CVB: The Constrained Vapor Bubble 40 mm Capillary Experiment on the ISS

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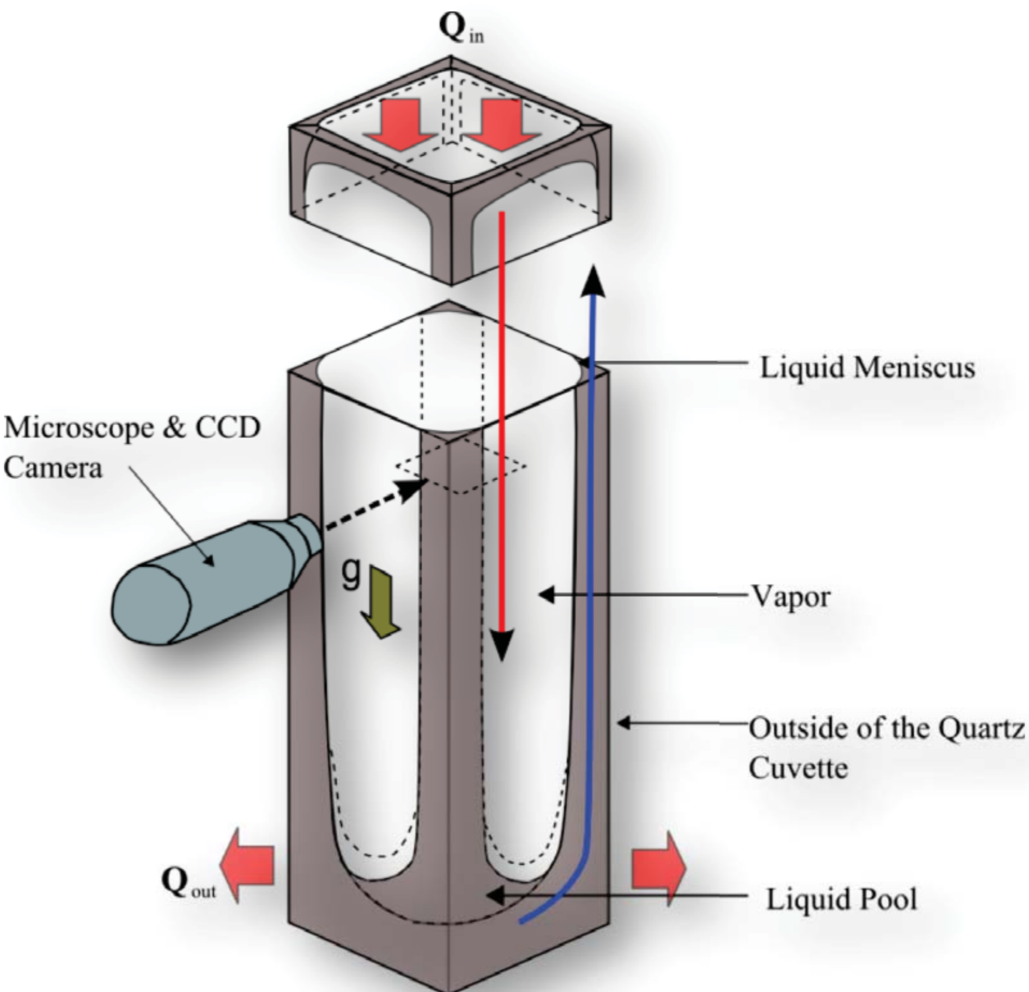
THE CVB HEAT TRANSFER SYSTEM



- The CVB is a Constrained Vapor Bubble inside a quartz cuvette with a working fluid like pentane.
- Inside 3mm x 3mm ~ 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 .

Micro-gravity Attributes

$$\text{Bond Number} = \frac{\text{"}gravitational\text{"}\ body\ \ force}{surface\ \ force} \rightarrow \ 0$$

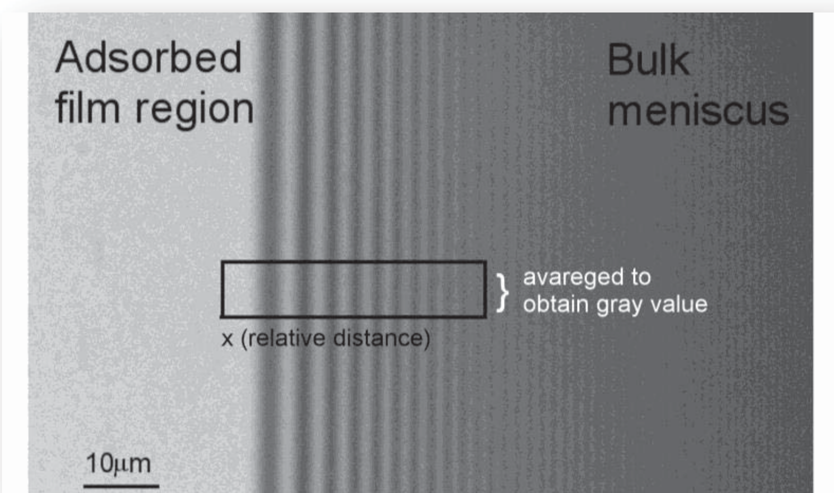
Interfacial Forces Dominate in μg

$$\frac{dK}{dx} \qquad \frac{U}{\quad} \div \frac{1}{R^2} = \frac{Capillary\ Number}{R^2}$$

Interfacial Curvature (*K = 1/R*) Gradient is Less in Large (R) Systems [i.e. more flow]; Simpler system without natural convection.

Use of pressure gradient due to interfacial forces that control fluid flow is optimized in μg
[capillarity (σK) for all thicknesses +
disjoining pressure (A/δ^n) for thickness < 100 nm]

$$(P_l \quad P_v)' \quad = \qquad K + \frac{A}{n} \div '$$



VISUAL
Reflectivity profile gives liquid film thickness profile & pressure gradient in liquid

Objectives

- Basic ***science*** study of transport processes due to interfacial phenomena.

- Basic ***engineering*** study of the CVB extended surface fin ("wickless heat pipe") for cooling hot surfaces.

- Generic study of phase-change heat transfer processes in a non-isothermal *constrained vapor bubble sub-system*.

Recorded Multi-Scale Data

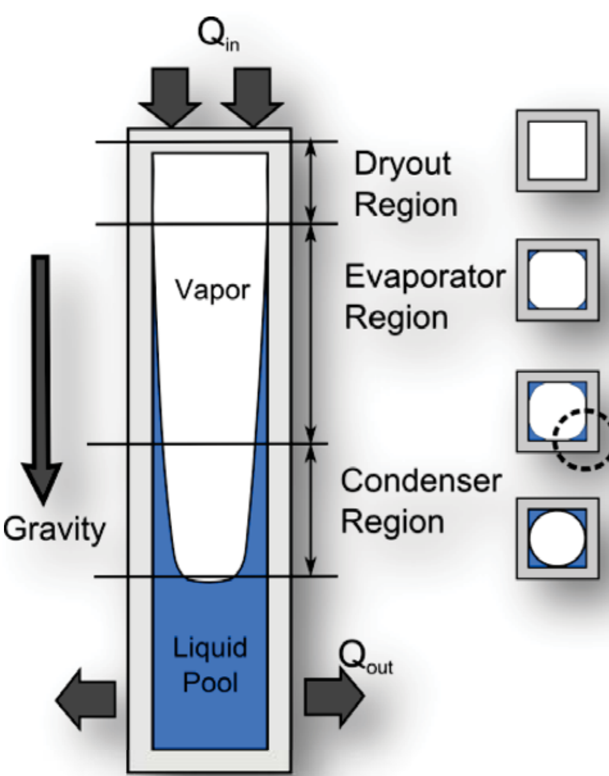
CVB

The macroscopic view – flow and heat transfer in the axial direction

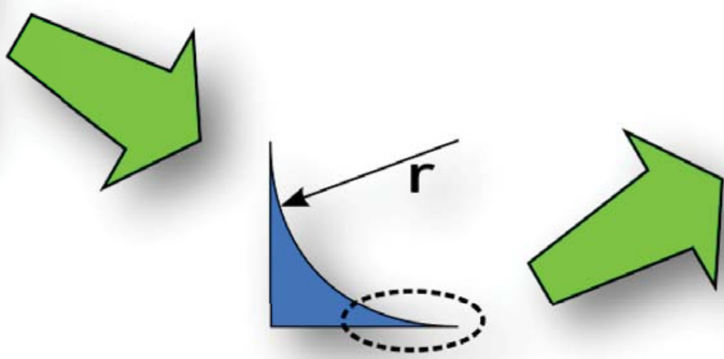
Dimensions ~ mm

The microscopic view – interfacial phenomenon at the contact line

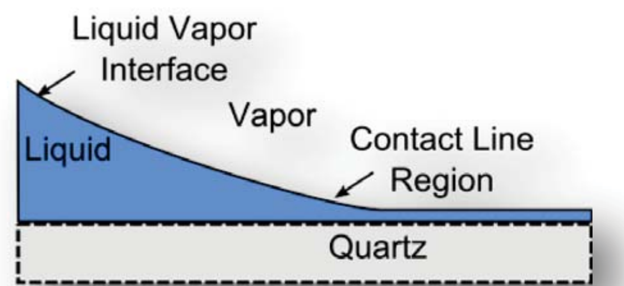
Dimensions ~ μm



Engineering (10x) Scale



Axial Corner Curvature Gradient



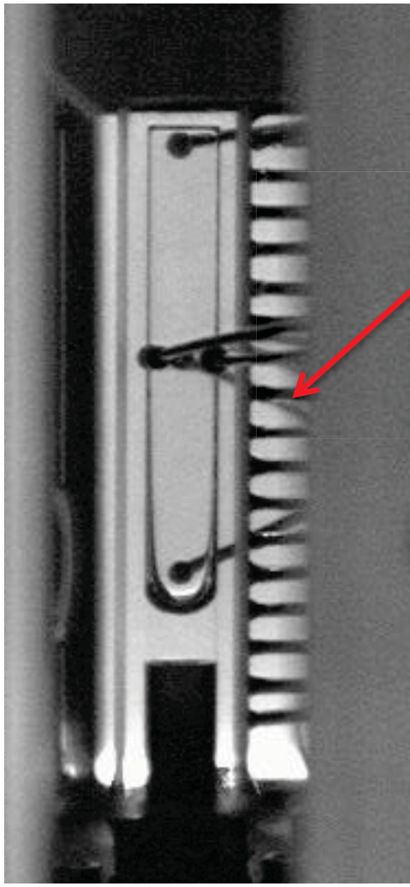
Science (50x) Scale

RECORDED EXTENSIVE DATA

- (MACRO) *Temperature field* from thermocouples gives information on the details of heat transfer.
- (MACRO) *Vapor pressure* data gives vapor purity and temperature.
- (MACRO) *Surveillance video* gives bubble location, stability, boiling.
- --
- (MICRO) *Liquid film thickness profile* from microscopic reflectivity gives local pressure gradient for fluid flow.
- (MICRO) *Transient Reflectivity Profile* from video camera on microscope gives transient data on microscopic details of pressure gradient and fluid flow.

- **WHICH SCALE DO WE ANALYZE FIRST ?**

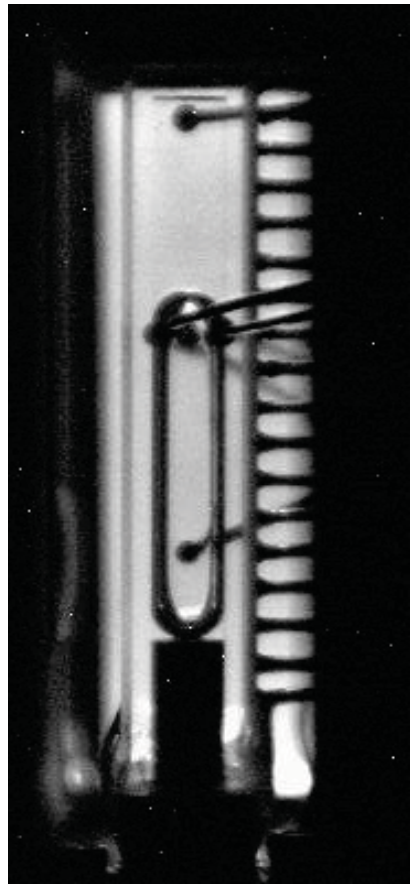
Surveillance Camera Images: MACROSCOPIC VIEW



Thermo
-couples

g

Isothermal
1g
Non-Symmetric



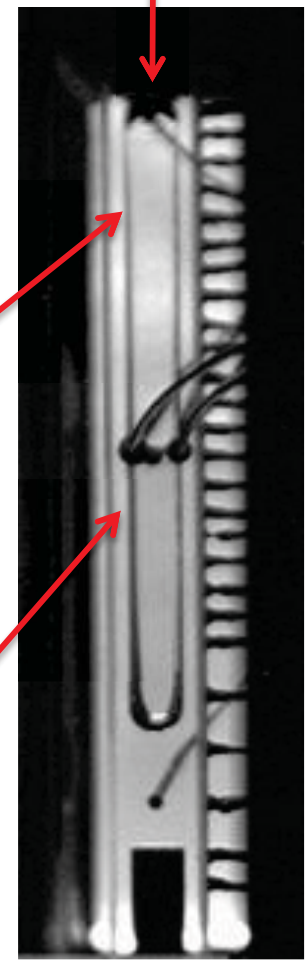
Isothermal
⌠g
Symmetric Bubble

Heated
end

Evaporating
Meniscus

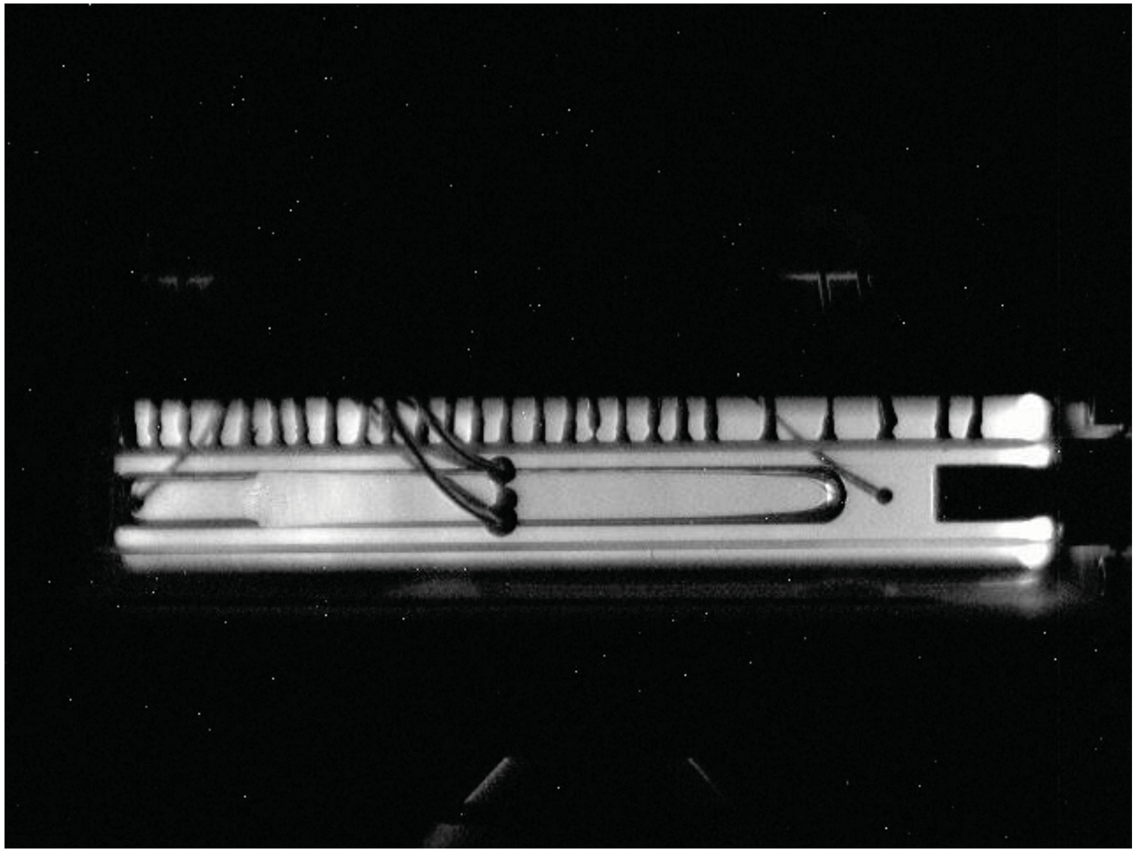
Fluid Flow in
Meniscus &
Condensation

Liquid at top



Heated
⌠g
Curvature Gradient

Surveillance Camera Image:
40 mm higher flux



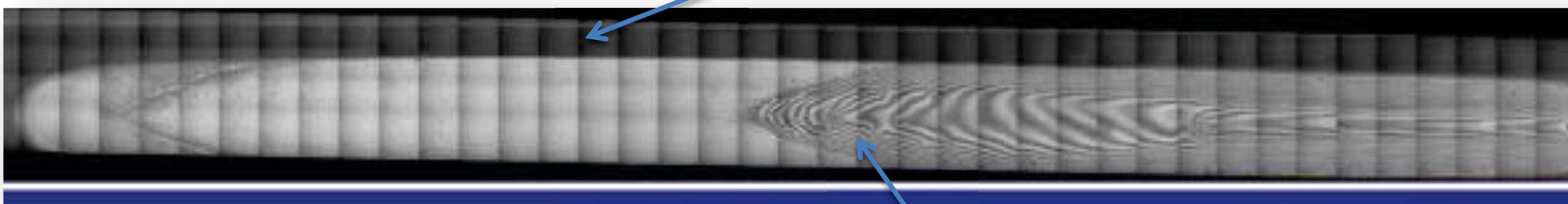
Visual Observations Support Experimental Heat Transfer Results Based on the Temperature Profile

Note: Excess fluid at hot end.

0.2 W 30 mm Cell – μg at *<u>10 x</u>*

← Evaporation → ← Condensation →

Corner meniscus



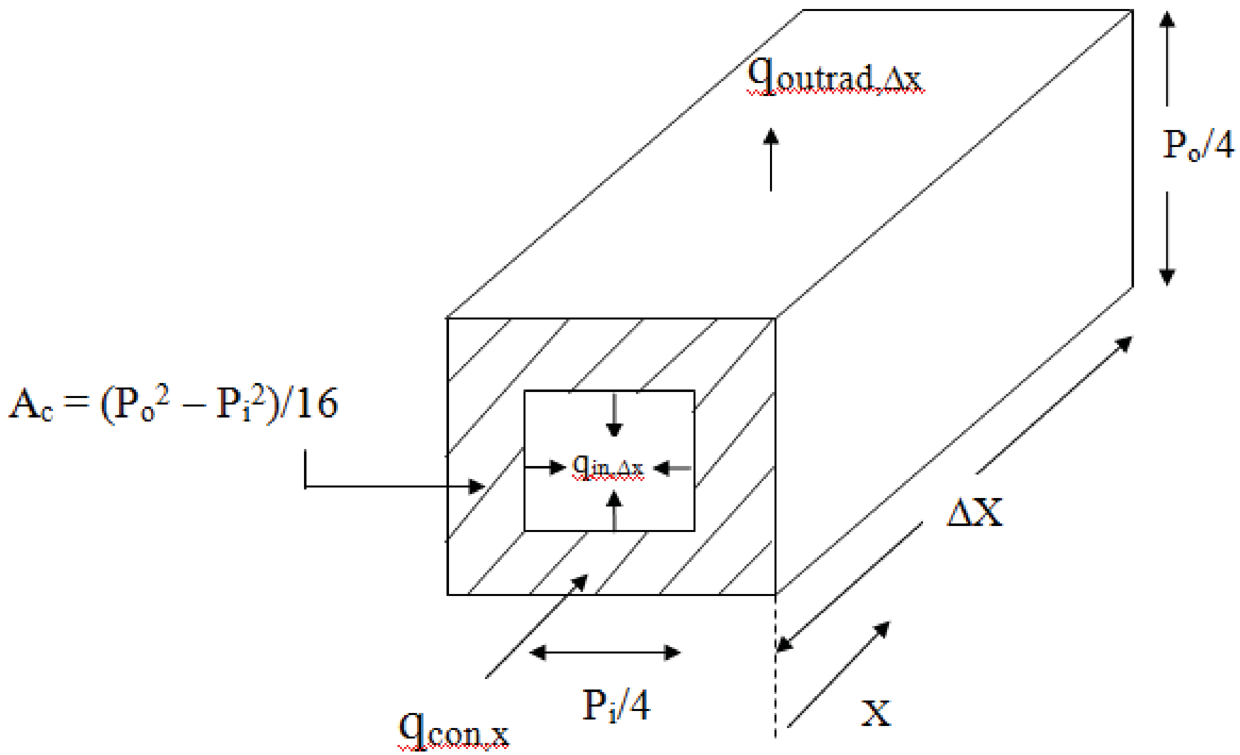
HEATER END

Film on flat side surface

FRINGES SHOW THE DETAILS OF
MANY DIFFERENT LOCAL ZONES
? HOW AND WHERE TO MODEL FIRST ?

ENGINEERING SCALE DATA

(SIMPLE 1D MODEL EASIER TO ANALYZE WHICH GIVES OVERALL VIEW OF TRANSPORT PROCESSES)



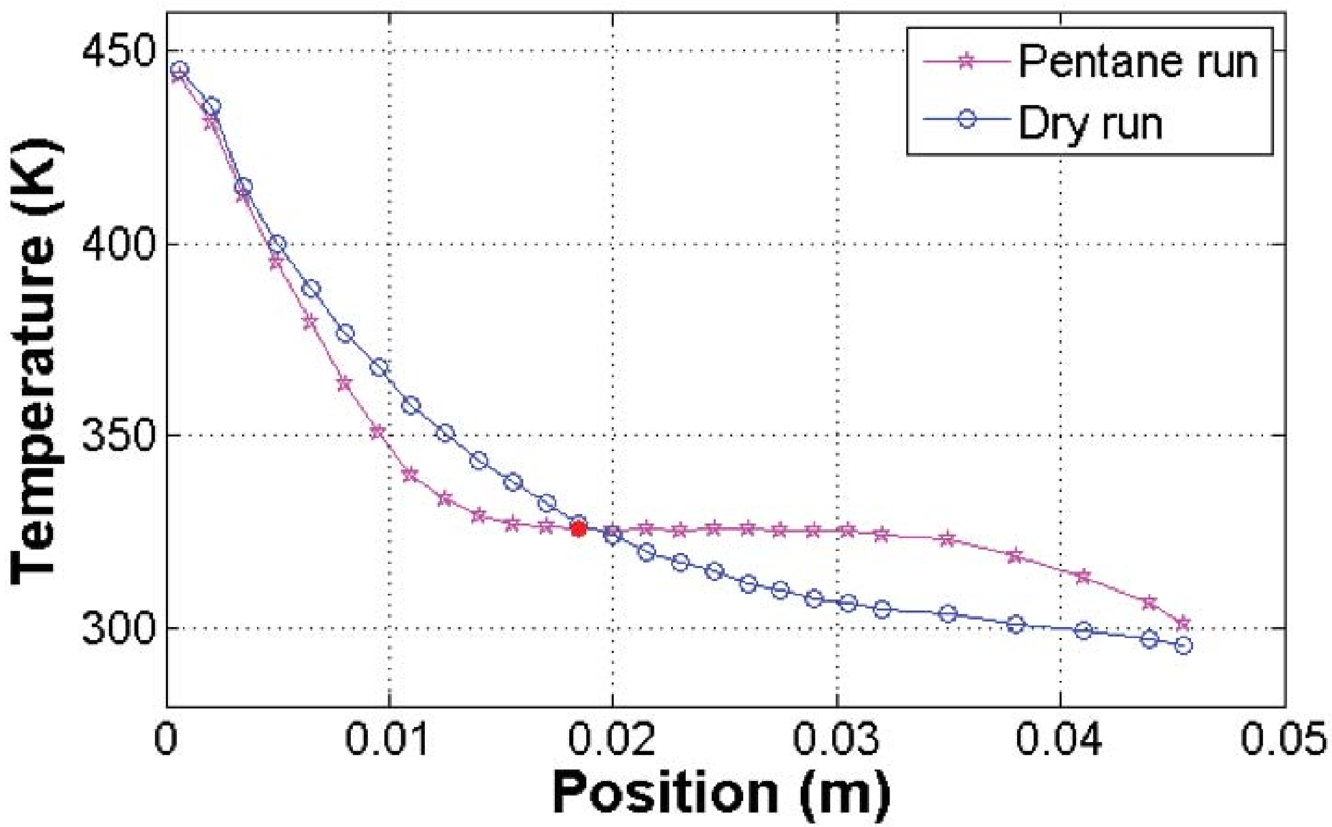
SIMPLE ONE DIMENSIONAL HEAT BALANCE

$$q_{in\ \ x} = \quad k\,A_c\left(\frac{d^2\,T}{dx^2}\right) + P_o \qquad \left(T^4 \quad T^4\right)$$

MEASUREMENTS: TEMPERATURE DATA GIVES OUTSIDE HEAT TRANSFER RATE PER UNIT LENGTH & CONDUCTION GRADIENT IN WALL

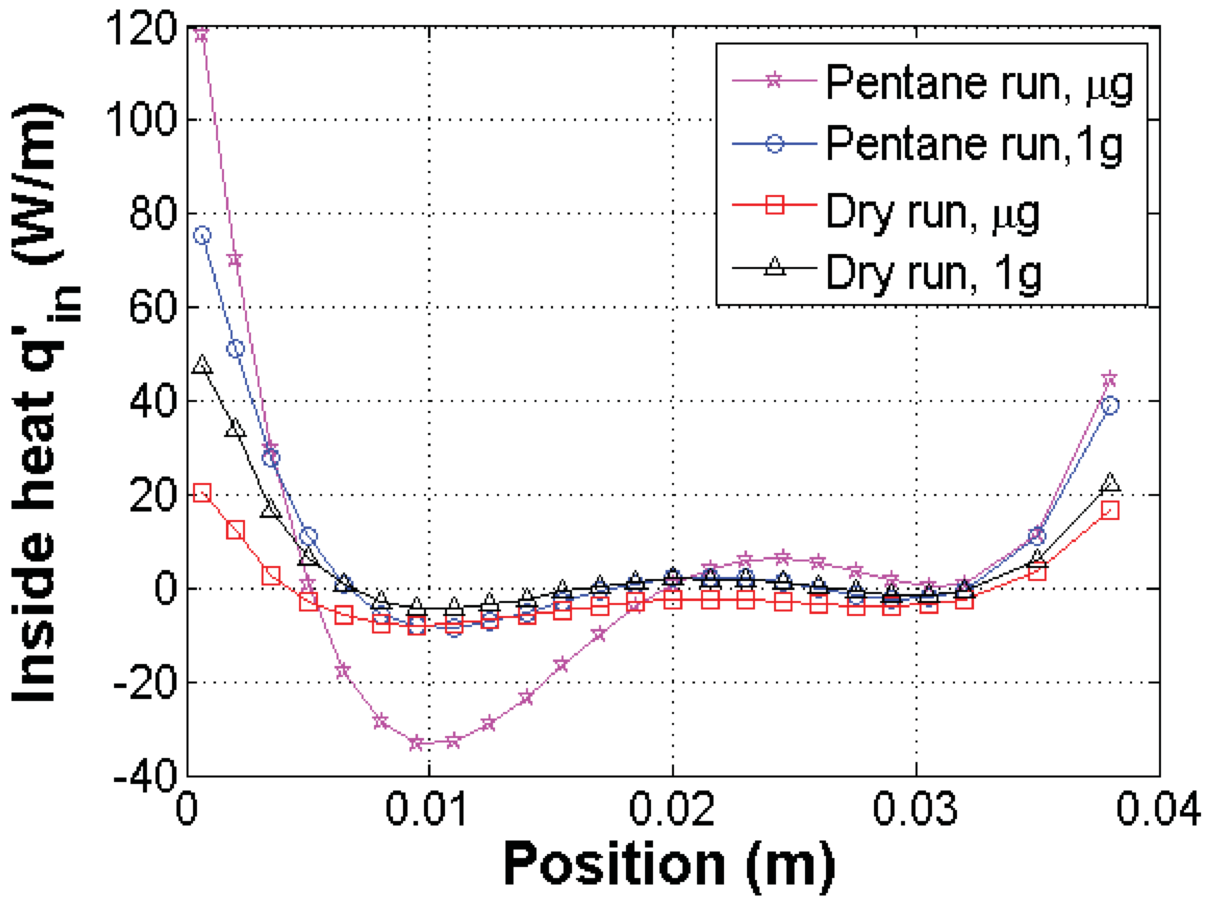
1 UNNOWN: $q_{in\Delta x}$, LOCAL INSIDE HEAT TRANSFER RATE PER UNIT LENGTH INCLUDES RADIATION & PHASE CHANGE

DRY CUVETTE VERSUS PENTANE VAPOR BUBBLE

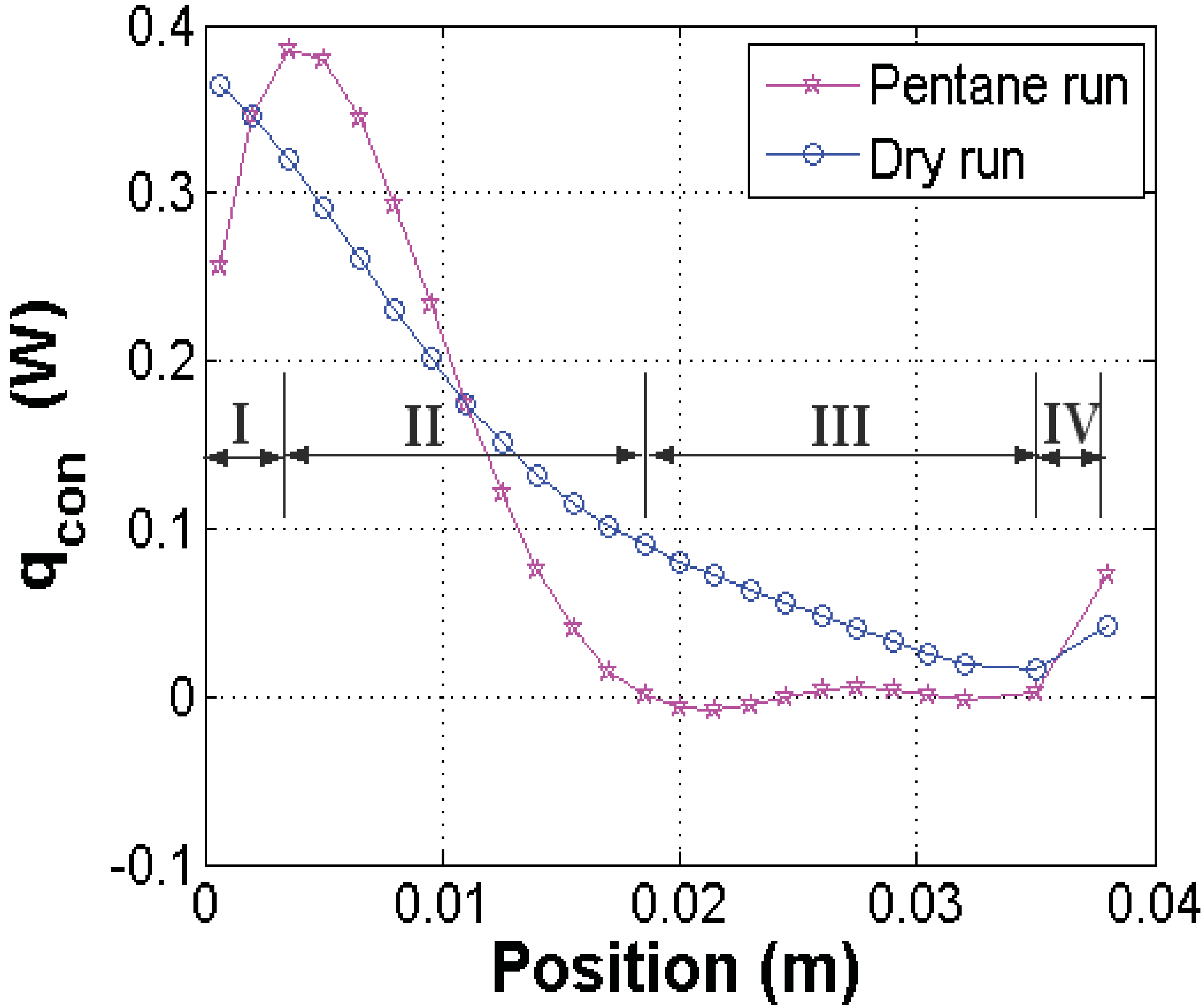


TEMPERATURE GIVES OBVIOUS CHANGE IN AXIAL CONDUCTION GRADIENT PER UNIT LENGTH, EXTERNAL RADIATION AND INSIDE HEAT TRANSFER

DRY CUVETTE VERSUS PENTANE VAPOR BUBBLE



Inside heat transfer per unit length for 2 W in μg. Only radiation present on inside and outside for the dry case. Net inside radiation field is thereby known.



0.4
0.3
0.2
0.1
0
-0.1
0
0.01
0.02
0.03
0.04
q_{con} (W)
Position (m)
Pentane run
Dry run
I
II
III
IV

Conclusions from μg

- Using temperature data, zones in the CVB and local heat transfer fluxes were determined.
- Phenomena in μg are very different –
  - because of low effective gravity, there is more fluid flow.
  - because of no natural convection, there is a change in the heat transfer profile.
- Surface of the CVB runs "hotter" in space due to lack of convective cooling.
- Macroscopic model shows expected trend – enhanced liquid flow and heat transfer coefficient for evaporative heat transfer.
- More microscopic models describing the details of the transport processes and stability are being evaluated.
- Visual Observation are Essential for Understanding.
- Loop Configuration Design Using the CVB Concept is Anticipated.

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