MODELING CONTACT LINE DYNAMICS IN EVAPORATING MENISCI

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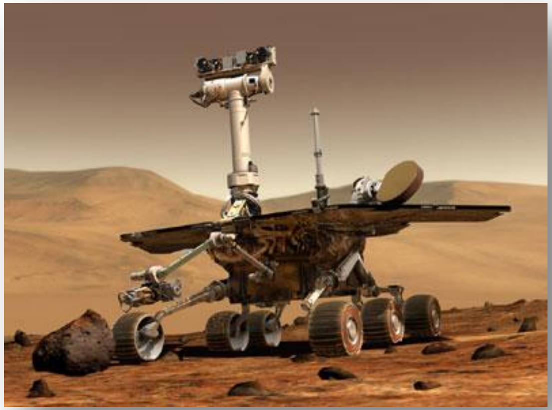
Electronic cooling

Space & Aviation

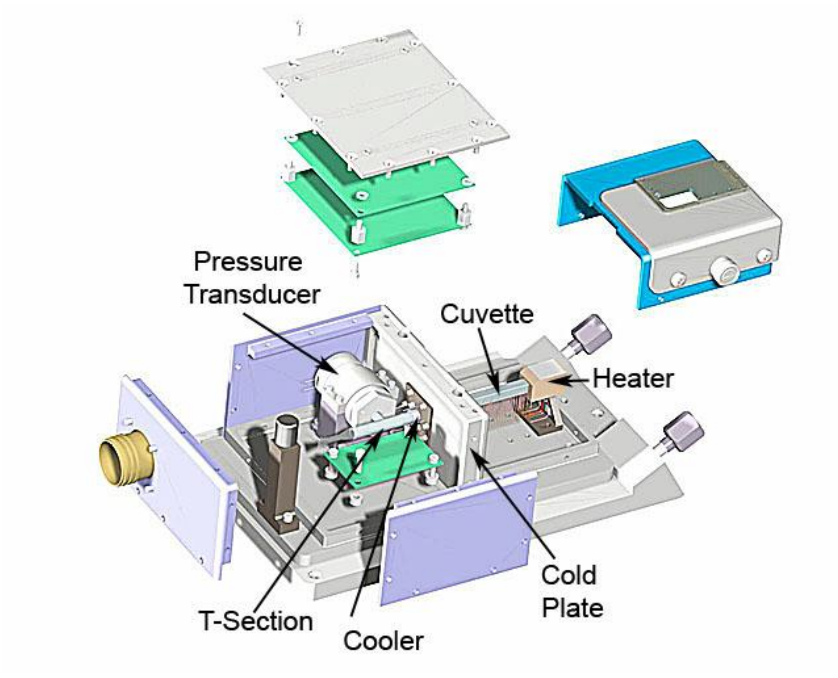
Evaporative Self Assembly



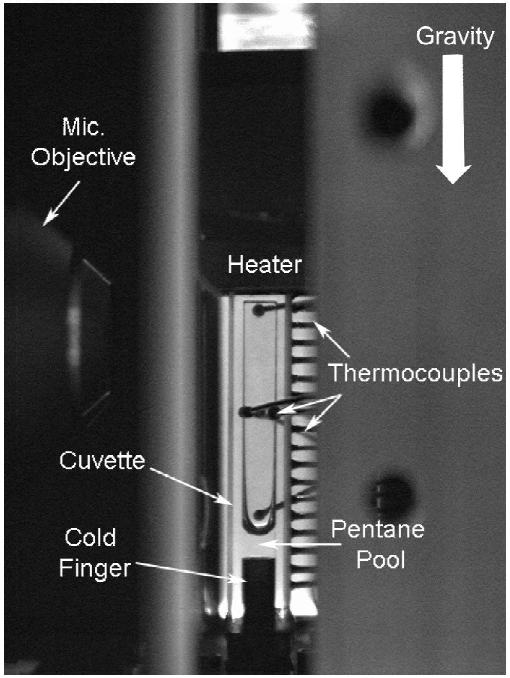
Excerpt from the Proceedings of the 2012 COMSOL Conference in Boston

Experimental System – CVB Experiment

ISS CVB Module

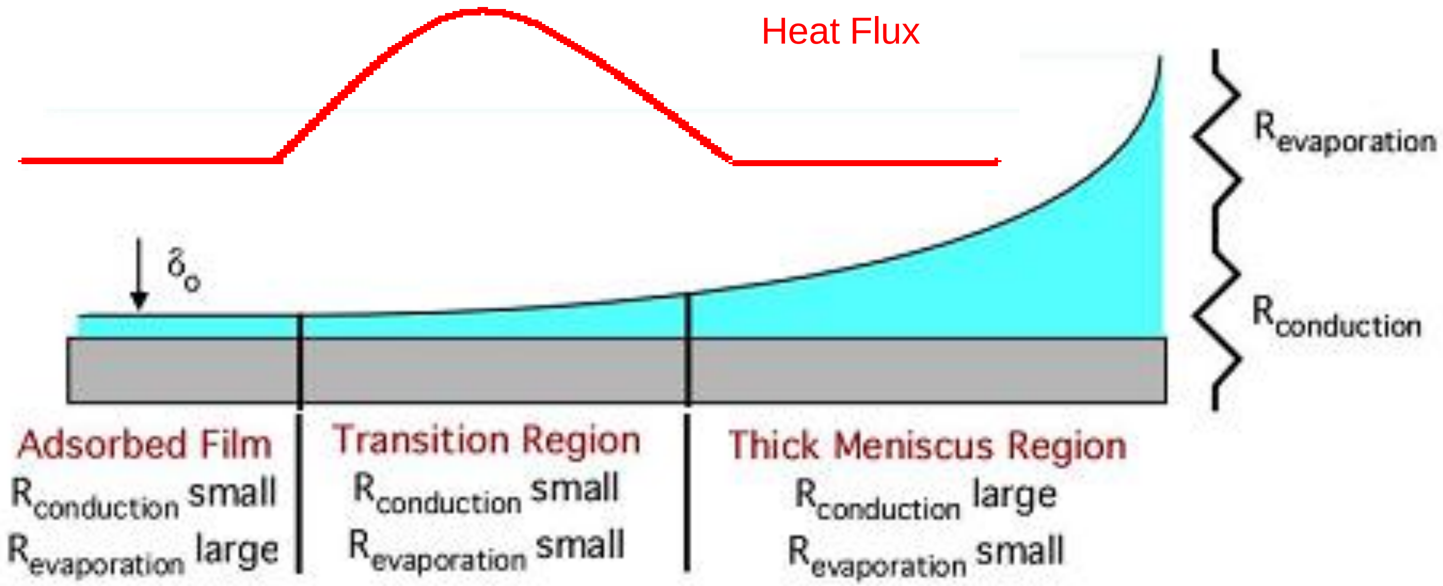


Photograph of Module



- Partially filled cell forms a Constrained Vapor Bubble (CVB) design.
- Wickless heat pipe with transparent walls.
- Goal is to measure the vapor and liquid distributions as the pipe is driven.

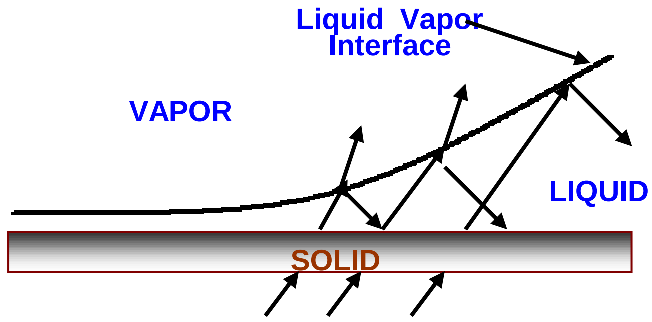
Evaporation from a Thin Film



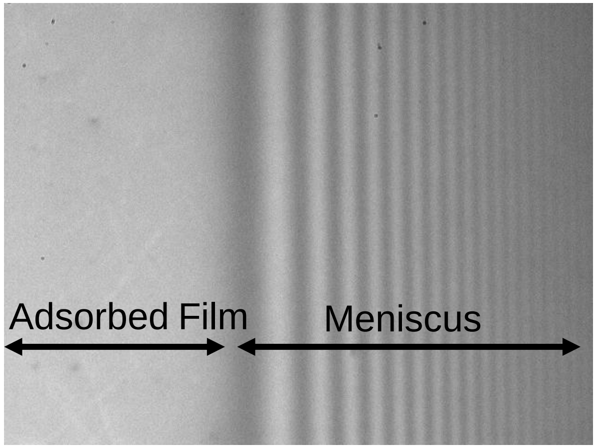
Transition region controls evaporation. Lowest overall resistance.

- Accurate modeling will enable us to engineer optimal surfaces

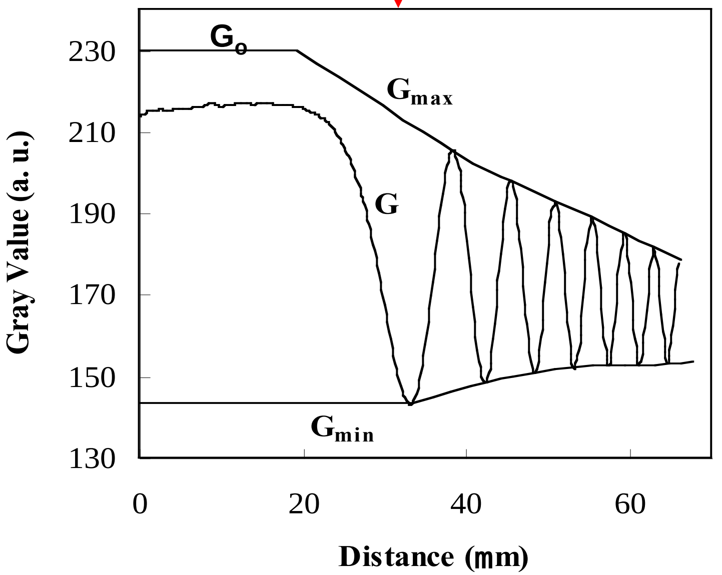
Reflectivity/Interferometry Technique



Varying thickness of the meniscus produces an interference pattern



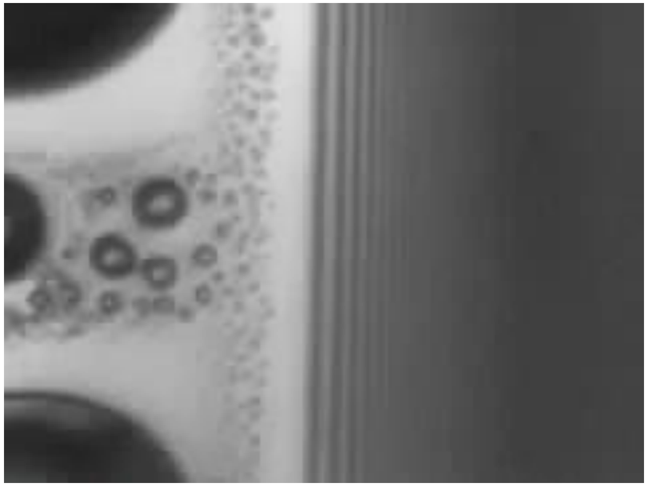
Interference pattern analyzed to obtain gray value at each pixel

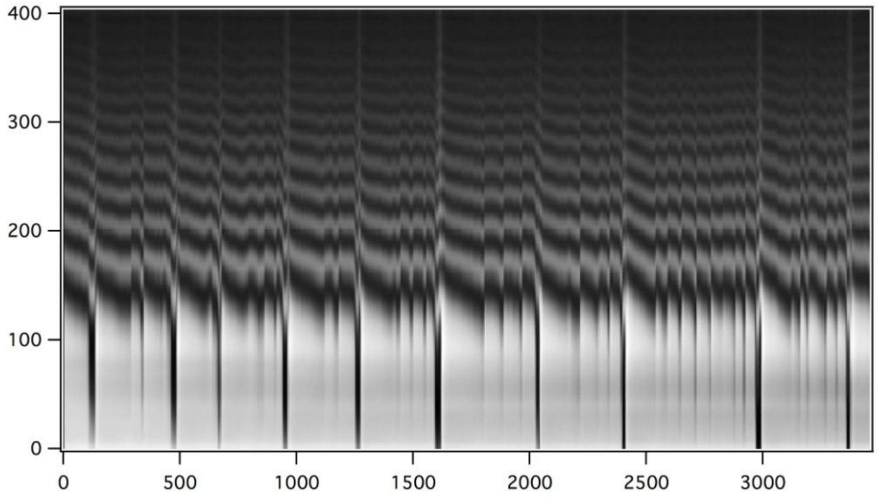


Analysis yields:

- Film thickness profile
- Contact angle
- Interface curvature

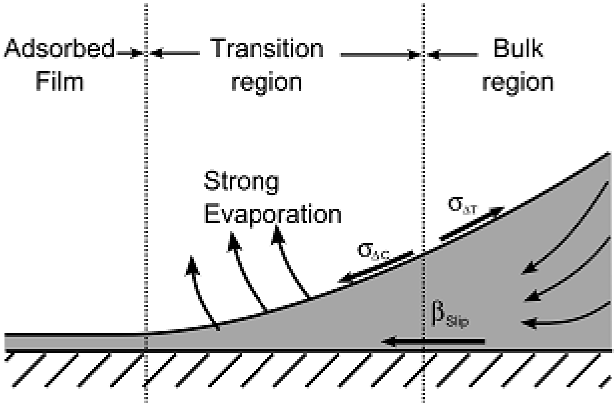
Evaporating Meniscus – HFE-7000





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

Fluid Flow Model



- Lubrication approximation used to model fluid flow.
- Navier slip (solid-liquid interface) and Marangoni shear (liquid-vapor interface) boundary conditions applied

$$\mu \frac{d^2u}{dy^2} = \frac{dP_l}{dx} \qquad y = 0, \quad u_s = \beta \left.\frac{du}{dy}\right|_{y=0}$$

$$P_l(x) = P_v - \left[\sigma(x)K(x) + \Pi(x)\right] \qquad y = \delta(x), \quad \tau_{yx} = \frac{d\sigma_{lv}}{dx}$$

- Temperature dependence of fluid properties accounts for the capillary, Marangoni and van der Waals forces.
- Mass balance, provides the evaporating mass flux at each pixel location.

$$\Gamma = \int_0^{\delta} \rho_l u \, dy \qquad \frac{d\Gamma}{dx} = -\dot{m}_{evp} \qquad q'' = -h_{fg} \frac{d\Gamma}{dx}$$

Heat Transfer at the Contact Line

- Heat transfer at the contact line was modeled using a Kelvin-Clapeyron approach.

$$\frac{d\Gamma}{dx} = -\dot{m}_{evp}$$

$$\dot{m}_{evp} = C\left(\frac{M}{2\pi RT}\right)^{1/2}\left\{\frac{P_v M h_{fg}}{RT_v T_i}\left(T_i - T_v\right) + \frac{V_l P_v}{RT_i}\underbrace{\left(P_l - P_v\right)}_{\text{Interface Shape}}\right\}$$

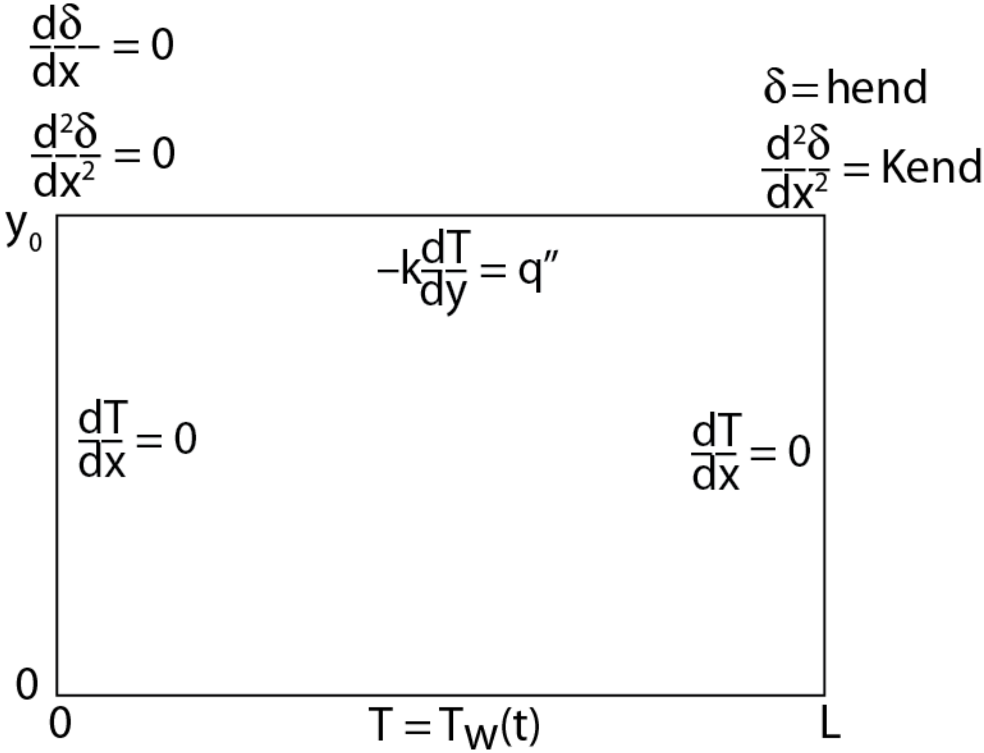
- The temperature difference across the liquid was tied to the mass flux to describe the driving force as a superheat.

$$T_i(x) - T_w = -\left(\frac{\dot{m}_{evp} h_{fg}}{k_l}\right)$$

- Final equation can be written as a 4th order differential equation for the film thickness.

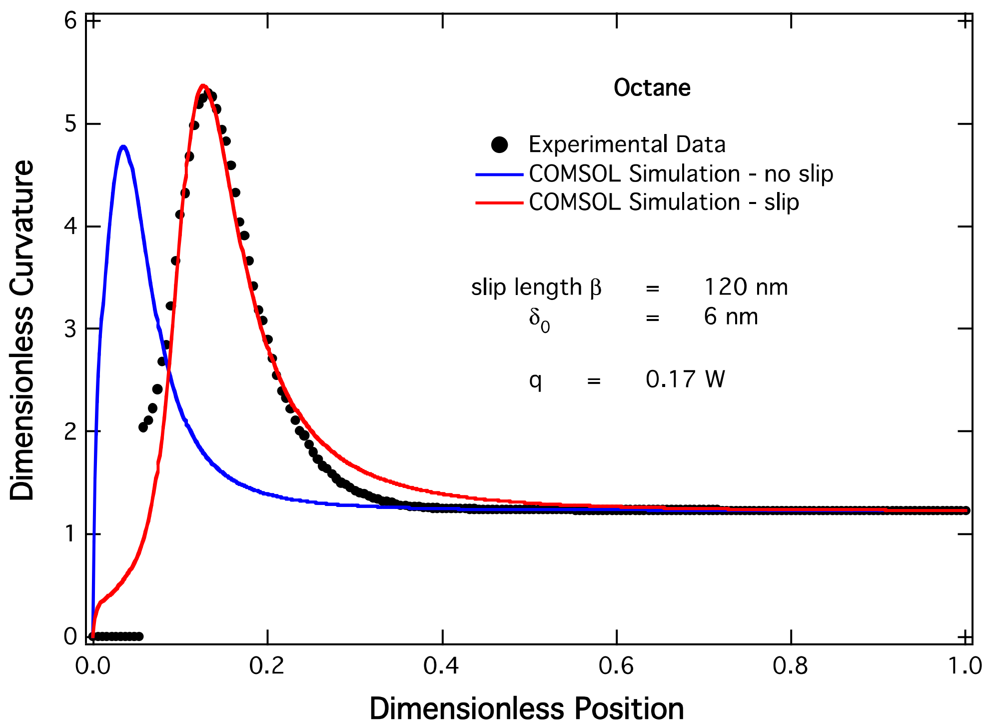
Comsol Set-Up

- Split the 4th order equation into two 2nd order equations for film thickness and interface curvature.
- 1-D weak form on the boundary.
- 2-D conduction heat transfer in the solid.
- Boundary conditions set film thickness and curvature at the thick end, and the curvature and slope at the start (perfectly wetting fluid).



Simulation Results – Steady-State

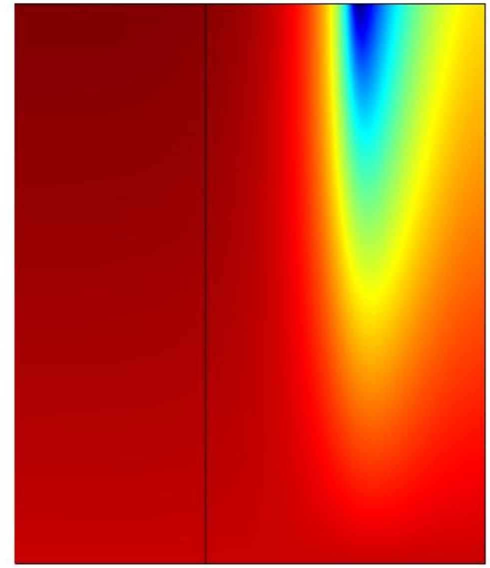
- COMSOL simulation was able to reproduce the experimental data from an octane meniscus.
- The incorporation of hydrodynamic slip was necessary to match both the position of the curvature peak and the spread of the peak.
- Peak height is controlled by the thickness of the adsorbed film ahead of the contact line.



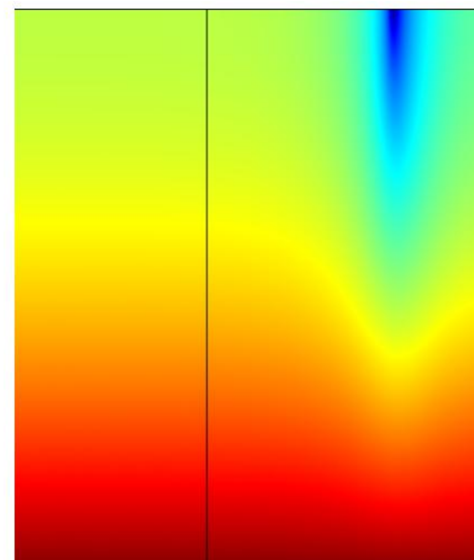
Simulation Results – Oscillation

- COMSOL simulation was applied to an pentane meniscus.
- Oscillation was established by varying the temperature on the underside of the substrate.
- Plots show snapshots of the temperature profile in the substrate for two different substrate materials at the same time during the oscillation.
- Higher thermal diffusivity leads to a different dynamic mismatch between heat delivered to the film and heat removed via evaporation.

SiO_2

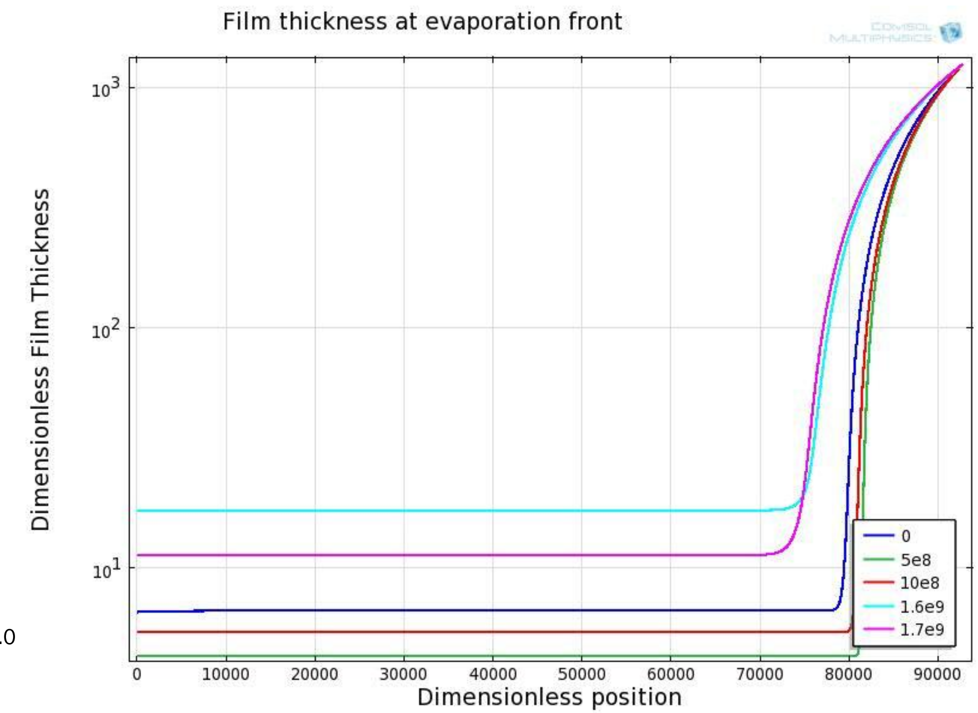


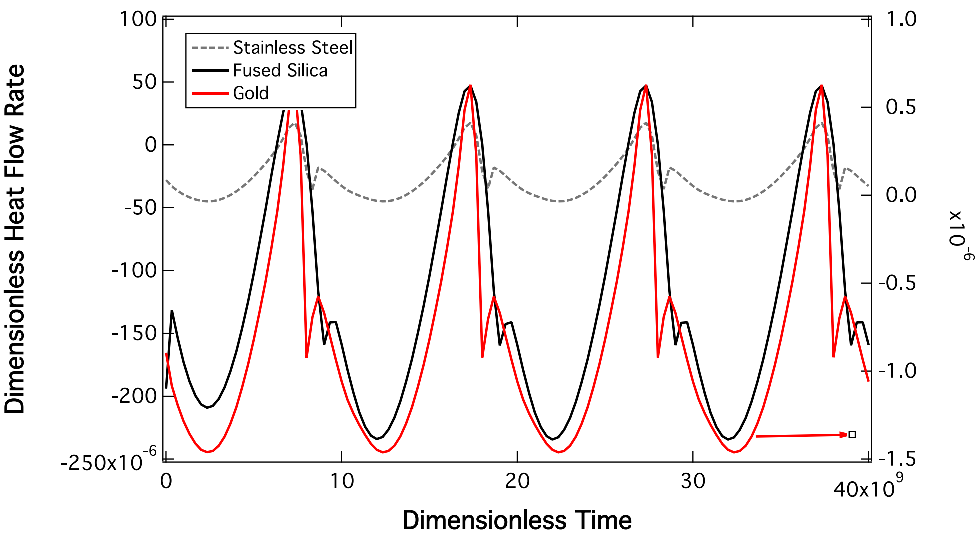
Au



Simulation Results – Oscillation

- Achieve large changes in film thickness for small differences in applied temperature (here ~ 0.01 ˚C)





- Dimensionless heat flow rate changes dramatically with substrate material. The oscillation phase also changes and for certain forcings, the film oscillates at higher frequency.

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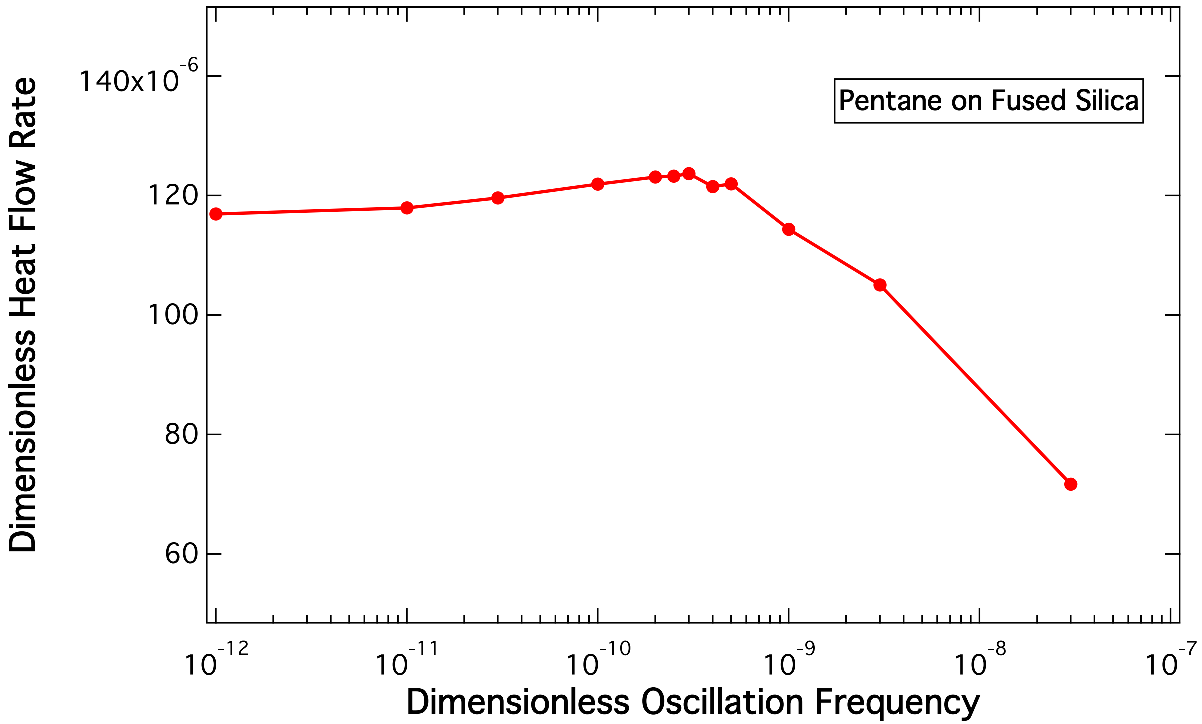
Simulation Results – Oscillation



- Film acting as a low-pass filter.
- There is a small resonance that we need to explore further.

Conclusions

- **We can reproduce some of what we observe in an oscillating evaporating meniscus.**

- **Oscillation amplitude and frequency are related to a mismatch between the heat dissipation rate in the film and the rate at which heat can be delivered from the substrate.**

- **Much more modeling work is needed to match up with actual experimental data and to mimic all the behaviors we observe in the thin film.**