TFAWS Active Thermal Paper Session

Computational Study of 3-Phase Contact Line: Effect of Oscillations on Heat Transfer

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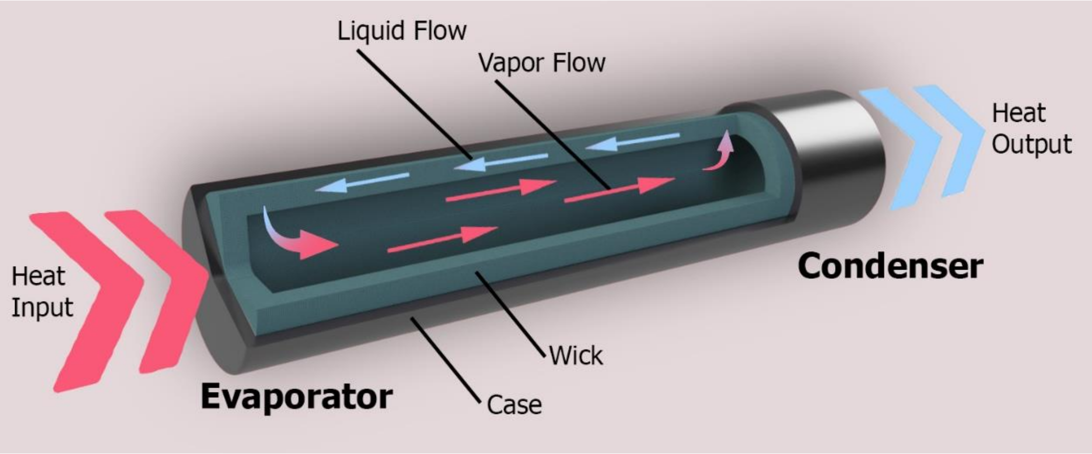
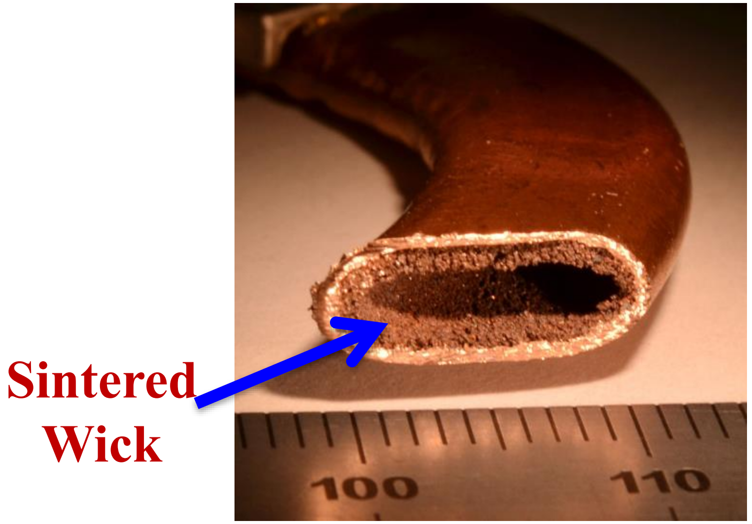
What is a Heat Pipe?

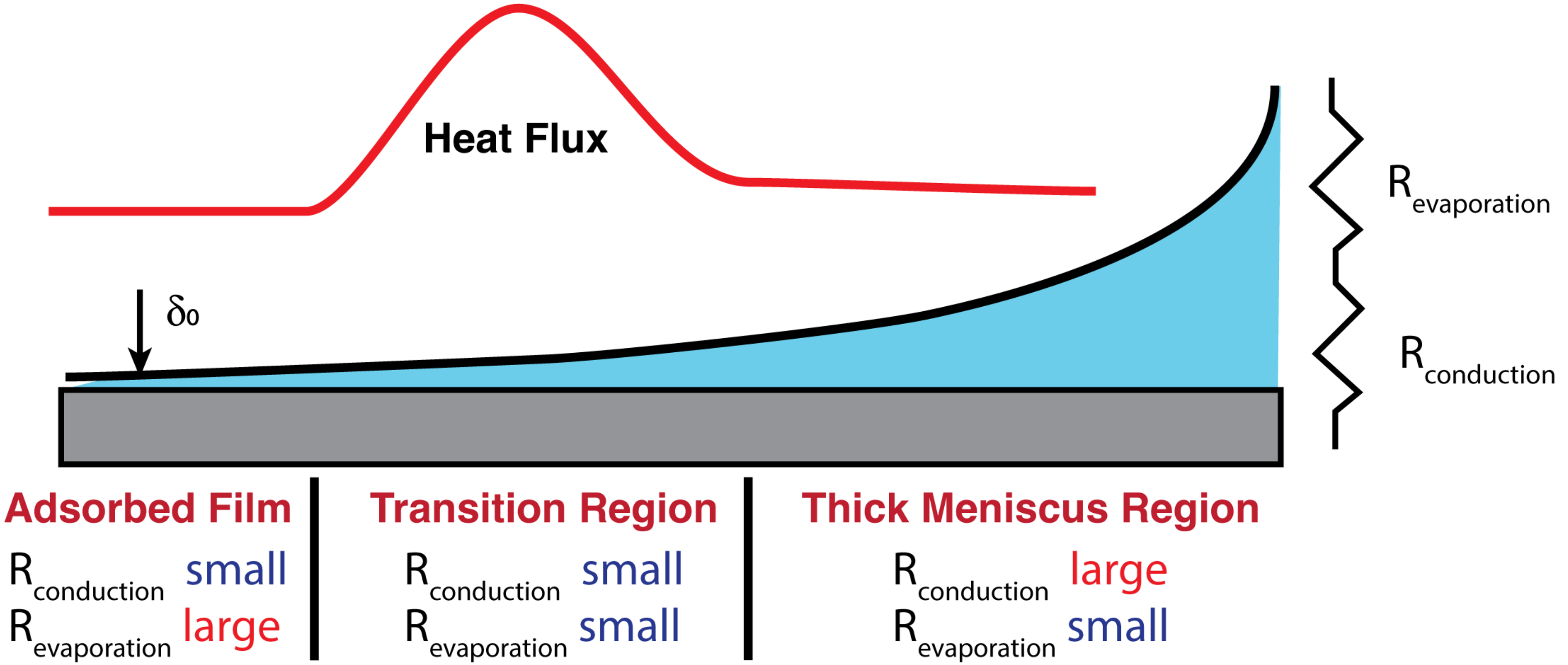


Conventional wicked heat pipe structure



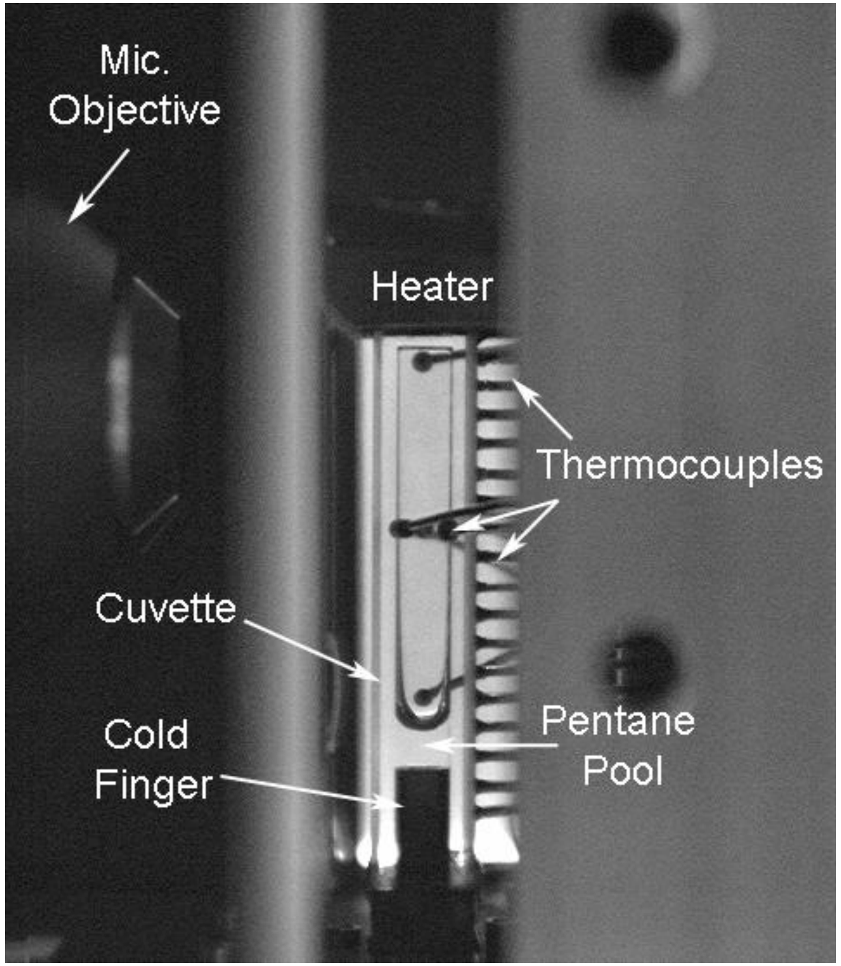
Cross section of a heat pipe
(Wikipedia.com)

- Self-contained, highly effective heat transfer system. No moving parts involved.
- At the heat source, liquid absorbs heat and vaporizes.
- The vapor travels to the heat sink, condenses, and releases its latent heat.
- The liquid returns to the hot end usually through capillary or gravitational forces.
- Wicks are used to “pump” the condensate back to the hot end.



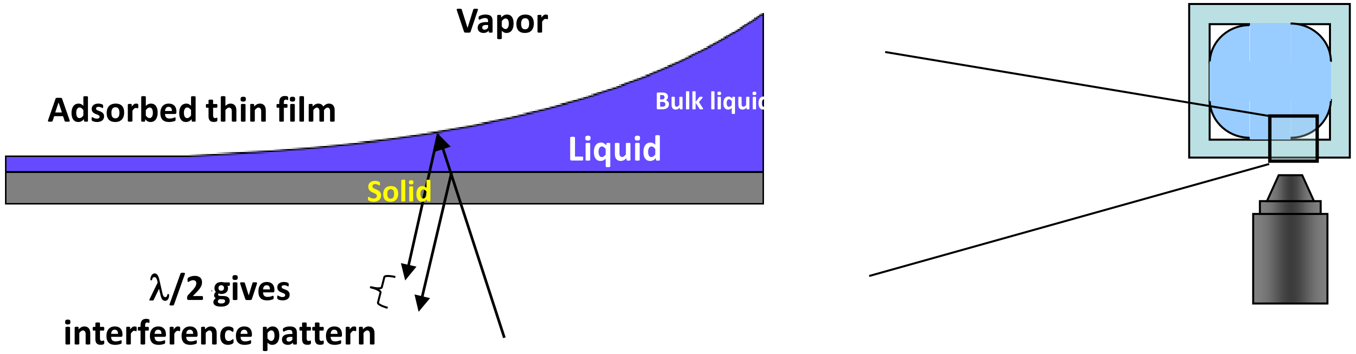
- Evaporation resistance is controlled by intermolecular forces and is proportional to **$1/h^3$**.
- Conduction resistance is proportional to **$1/h$**.
- Transition region controls evaporation. Lowest overall resistance

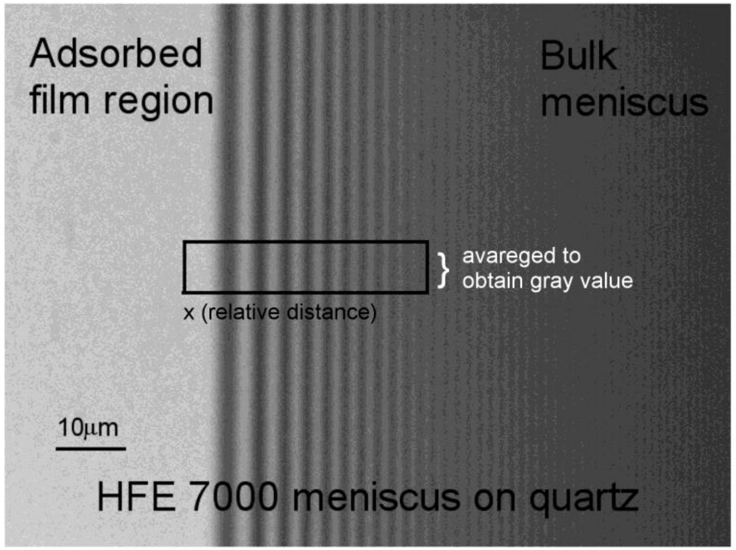
We Use a Transparent Heat Pipe



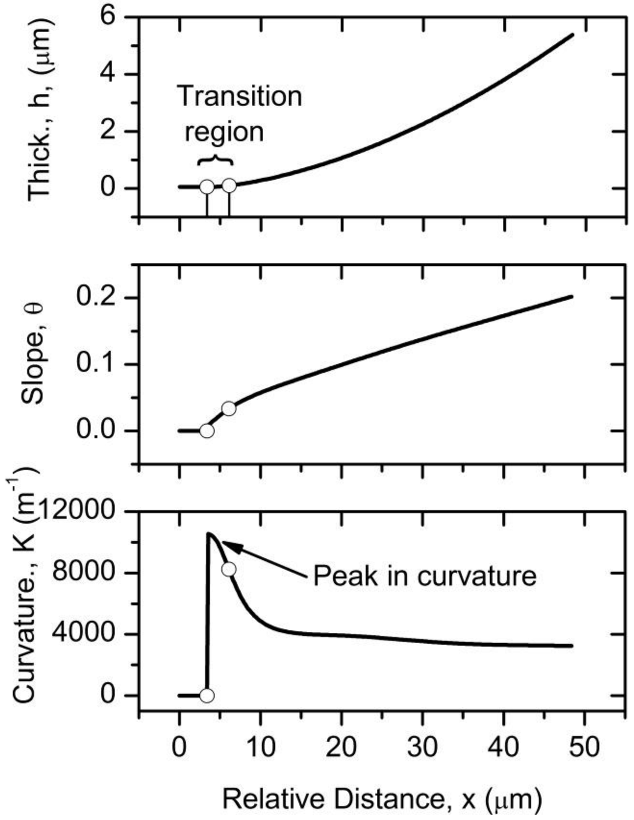
- The transparent heat pipe allows us to see the vapor-liquid interface and to measure the film thickness.
- It is technically a "wickless" heat pipe. Liquid is circulated via sharp corners.
- Made from a fused silica, spectrophotometer cuvette.
- 3mm x 3mm, 25 – 45 mm long (inside dimensions).
- Any working fluid can be used but we restrict ourselves to perfectly wetting fluids that spread over the surface.

This experiment was designed to optimize the detailed study of interfacial phenomena and phase change in microgravity.



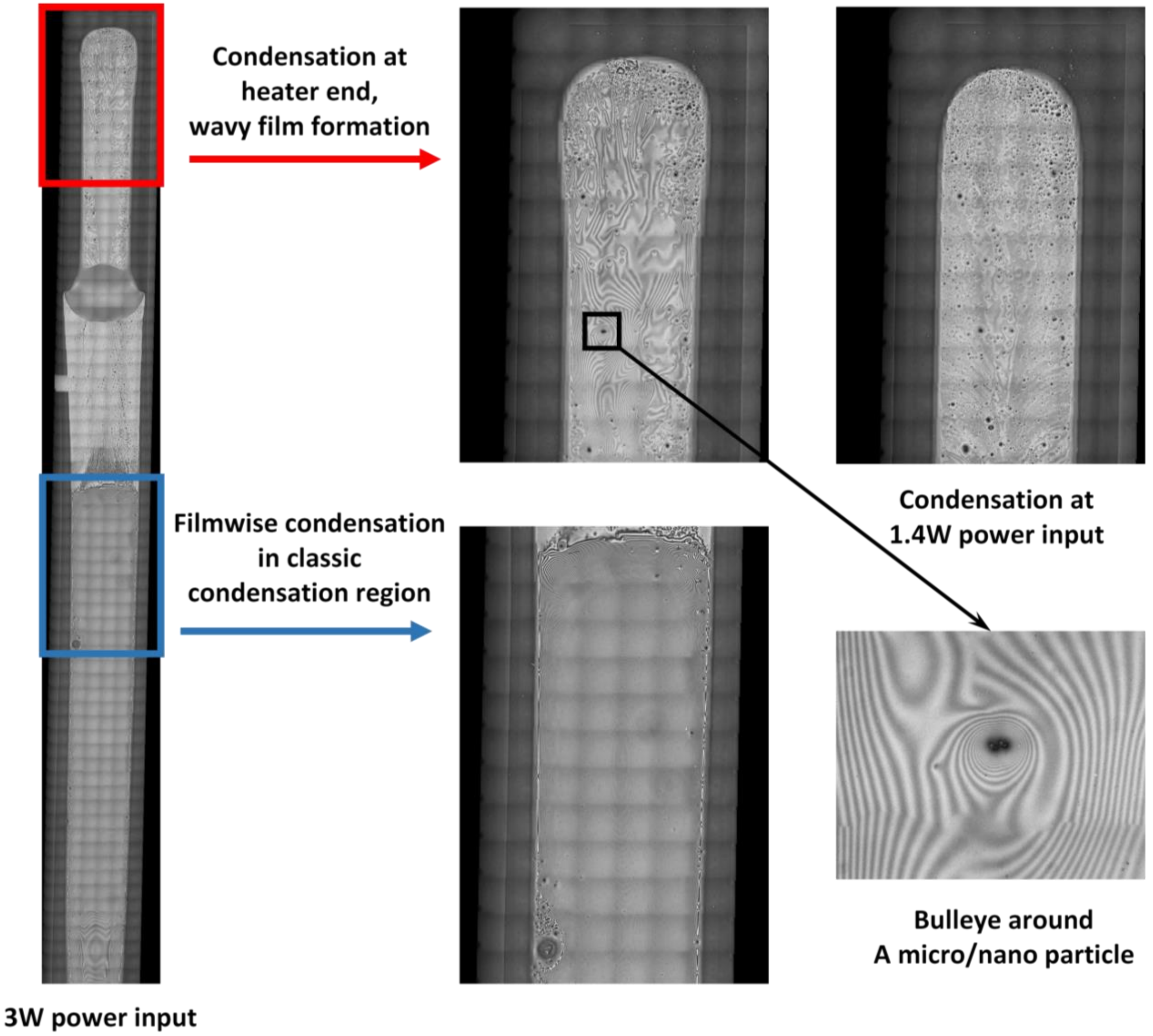


$$\underbrace{\bar{G}}_{Reflectivity} \rightarrow \underbrace{\delta}_{Thickness} \rightarrow \underbrace{\delta'}_{Slope} \rightarrow \underbrace{\delta''}_{Curvature}$$



- **Interferometry lets us map the vapor-liquid interface**

Heater End Flooding on ISS



- Where does the liquid come from?
- Thermal analysis suggests condensation at the heater end.
- Condensation confirmed by an increase in fringe density at the heater end.
- How and why should this occur?

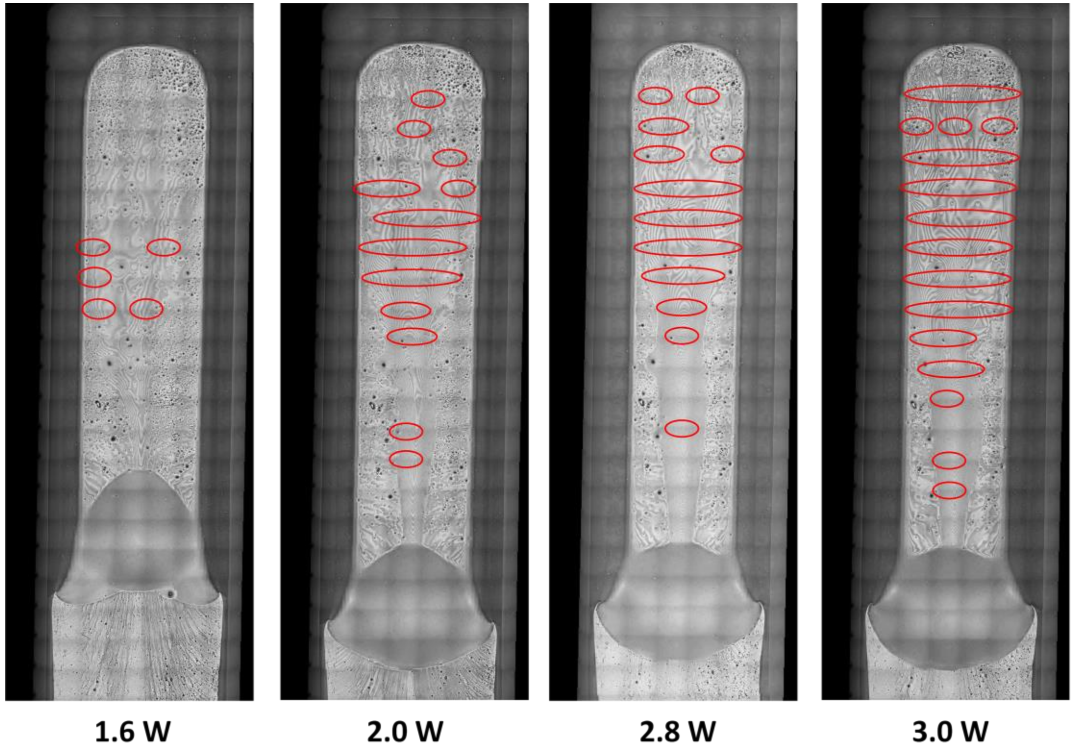
$$\dot{m}_e = a\underbrace{\left(T_{LV} - T_V\right)}_{\Delta T} - b\underbrace{\left(\sigma K + \Pi\right)}_{\Delta P}$$

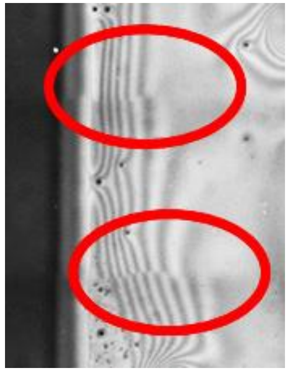
$\dot{m}_e < 0$ *Condensation*

Film Instability?

Does Instability Exist?

At 3 W, T_{wall} = 230 °C. T_v = 80 °C





- No high-speed camera for direct observation.
  - Had a form of time-lapse photography.
- Discontinuities between fringe images during mapping indicates time-dependent changes in film thickness.
  - Mismatch increases with increasing heat input.

- **Do any models confirm the instability should exist?**

Visible Fringes = Unstable Film

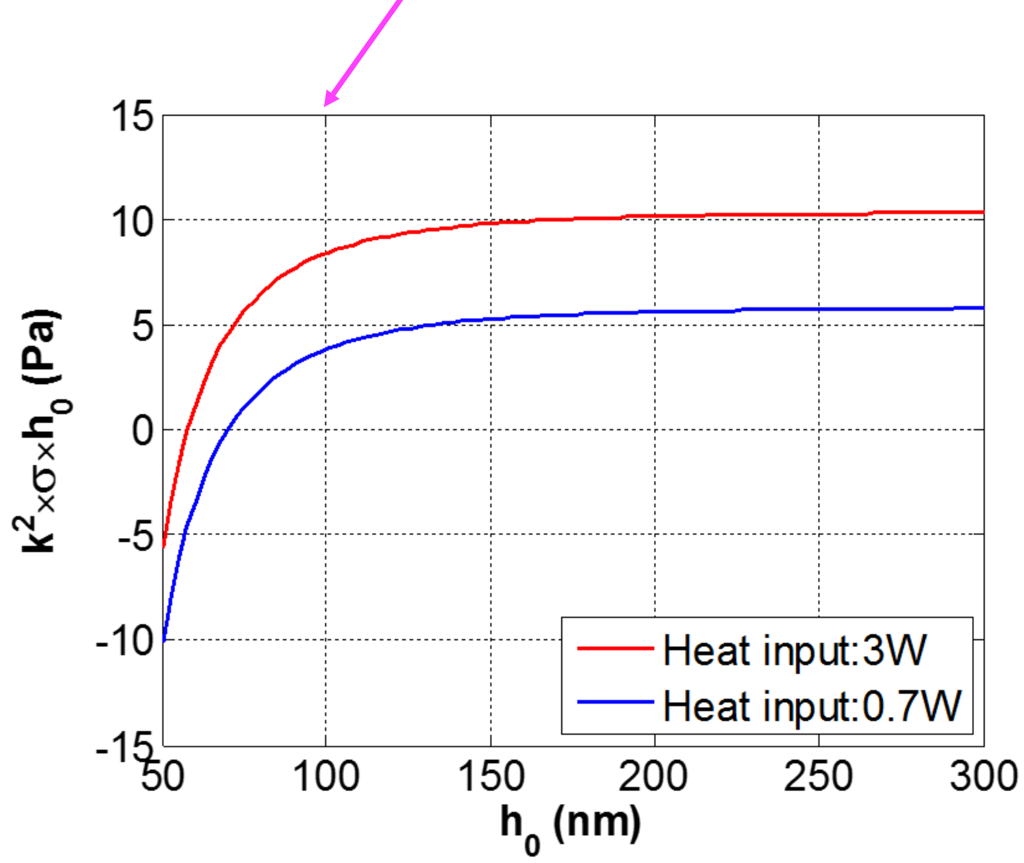
Evolution Equation[1]

$$3\mu\frac{\partial h}{\partial t}+\frac{3\alpha_T\Delta\sigma}{2k_T}\frac{\partial}{\partial x}\left(h^2\frac{\partial h}{\partial x}\right)+\frac{A}{2\pi}\frac{\partial}{\partial x}\left(h^{-1}\frac{\partial h}{\partial x}\right)+\rho g\left(h^3\frac{\partial h}{\partial x}\right)+\sigma\frac{\partial}{\partial x}\left(h^3\frac{\partial^3 h}{\partial x^3}\right)=0$$

Linear Stability Analysis

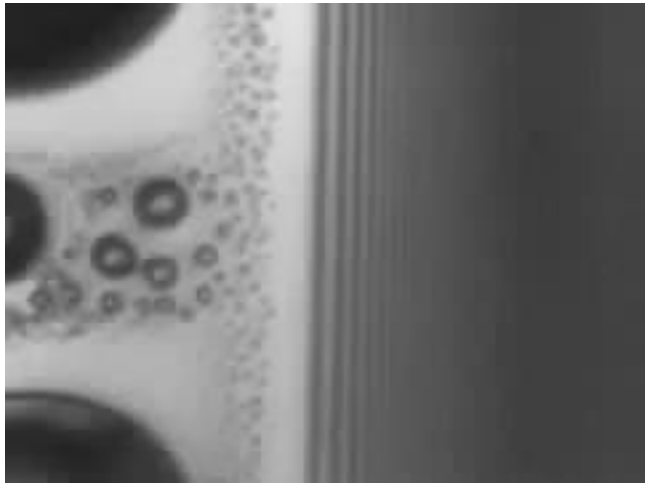
$$\underbrace{\frac{3\alpha_T\Delta\sigma}{2k_T}}_{\text{Marangoni Effect}}+\underbrace{\rho g h_0}_{\text{Gravity Force}} > \underbrace{\frac{|A|}{2\pi h_0^3}}_{\text{Disjoining Pressure}}$$

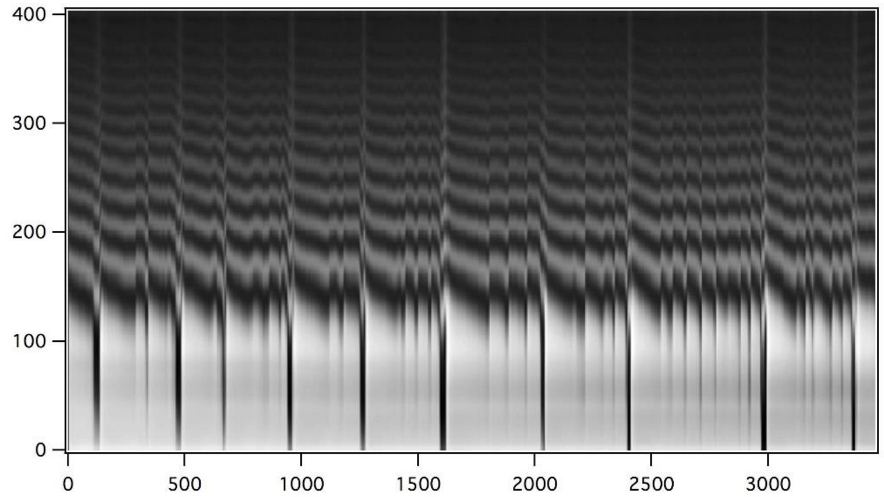
0th order fringe



- Does the instability enhance heat transfer?

[1]A. Oron, S.H. Davis, & S. G. Bankoff, *Rev. Mod. Phys.*, 69, 931-980 (1997). And others



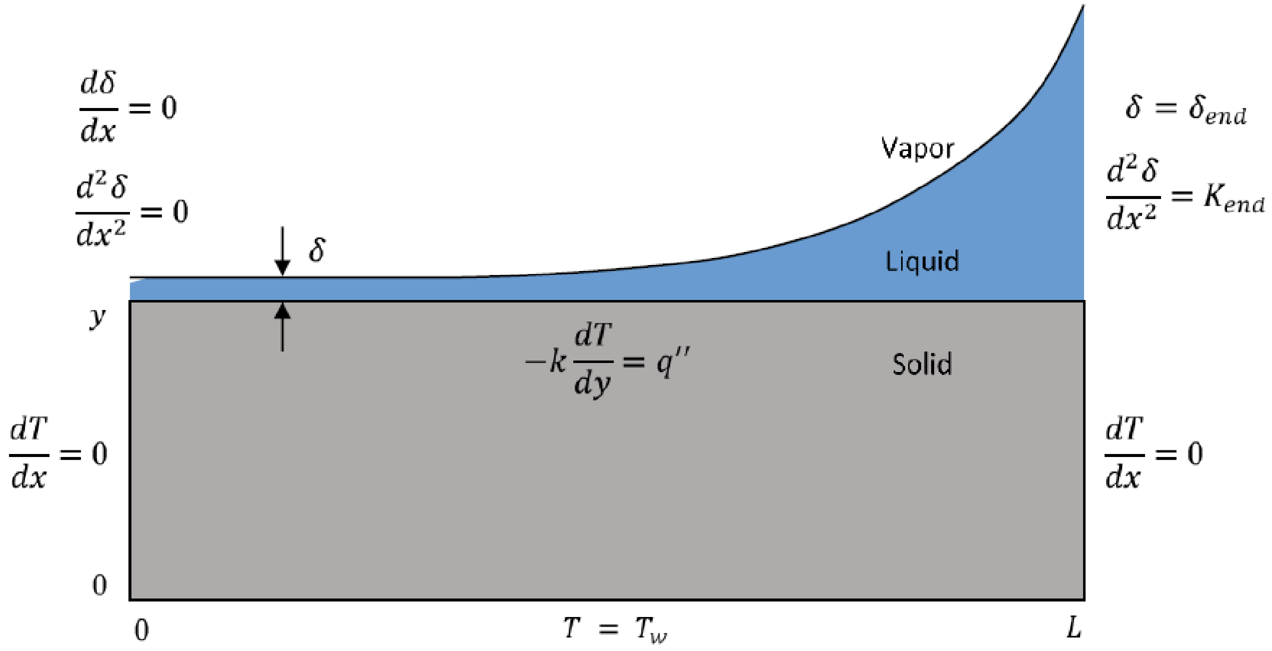


Fluid	Density (kg/m^3)	Viscosity (Ns/m^2)	Surface Tension (N/m)	Heat of Vaporization (J/kg)
HFE-7100	1400	5.80×10^{-4}	0.0136	113034

- **The menisci almost always seem to be unstable.**
- **When we look at the instability, it grows in amplitude and frequency with heat input.**
- **The strip chart above appears to show two frequencies, like an OHP, but FFT analysis shows that is not the case.**
- **Is there an advantage to the instability or do we need to develop surfaces to inhibit the oscillation?**

Current Model – Oscillating Base Temperature

- **Derive a meniscus model in the same manner as Bankoff and Davis.**
- **We include:**
  - Disjoining Pressure
  - Lubrication Approximation
  - Overall Continuity Equation
  - Evaporation Rate – Kelvin-Clapeyron Formulation (DT and DP driving forces)
  - Thermal Model in the Substrate
- **Scale to make system dimensionless.**
- **Film thickness differential equation is solved on the boundary of the substrate.**

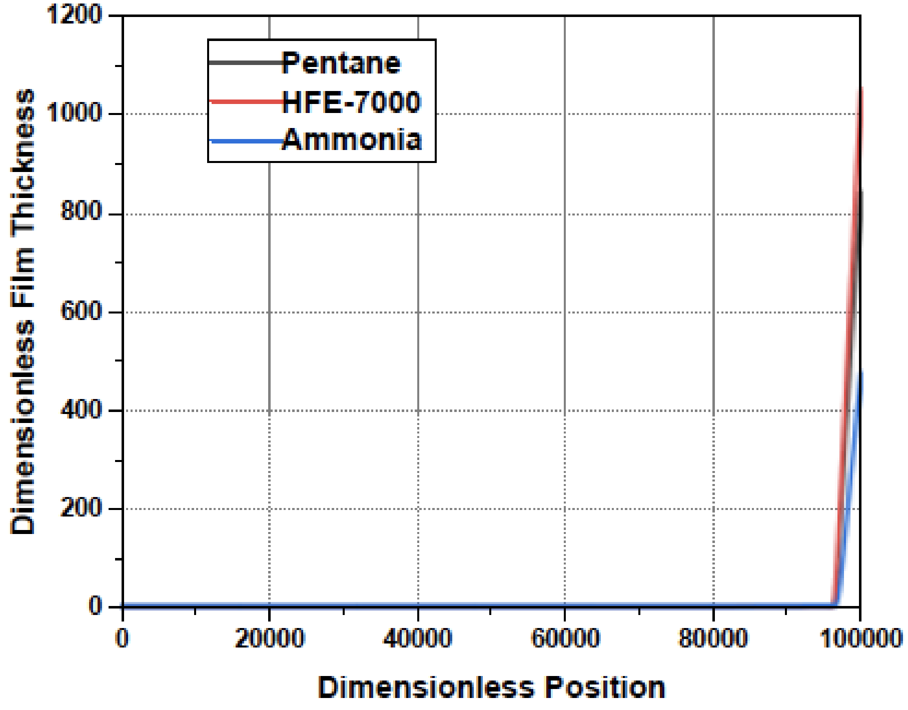


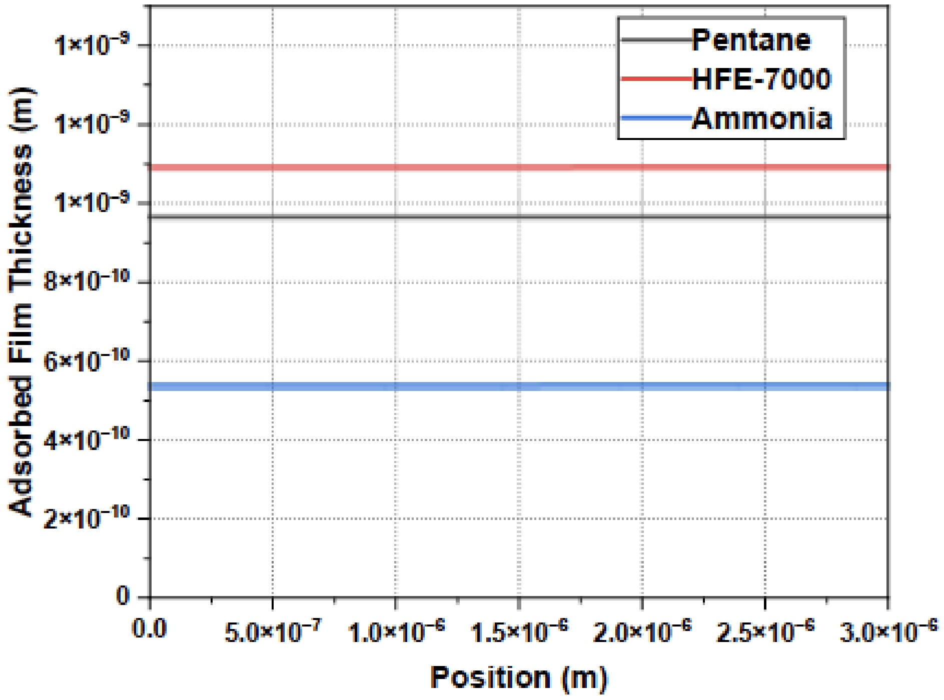
$$q = \frac{T}{T_V} \qquad h = \frac{d}{x_0} \qquad e = \frac{x}{x_0}$$

$$t = \frac{t}{t_0} \qquad x_0 = \left(\frac{A_0}{s_0}\right)^{1/2} \qquad t_0 = \frac{x_0^2}{n}$$

Start from a Steady-State

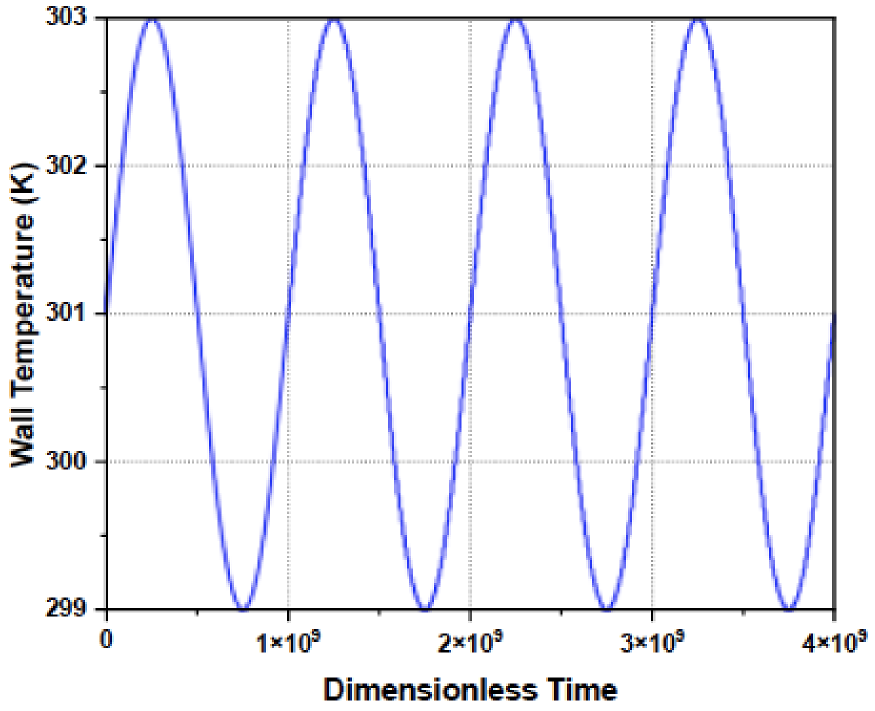
- First, we solve for the steady-state profile. In this case we set the bottom substrate temperature to be 1 ˚C higher than the liquid saturation temperature.
- We considered three different working fluids having different densities and different heats of vaporization.

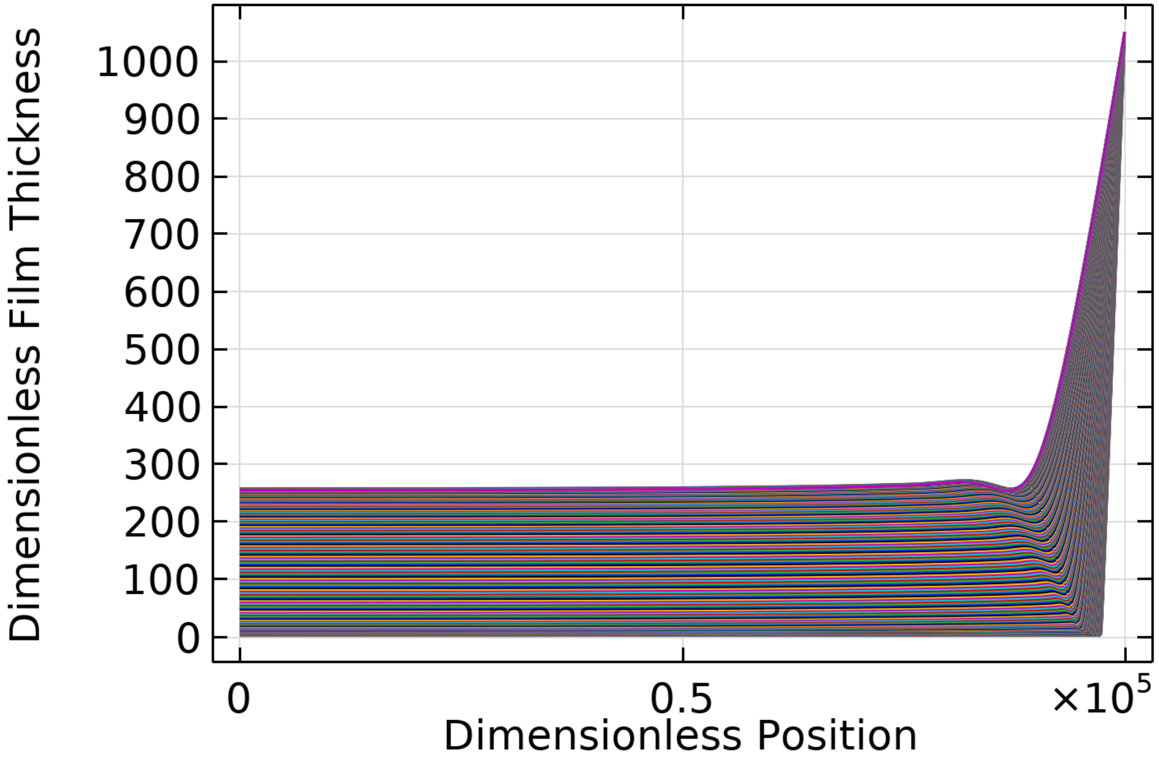




Induce Oscillations

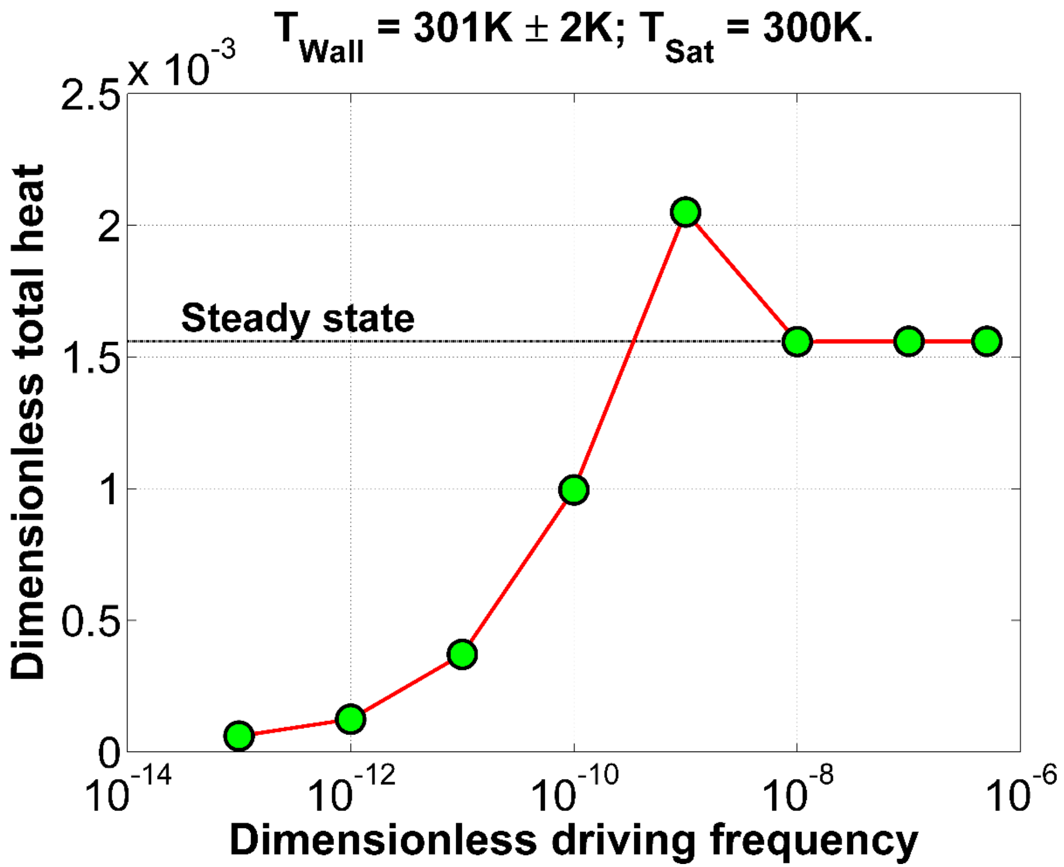
- We induce oscillations by varying the bottom temperature of the substrate ±2˚C or smaller.
- Dimensionless frequency is $1x10^{-9}$. We run several cycles to remove the initial transients and plot only the harmonic behavior.
- Example here is for HFE-7000 on silica.

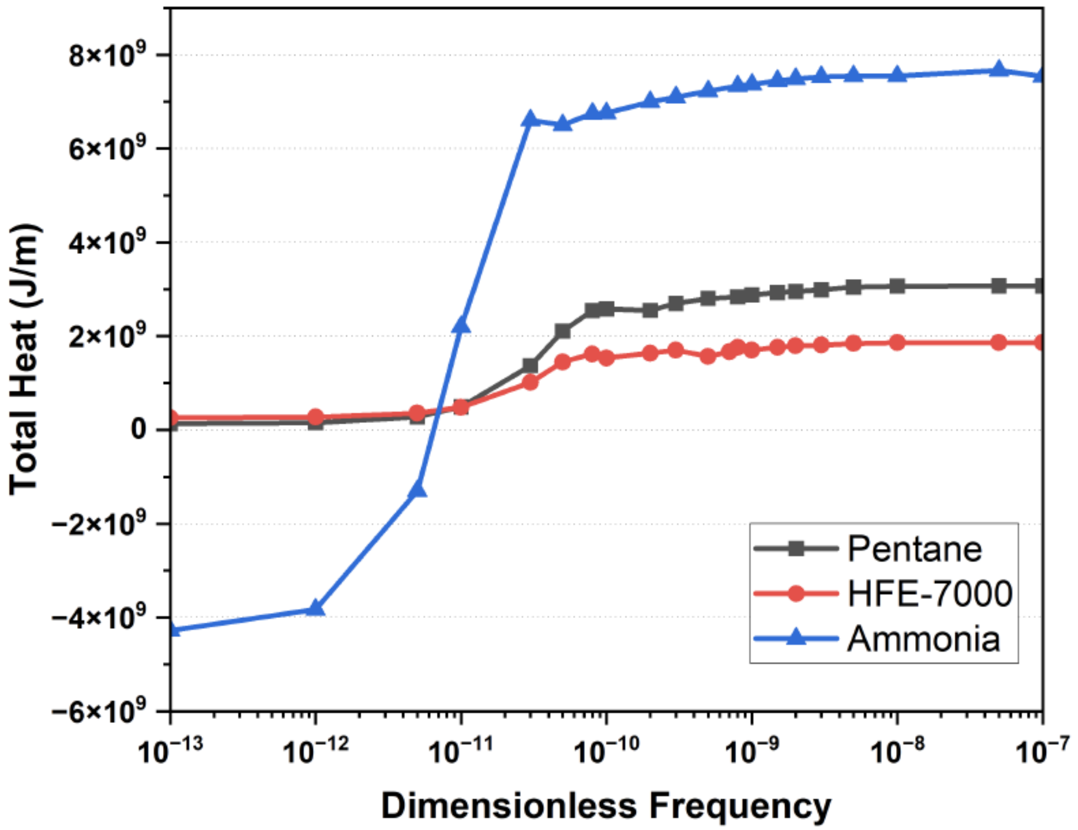




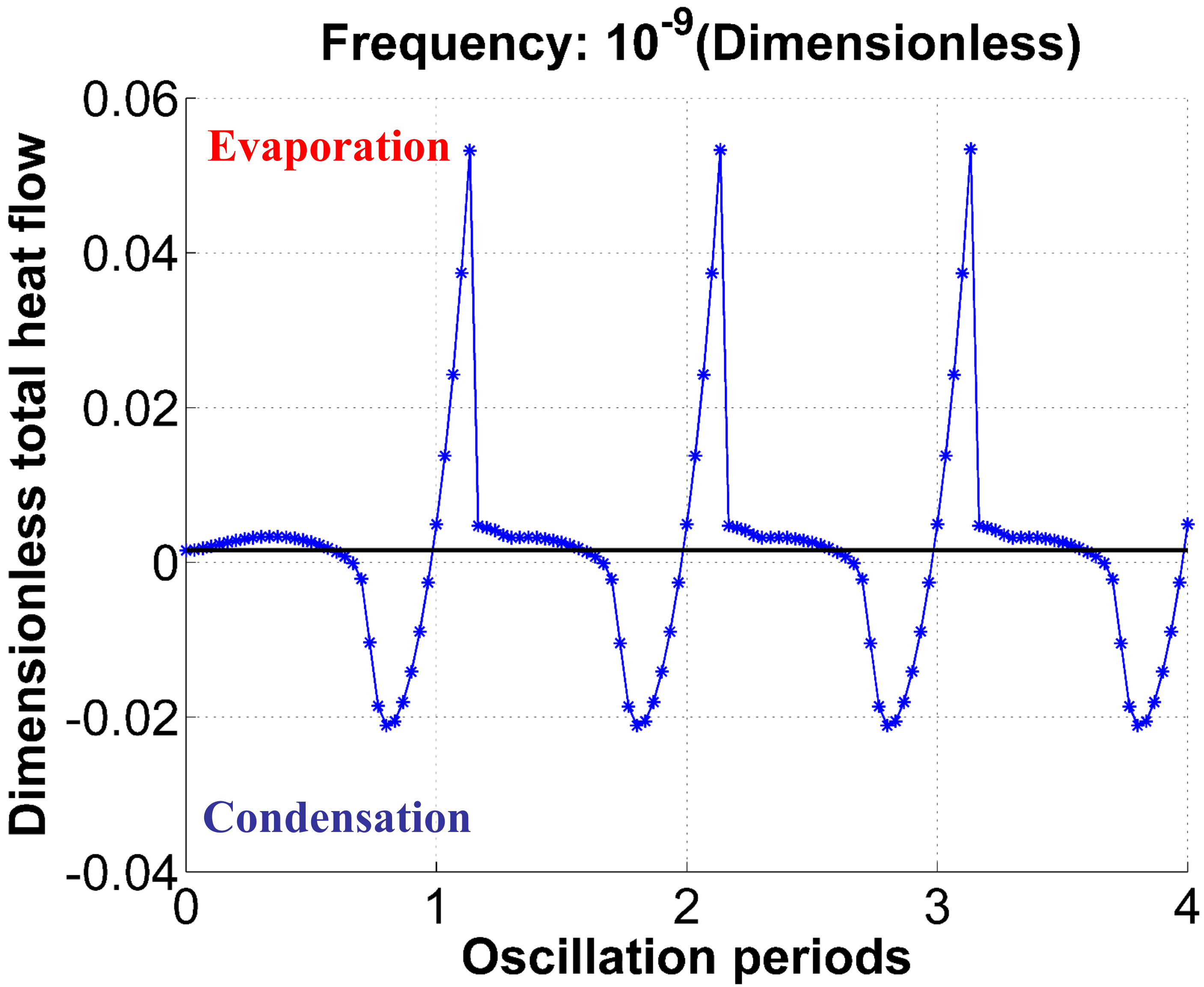
Heat Flow vs Frequency

- First results indicated an advantage to oscillation but only at a particular frequency.
- Further analysis using enhanced sampling and different fluids contradicted the original results.
- Ammonia was even worse.
- Problems including the sampling and method for inducing oscillation.





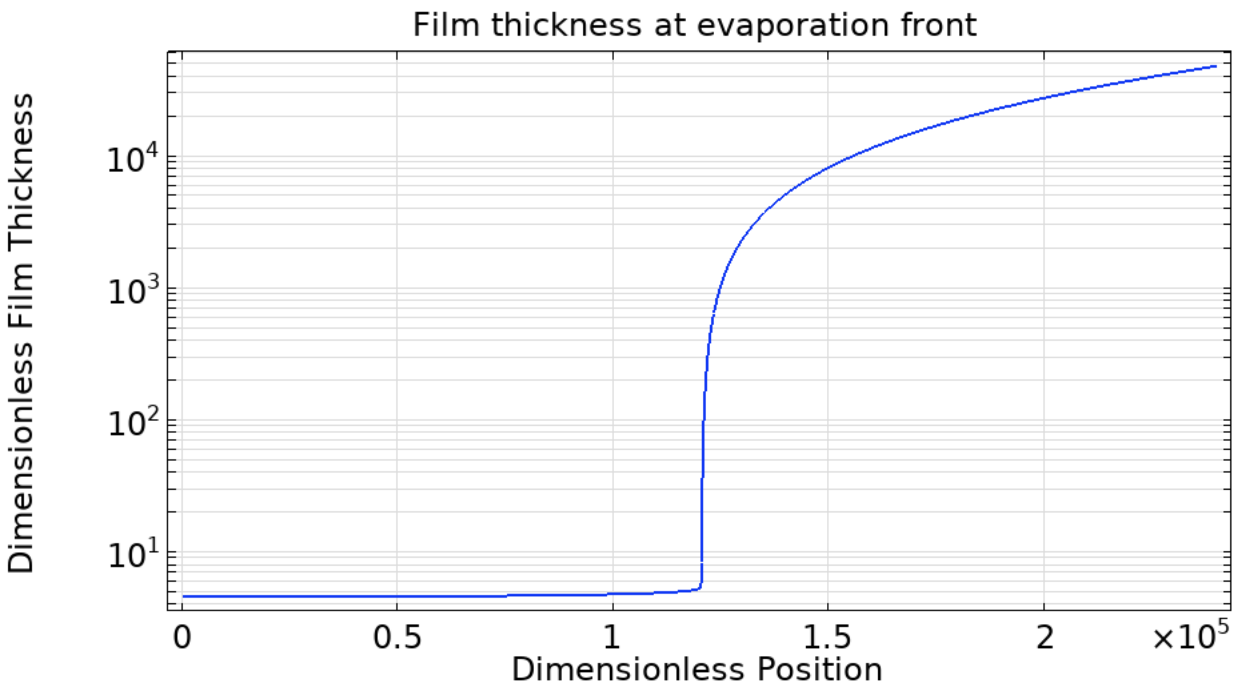
Heat Flow Profiles

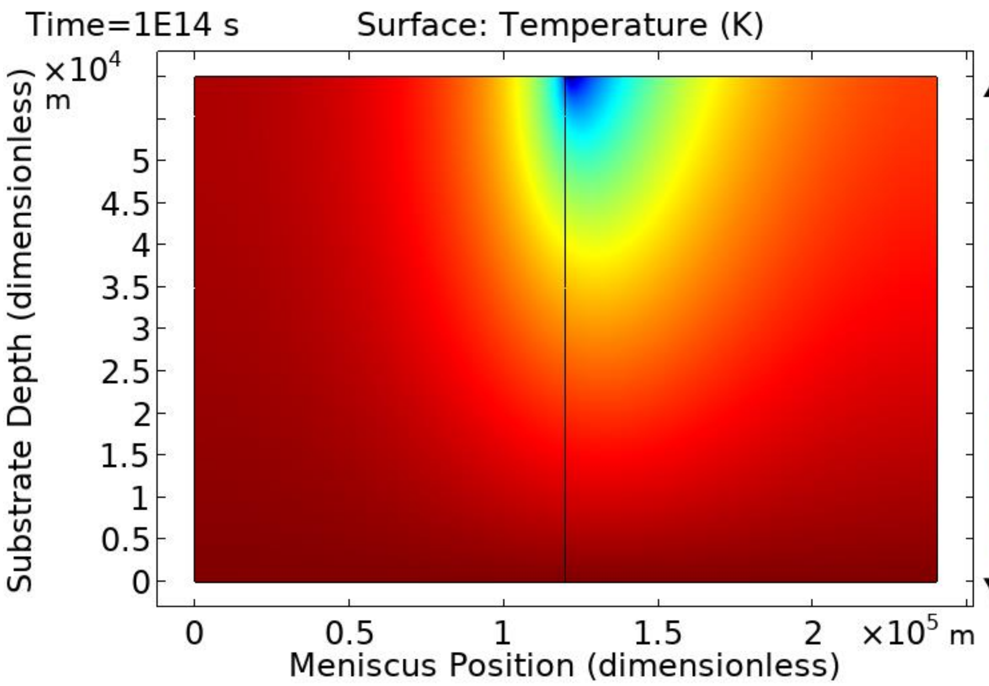


- Heat flow exhibits a characteristic profile.
- Sharp spike for evaporation followed by a longer lull and shallow dip when condensation occurs.
- Points here show original sampling.
- When we adapted sampling to be more uniform across the entire profile, we contradicted our original results.
- Need a new approach.

Alternative Method

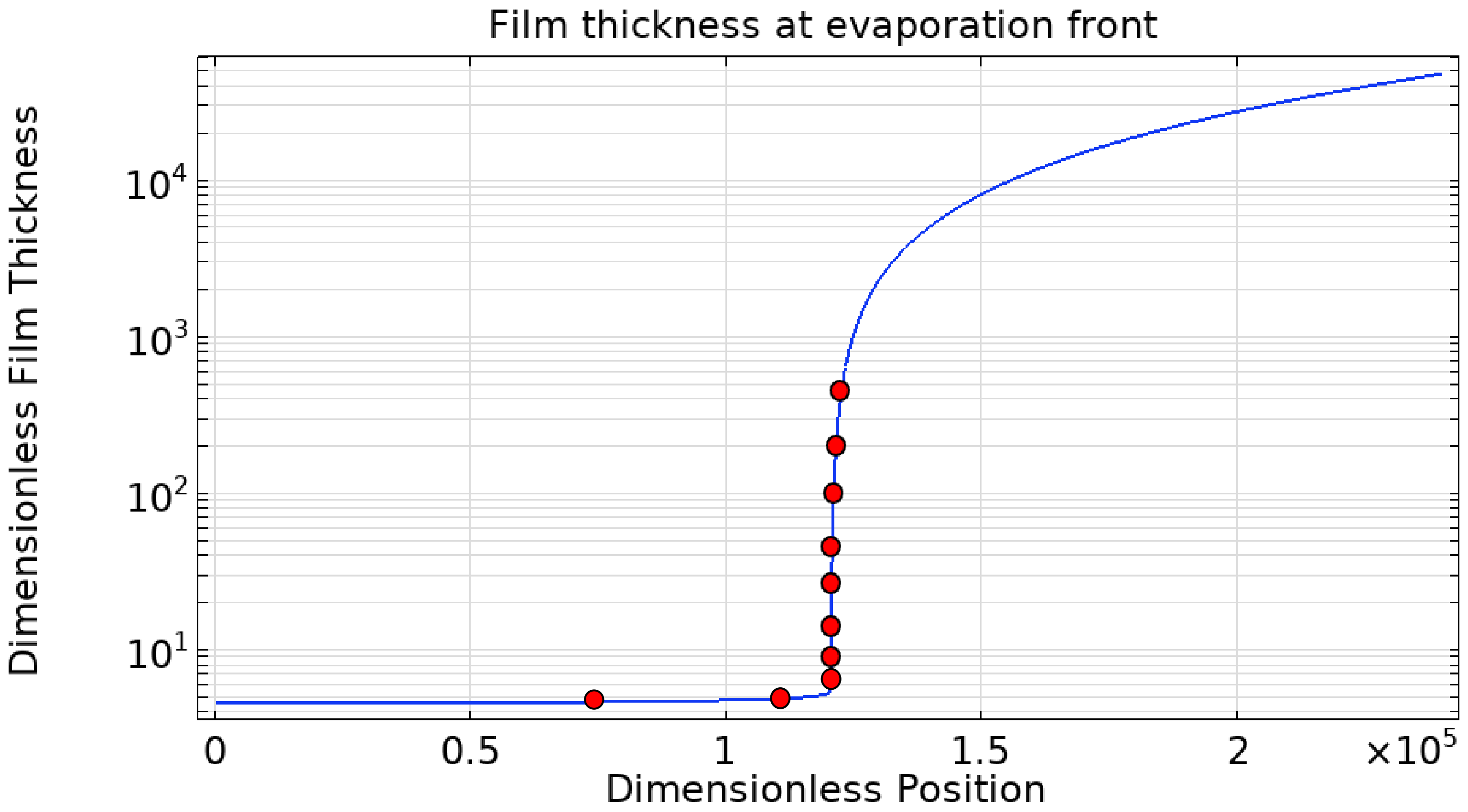
- Due to the limitations of the previous simulation, we searched for a way to improve the model and unambiguously determine whether oscillations occur to enhance heat transfer.
- We determined a way to wiggle the thickness of the film at discrete points on the surface.





Alternative Method

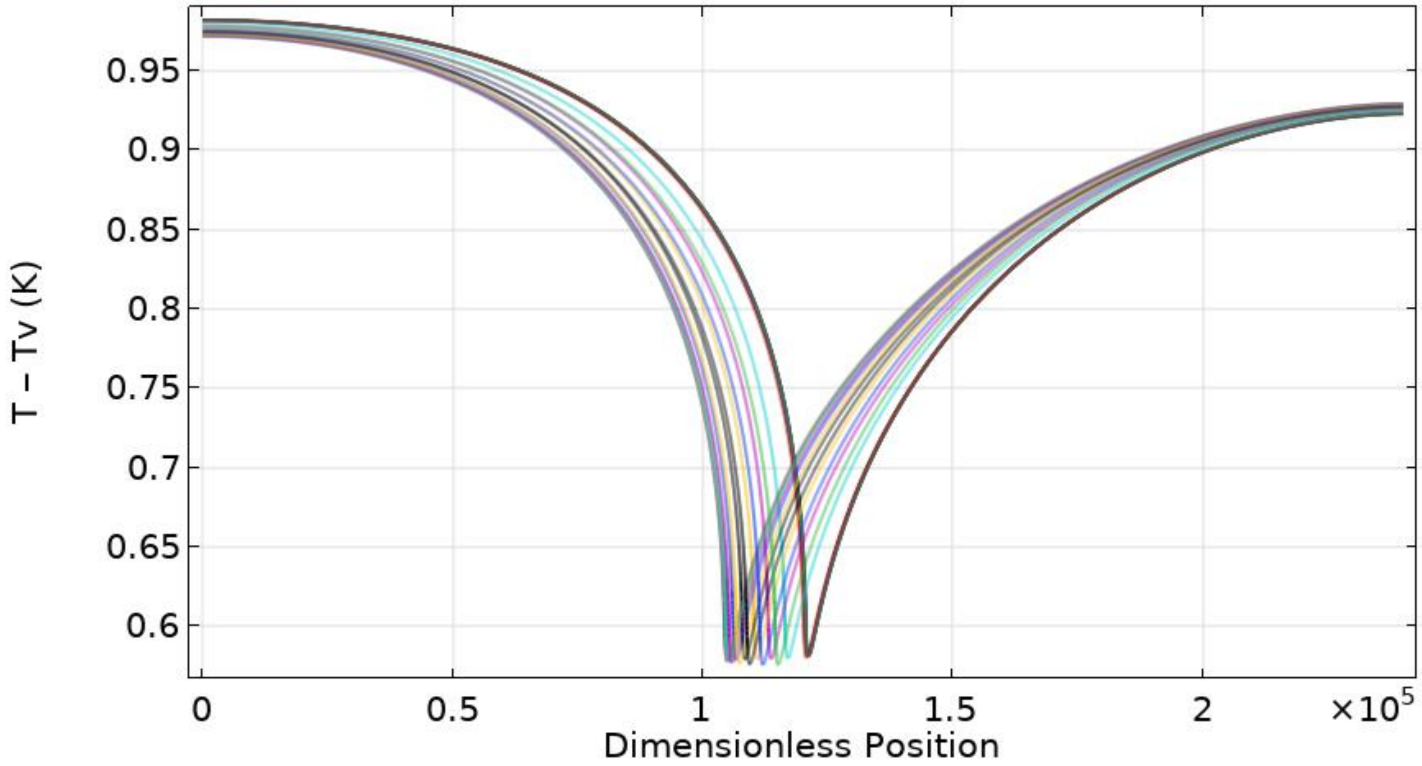
- We chose various positions along the length of the substrate to determine how the heat flow behaves when we wiggle the film thickness the same amount at each location.
- Red circles indicate the sampling points chosen at intervals of d/d_0



Superheat

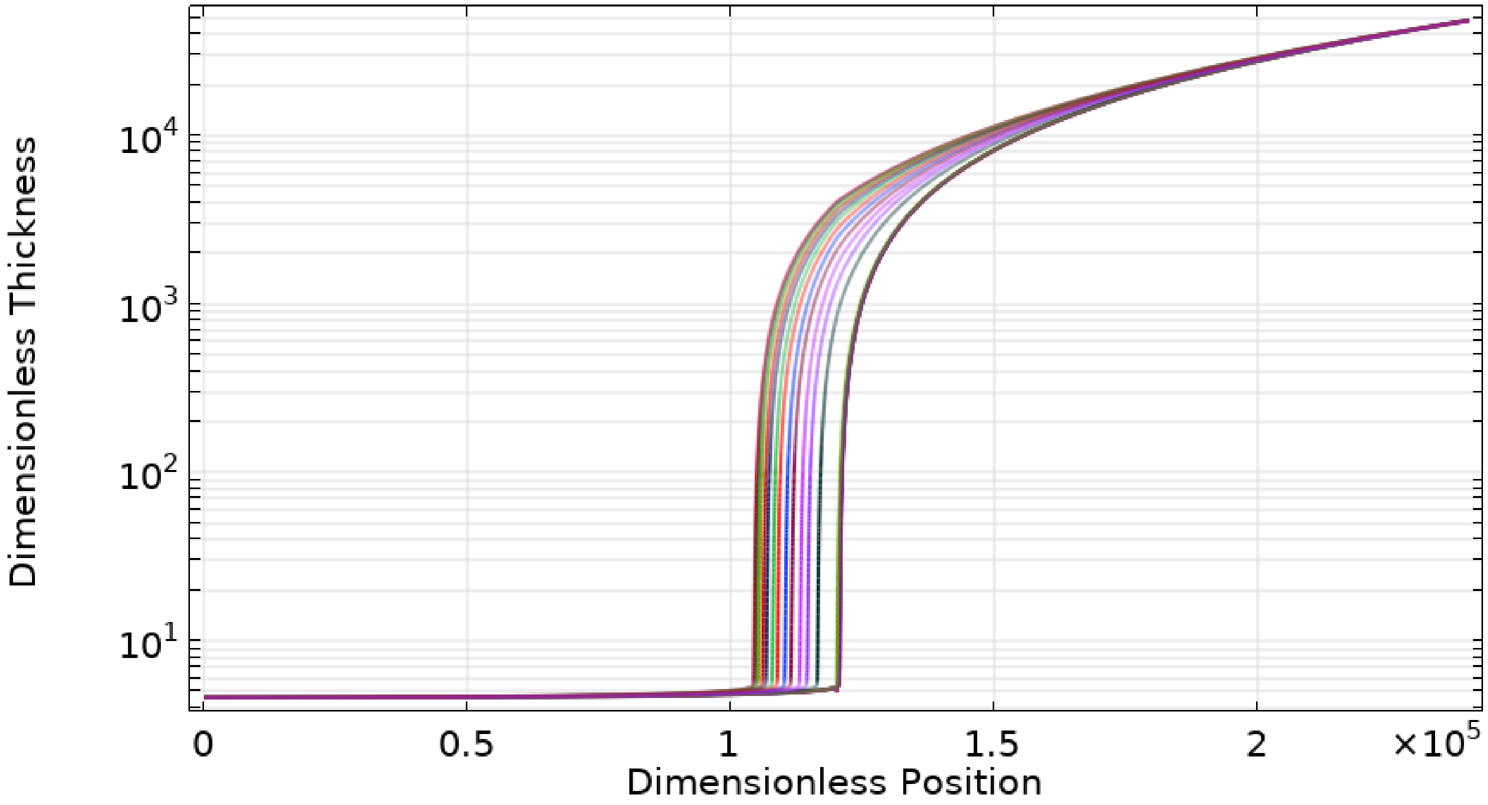
- Surface temperature follows the oscillations.
- As evaporation occurs from nearly the entire film, the surface temperature is depressed from the substrate temperature but always above saturation.
- As film oscillates the location of maximum evaporation changes but the magnitude remains almost constant.

Surface Temperature



Film Thickness Oscillations

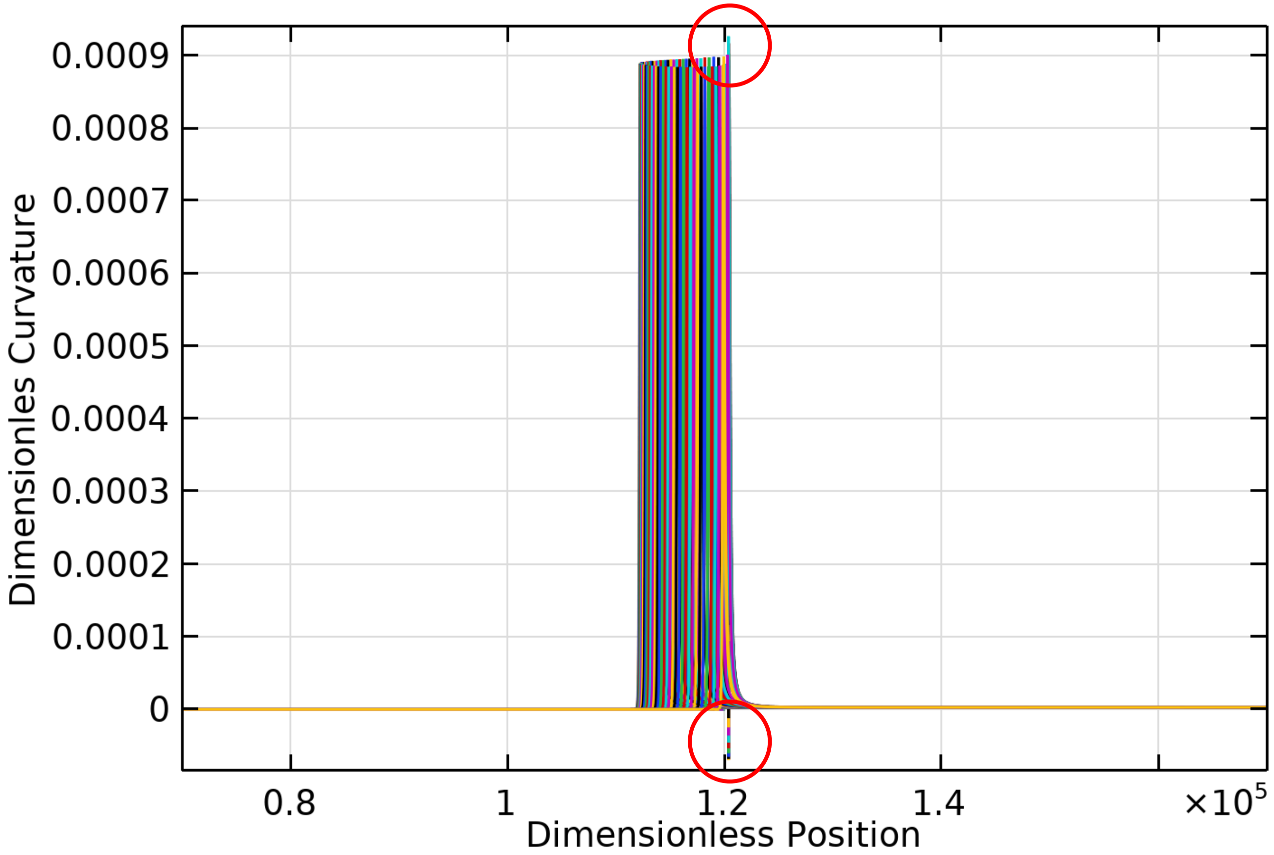
- If we place the oscillation point greater than the adsorbed film thickness, the film will oscillate with relatively large amplitude.
- Notice that though the film appears to oscillate, it does not alter the adsorbed film thickness to any great degree.



Film Thickness

Curvatures Oscillations

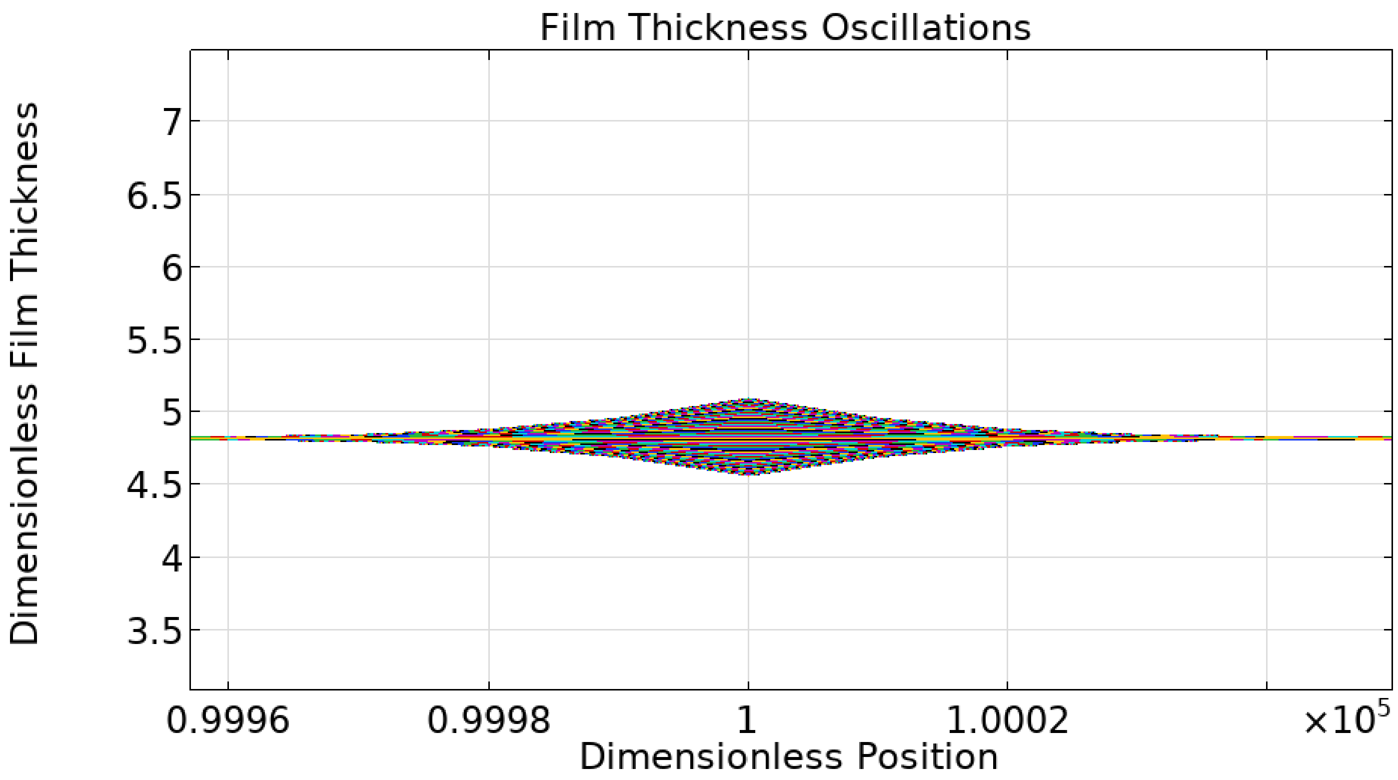
- The curvature profiles also follow the oscillation in film thickness.
- Notice the two points about maximum evaporation where we have a spike in curvature and negative curvature as the film changes and wants to spread on the surface.



Curvature

Film Thickness at Adsorbed Film

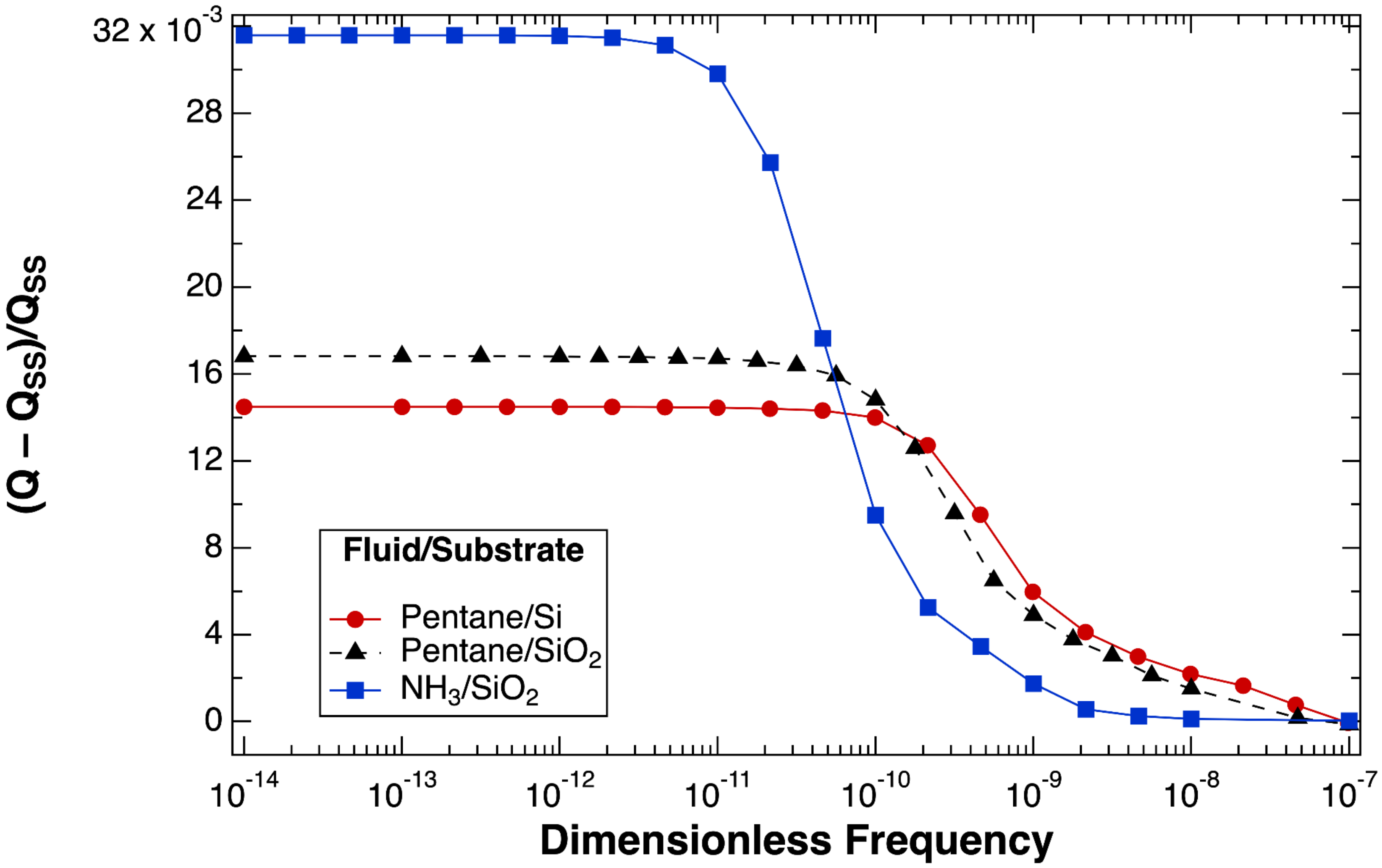
- Film thickness oscillations in the adsorbed film are fairly small.
- The forces holding the film to the surface are relatively strong.
- Oscillations don't penetrate very far from the locus of the oscillation.



Superheat Adosrbed Film Region

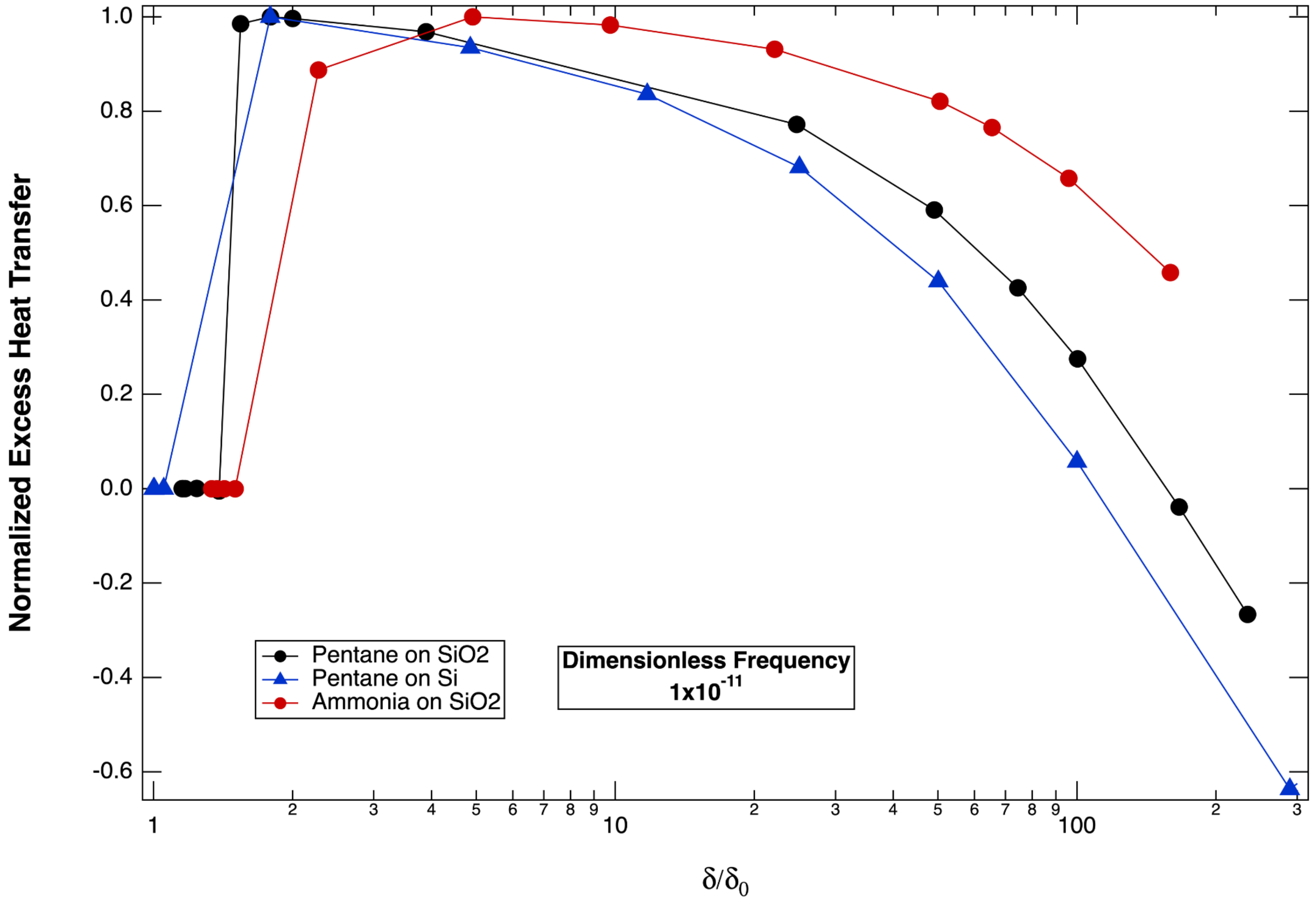
- Oscillations in the adsorbed film barely register in the superheat on the surface.

Excess Heat Flow vs Frequency



- Oscillations serve to increase the net heat transferred above the steady state at all frequencies.
- The oscillations are more effective on substrates that have lower thermal conductivity.
- The oscillations are more effective but roll off faster for fluids with higher heats of vaporization.

Position of Oscillation is Important



- The effect of oscillations depends upon where the locus of oscillation is located.
- Oscillations in the adsorbed film do not enhance or decrease the net heat transfer.
- The most effective region for oscillation occurs between about 1.5 – 2 times the adsorbed film thickness.
  - Maximum depends on fluid and substrate.
- Oscillations can be detrimental if the locus is beyond about 100x the adsorbed film thickness.

Conclusions

- Oscillating films occur in nearly all instances of heat transfer, if one looks in sufficient detail and sufficient magnification.
- Probing whether oscillation enhances, decreases, or is neutral with respect to the steady-state value depends on how one wants to induce the oscillation.
- If substrate temperature is cycled, the adsorbed film controls a lot of what is observed and oscillations have little effect.
- If specific points or regions of instability exist oscillations can enhance or decrease the heat transfer.
- It appears that the film and heat transfer are most sensitive to oscillation in the region where the film is 1.5 – 10x the adsorbed film thickness.
- Much more work is required to isolate if there is a natural frequency of oscillation and the trends predicted by the simulation.