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NEVADA VENTURES LP NANOSCIENCE PROGRAM UNIVERSITY OF NEVADA, RENO

Advanced Heat Exchangers Using Tunable Nanoscale-Molecular Assembly

(Innovative Concept Phase-I)

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Kwang Kim

Mechanical Engineering Dept. and

Nevada Ventures Nanoscience Program

University of Nevada, Reno

Team

- Kwang Kim, PI, Mechanical Eng. Dept, UNR
  - Srinivas Vemuri, PhD student in Mech. Eng.
- Thomas Bell, Co-PI, Chemistry Dept, UNR
  - Sailaja Govindaraju, PhD student in Chemistry

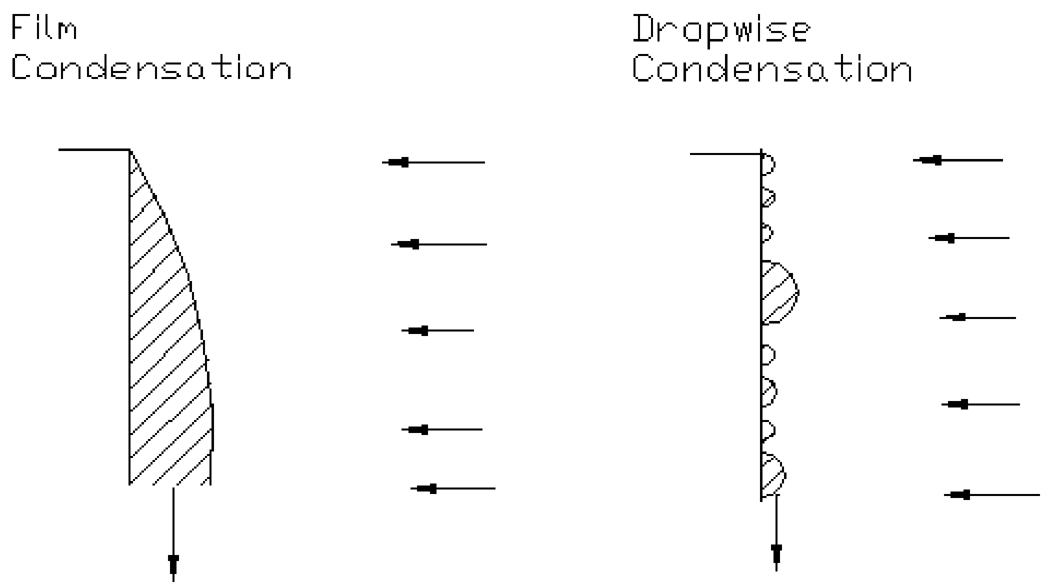
Objective/Task/Status of the Project

- Objective: to develop an innovative steam condenser technology using nano-tailored heat exchanger surfaces
- Tasks are:
  - Task 1: Fabrication of nano-tailored heat exchanger surfaces (80% completed)
    - Self assembled monolayer coats
    - Contact angles of the condensate
    - Long-term durability of nano self-assembled monolayers
  - Task 2: Thermal characterization (80% completed)
    - Steam condensation

Condensation

- Condensation **occurs when the temperature of** the vapor is reduced below its saturation temperature**.**
- **The solid surface whose temperature is below the saturation temperature of the vapor**
- **Two distinct forms of condensation:**
  - Filmwise condensation
  - Dropwise condensation

Filmwise and Dropwise Condensation



Heat transfer coefficient

$h_{film} << h_{drop}$

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Filmwise Condensation

- **When liquid formed by condensation wets the surface. It is a more common type of condensation to occur.**
- **In filmwise condensation liquid condensate forms a continuous film over the surface, this film flows down the surface under the action of gravity, shear force due to vapor flow, or other forces.**
- The layer of liquid condensate acts as a barrier to heat flow due to its very low thermal conductivity and hence low heat transfer rate.

Dropwise Condensation

- Dropwise condensation takes place when the liquid condensate does not wet the solid surface.
- The condensate does not spread, but forms separate drops.
- These drops in turn coalesce to form large drops and sweeping clean a portion of the surface, where again new droplets are generated.
- The average heat transfer coefficient for dropwise condensation is much higher than filmwise condensation.

Smooth Film Analysis

- The first attempt to analyze the film-wise condensation problem was done by Nusselt in 1916.
- By making certain assumptions;
  - The flow of condensate in the film is laminar,
  - Fluid properties are constant,
  - Sub cooling of the condensate may be neglected,
  - Momentum changes through the film are negligible,
  - The vapor is stationary and exerts no drag on the condensate,
  - Heat transfer is by conduction only, and
  - Surface is isothermal.

Average Heat transfer Coefficient

- For a vertical flat plate:

$$h_{vert} = 0.943\left(\frac{g\rho_l(\rho_l-\rho_v)h_{fg}k_l^3}{\mu_l(T_{sat}-T_s)L}\right)^{\frac{1}{4}}$$

- For a horizontal tube:

$$h_{horiz} = 0.729\left(\frac{g\rho_l(\rho_l-\rho_v)h_{fg}k_l^3}{\mu_l(T_{sat}-T_s)D}\right)^{\frac{1}{4}}$$

Factors Effecting Condensation Heat Transfer Rate

- Non-condensable gases: Significantly hinder the condensation rate. The increased partial pressure of these non-condensable gases near the vicinity of the condenser tubes thus lowering the overall heat transfer rate.
- Vapor velocity: With an increased vapor velocity heat transfer rate increases due to the shearing forces of the high vapor velocity.

Enhancement Techniques

- Condensation is still one of the most important heat transfer process in many energy conversion systems including coal power plants.
  - To increase the efficiency of the heat exchangers
    - To reduce the energy expenses
    - To reduce the costs involving in building of heat exchangers

Enhancement Techniques (continued..)

- Extended surfaces (fins)
- A thin layer of an organic polymer coating
- Use of heat transfer additives
- Noble metal coatings
- Self assembled monolayer coating

Extended Surfaces

- By enlarging the area of heat transfer and by reducing the condensate film thickness--finned or fluted surfaces.
- Condensate retention
  - The tendency for the condensate to collect in the interfin space
  - the fin geometry and on the ratio of the surface tension to the density of the liquid
  - Can be overcome by attaching drainage strips for the finned condenser tubes--enhances the condensation rate.

Organic Polymer Coating

- **Dropwise condensation can be achieved when the condenser surface has low surface energies--by coating organic polymers.**

- **To coat organic polymer on the metal substrate**
  - **PTFE(polytetraflouroethylene), silicon organics, and additives**
  - **Plasma polymerization/Ion-beam/Langmuir-Blodgett(L-B): a thin layer directly onto the metal substrates**

- **Organic coatings are difficult to maintain and require strong, long term adhesion forces between the coatings and metal substrates and require further study about the processing conditions.**

(Zhao 1991; Ma et al., 2002; Marto et al., 1986)

Novel Metal Coating

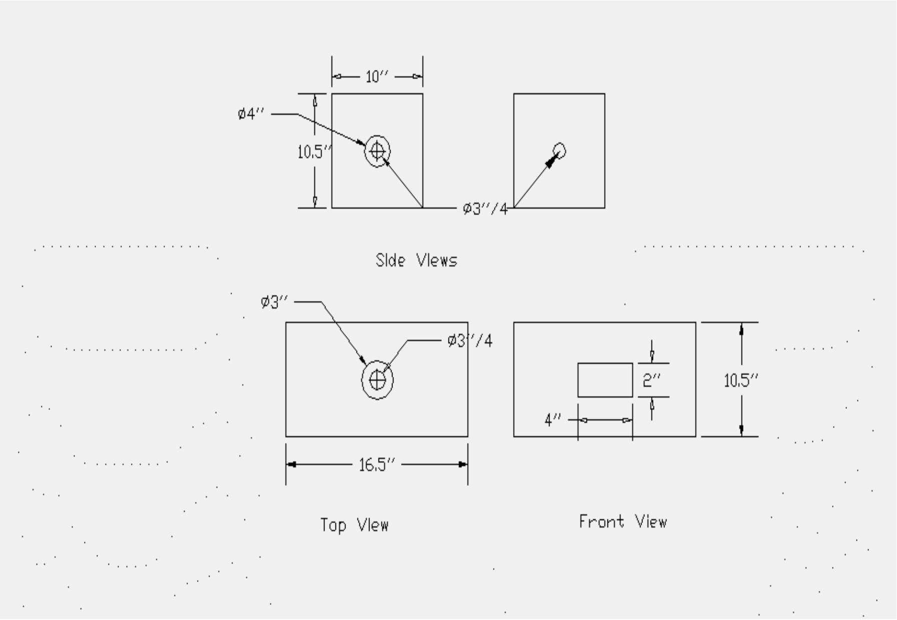
- **Gold, palladium and rhodium have exhibited good dropwise condensation for more than 12,500 hr.**
- **Uncontaminated gold and silver plated surfaces exhibited "filmwise" condensation**
  - **Gold and silver surfaces are powerful absorbers of organic material from surroundings and exhibited dropwise condensation.**
  - **Inconsistent results**

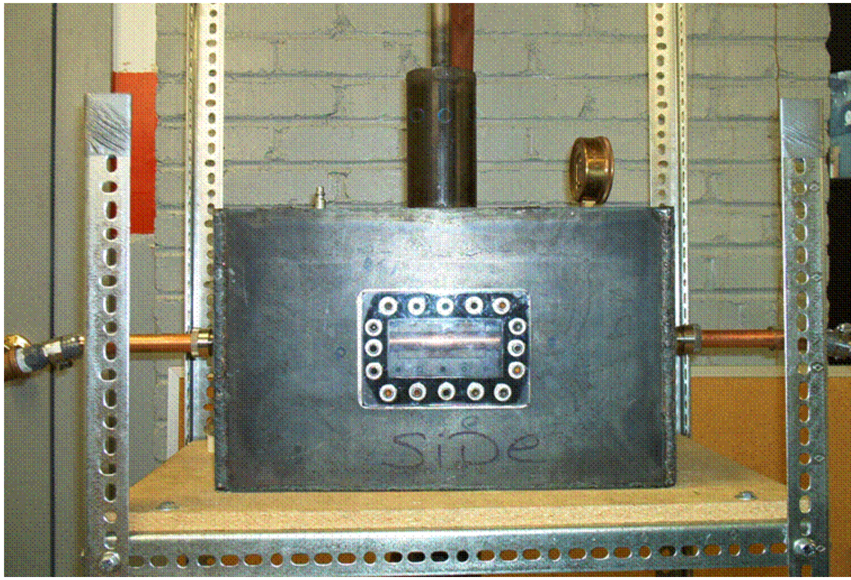
(O'Neil et al., 1986)

Self Assembled Monolayer Coating

- UNR's Experimental Study
  - Hydrophobic thin layer coats on Cu surface
    - Covalent bonding
    - Hydrogen bonding
  - Steam condensation with a single horizontal
- Limited study (Das et al., 2000)
  - Coinage metal surface/alkylthiol

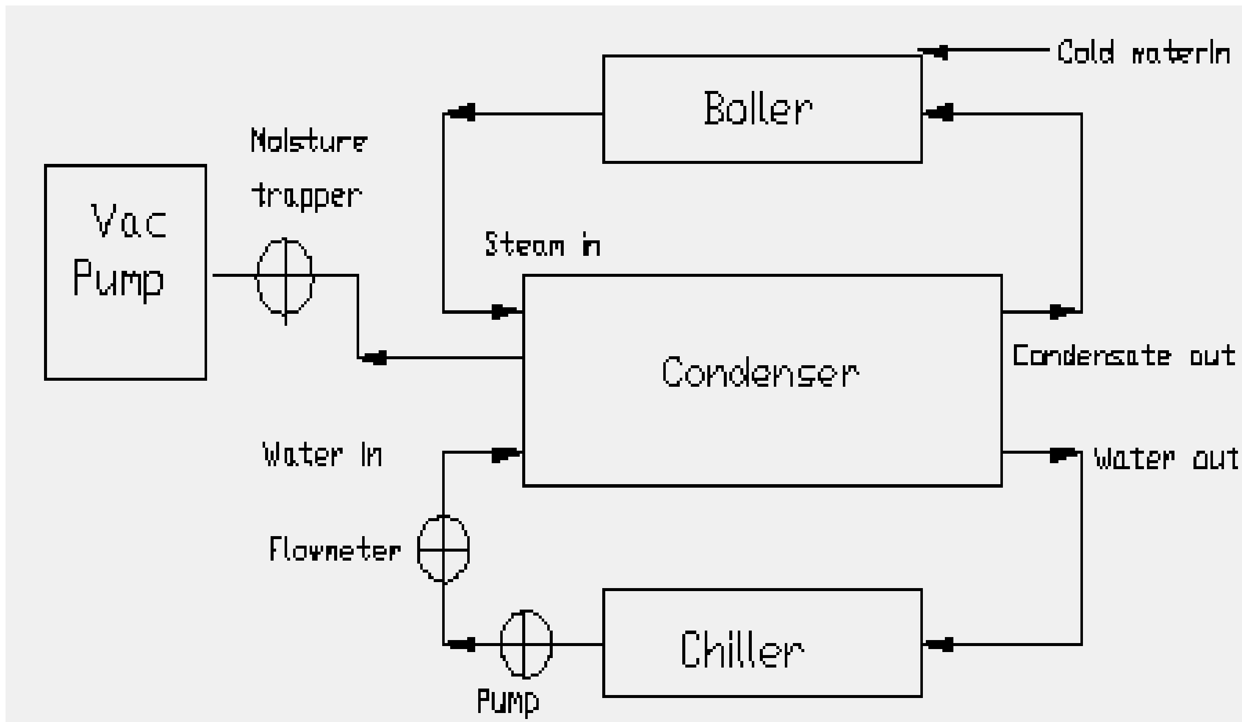
Condensing Camber





Without insulation
¾ inch tube

Experimental Apparatus



Data Reduction

- Overall heat transfer coefficient of the heat exchanger

$$U_o = \frac{1}{A_o\left(\frac{1}{h_o \times A_o} + R_w + \frac{1}{h_i \times A_i}\right)}$$

  - U_o = Overall heat transfer coefficient
  - h_i= Tube side heat transfer coefficient
  - h_o = Condensation heat transfer coefficient
  - R_w = Wall resistance

Overall heat transfer rate

$$Q_o = \dot{m} \cdot c_p \cdot (T_{out} - T_{in})$$

m= mass flow rate of the water in tube
c_p= Specific heat of water
T_{out}= Temperature of water leaving the condenser tube
T_{in}= Temperature of water entering the condenser tube

Overall heat transfer coefficient

$$U_o = \frac{Q_o}{A_o \cdot LMTD}$$

U_o= Overall heat transfer coefficient
Q_o= Overall heat flux
A_o= Outside condensing surface area
LMTD= Log mean temperature difference

Wall resistance

$$R_w = \frac{\ln\left[\frac{d_o}{d_i}\right]}{2 \cdot \pi \cdot l \cdot K_{tube}}$$

K_{tube}= Thermal conductivity of condensing tube
d_i= Inside tube diameter : d_o= Outside tube diameter
l= Length of the condensing surface

Tube side heat transfer coefficient correlations for relatively short tubes (Ma et al. 2002)

$$h_i = \frac{0.062 \times K}{d_i} \times \mathrm{Re}^{0.75} \times \mathrm{Pr}^{0.353}$$

K= Thermal conductivity of water : d_i= Inside tube diameter
Re= Reynolds number : Pr= Prandtl number

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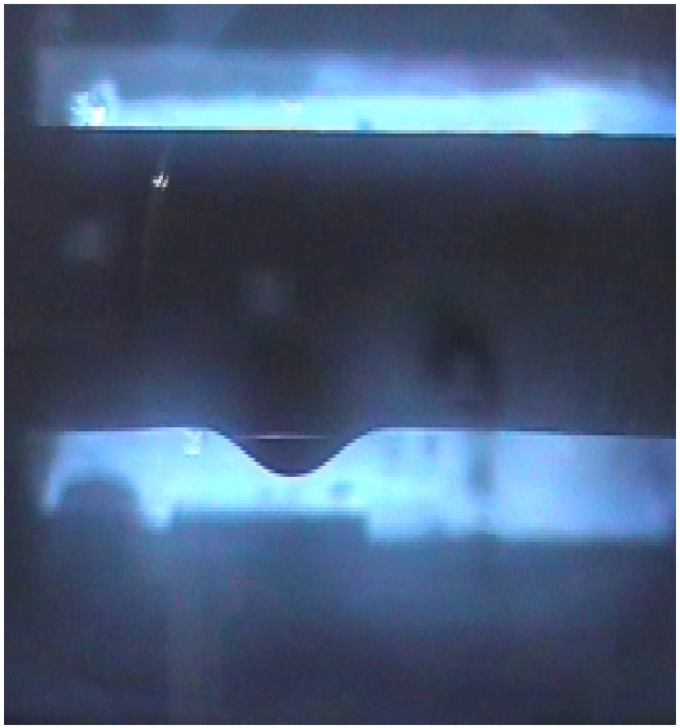
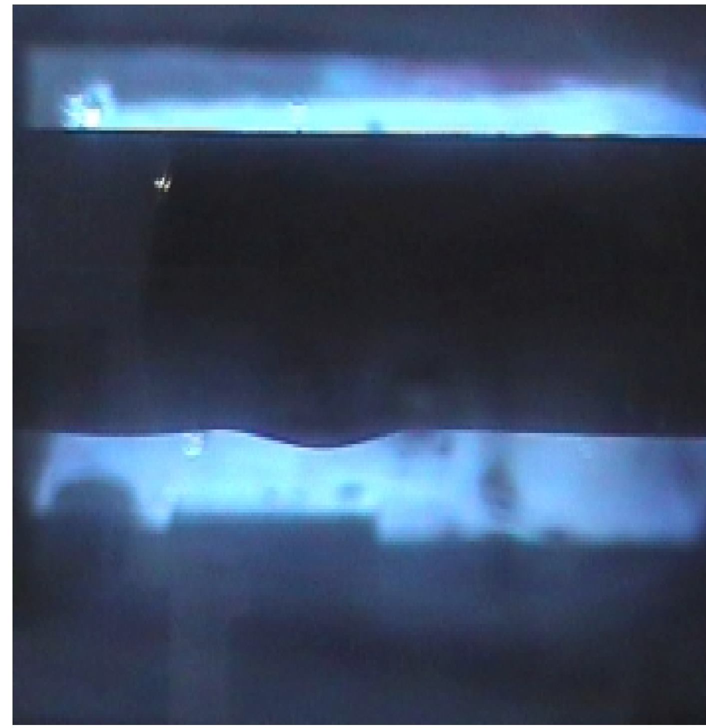
Experimental Conditions/Preparation

- Steam condensation at vacuum (10 in-Hg)
- Non-condensable gases
  - Degassing
  - Leak checks
  - Careful evacuation
- Tube surface cleaning sand paper with grit sizes varying from 120,180,220,320,600 and 1000.
  - DI-water cleaning

Filmwise Condensation Mode





Tube o/d = ¾''; P=10 in Hg

Tube: Plain copper tube

SAM Coated Tubes

- An ultra thin layer of SAM coating using n-octadecyl mercaptan (covalent bonds)
  - Copper brass alloy tube, with dimensions of 3/4" OD and 2.5 ft. length, was finely polished.
  - An oxide layer was formed on the surface of the tube by immersing the tube into 30% Hydrogen peroxide solution for 8hr, while stirring using a stir bar.
  - The tube was then removed from the Hydrogen peroxide solution and immersed into a 2.5 mM solution of n-octadecyl mercaptan in ethanol to form the ultra thin organic film

SAM Coated Tubes

(continued..)

- The hydrophobicity of the organic layer on the copper tube was tested using contact angle measuring equipment.

1. $2\ Cu + H_2O_2 \longrightarrow 2\ CuO + H_2$

2. $2\ HSC_{18}H_{37} + CuO \longrightarrow (SC_{18}H_{37})_2 + Cu + H_2O$

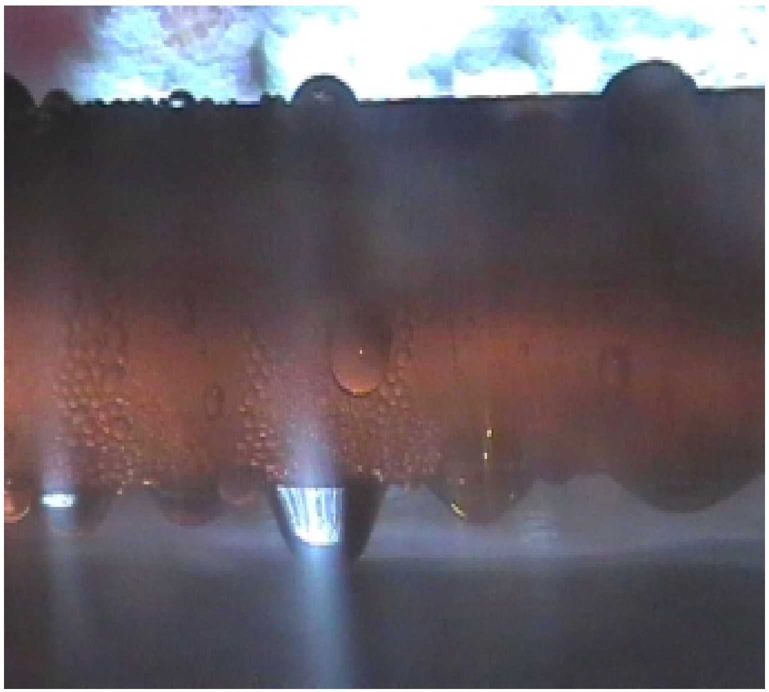
3. $HSC_{18}H_{37} + Cu \longrightarrow C_{18}H_{37}SCu + {}^{1}/_{2}\ H_2$

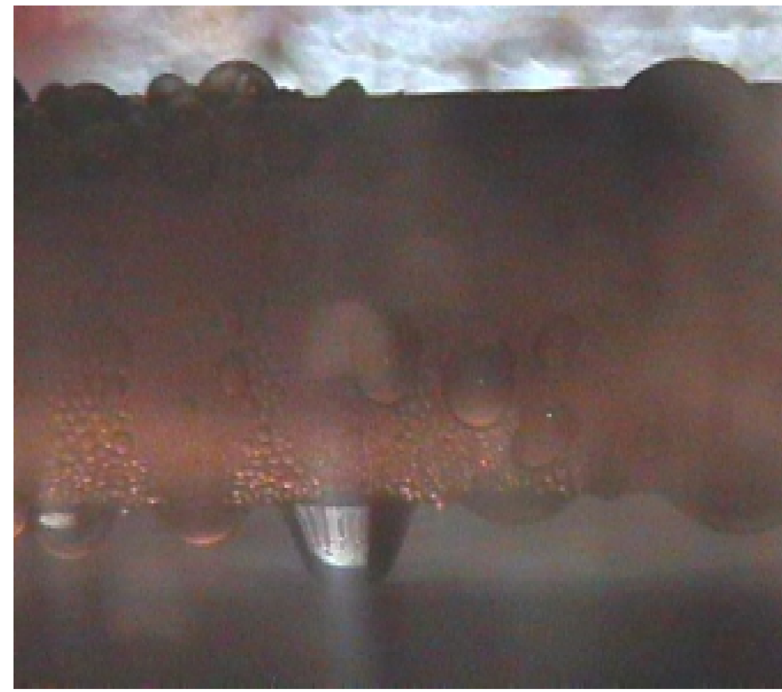
SAM Coated Tubes

(continued..)

- An ultra thin layer of SAM coating using stearic acid (hydrogen bonding)
  - The surface oxidation using H_2O_2.
  - Drying.
  - The tube was placed in a 2.5mM solution of stearic acid in hexane.
  - Washing with hexane.

Dropwise Condensation Mode

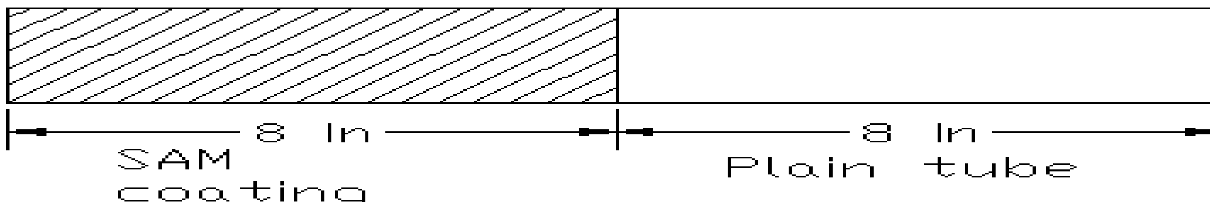


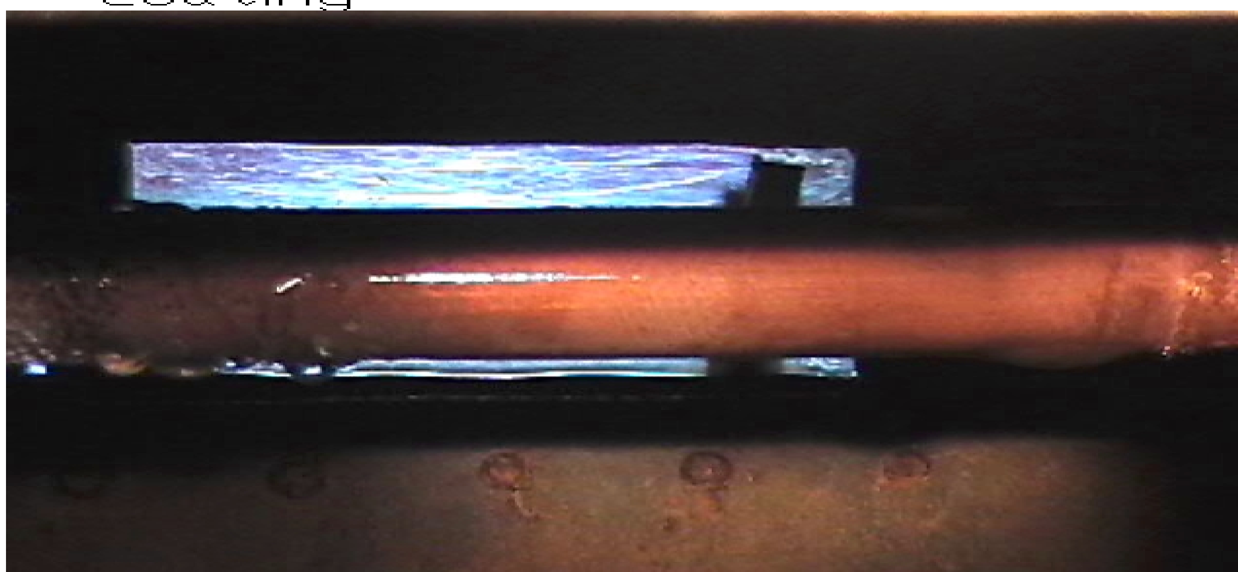


Tube o/d = ¾''; P=10 in Hg

Tube: n-octadecyl mercaptan coated copper tube

Co-existing Dropwise and Filmwise Condensation Modes

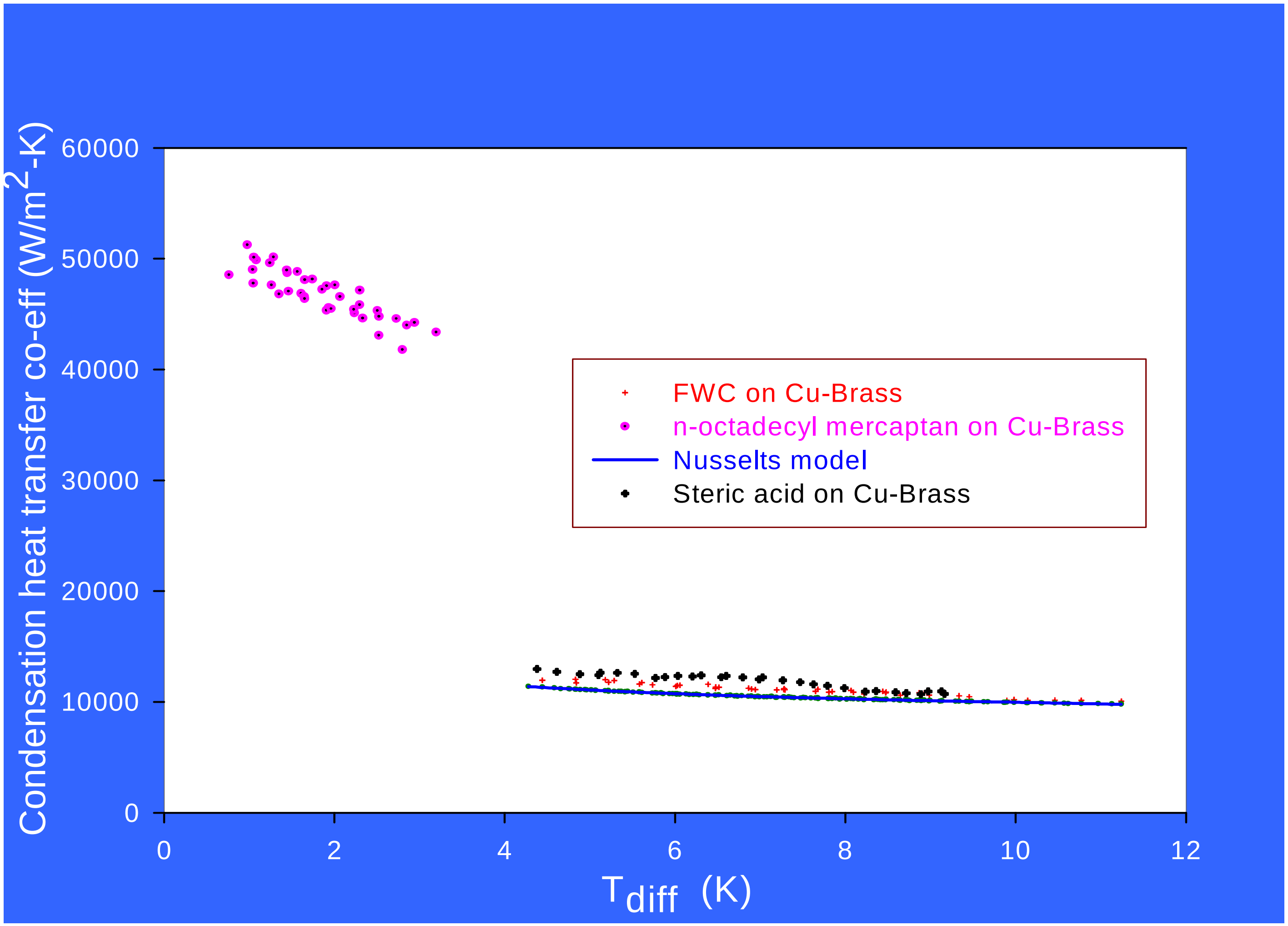




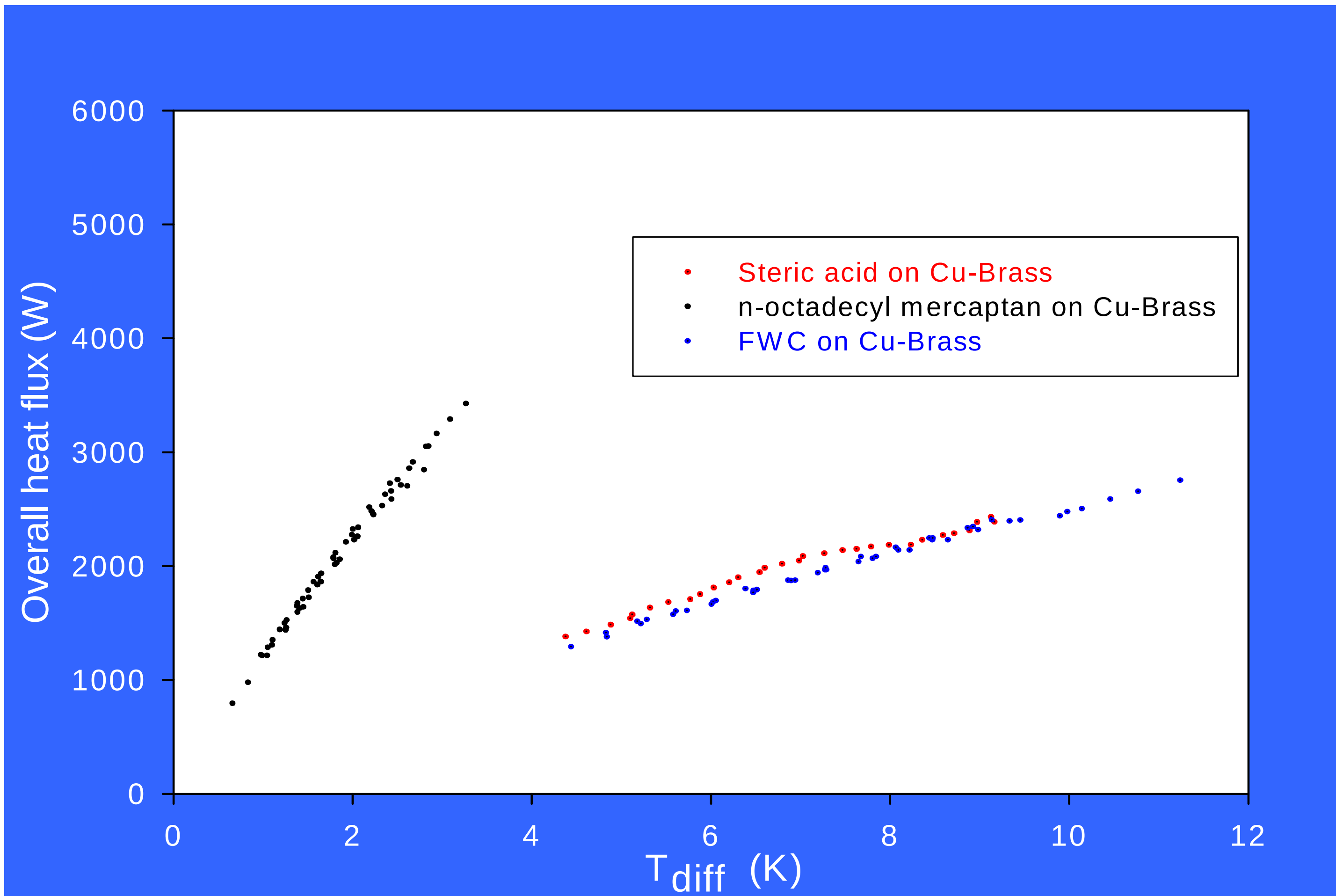
Tube o/d = ¾''; P=10 in Hg

Tube: half n-octadecyl mercaptan coated and half plain copper tube

Condensation Heat Transfer Coeff v/s Temp. Difference Across the Condensate Film and Vapor



Overall Heat Flux v/s Temp. Difference Across the Condensate Film and Vapor



Contact Angle

- A quantitative measure of the wetting of a solid by a liquid.
- Defined geometrically as the angle formed by a liquid at the three phase boundary where a liquid, gas, and solid intersect.
- Effective to predetermine the condensation mode.

Contact Angle

(continued..)

- If the contact angle is less than 90º the liquid is said to wet the solid, and greater than 90º it is said to be non-wetting.

Contact Angle	Condensation mode
$90^{\circ} \leq \theta \geq 0^{\circ}$	Film wise
$\theta \geq 90^{\circ}$	Drop wise

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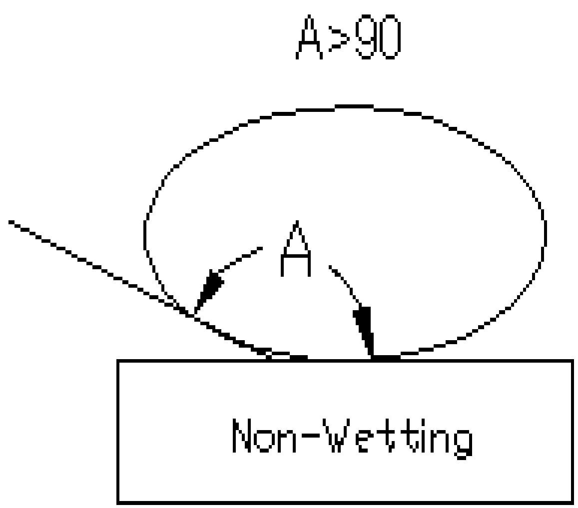
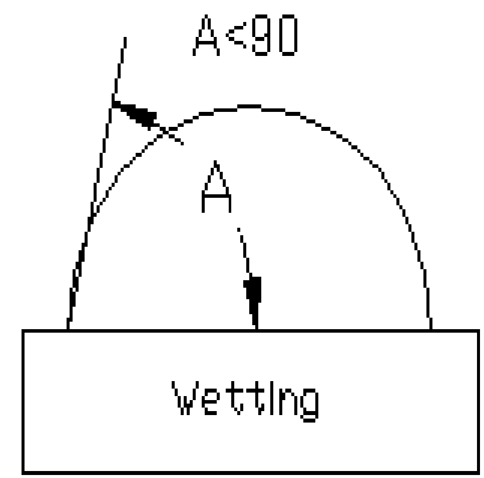
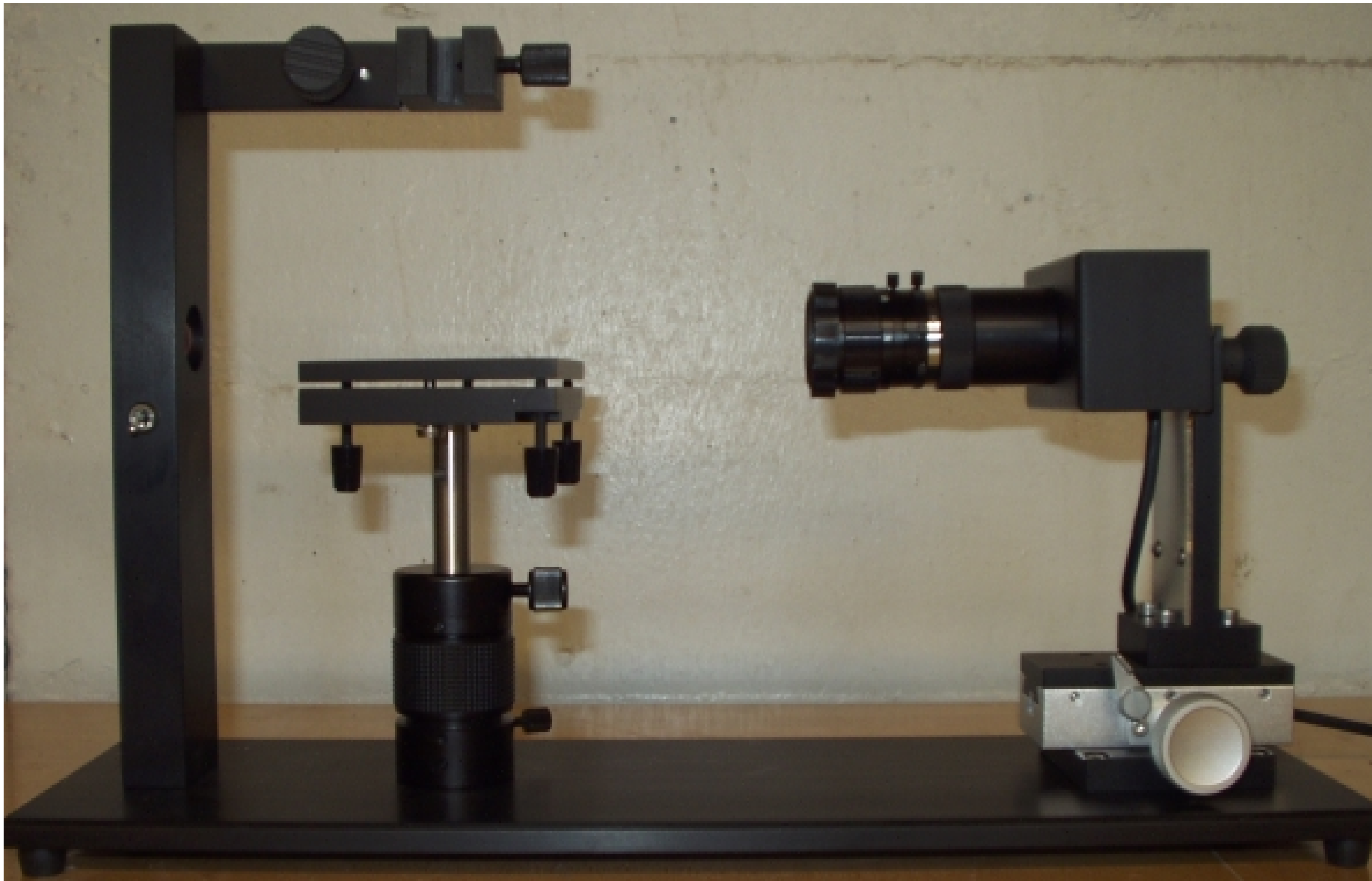




Wettability of a surface.

For contact angles greater than 90°, the surface is said to be non-wetting.

For a contact angle, A, less than 90° the surface is said to be wetting



CAM-100 Contact angle measuring equipment

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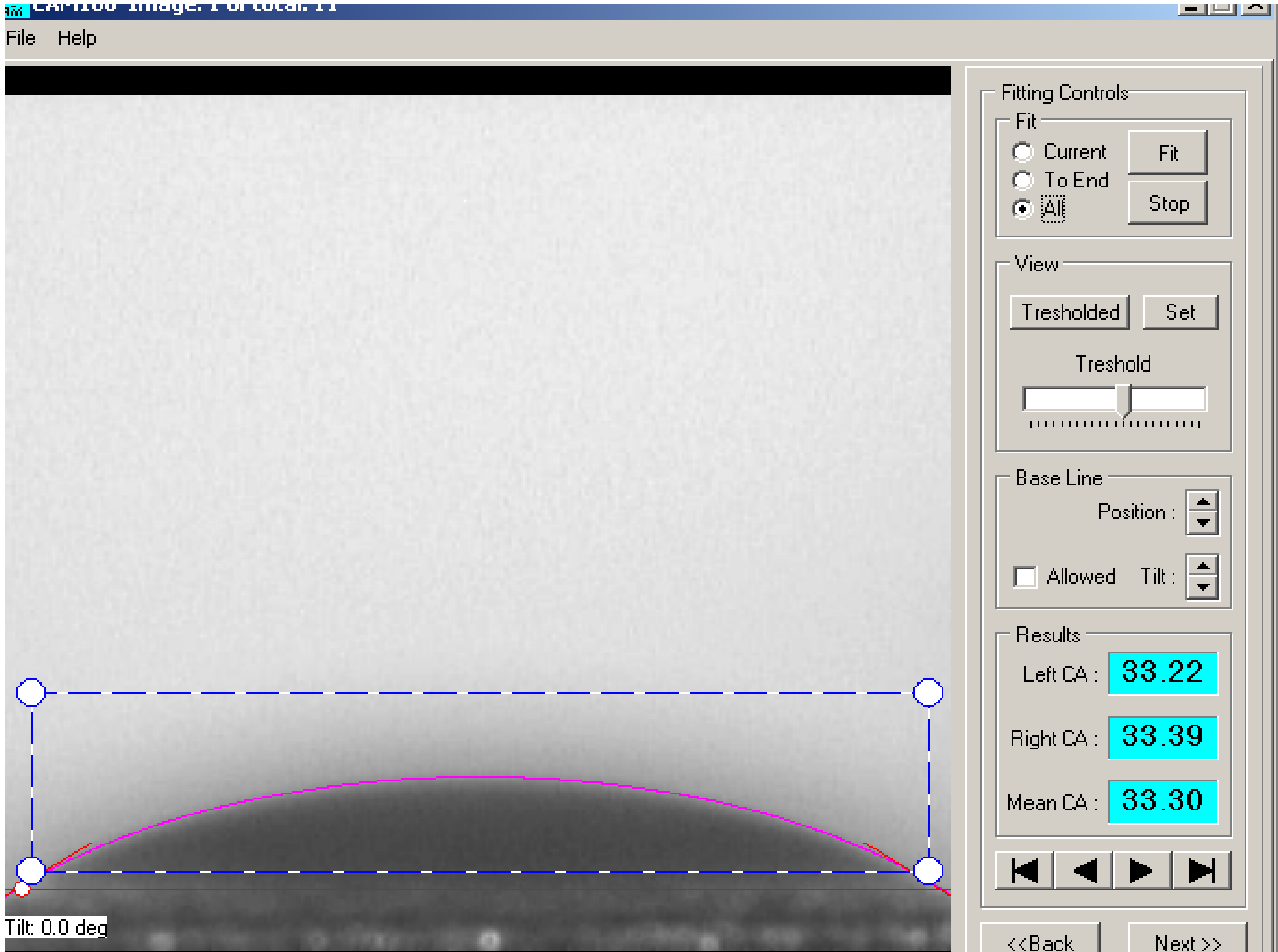
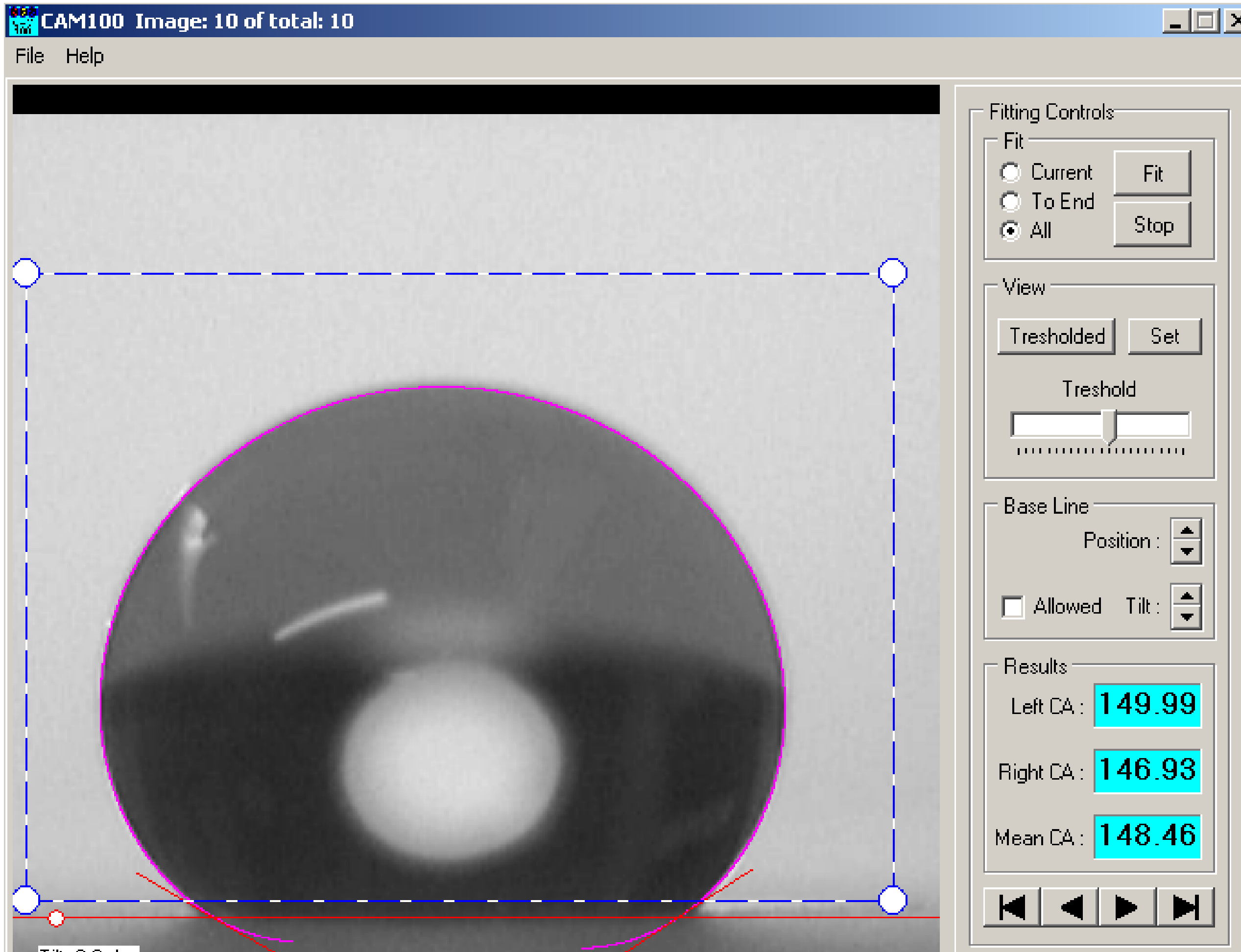
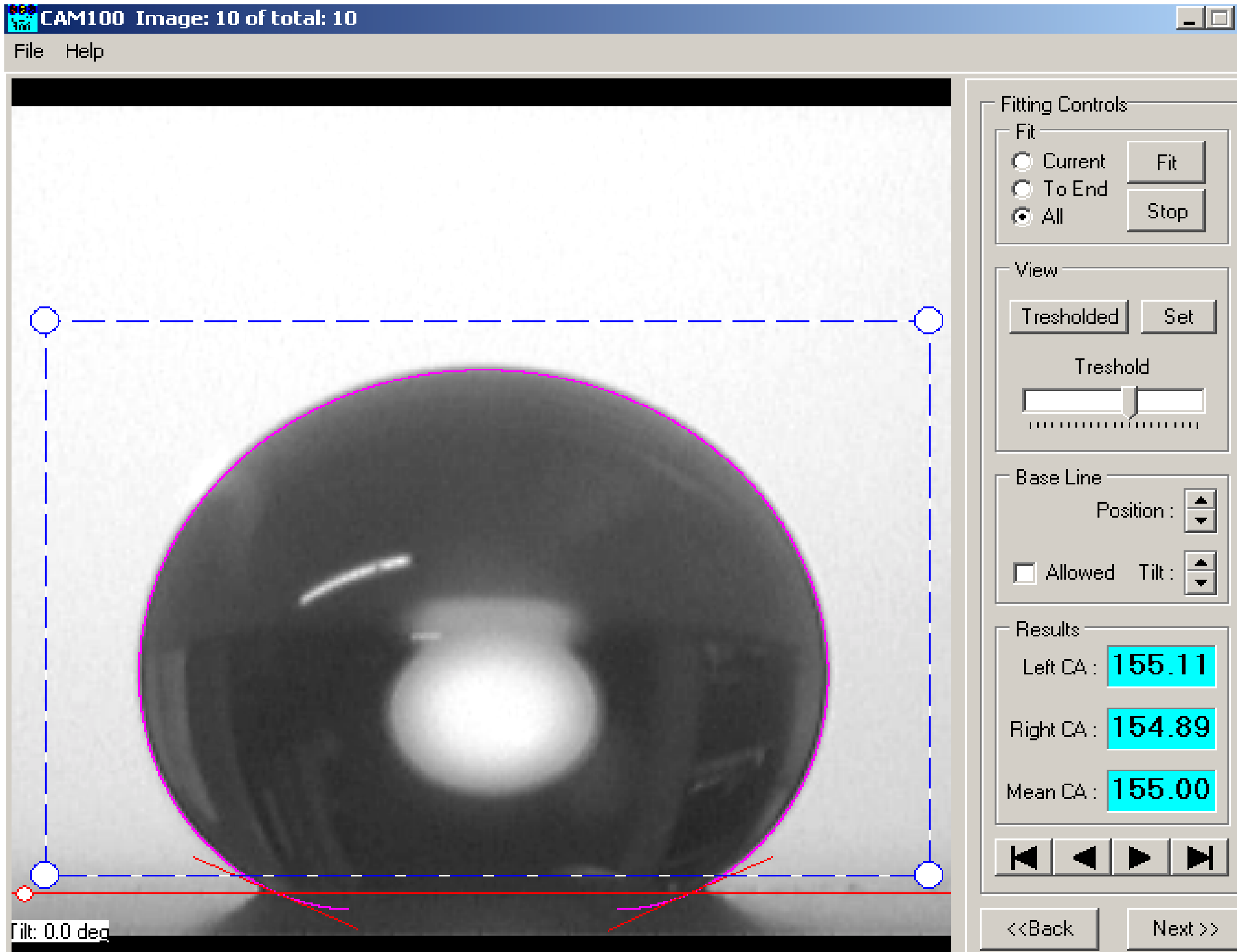


Contact angle data for plain copper tube



Contact angle data for n-octadecyl mercaptan coated tube



Contact angle data Stearic acid coated tube

Conclusions

- There is an enhancement up to 3 times in condensation heat transfer rate for drop wise condensation over film wise condensation.
- Self-assembled monolayers (SAMs) system with a long-chain, hydrophobic group is nano-resistant, meaning that such a system forms a protective hydrophobic layer with low heat transfer resistance but much stronger bond than that of other organic promoters.
- Stearic acid coated tube had a contact angle of 155^{o} (drop wise) but when the experiment was conducted it gradually turned to film wise condensation mode this may be due to weak electrostatic attraction of hydrogen bonding to the tube surface.

Conclusions

(continued..)

- Lifetime of maintaining drop wise condensation is greatly dependent on the processing conditions.
- Condensation mode can be predetermined by measuring the contact angle of liquid with the surface.

SAM coating	Condensation Mode
Stearic acid	Film wise
n-octadecyl mercaptan	Drop wise

Future Studies (Phase II)

- Experimentation would be continued for the different chemical configurations of SAM coated tubes.
- Modeling of condensation process.
- The results obtained would be incorporated to design and build multi tube condensers and ultimately implementing these drop wise condensation heat transfer surfaces in industrial condensers.

Future Studies (Phase II)

- **Film characterization**
  - **Mechanical properties of SAMs: Nano-indentation (AFM)**
  - **XPS (binding energy)**
  - **Long-term effectiveness**
- **Manufacturing process development:**
  - **SAM coatings (in terms of additives)**

Future Studies (Phase II)

- **A Reversible Switching Surface (Robert Langer of MIT, in Science 2003)**