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
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

$1 \, g_e$

Heat Flux

CHF = 26 W/cm²

CHF = 20 W/cm²

CHF = 5 W/cm²

0°

90°

180°

Saturated PF-5052

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
- 12.7 mm
- U = 0.5 m/s

- 60% CHF

- CHF

- Flow Boiling
One-g Flow Boiling CHF Apparatus

Test Module

Rotation Stage

Flow Channel
Heater Block
Heated Wall
Thermocouple Array
Test Module Bottom Plate
Flow

Heater
Boiling Apparatus

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Vapor Behavior for Saturated Flow

Downward-facing heater ↔ Upward-facing heater

Upflow

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

$0^\circ$, $90^\circ$, $180^\circ$, $270^\circ$

$\theta = 90^\circ$

Downflow

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

$0^\circ$, $90^\circ$, $180^\circ$, $270^\circ$

Upward-facing heater

Downward-facing heater

$g_e$

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

- **Wavy Vapor Layer Regime**
  - $\theta = 90^\circ$
  - $U = 1.5 \text{ m/s}$

- **Pool Boiling Regime**
  - $\theta = 0^\circ$
  - $U = 0.1 \text{ m/s}$

- **Stratification Regime**
  - $\theta = 180^\circ$
  - $U = 0.1 \text{ m/s}$

- **Vapor Counterflow Regime**
  - $\theta = 225^\circ$
  - $U = 0.1 \text{ m/s}$

- **Stagnation Regime**
  - $\theta = 270^\circ$
  - $U = 0.1 \text{ m/s}$

- **Separated Concurrent Vapor Flow Regime**
  - $\theta = 270^\circ$
  - $U = 0.5 \text{ m/s}$
Wavy Vapor Layer Regime

5.0 mm

$g_e$

Flow

$U = 1.5 \text{ m/s}$
\[ P_f - P_g = \sigma \delta \left( \frac{2\pi}{\lambda} \right)^2 \]

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

\[ \rho_g U_g^2 u A_w \]
Interfacial Lift-off Model

- Critical Wavelength:

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

- Interfacial Pressure Difference:

\[
\frac{P_f - P_g}{\rho_f} = \frac{4 \rho_f \rho_g}{\sigma} b^2 \sin (b \lambda_c)
\]

- Interfacial Lift-Off Heat Flux:

\[
q_w = \rho_f (c_p, f \Delta T_{sub,i} + h_{fg}) \left( \frac{P_f - P_g}{\rho_g} \right)^{1/2}
\]

- Heater Energy Balance:

\[
q_m = b q_w
\]

- Critical Heat Flux:

\[
q_m = \rho_f (c_p, f \Delta T_{sub,i} + h_{fg}) \left[ \frac{4 \rho_f \rho_g}{\sigma} \sin (b \lambda_c) \right]^{1/2} \left( \frac{\lambda_c}{\sigma} \right)^{1/2}
\]
Comparison of Measured and Predicted CHF at 1 g_e

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

Pool Boiling Regime

Wavy Vapor Layer Regime

Stratification Regime

Vapor Counter-Flow Regime

Stagnation Regime

Pool Boiling Regime

0.1 m/s

0.1 m/s

0.1 m/s

0.1 m/s

0.1 m/s

Comparison of Measured and Predicted CHF at 1 g_e

Pool Boiling CHF (Zuber et al., 1961)

Wavy Vapor Layer Regime

Stratification Regime

Vapor Counter-Flow Regime

Stagnation Regime

Pool Boiling Regime

Lift-off CHF Model (Zhang et al., 2002)

0.1 m/s

Measured CHF U = 1.5 m/s

0.1 m/s

Measured CHF U = 0.1 m/s

Flooding (Nejat, 1981)

0

0

q''_m (W/cm²)

Orientation, θ

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**Minimum Velocity Required to Overcome Body Force Effects**

### Negligible Component of Body Force Perpendicular to Wall

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

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

\[
B_0 = \frac{(\rho_f - \rho_g) g L^2}{\sigma}, \quad We = \frac{\rho_f \rho_g U^2 L}{(\rho_f + \rho_g) \sigma}
\]

### Negligible Component of Body Force Parallel to Wall

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

\[
1 = \frac{\rho_f - \rho_g}{\rho_f U^2} g D_h \leq 0.13
\]
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 = 2π, L = 0.01 m
- We_L = 2π, L = 0.1 m

Bo / We^2 = 0.09
1 / Fr = 0.13

a / g_e
Reduced Gravity Flow Boiling CHF Apparatus

Flight Rack

Two-Phase Loop

Light Source

Video Camera

Flow Boiling Module

Phase Change Photo Library (Mudawar, 1984 - 2004)

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NASA Glenn Research Center, April 2004

Flight Trajectory

Maneuver Time (s)

Altitude (ft)

20 45 65

1.8g_e Zero-g_e 1.8g_e

KC-135 Microgravity Experiments

Operators:
Dwayne Kiefer (QSS)
Dr. Charles Niederhaus (NASA)
Dr. Juan Agui (NASA)

Phase Change Photo Library
(Mudawar, 1984 - 2004)
Reduced Gravity Flow Loop

Water

Accumulator

Heat Exchanger

Data Acquisition System

Coolant Reservoir (Detachable)

Air

Flow Boiling Module

AC

In-line Heater

Turbine Flowmeter

Filter

Control Valve

Pump

AC
Reduced Gravity Flow Loop

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

- Heated Wall
- Flow Channel

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

All dimensions in mm

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Thermal Response of Heater

Temperature $T$ vs. time $t$

Heat flux $q''$ vs. time $t$

Graph showing the thermal response of a heater over time with temperature and heat flux plotted against time.
Parabolic Flight Results

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

Sequential Images 8 ms apart

$1.8g_e$
$0.17g_e$
$(\text{Lunar})$

Zero-$g_e$

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

FC-72, U = 1.40 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-gₐ

Zero-gₑ

FC-72

ΔTₘₜₙ,₀ = 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.
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.