Flow Boiling Critical heat Flux in Reduced Gravity

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Rationale

- Critical heat flux (CHF) is key design parameter for heat-flux-controlled devices
- Ability to predict CHF is of paramount importance to both safety and reliability of two-phase systems
- Vast majority of reduced-gravity boiling studies focused on pool rather than flow boiling
- There are conflicting recommendations concerning viability of pool boiling in microgravity
- Flow boiling is proven method for enhancing CHF relative to pool boiling
- Bulk motion increases CHF by flushing bubbles away from heated wall before they coalesce into insulating vapor blanket, and by constantly replenishing wall with bulk liquid
- Low pumping power favors reducing flow velocity
- Minimum velocity is therefore sought which can adequately increase CHF and suppress detrimental effects of reduced gravity

Focus Area: Thermal Systems and Phase Change Processes

- Future missions for exploration of solar system will require enabling technologies for efficient and reliable energy generation (nuclear, chemical, solar sources), storage (rechargeable batteries, regenerative fuel cells, flywheels, latent heat phase change), and transfer (cabin temperature control, space suit temperature regulation).

- Need for improved energy-to-mass ratios suggests replacing present single-phase operations with two-phase systems. Future design of important thermal subsystems in boilers, condensers, evaporators, heat exchangers, cryogenic fluid storage units, fuel cells, radiators and heat pipes involve complex multiphase fluid flow and transport issues.

- Full understanding of multiphase transport phenomena associated with operation of thermal and phase change subsystems in microgravity needed for both design and safe and efficient operation in space.
High Priority Recommendations:

- Attainment of phenomenological understanding and accumulation of empirical data for two-phase flow in micro- and macro-geometries, boiling heat transfer, and phase-distribution and phase-transition phenomena in microgravity.
- Development of empirical correlations, theoretical models and scaling laws for two-phase flow in complicated geometries, boiling and condensation heat transfer, and phase-distribution and phase-transition phenomena in microgravity.
- Development of stability criteria for two-phase heat transfer loops in microgravity.
- Development of advanced, efficient, and reliable vapor compression heat pump technology.

Challenge

Reduced gravity flow boiling heat transfer and critical heat flux data and models virtually nonexistent!!!
Effects of Orientation on Pool Boiling CHF at One \( g_e \)

CHF from a horizontal surface

- \( 1 \, g_e \) (Saturated PF-5052)
  - CHF = 26 W/cm²

Heat Flux

- 0°
  - CHF = 20 W/cm²
- 90°
  - CHF = 5 W/cm²
- 180°
  - CHF = 5 W/cm²

Phase Change Photo Library (Mudawar, 1984 - 2004)

Howard & Mudawar (1999)
Bubble Coalescence Effects

**Incipient Flow Boiling**
- 0.35 m/s
- 0.75 m/s
- 1.50 m/s

Flow

**Pool Boiling**
- 0.50 mm

(50% CHF)

**Flow Boiling**

- < 20% CHF
- 60% CHF
- CHF

Flow

U = 0.5 m/s

6.4 mm

12.7 mm

- 1
- 2
- 3

Flow Boiling

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One-g Flow Boiling CHF Apparatus

Test Module

Rotation Stage

Heater Block

Heated Wall

Thermocouple Array

Test Module Bottom Plate

Flow Channel

Flow

Heater

Boiling Apparatus

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Vapor Behavior for Saturated Flow

- Downward-facing heater
- Upward-facing heater
- Upflow
- Downflow

- $U = 0.1 \text{ m/s}$
- $U = 1.5 \text{ m/s}$

- $\theta = 90^\circ$
- $\theta = 90^\circ$

- $g_e$
Variation of CHF with Orientation and Flow Velocity at 1 g_e
CHF Regime Map

Orientation, $\theta$

Flow

- $\theta = 90^\circ$ $U = 1.5$ m/s
- $\theta = 0^\circ$ $U = 0.1$ m/s
- $\theta = 180^\circ$ $U = 0.1$ m/s
- $\theta = 225^\circ$ $U = 0.1$ m/s
- $\theta = 270^\circ$ $U = 0.1$ m/s
- $\theta = 270^\circ$ $U = 0.5$ m/s

Wavy Vapor Layer Regime
Pool Boiling Regime
Stratification Regime
Vapor Counterflow Regime
Stagnation Regime
Separated Concurrent Vapor Flow Regime
Wavy Vapor Layer Regime

$U = 1.5 \text{ m/s}$

$5.0 \text{ mm}$

Flow
Vapor Momentum vs Interfacial Pressure

\[ P_f - P_g \]

\[ \sigma \delta \left( \frac{2\pi}{\lambda} \right)^2 \]

\[ \frac{4\pi \sigma \delta}{b \lambda^2} \sin(b\pi) A_w \]

\[ \rho_g U_g^2 u A_w \]

Wetting Front

Pressure Force

Vapor Momentum

Vapor

Liquid

2δ

bλ

λ
**Interfacial Lift-off Model**

- **Critical Wavelength:**
  \[
  \frac{2\pi}{\lambda_c} = \frac{\rho_f \rho_g (U_g - U_f)^2}{2 \sigma \rho_f + \rho_g} + \left( \frac{\rho_f \rho_g (U_g - U_f)^2}{2 \rho_f + \rho_g} \right)^{1/2} + \frac{(\rho_f - \rho_g) g \cos \theta}{\sigma}
  \]

- **Interfacial Pressure Difference:**
  \[
  P_f - P_g = \frac{4 \rho_f \rho_g}{\lambda_c^2} \sin (b \lambda)
  \]

- **Interfacial Lift-Off Heat Flux:**
  \[
  q_w = \rho_g \left( c_{p,f} \Delta T_{sub,i} + h_{fg} \right) \left( \frac{P_f - P_g}{P_g} \right)^{1/2}
  \]

- **Heater Energy Balance:**
  \[
  q_m = b q_w
  \]

- **Critical Heat Flux:**
  \[
  q_m = \rho_g \left( c_{p,f} \Delta T_{sub,i} + h_{fg} \right) \left[ \frac{4 \rho_f \rho_g}{\lambda_c^2} \sin (b \lambda) \right]^{1/2} \left( \frac{\lambda_c^{1/2}}{\lambda_c} \right)
  \]
Comparison of Measured and Predicted CHF at 1 g_e

Wavy Vapor Layer Regime (U = 1.5 m/s)

Pool Boiling Regime
0.1 m/s

Wavy Vapor Layer Regime
0.1 m/s

Vapor Stratification Regime
0.1 m/s

Vapor Counter-Flow Regime
0.1 m/s

Stagnation Regime
0.1 m/s

Pool Boiling Regime
0.1 m/s

Pool Boiling CHF (Zuber et al., 1961)

Measured CHF
U = 1.5 m/s

Lift-off CHF Model (Zhang et al., 2002)
U = 1.5 m/s

Flooding (Nejat, 1981)

Measured CHF
U = 0.1 m/s

q''_m (W/cm^2)

Orientation, \( \theta \)

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Negligible Component of Body Force Perpendicular to Wall

\[
\frac{2\pi \sigma (\rho_f + \rho_g)}{\lambda \rho_f \rho_t (\Delta U)^2} = \frac{1}{2} \left[ 1 + \frac{1 + 4 (\rho_f - \rho_g)(\rho_f + \rho_g)^2 \sigma g}{\rho_f^2 \rho_t^2 (\Delta U)^4} \right] \leq 0.09
\]

\[
\frac{Bo}{We^2} = \frac{(\rho_f - \rho_g)(\rho_f + \rho_g)^2 \sigma g}{\rho_f^2 \rho_g^2 U^4} \leq 0.09
\]

Negligible Component of Body Force Parallel to Wall

\[
U_n \sim \left[ \frac{(\rho_f - \rho_g)g D_h}{\rho_f^{1/2}} \right]^{1/2} \ll U
\]

\[
1 = \frac{1}{Fr} = \frac{(\rho_f - \rho_g)g D_h}{\rho_f U^2} \leq 0.13
\]
Minimum Velocity Required to Overcome Body Force Effects

U > 1.5 m/s to overcome body force effects below 1 g_e

FC-72
P = 1.3 bar

We_L = 2\pi, L = 0.01 m

We_L = 2\pi, L = 0.1 m

Bo / We^2 = 0.09

1 / Fr = 0.13

Earth
Moon
Mars

a / g_e

U (m/s)

10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}
Reduced Gravity Flow Loop

Coolant Reservoir
Accumulator
Heat Exchanger
Flow Boiling Module
Pump
Filter
Turbine
In-Line Heater
Flowmeter
Flow Boiling Module

188 Ohm Resistive Layer (covered with Glass Passivation)

Solder Layer (96% Tin - 4% Gold Metallization)

Al₂O₃ Substrate

Solder Pads

Thermocouple hole

Oxygen-Free Copper Slab

Resistive Heater

Transparent Polycarbonate Plastic Plate

Heated Wall

Flow Channel

All dimensions in mm

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Thermal Response of Heater

\[ T(\circ C) \]

\[ q'' (W/cm^2) \]

\[ t (s) \]
Parabolic Flight Results

FC-72, \( U = 0.14 \text{ m/s} \)

1.8\( g_e \)  
0.17\( g_e \) (Lunar)  
Zero-\( g_e \)

Sequential Images 8 ms apart

Phase Change Photo Library  
(Mudawar, 1984 - 2004)
Parabolic Flight Results

FC-72, $U = 1.40 \text{ m/s}$

1.8$g_e$

0.377$g_e$
(Martian)

Zero-$g_e$

Sequential Images 8 ms apart

Phase Change Photo Library
(Mudawar, 1984 - 2004)
Parabolic Flight Results

CHF (W/cm²) vs. U (m/s)

One-g

Zero-g

FC-72

ΔT_{sub,o} = 2.6 - 12.3 °C

Phase Change Photo Library
(Mudawar, 1984 - 2004)
Conclusions

One-G Flow Orientation Study

- At high velocities, CHF at all orientations dominated by Wavy Vapor Layer Regime. Vapor layer layer propagates along heated wall permitting liquid contact only in troughs of interfacial waves. CHF occurs when liquid contact regions are lifted from wall due to intense vapor effusion.

- Interfacial Lift-off Model very effective at capturing overall dependence of CHF on orientation in Wavy Vapor Layer Regime.

- Flooding limit better suited to CHF prediction in low velocity downflow orientations.

- Dimensionless criteria developed for minimum flow velocity required to overcome body force effects on flow boiling CHF.
**Conclusions**

**Reduced Gravity Study**

- Body force has significant effect on nucleate flow boiling at low flow velocities.
- Very low coolant velocities (especially below 0.5 m/s) greatly reduce CHF in microgravity.
- Increasing flow velocity reduces CHF sensitivity to body force and can eliminate detrimental effects of microgravity on CHF.
- Experimental CHF data corresponding to microgravity, lunar and Martian environments demonstrate existence of minimum velocity above which effects of body force on CHF are suppressed.
- Experimental CHF data support predictions of theoretical dimensionless minimum velocity criteria.
Conclusions

Practical Implications

- This study provides systematic method for reducing power consumption in reduced gravity systems by adopting minimum velocity required to provide adequate CHF and preclude detrimental effects of reduced gravity

- This study proves it is possible to use existing 1 g_e flow boiling and CHF correlations and models to design reduced gravity systems provided minimum velocity criteria are met