CVB: The Constrained Vapor Bubble Capillary Experiment on the International Space Station

MARANGONI FLOW REGION

Peter C. Wayner, Jr., Akshay Kundan, & Joel Plawsky
Rensselaer Polytechnic Institute
Troy, NY, USA,

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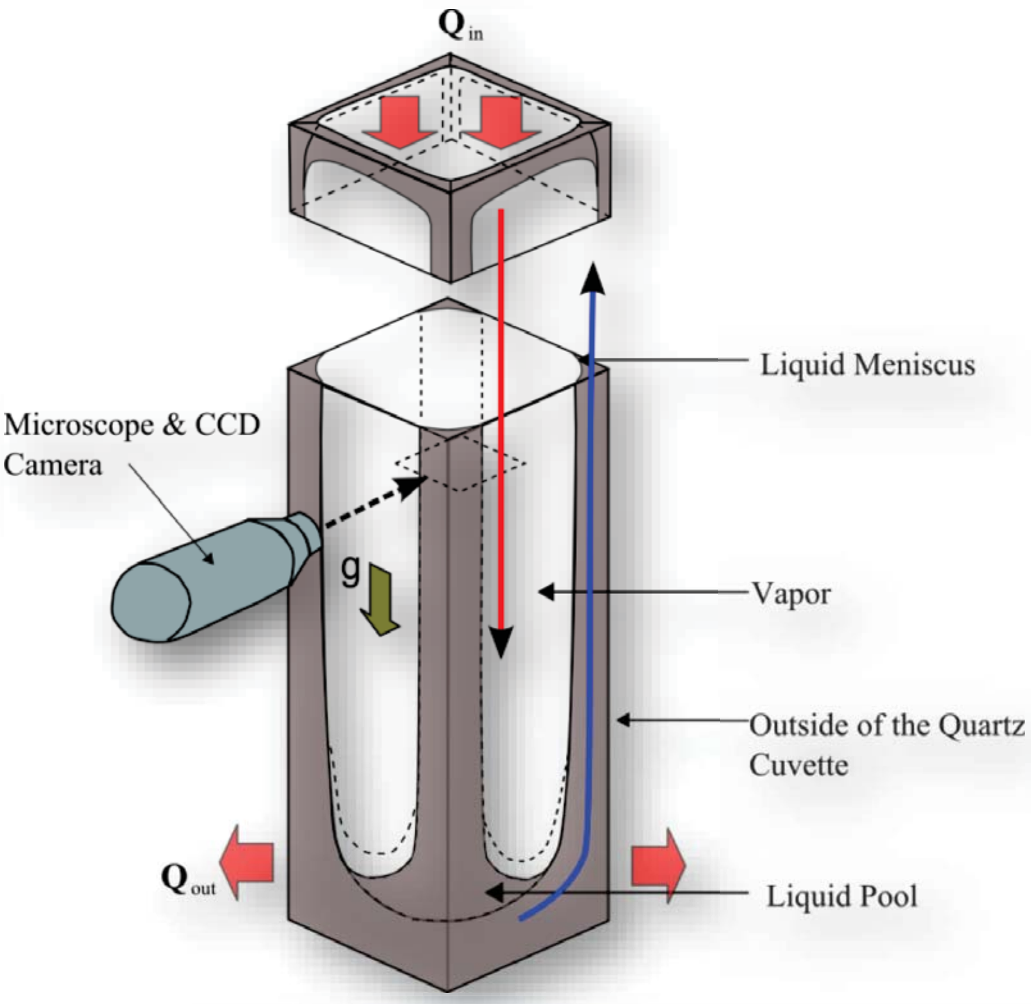
THE CVB HEAT TRANSFER SYSTEM



- The CVB is a Constrained Vapor Bubble inside a quartz cuvette with a working fluid like pentane.
- Inside 3mm x 3mm ~ 30 or 40 mm long
- Liquid rises along the sharp corners and across the flat surfaces due to interfacial forces.
- Heat source at one end.
- Inside Radiation and Radiation to the surroundings Important
- Evaporation from the hotter regions; condensation in the cooler regions;.
- Important visual observation through the cuvette gives unprecedented insight into transport processes.
- Emissivity = 0.775 for thermal radiation frequencies.

A transparent “heat pipe” – ideal for studying basic fluid flow and heat transfer due to interfacial forces inside .

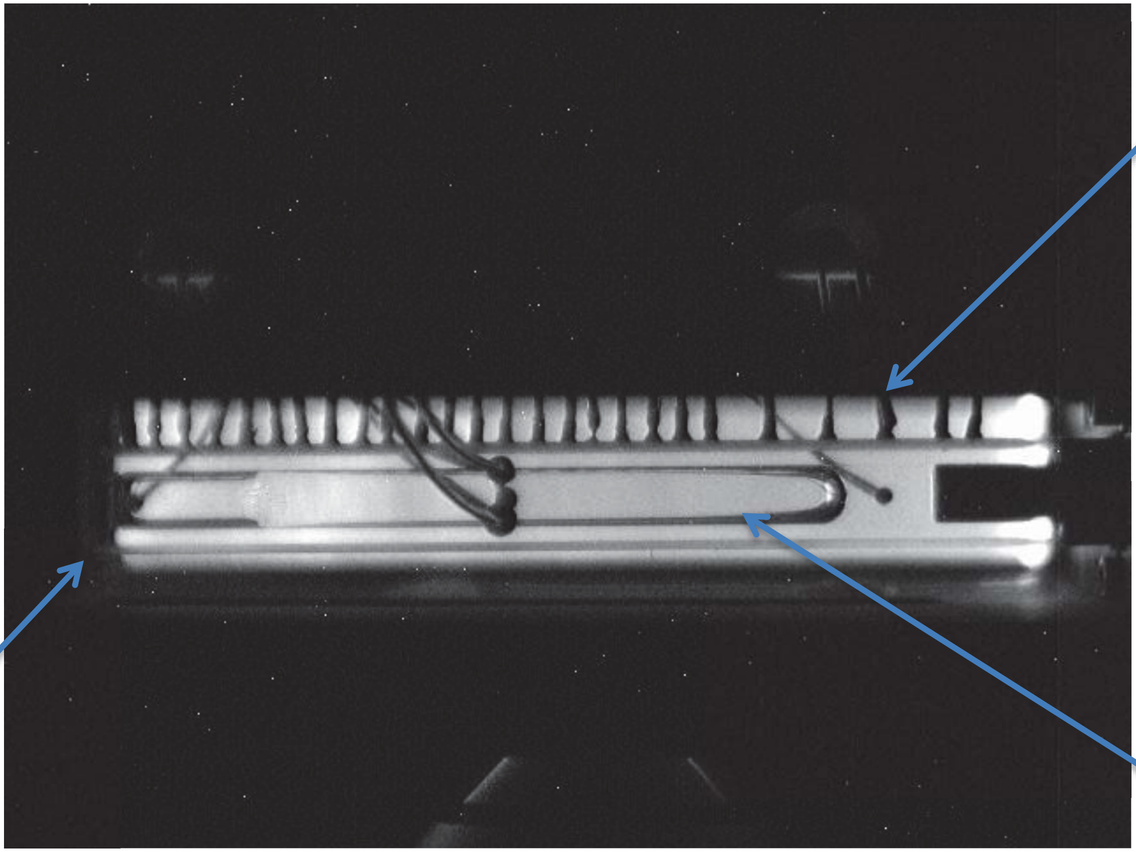
APPARENTLY SIMPLE CONCEPT

HOWEVER, WE FIND EXPERIMENTALLY

THAT THERE ARE MANY COMPLEX

3D INTERFACIAL REGIONS

Surveillance Camera Image:
40 mm higher flux



THERMOCOUPLES

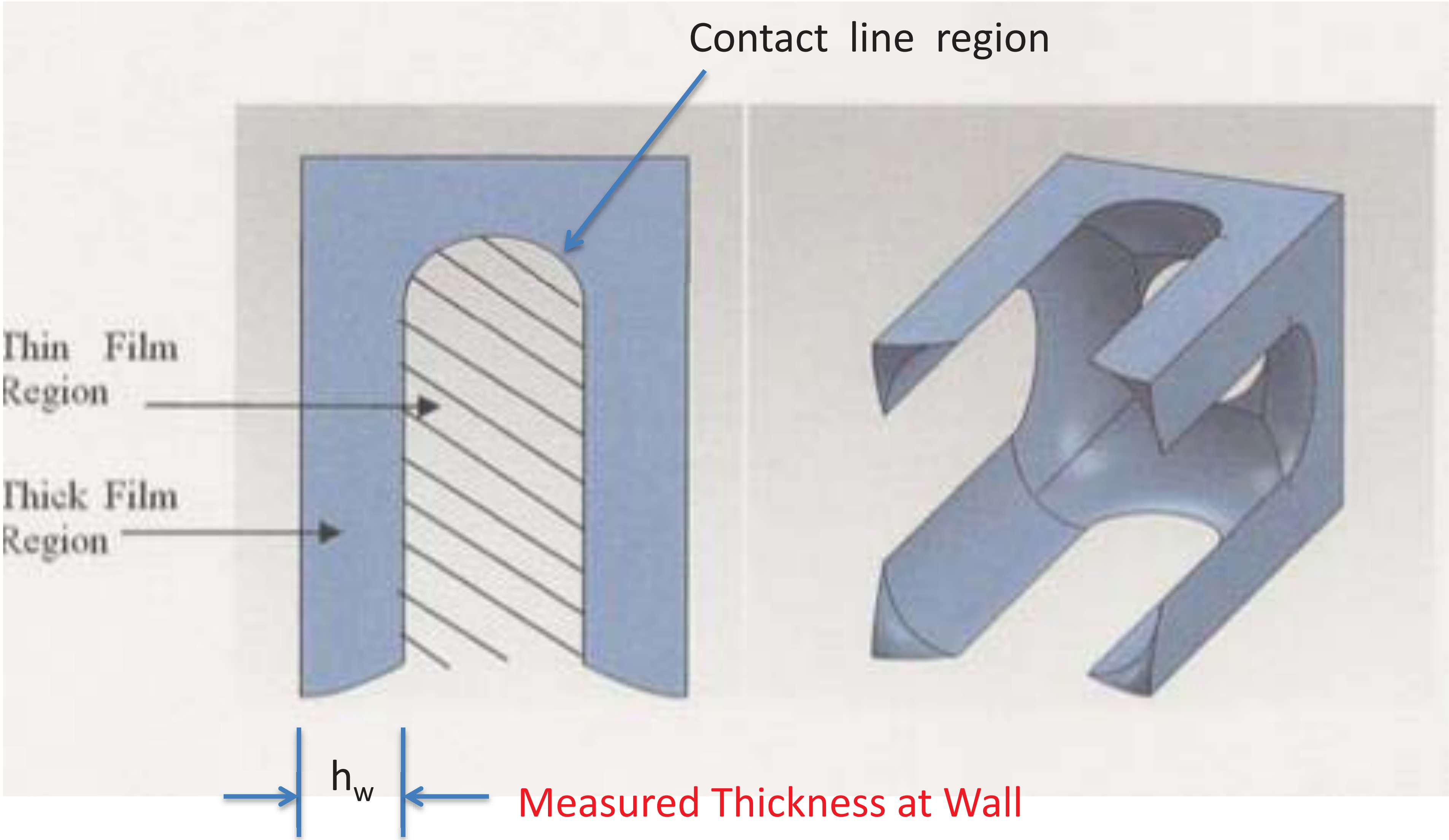
HEATED END

COLD END DUE TO RADIATION TO THE SURROUNDINGS ALONG THE LENGTH

CORNER MENISCI WITH CURVATURE GRADIENT

"Excess" fluid flooding at hot end due to large capillary flow, which we will discuss.

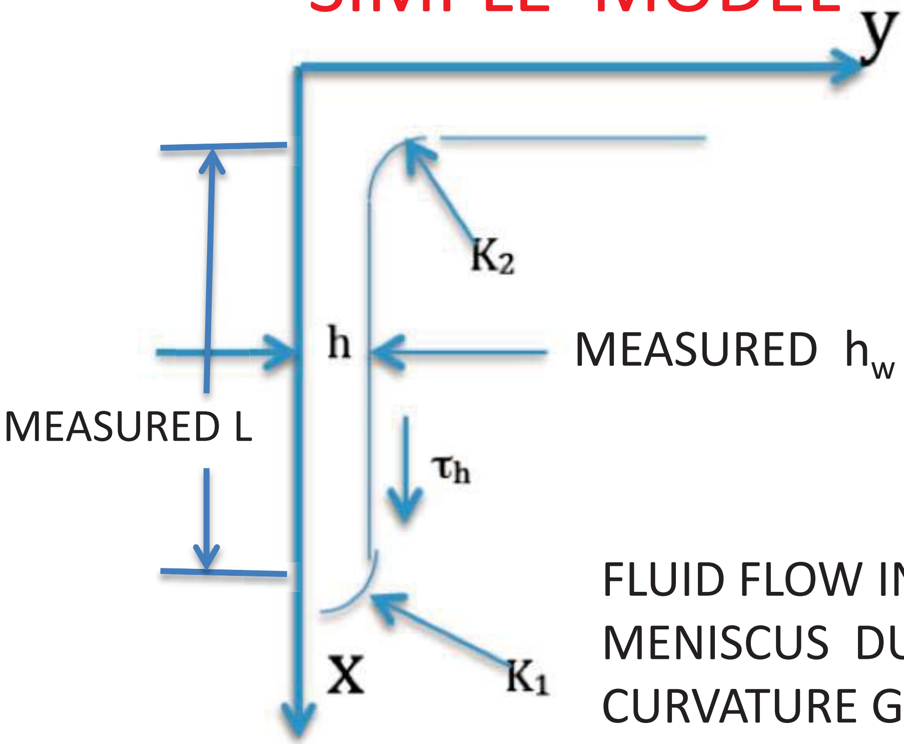
SKETCH OF 3D CORNER MENISCI WITH THIN FILM IN THE HOT END REGION



Measured Thickness at Wall

BALANCE OF PRESSURE GRADIENT, $(\sigma K)'$, DUE TO CAPILLARITY AND MARANGONI SHEAR, τ_h , DUE TO TEMPERATURE GRADIENT

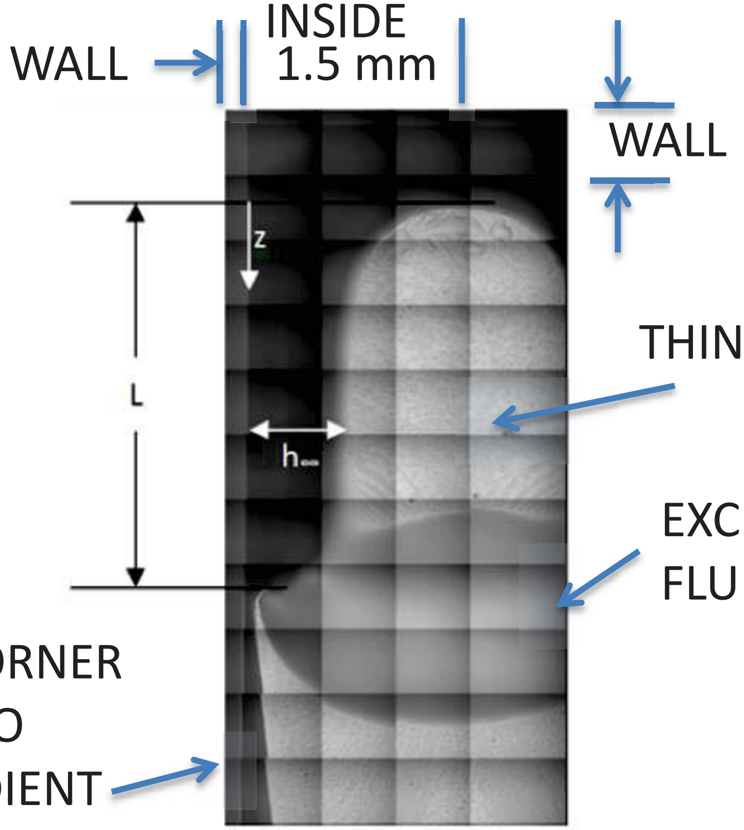
SIMPLE MODEL



MEASURED h_w

MEASURED L

FLUID FLOW IN CORNER
MENISCUS DUE TO
CURVATURE GRADIENT
GIVES "EXCESS FLUID"

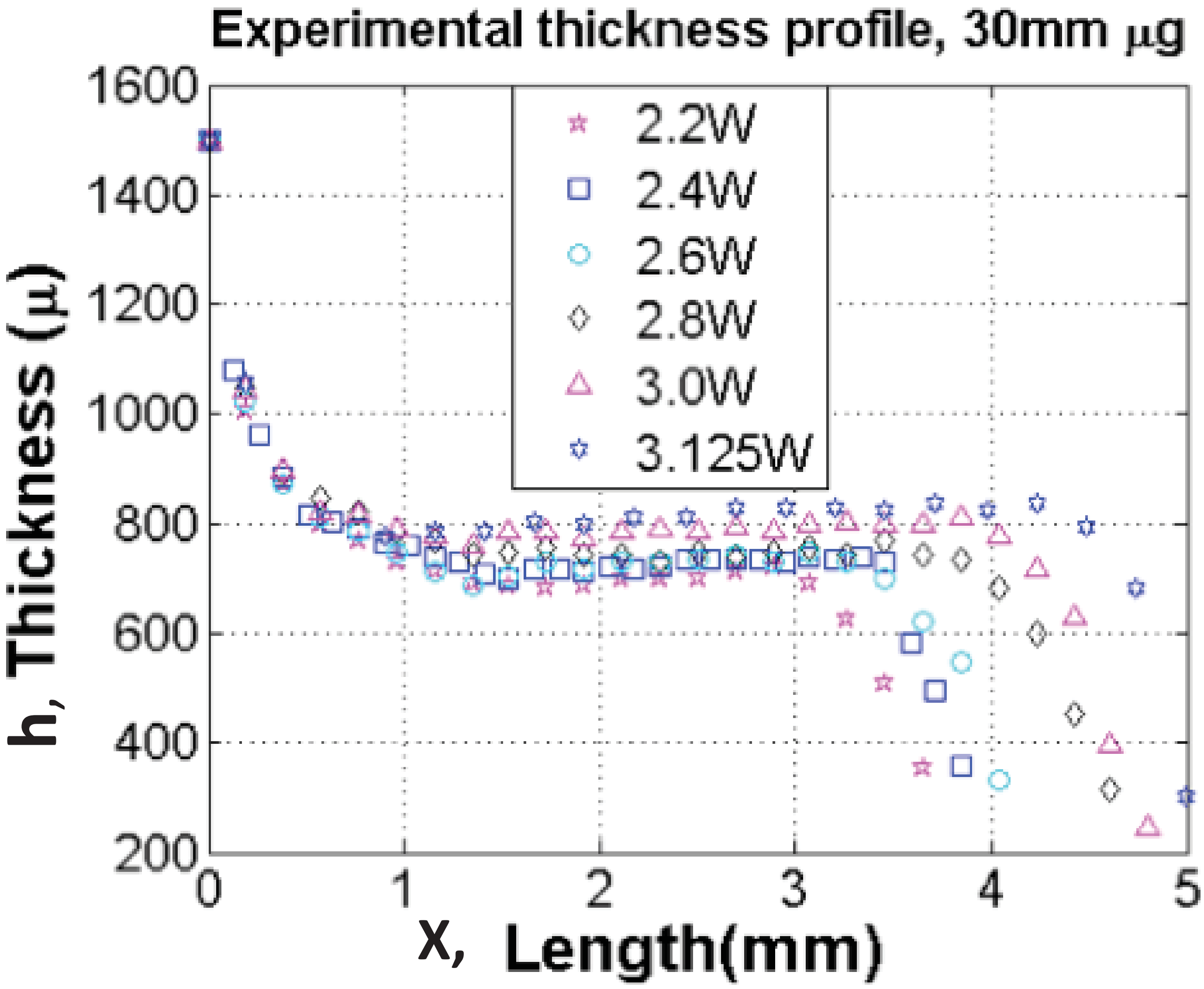


THIN FILM

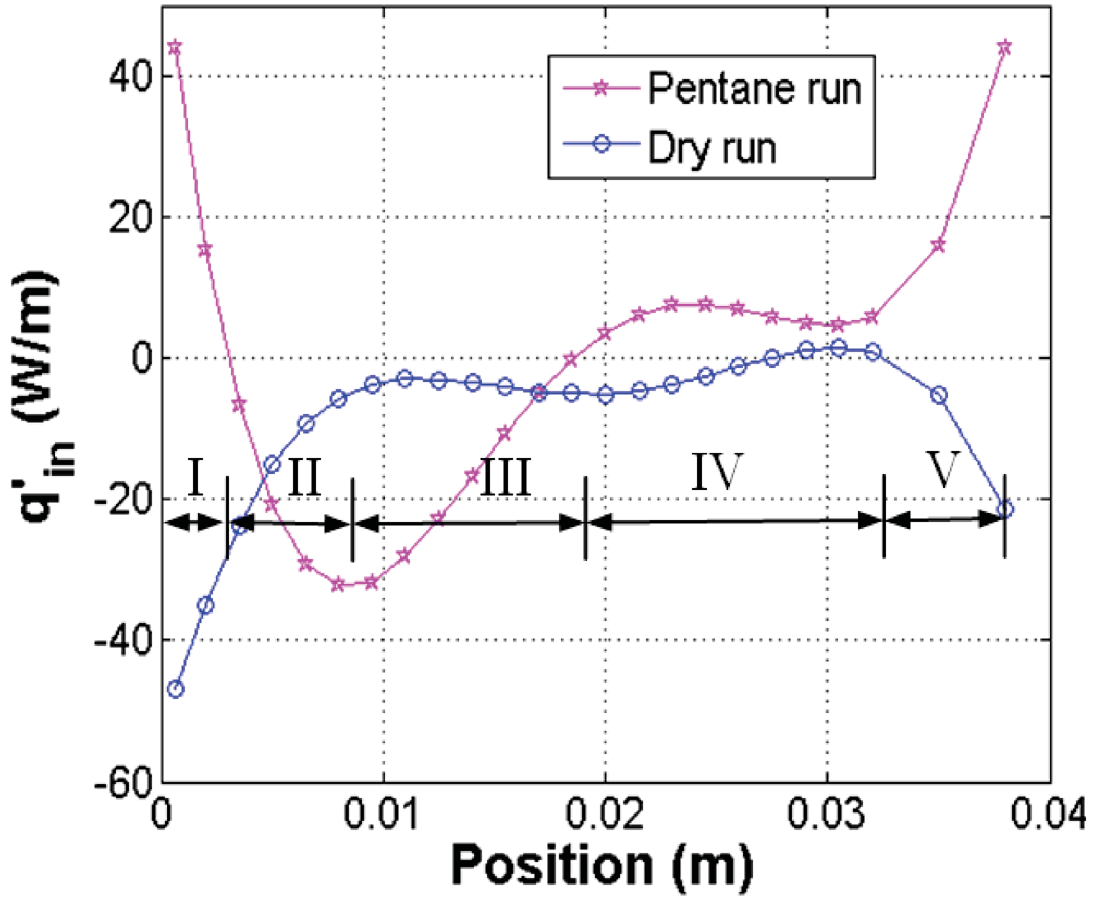
EXCESS
FLUID DROP

10 X PICTURES STITCHED TOGETHER
MEASURED K1 REGION AFFECTED
BY DROP AND FLOW IN MENISCUS

Liquid thickness at wall, $h_w = f(x)$, in the Marangoni dominated region.



1D Heat Analysis Model



Inside heat transfer rate per unit length for 2W 40 mm µg run

Pentane Run

- Region I: Radiation emitted by heater wall.
- Region II: Marangoni flow at the heated end with net evaporation.
- Region III: Classic evaporation.
- Region IV: Classic condensation.
- Region V: Accumulation of liquid near the cooler end due to interactions with the cold finger.

$q'_{in} < 0$: flux out of wall

INITIAL EVALUATION OF TRANSPORT PROCESSES

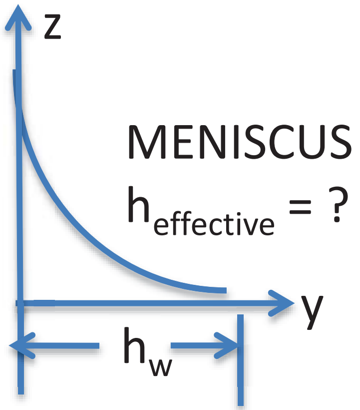
VERY SIMPLE FLUID FLOW MODEL WITH INTERFACIAL PHASE CHANGE

ASSUMPTIONS:

- the flow is 1D
- steady state with phase change, Γ
- The capillary pressure gradient due to cohesion adjusts to a constant over the distance L and is balanced by Marangoni surface shear

$$\frac{d\tau_{yx}}{dy} - \frac{dP}{dx} = 0$$

VELOCITY PROFILE IN CORNER MENISCUS



- ASSUMING

$$v_x = 0 \qquad at\ y = 0$$

$$\square_h = \frac{d\square}{dx} = \frac{d\square}{dT}\frac{dT}{dx} \qquad at\ y = h_w$$

$$\Gamma = \int_0^{h_w} v_x\, dy$$

Γ, MEASURED PHASE CHANGE FROM HEAT BALANCE

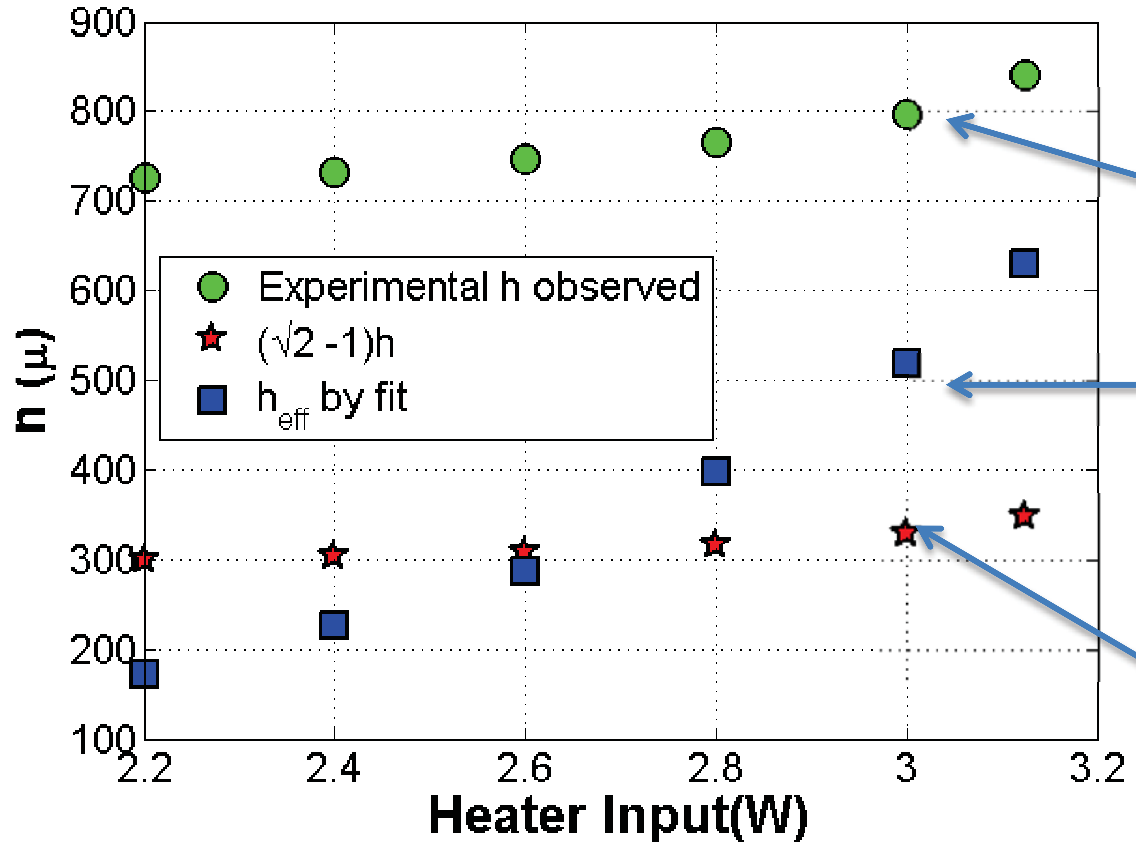
SOLVE FOR h_w ➔ $h_{effective}$

PREDICT EFFECTIVE FILM THICKNESS

$$h^3 - \frac{1}{2}\left(\frac{3\,L}{(K_2 - K_1)\,\gamma}\right)\tau_h h^2 + \left(\frac{3\,L}{(K_2 - K_1)\,\gamma}\right)\mu\Gamma = 0$$

- SOLVE FOR EFFECTIVE FILM THICKNESS USING MEASUREMENTS OF PHASE CHANGE, Γ, FILM LENGTH, L, AND CURVATURES, K.

PREDICTED EFFECTIVE THICKNESS, h_{eff}



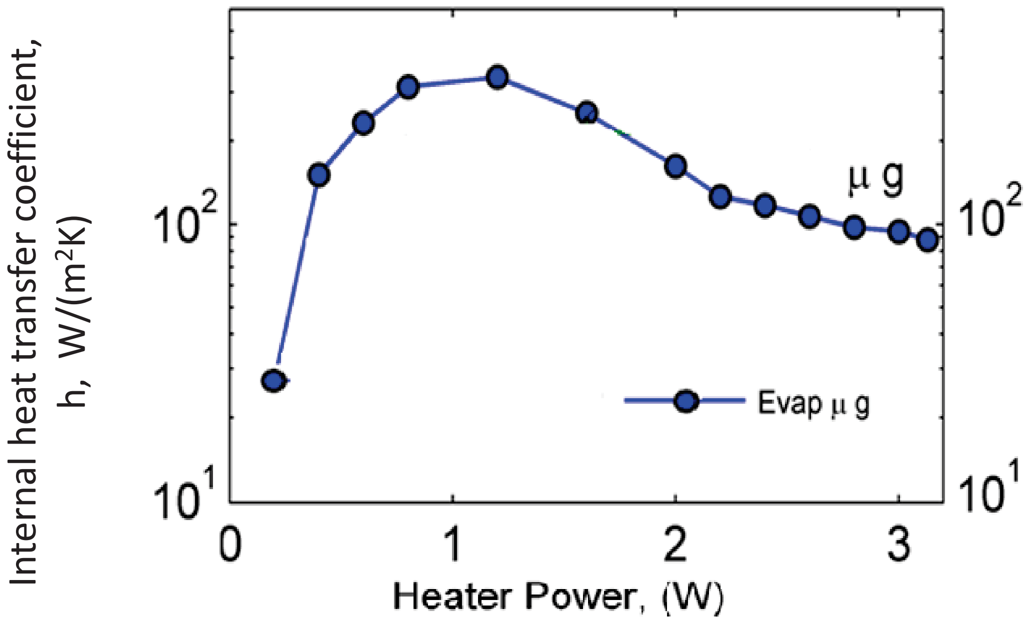
h_{wall} at wall

h_{eff}

Average thickness
CORNER MENISCUS
WITH CONSTANT
CURVATURE & h_w

FLOODING INCREASES WITH HEAT FLUX

Internal Heat Transfer Coefficient of the CVB



Effective length of the heat pipe

- Earlier theoretical mathematical analysis have predicted ‘Dryout region’.[1-2]
- Maximum internal heat transfer coefficient at 1.2 W
- Marangoni dominated flow starts from 1.6 W onwards
- Internal resistance to the heat transfer of the heat pipe increases due to onset of ‘Flooding’ of the heater end and not due to ‘Dryout’ of the heater.
- The effective length of the heat pipe is decreased.

1. Savino, R., and Paterna, D., “Marangoni effect and heat pipe dryout”, *Phys. Fluids,* 18, 118103, (2006).
2. Yang, L., and Homsy, G. M., “Steady three-dimensional thermocapillary flows and dryout inside a V-shaped wedge”, *Phys. Fluids,* 18, 042107, (2006).

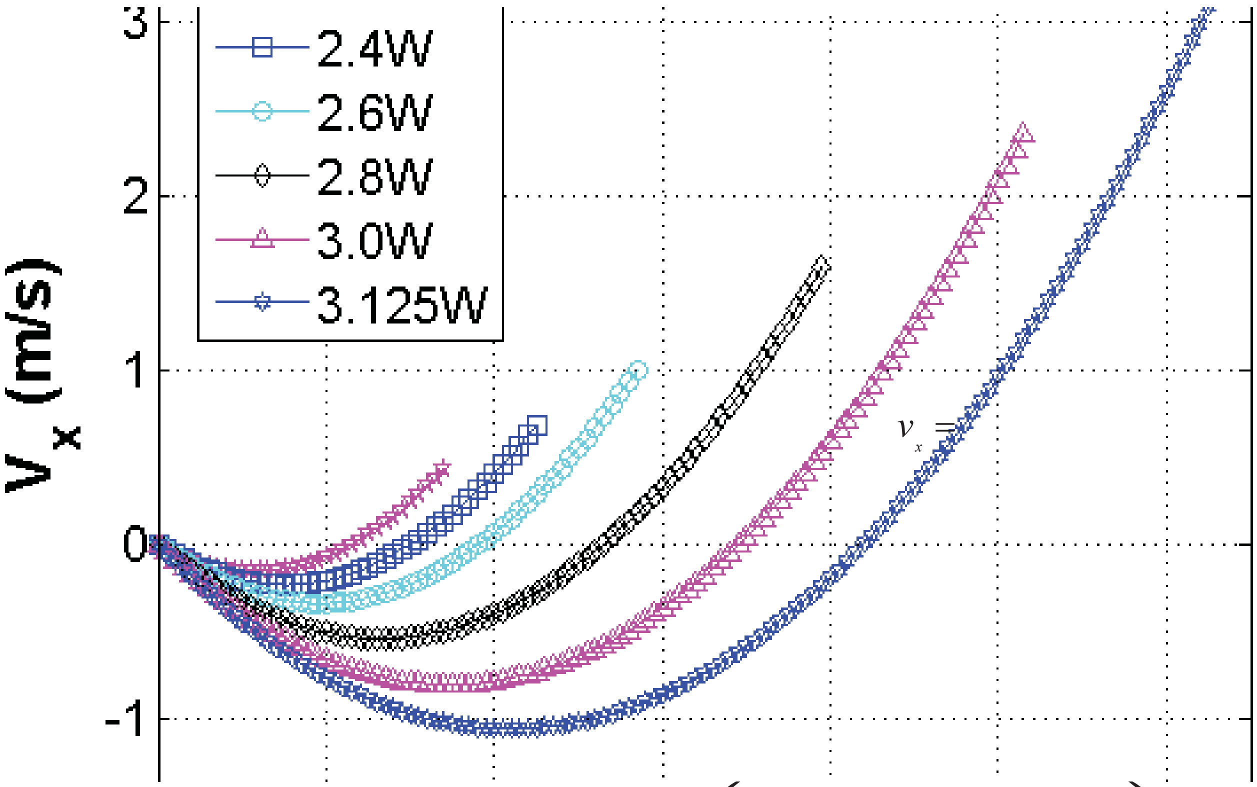
CONCLUSIONS

- Apparently “simple ‘wickless heat pipe’ system” has multiple complex 3D zones of fluid flow, evaporation, condensation, and radiation.
- A simple 1D Marangoni stress model confirms that there is significant evaporation in the steady state region at the heated end.
- There is flooding (not dry-out)
  at the heated end in μg,
  which gives a decrease in performance.

THANK YOU

EXTRA MATERIAL

VELOCITY PROFILE (Γ ‾ 0)
USING h_{eff} AS THE UNKNOWN



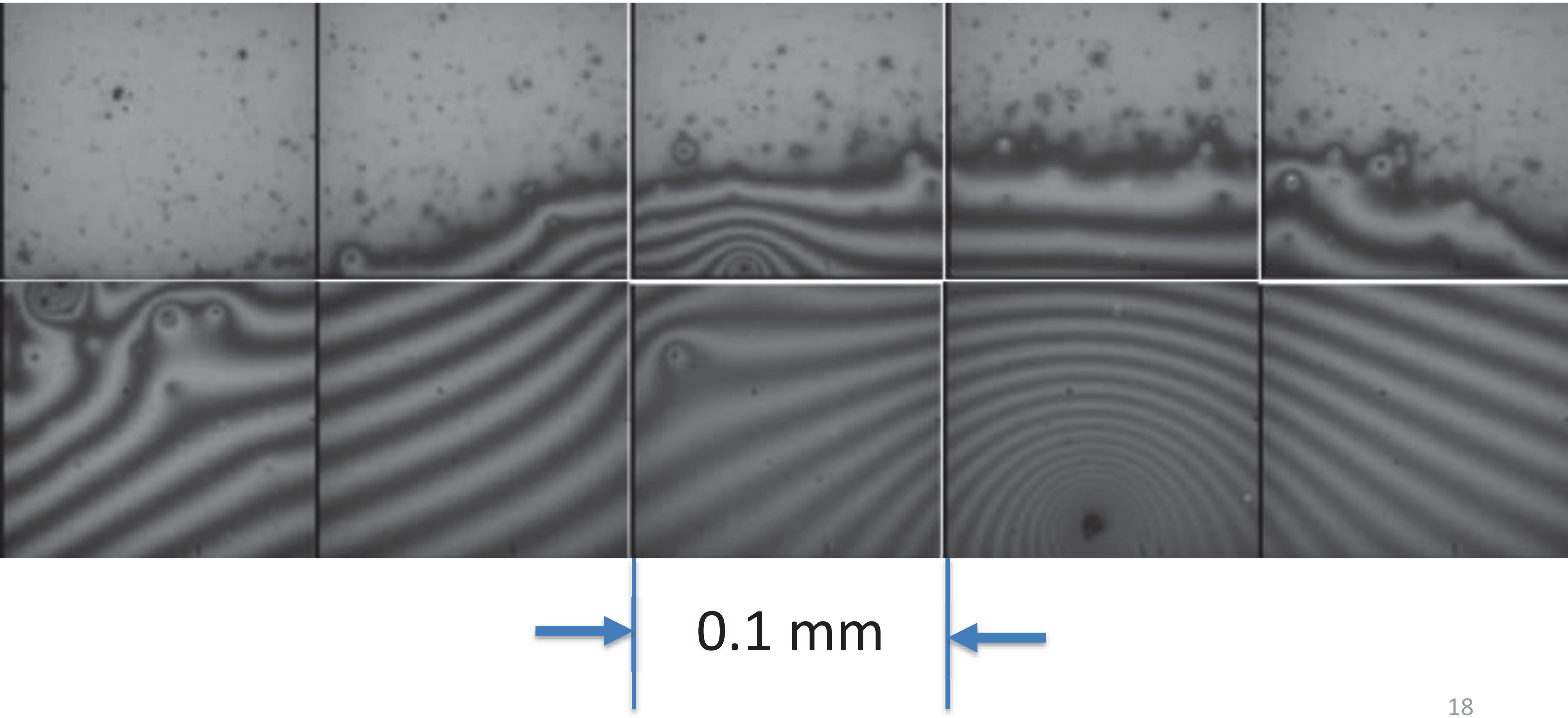
Flow towards cold end, $V_x > 0$

$$v_x = \frac{\square P}{\square L}\left(\frac{y^2}{2} \square y h_{eff}\right) + \frac{\square_h}{\square} y$$

50x images stitched together: condensation region at the leading edge of the liquid.

Fringes give pressure field.

Note the effect of very small particles.



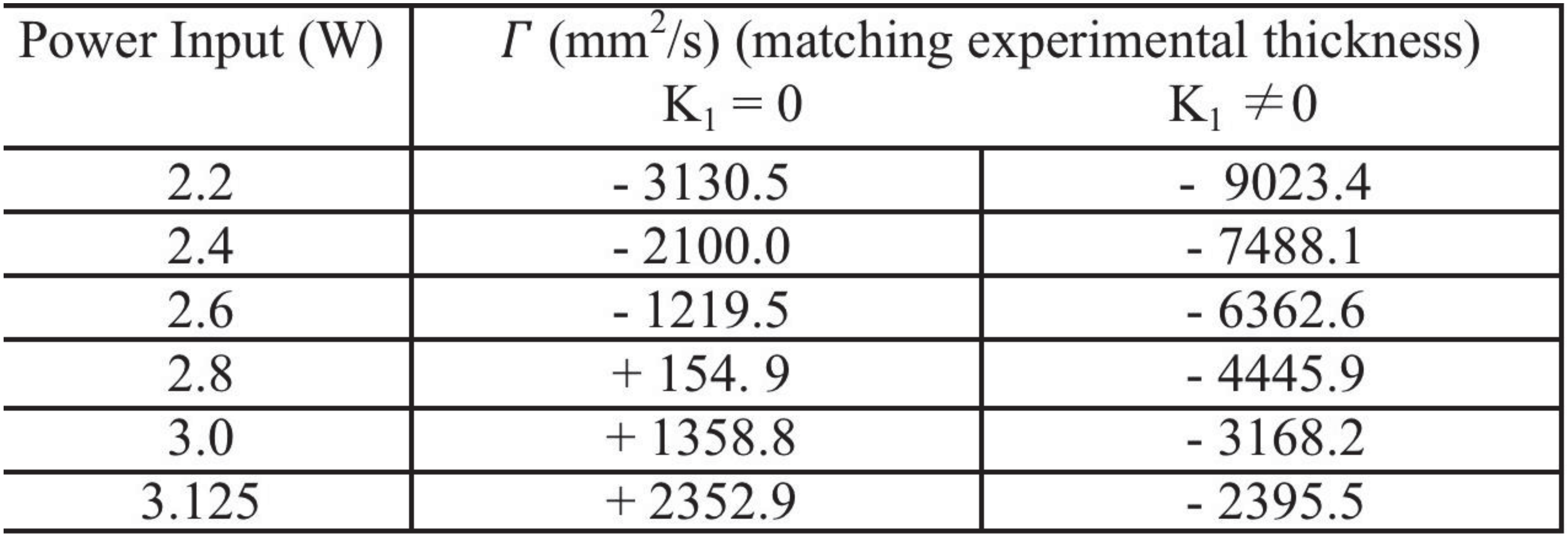
PHASE CHANGE RATES, Γ

BASED ON EXPERIMENTAL h_w

$\Gamma < 0$ EVAPORATION

K_1 = CURVATURE AT COOLER END OF FILM

REQUIRES ADDITIONAL EVALUATION



Power Input (W)	Γ (mm^2/s) (matching experimental thickness)	
	$K_1 = 0$	$K_1 \neq 0$
2.2	- 3130.5	- 9023.4
2.4	- 2100.0	- 7488.1
2.6	- 1219.5	- 6362.6
2.8	+ 154. 9	- 4445.9
3.0	+ 1358.8	- 3168.2
3.125	+ 2352.9	- 2395.5

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