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

MARANGONI FLOW REGION

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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
“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

Contact line region

Measured Thickness at Wall

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

SIMPLE MODEL

FLUID FLOW IN CORNER MENISCUS DUE TO CURVATURE GRADIENT GIVES “EXCESS FLUID”

10 X PICTURES STITCHED TOGETHER MEASURED \(K_1\) 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**

**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.

\[ q'_{in} < 0 : \text{flux out of wall} \]
INITIAL EVALUATION OF TRANSPORT PROCESSES
VERY SIMPLE FLUID FLOW MODEL
WITH INTERFACIAL PHASE CHANGE

ASSUMPTIONS:

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

\[
\frac{d \gamma_{yx}}{dy} \frac{dP}{dx} = 0
\]
VELOCITY PROFILE IN CORNER MENISCUS

• ASSUMING

\[ \nu_x = 0 \quad \text{at} \quad y = 0 \]

\[ \frac{d\theta}{dx} = \frac{dT}{dx} \quad \text{at} \quad y = h_w \]

\[ \Gamma, \text{ MEASURED PHASE CHANGE FROM HEAT BALANCE} \]

\[ = \int_{0}^{h_w} \nu_x \, dy \]

SOLVE FOR \( h_w \rightarrow h_{\text{effective}} \)
PREDICT EFFECTIVE FILM THICKNESS

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

• SOLVE FOR EFFECTIVE FILM THICKNESS USING MEASUREMENTS OF PHASE CHANGE, \( \Gamma \), FILM LENGTH, \( L \), AND CURVATURES, \( K \).
PREDICTED EFFECTIVE THICKNESS, $h_{\text{eff}}$

Flooding increases with heat flux

Average thickness CORNER MENISCUS WITH CONSTANT CURVATURE & $h_w$

$h_{\text{wall}}$ at wall

$h_{\text{eff}}$

Experimental $h$ observed

$(\sqrt{2} - 1)h$

$h_{\text{eff}}$ by fit

Heater Input (W)

$\mu$

100 200 300 400 500 600 700 800 900
Internal Heat Transfer Coefficient of the CVB

- 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.

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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 $\mu$g, which gives a decrease in performance.
THANK YOU
EXTRA MATERIAL
Flow towards cold end, $V_x > 0$

$$v_x = \frac{P}{L} \left( \frac{y^2}{2} y h_{\text{eff}} \right) + \frac{h}{y}$$
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, $\Gamma$

BASED ON EXPERIMENTAL $h_w$

$\Gamma < 0$ EVAPORATION

$K_1 =$ CURVATURE AT COOLER END OF FILM
REQUIRES ADDITIONAL EVALUATION

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<th>Power Input (W)</th>
<th>$\Gamma$ (mm$^2$/s) (matching experimental thickness)</th>
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