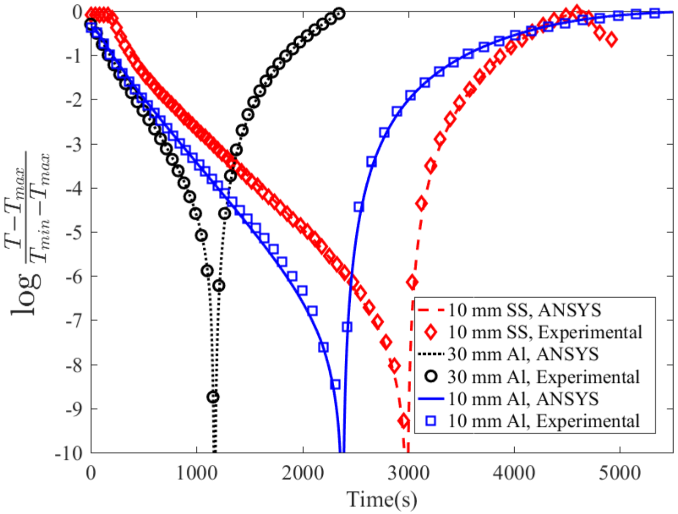
CFD Thermal model

Contact resistances @ solid-solid interfaces



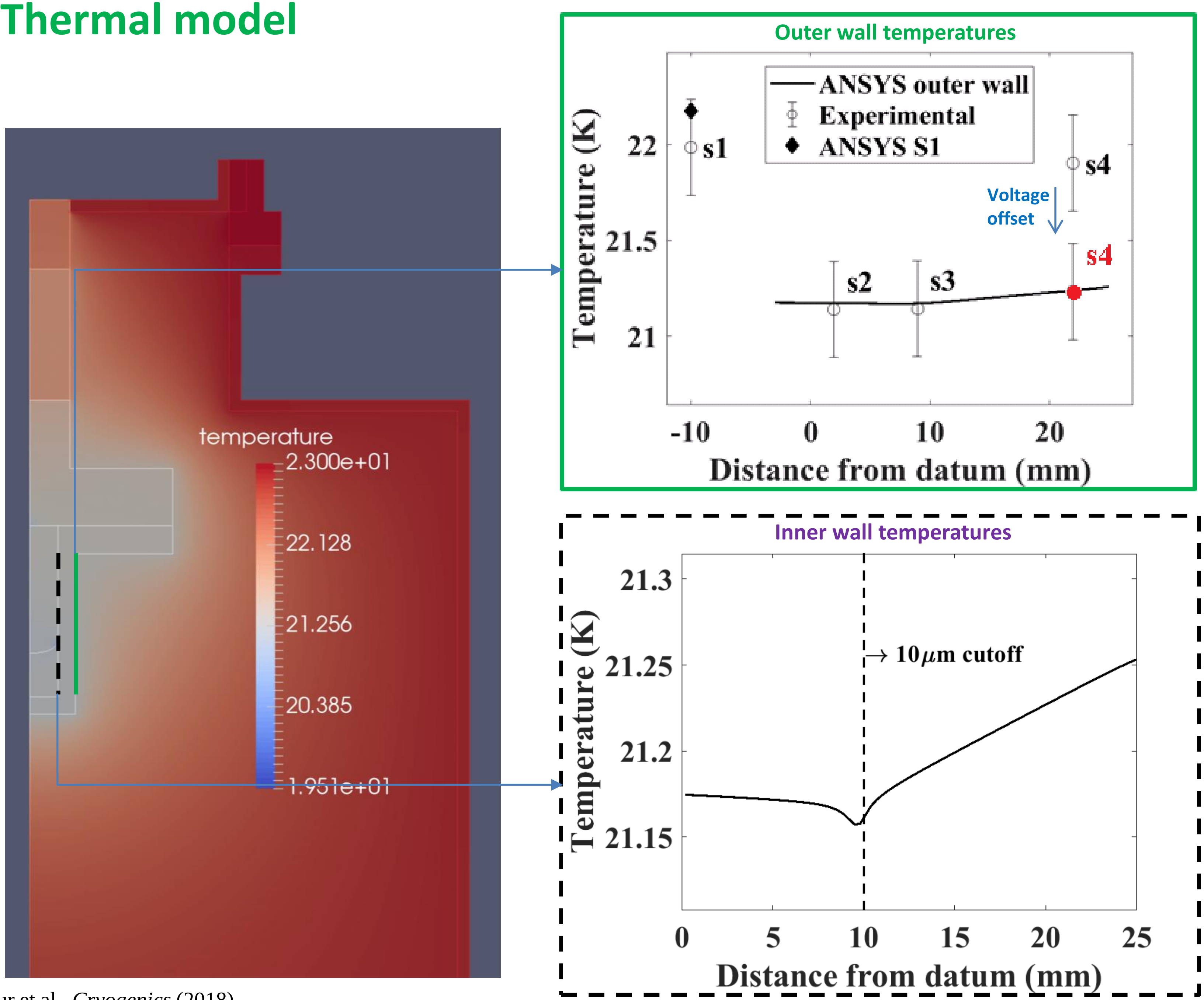
Contact resistances are "tuned" with dry test thermal cycling data



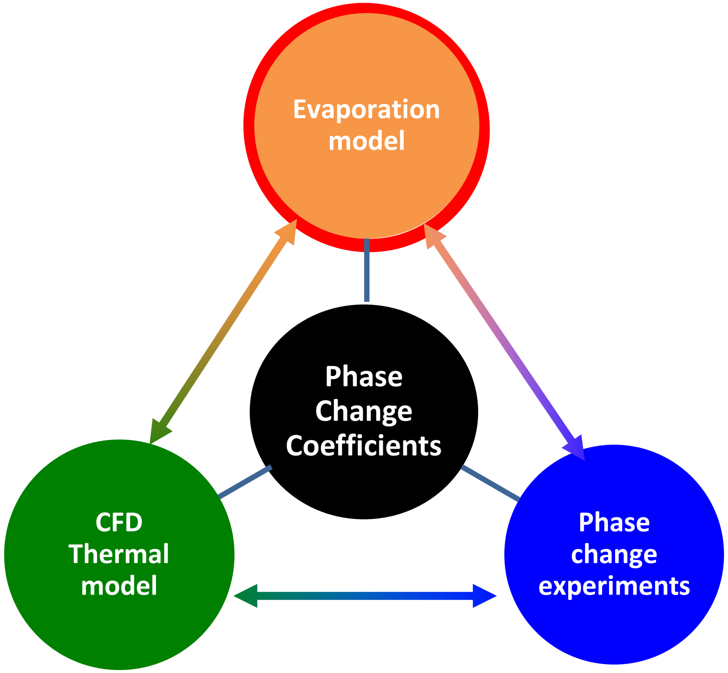


Bellur et al., *Cryogenics* (2018)

CFD Thermal model



Bellur et al., *Cryogenics* (2018)


Evaporation model

Phase Change Coefficients

CFD Thermal model

Phase change experiments

Multi-scale Evaporation Model

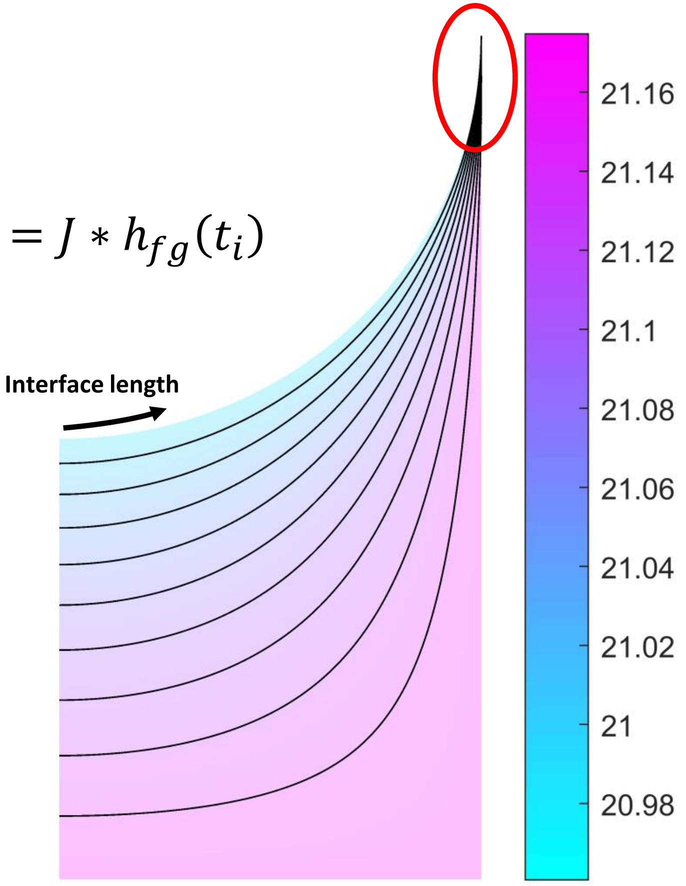
Macro Model

$$J = \frac{2\alpha}{2-\alpha}\sqrt{\frac{M}{2\pi R T_i}}\left[\frac{p_v M h_{fg}}{R T_v T_i}(T_i - T_v) + \frac{p_v V_l}{R T_i}(\overset{\substack{\text{Disjoining Pressure}\\ \downarrow}}{\Pi} + \sigma \overset{\substack{\text{Curvature}\\ \downarrow}}{K})\right]$$

Wayner, *Coll. Surf* (1991).

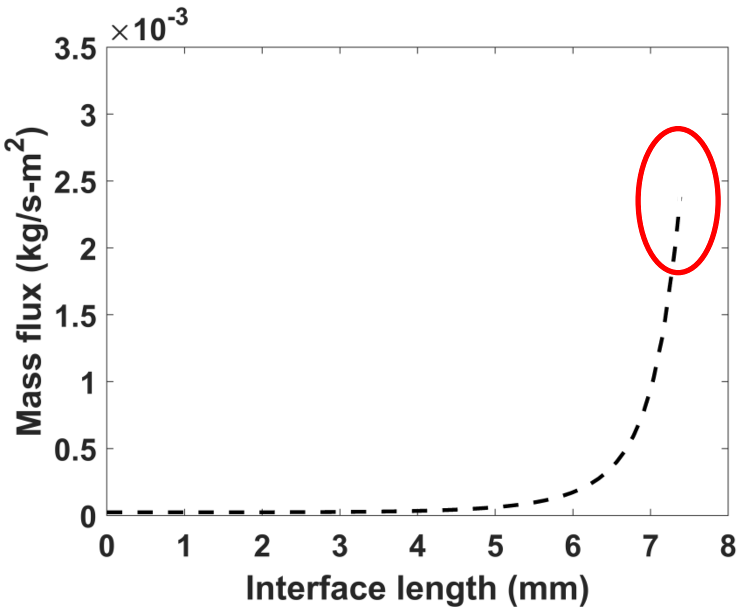
← Modified Schrage eqn

$$Q''_{loss} = J * h_{fg}(t_i)$$



2D FEA model of thermal transport

Cannot resolve with macro model!



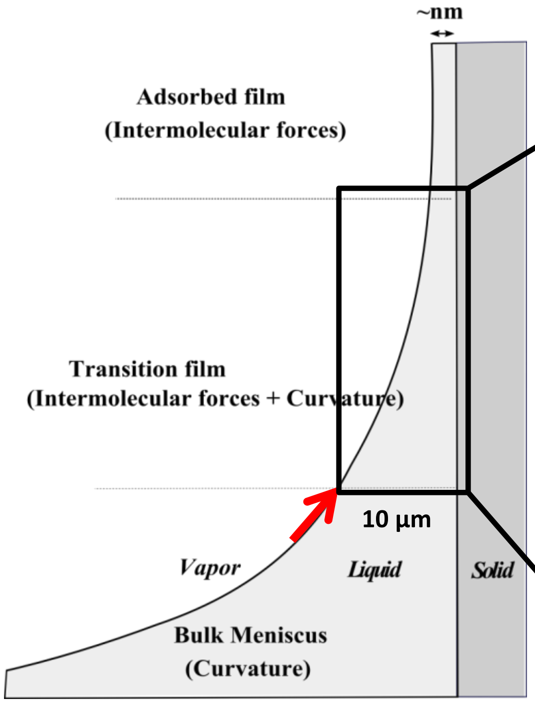
Transition Film Model

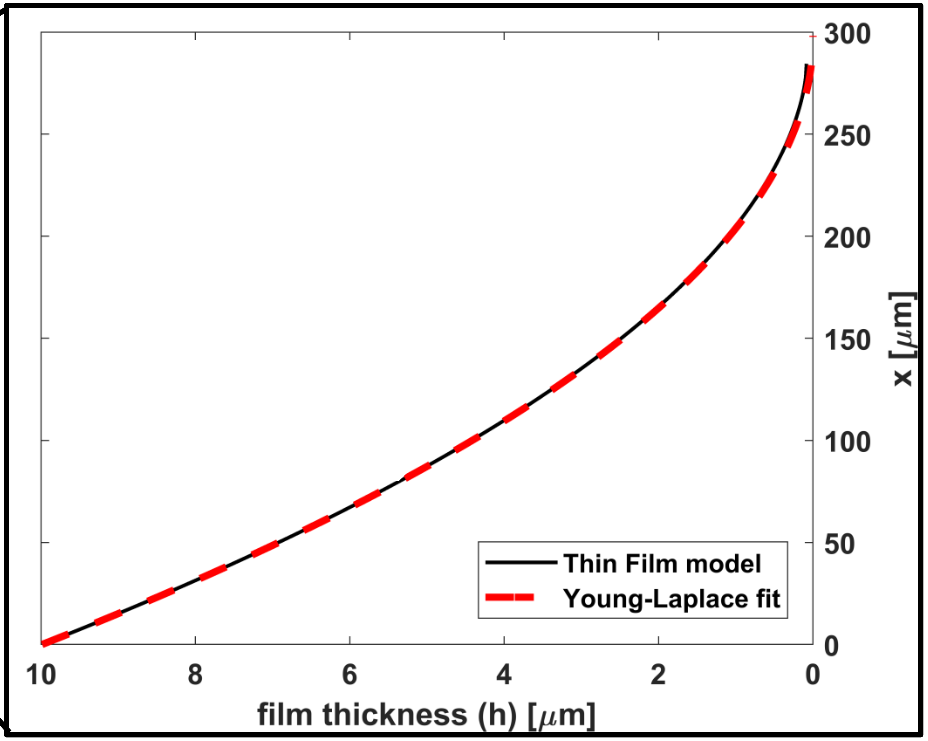
Augmented Young-Laplace equation : $P_v - P_l = \sigma\kappa + \Pi$

$$\downarrow$$

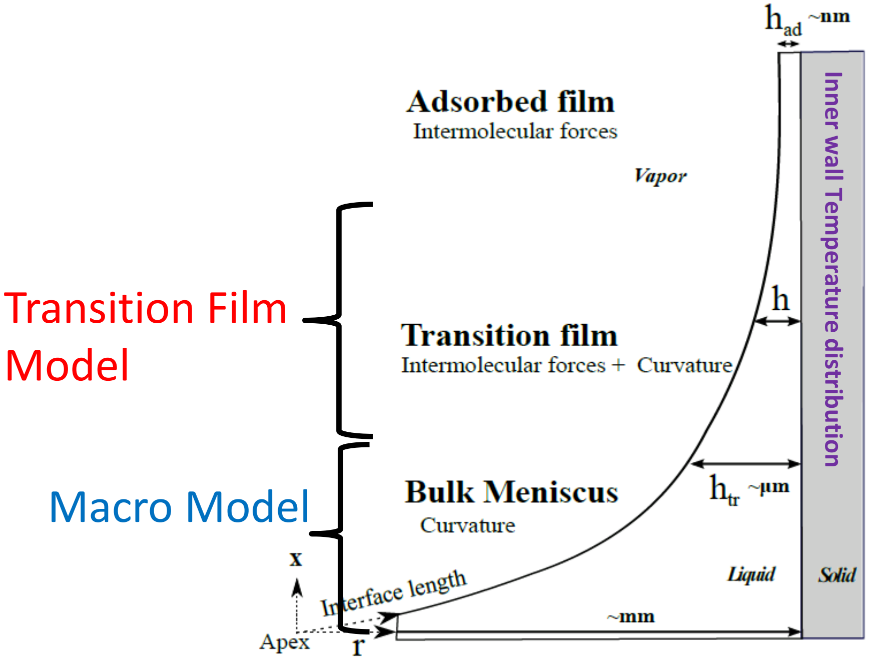
$$h_{xxx} - \frac{3h_{xx}^2 h_x}{1+h_x^2} - \frac{h_{xx}h_x}{r_{ij}-h} + \frac{h_x(1+h_x^2)}{\left(r_{ij}-h\right)^2} + \frac{\gamma}{\sigma}\left\{\frac{1+h_x^2}{r_{ij}-h} + h_{xx}\right\}\frac{dT_i}{dx} + \frac{1}{\sigma}(1+h_x^2)^{\frac{1}{2}}\left(\frac{dp_l}{dx} + \frac{d\Pi}{dx}\right) = 0$$

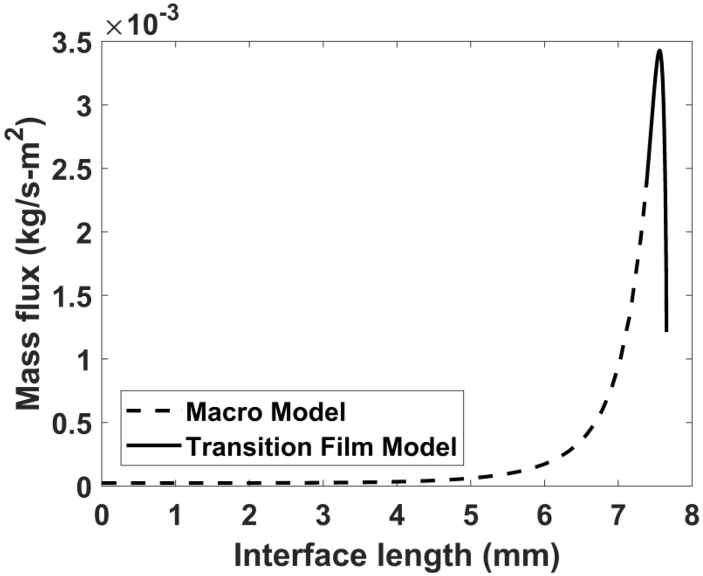
Film evolution expressed as function of film thickness and its derivatives

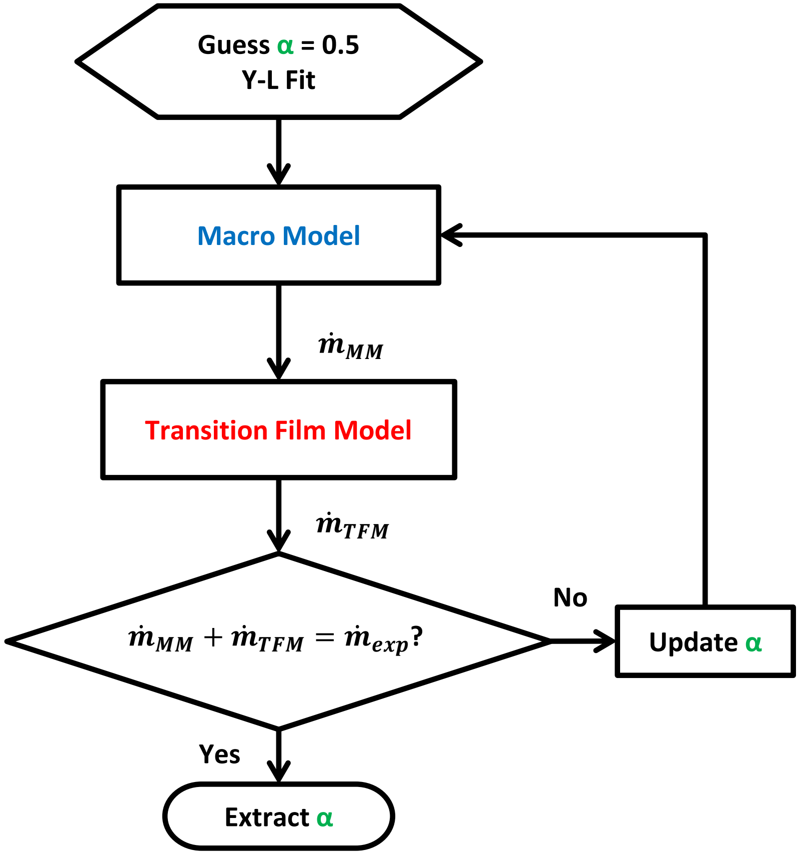




Multi-scale approach







Guess α = 0.5
Y-L Fit

Macro Model

$\dot{m}_{MM}$

Transition Film Model

$\dot{m}_{TFM}$

$\dot{m}_{MM} + \dot{m}_{TFM} = \dot{m}_{exp}$?

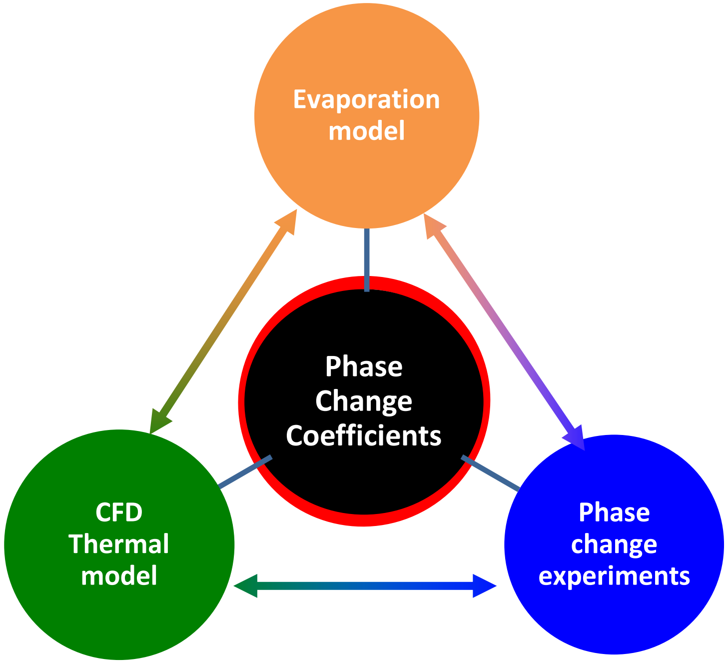
No

Update α

Yes

Extract α

Bellur et al., *Physical Review Fluids* (2020).



Evaporation model

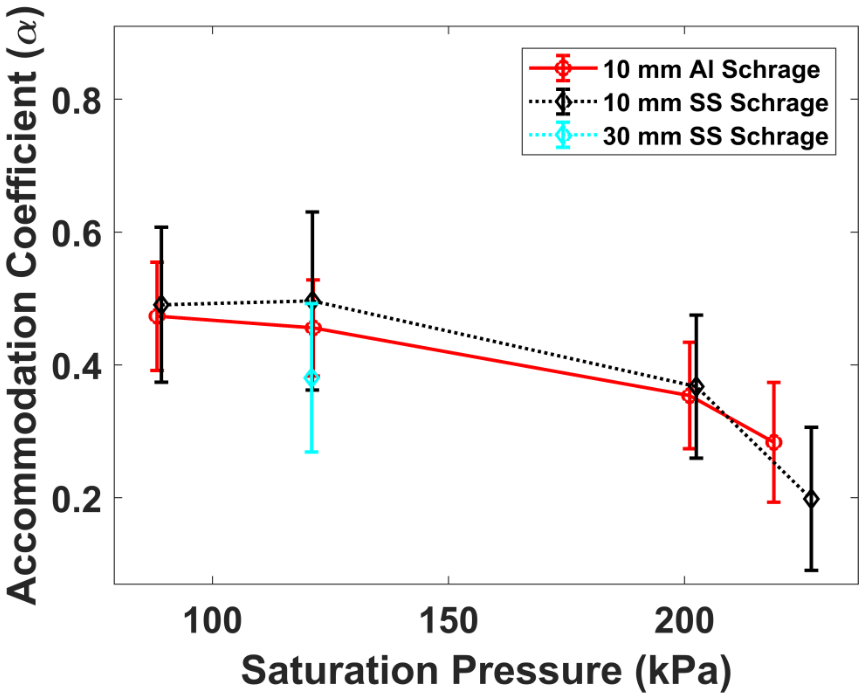
Phase Change Coefficients

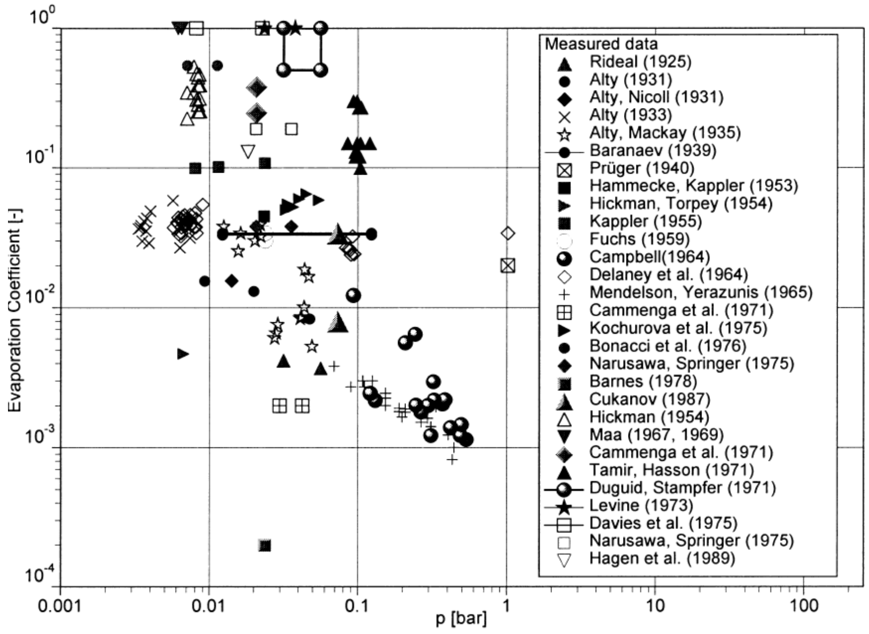
CFD Thermal model

Phase change experiments

Phase Change Coefficients

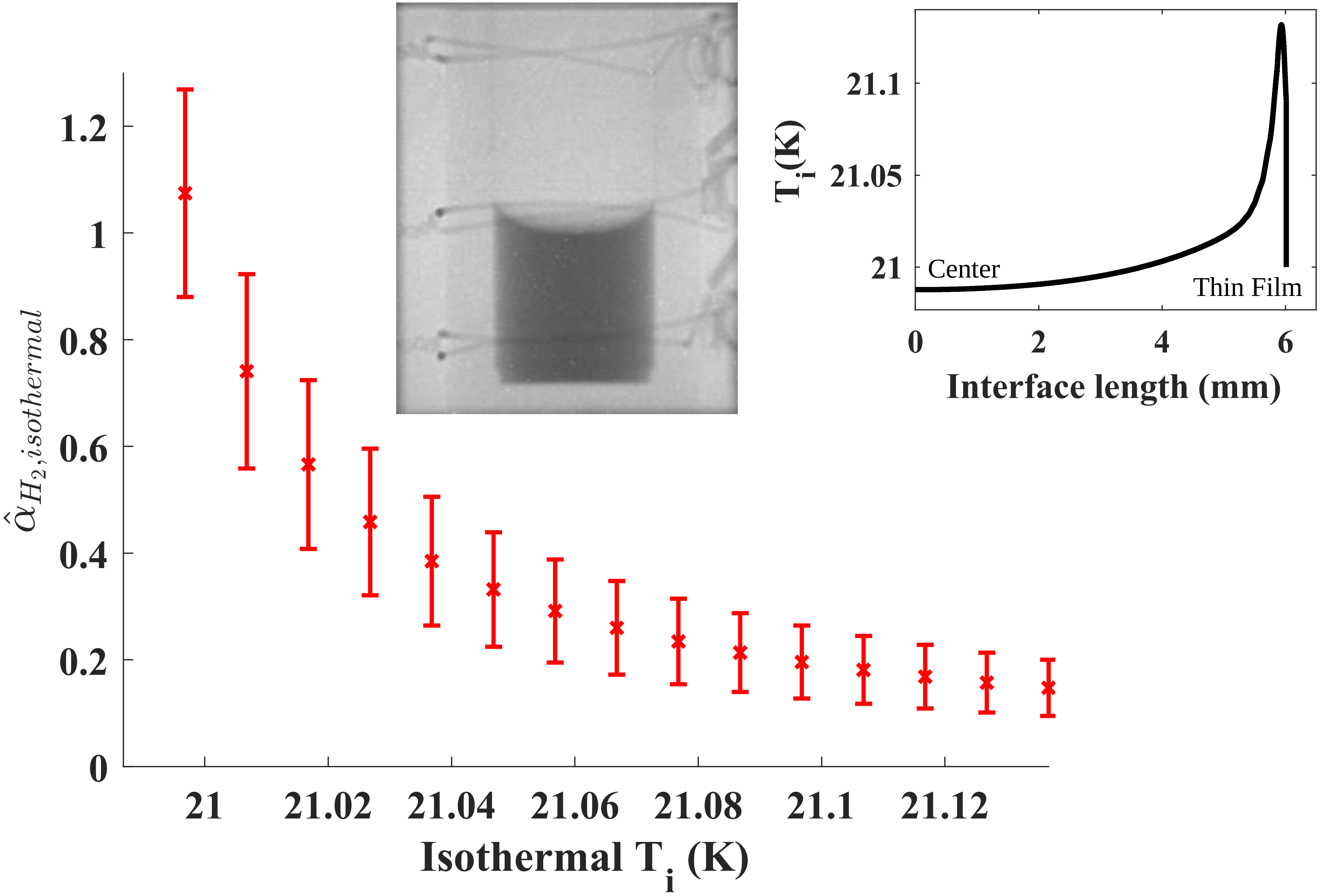
Phase change coefficients


Calculated results for LH2


Reported results for H_2O (Marek & Straub, 2001)

- α decreases with pressure
- α variation with test cell size (10 mm vs 30 mm) is within measurement error
- α variation with cell wall material (Al vs SS) is within measurement error

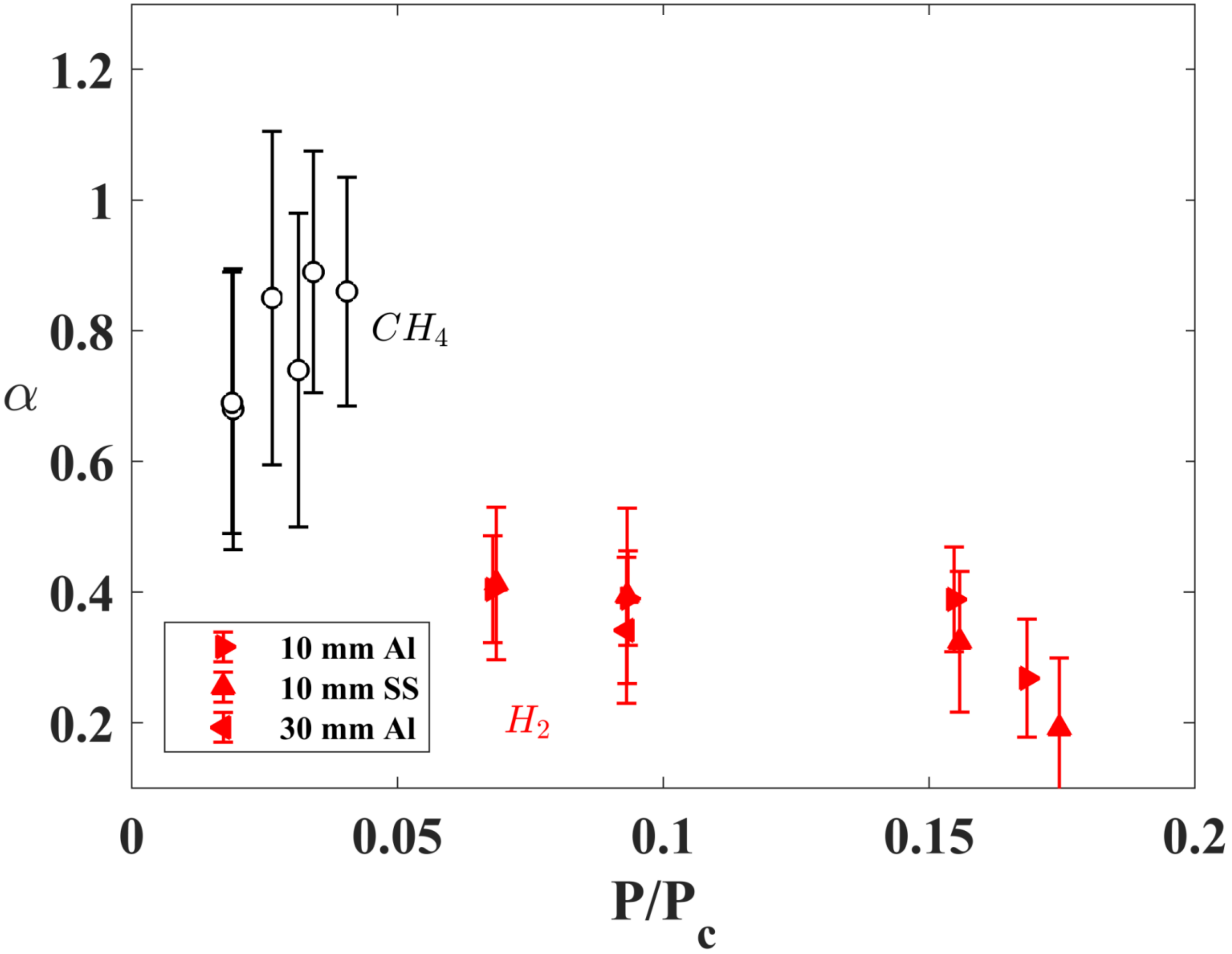
Phase change coefficients: isothermal assumption



Coefficient is sensitive to how temperature is sampled.

Bellur et al., *Colloids and Surfaces A* (2023)

Phase change coefficients: LH2 + LCH4



Coefficient is predictable!

Bellur et al., *Colloids and Surfaces A* (2023)

Questions/Comments?

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- Cryogenic Experiments: **John McQuillen**, NASA Glenn

NIST Support:
- Neutron Imaging Facility: **Daniel Hussey**
  David Jacobson
- Cryogenic Hardware: **Juscelino Leao**

Supplementary Material

Kinetic Theory Of Phase Change

Hertz (1882)

- Measured evaporation of Mercury
- Determined maximum rate of phase change from Kinetic theory

Maxwellian Distribution

$$J = \sqrt{\frac{m}{2\pi k_B}}\left(\underbrace{\frac{P_{Li}}{\sqrt{T_{Li}}}}_{\text{Evaporation}} - \underbrace{\frac{P_{vi}}{\sqrt{T_v}}}_{\text{Condensation}}\right)$$

Hertz-Knudsen equation

Knudsen (1915)

- Measured rate always lower than maximum rate predicted by kinetic theory
- Evaporation and Condensation Coefficients

Schrage (1953)

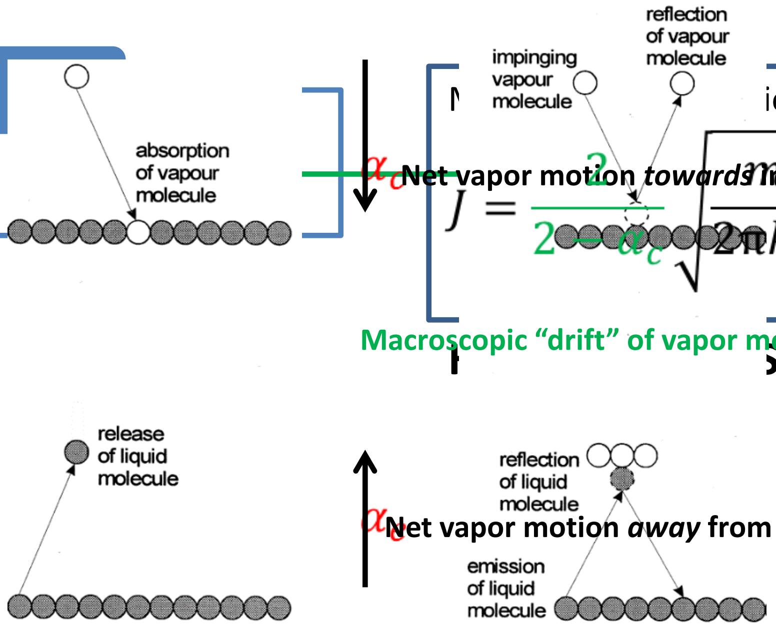
- Drift velocity correction

ion with drift velocity

$$J = \frac{2}{2-\alpha_c}\sqrt{\frac{m}{2\pi k_B}}\left(\alpha_e \frac{P_{Li}}{\sqrt{T_{Li}}} - \alpha_c \frac{P_{vi}}{\sqrt{T_v}}\right)$$

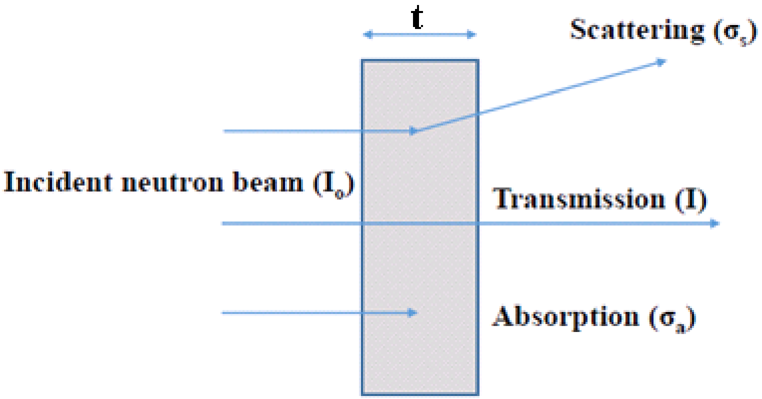
Schrage Equation

Macroscopic “drift” of vapor molecules must be accounted for!



Marek and Straub (2001)

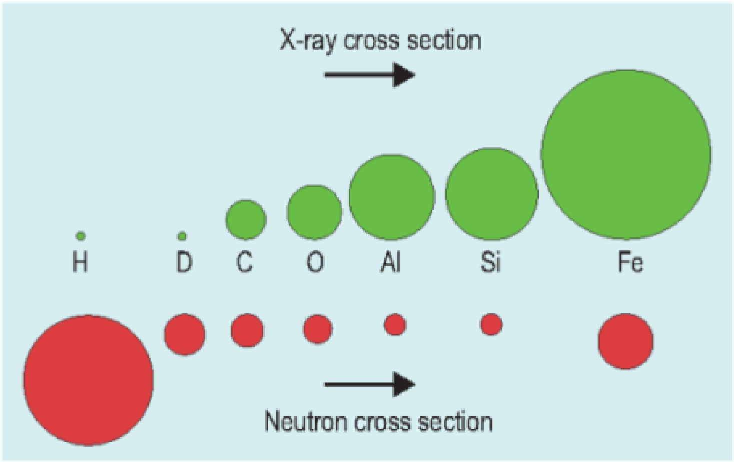
Neutron Imaging



$$I = I_0 e^{-\mu t}$$

Beer-Lambert Law

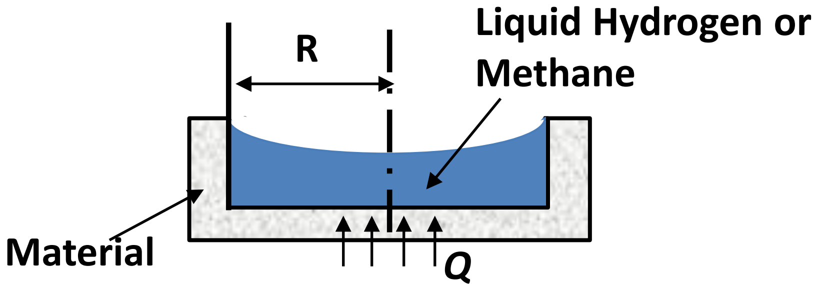
μ: Attenuation coefficient (cm^{-1})



http://www.ncnr.nist.gov/AnnualReport/FY2003_html/RH2/

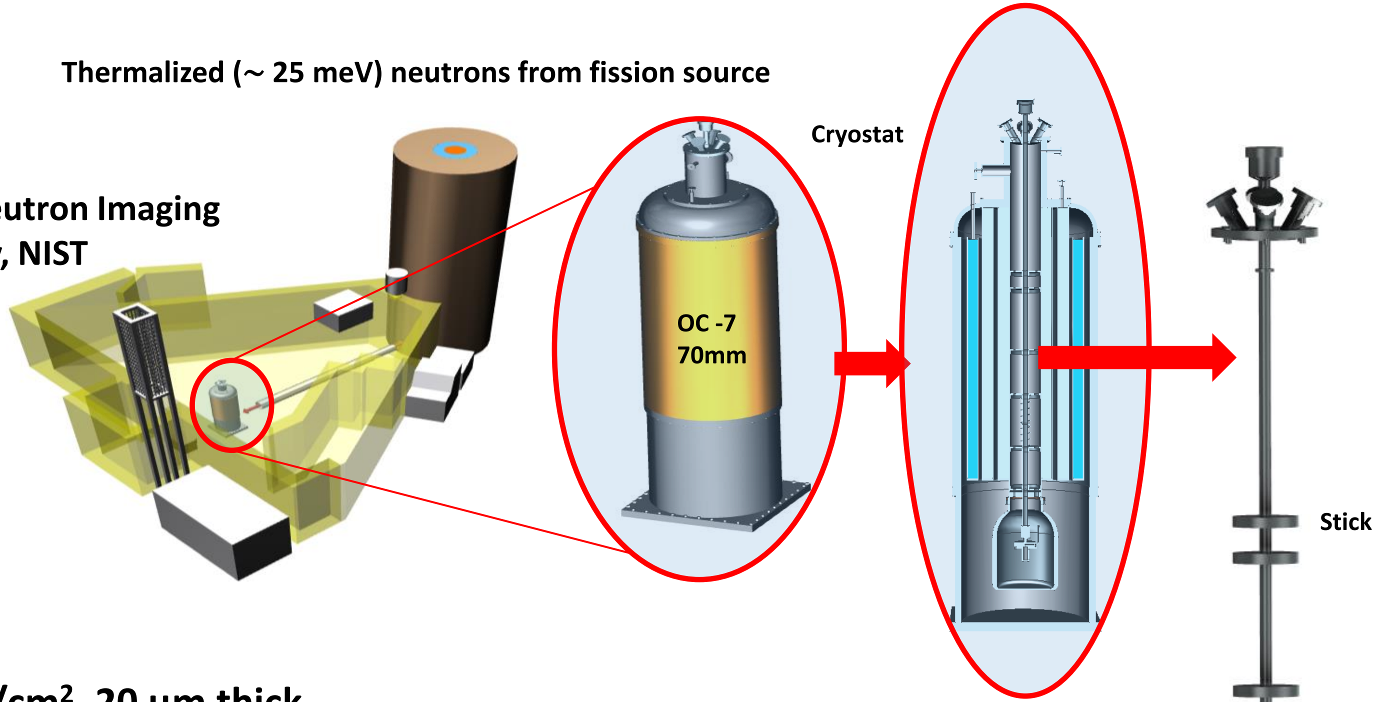
P_v (vapor pressure)

Control Parameters



Species	σ (b)	Density (g/cm^3)	μ (cm^{-1})
Hydrogen(liquid)	33.75	0.0707	1.437
Hydrogen(vapor)	33.75	0.0013	0.026
Aluminum	1.34	2.7	0.083
Carbon	5.02	2.25	0.566

Experimental setup – Neutron imaging and Cryostat



Scintillator: 7.6 mg/cm^2, 20 µm thick Gadoxysulfide screen

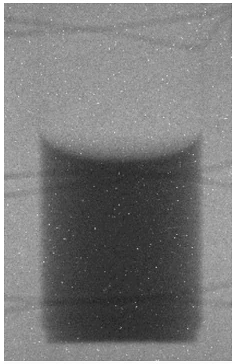
Imaging: Andor NEO sCMOS camera, 6.5 µm pixel pitch; Nikon lens with PK13 extension tube

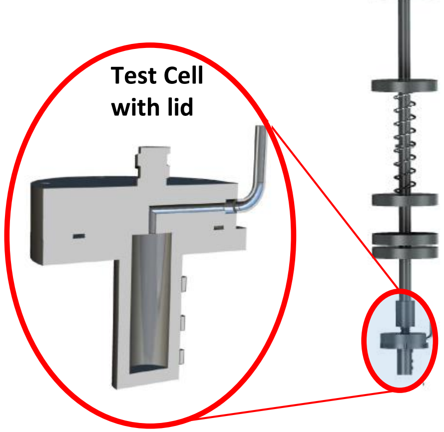
Images: 16 bit FITS format

Resolutions:

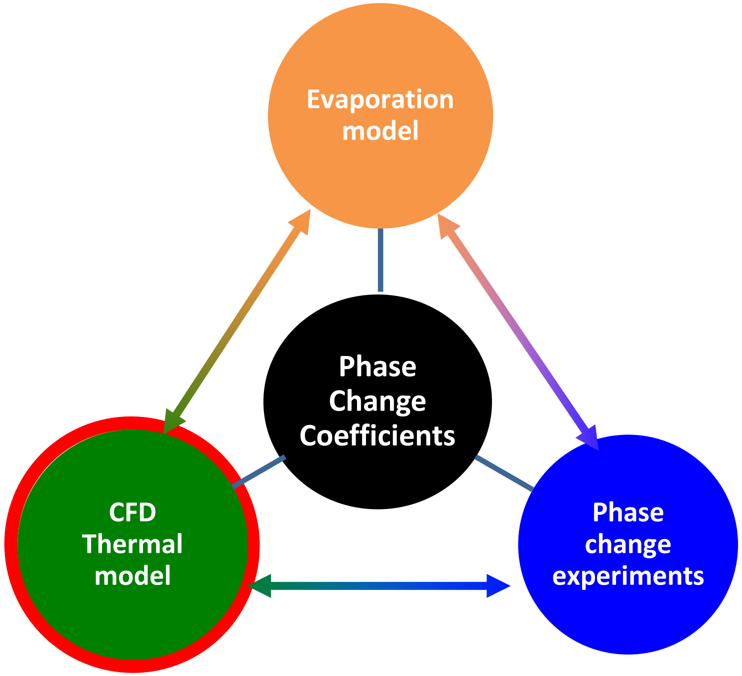
14 µm spatial resolution
10 s temporal resolution

Typical Neutron Image



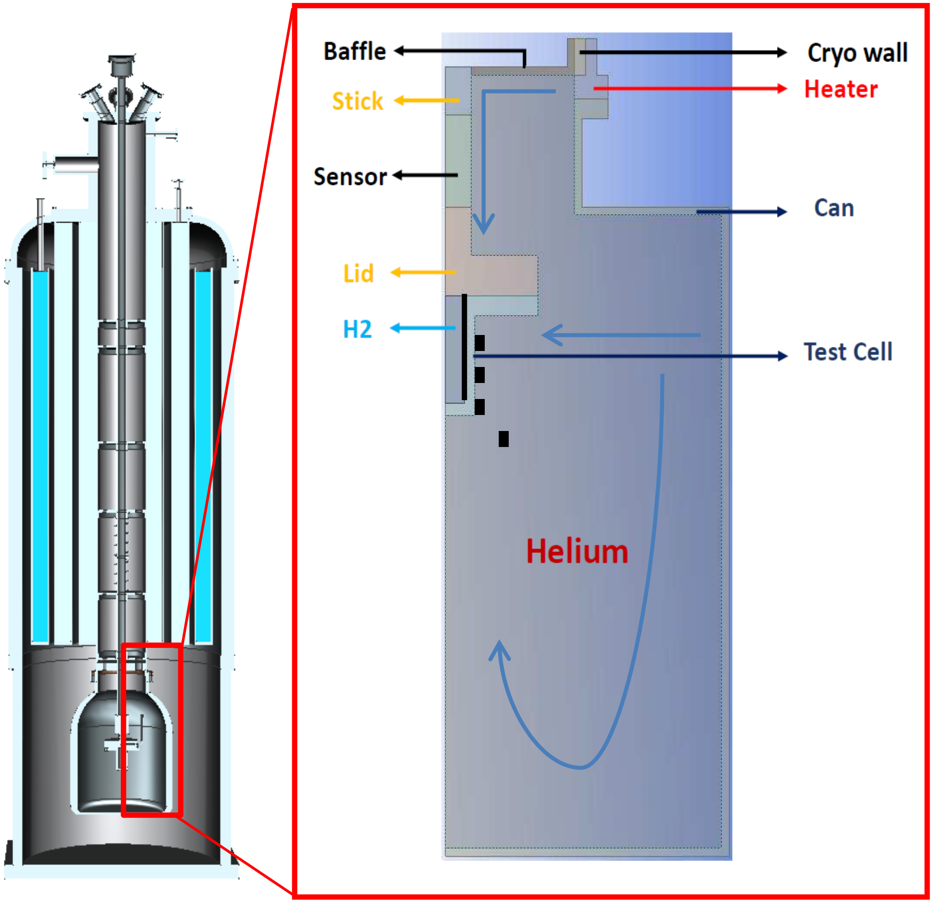


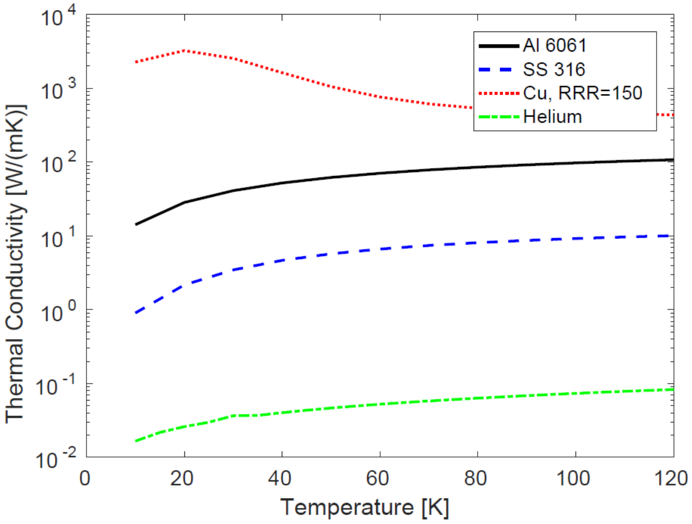
Bellur et al, *Cryogenics* (2016).

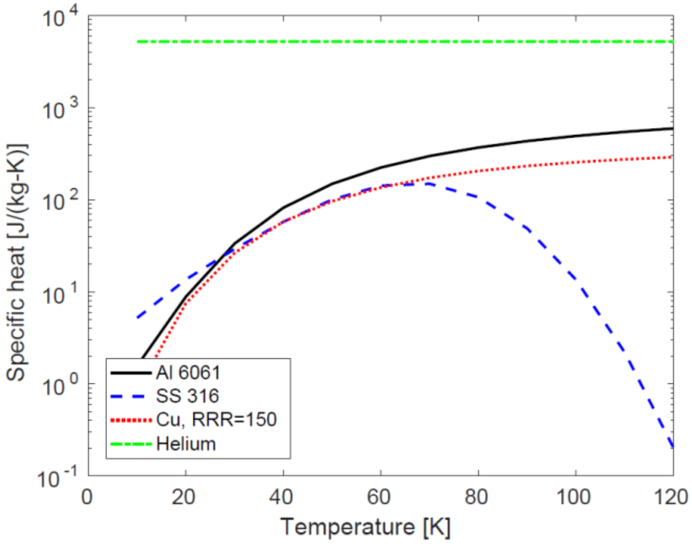


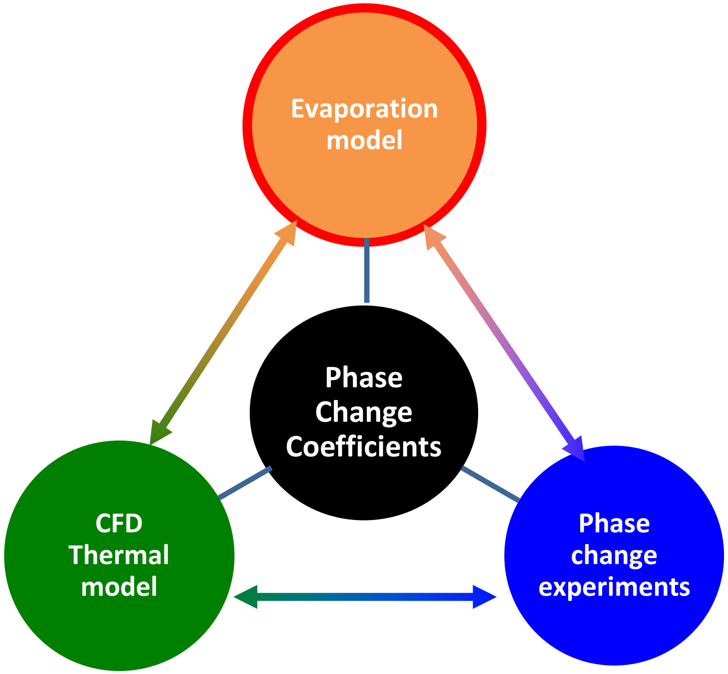
CFD Thermal Model

CFD Thermal model









Evaporation model

Phase Change Coefficients

CFD Thermal model

Phase change experiments

Multi-scale Evaporation Model

Macro Model

Disjoining Pressure **Curvature**

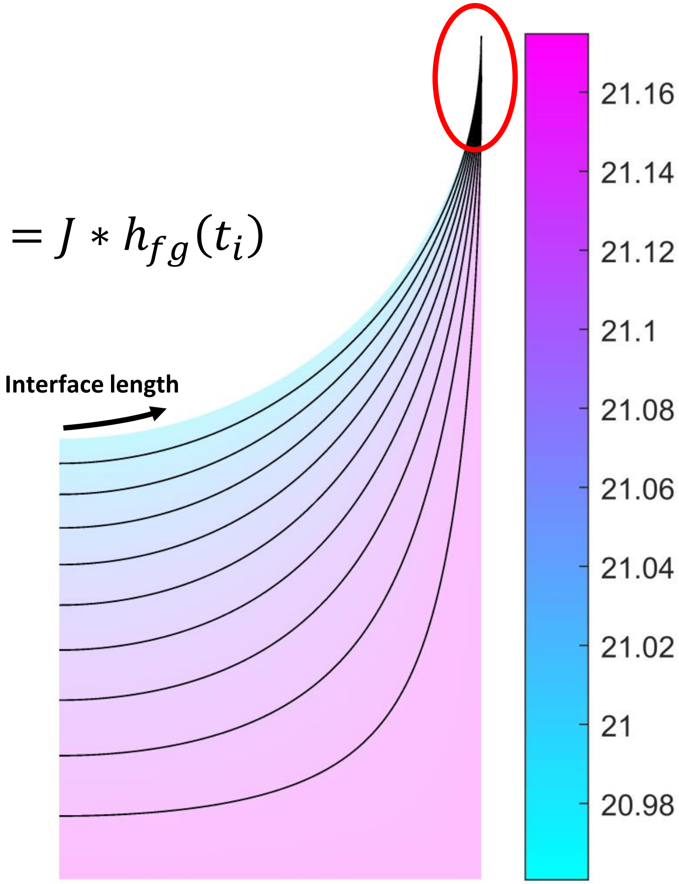
$$J = \frac{2\alpha}{2-\alpha}\sqrt{\frac{M}{2\pi R T_i}}\left[\frac{p_v M h_{fg}}{R T_v T_i}(T_i - T_v) + \frac{p_v V_l}{R T_i}(\Pi + \sigma K)\right]$$

Wayner, *Coll. Surf*, 52, 71-84, 1991.

$$\Pi = -\frac{A}{h^3}$$

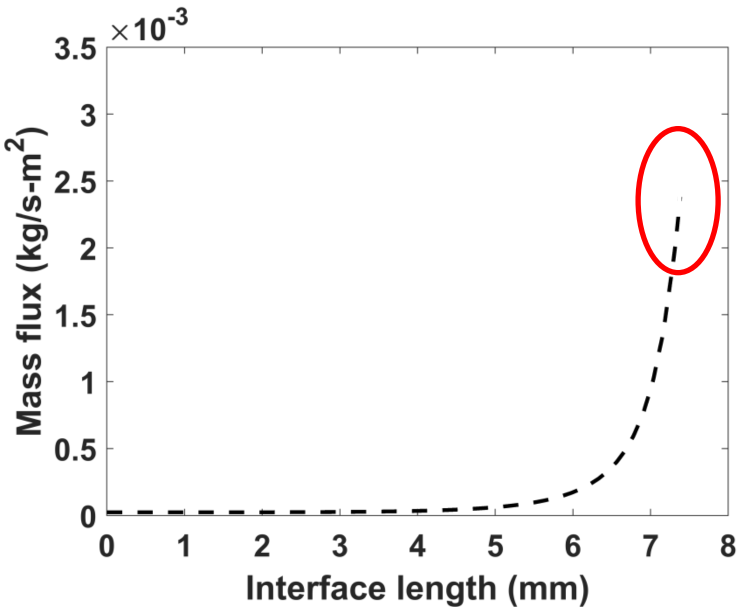
$$K = \left(\frac{1}{r-h}\right)(1+h_x^2)^{-\frac{1}{2}} + h_{xx}(1+h_x^2)^{-\frac{3}{2}}$$

$$Q''_{loss} = J * h_{fg}(t_i)$$



2D FEA model of thermal transport

Cannot resolve with macro model!



Transition region balance laws

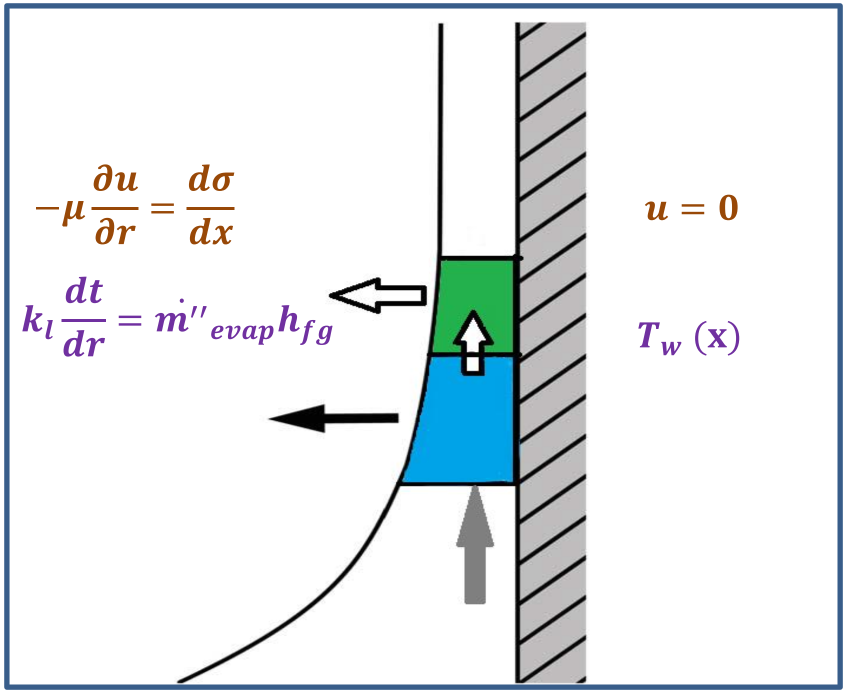
Lubrication approximation of the NS equations in cylindrical form:

$$\boxed{\dot{m}''_{evap}} = \int_{r_{ij-h}}^{r_{ij}} \rho_l \left[\frac{1}{4\mu_l}\boxed{\frac{dp_l}{dx}}r^2 + C_1 \ln(r) + C_2\right] 2\pi r\, dr$$

Mass

Evaluate

From modified Schrage equation



$$-\mu\frac{\partial u}{\partial r} = \frac{d\sigma}{dx}$$

$$k_l\frac{dt}{dr} = \dot{m}''_{evap}h_{fg}$$

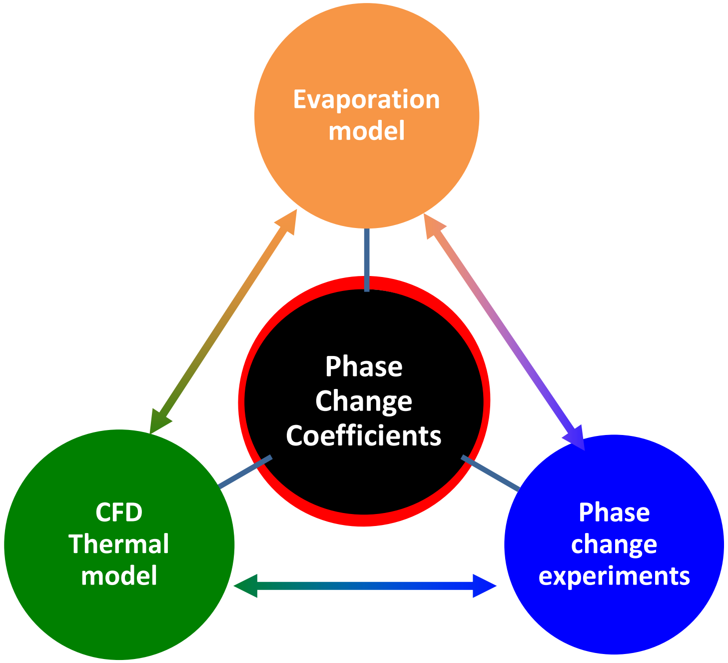
$u = 0$

$T_w\,(x)$

$$\boxed{T_i} = -\boxed{\dot{m}''_{evap}}\frac{h_{fg}}{k_l}(r_{ij}-h)ln\left(\frac{r_{ij}}{r_{ij}-h}\right) + T_w$$

Energy

Evaluate



Evaporation model

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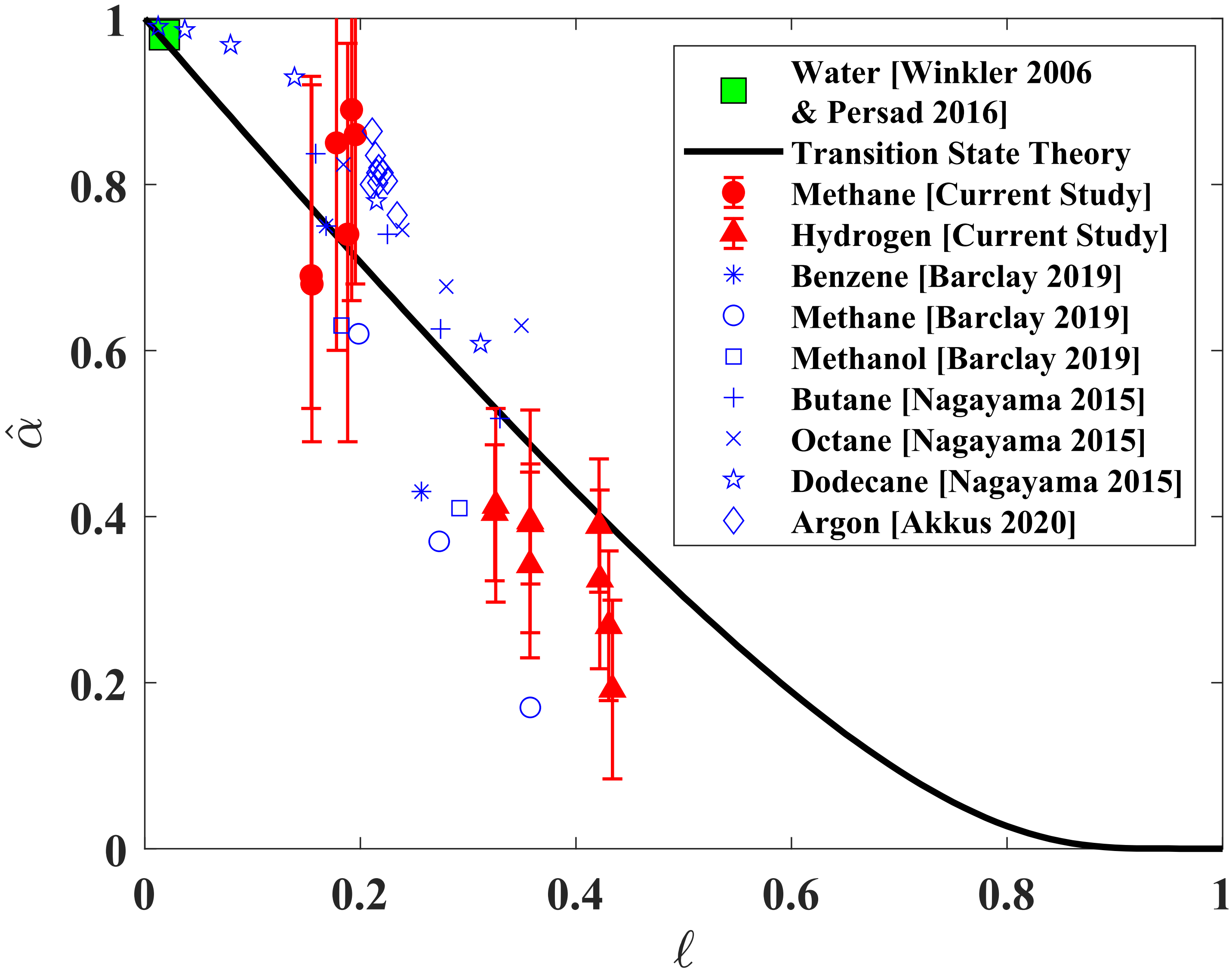
Phase change experiments

Phase Change Coefficients

Phase change coefficients



Coefficient is fluid independent!?

Bellur et al., *Colloids and Surfaces A* (2023)