Gravity Effects in Condensing and Evaporating Films

J.C. Hermanson and S.M. Som
University of Washington, Seattle, WA

J.S. Allen
National Center for Microgravity Research, Cleveland, OH

P.C. Pedersen
Worcester Polytechnic Institute, Worcester, MA

Strategic Research to Enable NASA’s Exploration Missions
June 23, 2004
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 \( \approx 0.01g \) (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

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 $T_{\text{sat}} - T_{\text{wall}} = 4 - 16$ 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 $n$-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

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

Video real time

Click here to play movie
Condensing n-Pentane Film in Normal Gravity (-1g) with Cyclic Pressure

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

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
Unstable (-1g) condensing n-pentane film

\[ T_{\text{wall}} = 11 \, ^\circ\text{C}, \quad T_{\text{sat}} = 17 \, ^\circ\text{C}, \quad P_{\text{sat}} = 50 \, \text{kPa} \]
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
Ultrasound Measurement of Film Thickness

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

![Graph showing film thickness over time for N-pentane film in an 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?

Research supported by NASA OBPR Cooperative Agreements NAG3-2395 and NNC04GA76G