Gravity Effects in Condensing and Evaporating Films

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Strategic Research to Enable NASA’s Exploration Missions
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Research Overview

- **Objective**
  - Understand film condensation/evaporation behavior (and implications for heat transfer) in variable gravity environments

- **Problems studied**
  - Film condensation and evaporation on planar surfaces at normal gravity (+1g, -1g) and reduced gravity ≈ 0.01g (aircraft)
  - 2-3 minutes of low-gravity testing desirable
NASA Recognizes Critical Need for Condensation & Evaporation Research to Enable Human Exploration of Space


Condensation and Evaporation Research in Reduced Gravity is Enabling for AHST Technology Needs

- **Humidity Control**
  - Mechanisms which inhibit or exacerbate liquid film motion
  - Condensate control in ducts
  - Condensers/evaporators for crew atmosphere

- **Air Revitalization (O₂ production via electrolysis)**
  - Control of water transport
  - Separation of dissolved gases from water

- **Water Purification (Potable Water via VCD)**
  - Stability of large area condensed liquid films
  - Mechanisms for shedding condensed films in reduced gravity

- **Environmental Control and Heat Rejection**
  - Evaporation and condensation heat transfer
  - Stability of evaporating/condensing films
Differing Role of Surface Tension on Condensing/Evaporating Film Stability

Evaporating film - surface tension variations de-stabilizing

Cold Ambient

Warm - Low Surface Tension

Cool - High Surface Tension

Hot Surface

Warm Ambient

Cold - High Surface Tension

Warmer - Low Surface Tension

Cold Surface

Condensing film - surface tension variations stabilizing
Fluid Mechanisms in Condensing and Evaporating Films in Reduced Gravity

Condensing film in low-g

Evaporating film in low-g
Research Plan

- 1-g (normal gravity) laboratory experiments (UW/WPI)
- Reduced gravity experiments on board NASA parabolic-trajectory aircraft (NASA Glenn Research Center)
- Numerical modeling using unsteady Navier-Stokes equations by a finite element method based on a front tracking technique (Prof. A.N. Alexandrou, University of Cyprus)
Experimental Configurations for Condensing Films

- **Geometries**
  1) Stabilizing gravitational body force (+1g, condensing surface “upwards”)
  2) De-stabilizing gravitational body force (-1g, “downwards”)
  3) Reduced gravity with external perturbation

- **Fluid configurations**
  1) Condensing film (thermal plus mass addition effects)
  2) “Pumped” film with isothermal mass addition through porous substrate
Experimental Configurations for Evaporating Films

- **Geometries**
  1) Stabilizing gravitational body force (+1g, evaporating surface “upwards”)
  2) De-stabilizing gravitational body force (-1g, “downwards”)

- **Fluid configurations**
  1) Evaporating film (thermal and mass removal effects)
  2) Heated, non-volatile film (thermal effects only)
Laboratory Condensation Test Cell

Schematic

Actual
Aircraft Experiment

Aircraft rig with volume control system

A/C rig test cell with dual thermoelectric elements
Condensation Study
Current Test Conditions

- Condensation experiments
  - 10 cm diameter cooled brass plate
  - Fluids: Methanol and n-pentane
  - Enclosed test cell, typical operating pressure 50-70 kPa
  - Subcooling range $T_{\text{sat}} - T_{\text{wall}} = 4 - 16 \, ^{\circ}\text{C}$

- “Pumped film” experiments
  - 10 cm diameter perforated stainless plates
  - Fluids: Silicone oil (125 and 50 cSt)
  - Pumping rates 2-12 ml/min
Diagnostics

- **Double-pass shadowgraph imaging**
  - Synchronized with data acquisition
  - Disturbance wavelengths
  - Time to drop formation/break off (condensation) or dry-out (evaporation)

- **Thermal measurements**
  - Thermocouples (surface, vapor temperatures)
  - Imbedded heat transfer sensors
  - Numerical inverse method employed to determine surface heat flux

- **Ultrasound gauging**
  - Single and multiple sensors
  - Film thickness and growth rate
Shadowgraph Images of Condensing \textit{n}-pentane Film in Unstable (-1g) Configuration

\[ T_{\text{wall}} = 11 \, \text{C}, \quad T_{\text{sat}} = 17 \, \text{C}, \quad P_{\text{sat}} = 50 \, \text{kPa} \]

At start of condensation

37 s after the start of condensation
Condensing n-Pentane Film in Normal Gravity (-1g) at Constant Pressure

$P_{sat} = 50 \text{ kPa}, \quad T_{sat} = 16.5 \text{ C}, \quad T_{wall} = 11 \text{ C}$

Video real time
Condensing n-Pentane Film in Normal Gravity (-1g) with Cyclic Pressure

$P_{sat} = 36\text{-}48 \text{ kPa}\quad T_{sat} = 8.8\text{-}15.5 \text{ C},\quad T_{wall} = 11 \text{ C}$

Cycle period 180 s; video rate 2.4 x real time
Non-condensing “Pumped” Film in Normal Gravity (-1g)

50 cSt Silicone Oil

Pumping rate 4 ml/min
→ average film growth rate = 8.2 μm/s
Video rate 0.4 x real time
Non-condensing “Pumped” Film in Normal Gravity (-1g)

50 cSt Silicone Oil

Click here to play movie

Pumping rate 12 ml/min
→ average film growth rate = 24.7 μm/s
Video rate 0.4 x real time
Non-condensing “Pumped” Film in Normal Gravity (-1g)

Silicone Oil

Time to first droplet break-off decreases with increasing pumping rate

Film thickness at first droplet break-off increases with increasing pumping rate
Heat Transfer Coefficient in Developing, Unstable Condensing Film in Normal Gravity

Unstable (-1g) condensing n-pentane film

$T_{wall} = 11 \, ^\circ C$, $T_{sat} = 17 \, ^\circ C$, $P_{sat} = 50 \, kPa$
Heat Transfer for Unsteady Condensing Film (-1g)

\[
P_{\text{sat}} = 36-48 \text{ kPa} \quad T_{\text{sat}} = 8.8-15.5 \text{ C} \quad T_{\text{wall}} = 11 \text{ C}
\]
Ultrasound Measurement of Film Thickness

N-pentane Film, Stable (+1g) Configuration

![Graph showing the measurement of film thickness over time for N-pentane film under stable (+1g) configuration using two transducers.](image-url)
Ultrasound Measurement of Film Thickness

N-pentane Film, Unstable (-1g) Configuration
Summary

- Condensation and evaporation research is critical to meeting the technology needs of the AHST development effort
  - Evaporation and condensation heat transfer and film stability and phase separation phenomena are strongly dependent on gravity level
  - Development of empirical correlations, theoretical models, CFD codes for these processes are all important to the success AHST technology development

- Research conducted to date in the current project includes
  - Film imaging and heat transfer measurements of steady and unsteady condensing films in the laboratory
  - Ultrasound gauging to determine the thickness of stable condensing and non-condensing films and in recording fluctuations in unstable films
  - The use of non-condensing, mechanically pumped films which simulate the growth and instability associated with unstable condensing films in the absence of thermal effects
Questions?

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