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Boiling Configurations
Constant pursuit of more compact and lightweight packaging, and better performance (lower junction temperature) has lead to alarming increases in power density.

Because thermal management is mostly an afterthought, pushing limits of existing cooling solutions (e.g., using air-cooled heat sinks) often results in costly upper bounds to many technologies.

What is presently needed is a new class of thermal management solutions capable of dissipating very high power densities.

With this capability, these solutions will allow vast advances in performance without the need for costly changes in system packaging.

Systems utilizing liquid-to-vapor phase-change are the most effective thermal management solutions for high-power-density applications.
Boiling and Two-Phase Flow
Laboratory (BTPFL)

Boiling on a Wire

Nucleate Boiling

Critical Heat Flux

Film Boiling

Key Merits of Boiling:

(1) Modest changes in device temperature corresponding to broad changes in device heat flux (in nucleate boiling region)

(2) Much lower device temperatures than with single-phase cooling. For this device:

$q'' < 50 \text{ W/cm}^2$

$T_s < 85 \degree \text{C}$

Region where:

FC-72 at $T_f = 20 \degree \text{C}$

$T_s = 525 \degree \text{C}$ at $50 \text{ W/cm}^2$ without boiling

$T_s = 70 \degree \text{C}$ at $50 \text{ W/cm}^2$ with boiling

$T_s = 525 \degree \text{C}$ at $50 \text{ W/cm}^2$ without boiling
Boiling Configurations: Pool Boiling Thermosyphons

Air-cooled: Microprocessor Cooling

- Fan
- Finned condenser
- Fluorinert vapor
- Fluorinert liquid
- Finned attachment
- Device

Liquid-cooled: Multi-Chip Modules

- Water-Cooled Condenser
- Dielectric Vapor
- Water
- Dielectric Liquid

Phase Change Photo Library (Mudawar, 1984 - 2014)
Boiling and Two-Phase Flow
Laboratory (BTPFL)

Boiling Configurations: Channel Flow

CHF = 361 W/cm²

Phase Change Photo Library (Mudawar, 1984 - 2014)
Boiling Configurations: Mini/Micro-channel Flow

Slug Flow

Annular Flow

Bubbly/Slug Flow

Liquid/Slug

Liquid/Annular Flow

Boiling and Two-Phase Flow Laboratory (BTPFL)
Boiling Configurations: Mini/Micro-channel Flow/Carbon Nanotubes

Khanikar, Mudawar & Fisher (2009)

G = 368 kg/m².s, Tₕ = 30°C, after 5 tests

Water Tₕ = 30°C

Isolated cellular formations

G (kg/m².s)

<table>
<thead>
<tr>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>368</td>
</tr>
<tr>
<td>228</td>
</tr>
<tr>
<td>86</td>
</tr>
</tbody>
</table>

Dominant ‘fish-scale’ pattern

Boiling and Two-Phase Flow Laboratory (BTPFL)

Research Presentation

Fall 2014
Stable flow boiling never achieved due to CHF occurrence shortly following onset of boiling

Severe nano particle deposition inside micro-channels

Particle clustering began forming at channel outlet, then propagated rapidly upstream

Temperature of heat sink rose continuously after particle clogging

Enhancement efforts should focus on surface itself, not fluid!

Lee & Mudawar (2006)
Boiling and Two-Phase Flow
Laboratory (BTPFL)

Research Presentation

Fall 2014

Boiling Configurations: Mini/Micro-channel Flow using Smart, Pump-Free Loop

- **Device (Boiler)**
- **Condenser**
- **Reservoir**
- **Fan**

COLD Tube
\[ \alpha = 0 \]
\[ \rho = \rho_f \]
\[ \Delta P_G \text{ constant} \]

HOT Tube

\[ \alpha \neq 0 \]
\[ \rho \neq \rho_f \]

- **Insulation**
- **Housing (G-10)**
- **Flush-Mounted Base Area**
- **Boiler Gap**
- **Transparent Cover**
- **Flow**
- **Transparent Cover (Lexan)**

**Mukherjee & Mudawar (2003)**

- **FC-72**
  0.51 mm gap
  50% CHF

- **Water**
  0.13 mm gap
  50% CHF

**CHF (W/cm²)**

- **Gap (mm)**
Boiling Configurations: Curved Channel Flow

Curved Channel

Concave Heater

Phase Change Photo Library (Mudawar, 1984 - 2014)

Galloway & Mudawar (1995)

Galloway & Mudawar (1995)

Saturated FC-72
U = 1 m/s

0
25
50
75
101.6 mm

Concave Heated Wall
Insulated Wall
Flow
Boiling and Two-Phase Flow

Laboratory (BTPFL)

Research Presentation

Fall 2014

Boiling Configurations: Centrifugal Flow

Phase Change Photo Library (Mudawar, 1984 - 2014)

Galloway & Mudawar (1992)

Test Apparatus

Stirrer Assembly
Boiling and Two-Phase Flow Laboratory (BTPFL)

Boiling Configurations: Jet Impingement

Free Jet Cooling

Free Jet

Jet Impingement

Liquid Splashing

Confined Jet

Confined Jet Module

Highest CHF of 411 W/cm² achieved with subcooled flow boiling FC-72 & Surface Enhancement

Confined Jet Module Parts

Wadsworth & Mudawar (1990)

Phase Change Photo Library (Mudawar, 1984 - 2014)

Estes & Mudawar (1995)
Boiling Configurations: Spray Cooling

- Condenser
- Reservoir
- Immersion Heater
- Heat Exchanger
- Air Flow Meters
- Rotameters
- Valves
- Data Acquisition System
- In-line Heater
- Deaeration Chamber
- Spray Chamber
- Pumps
- Filters

Visaria & Mudawar (2008)
Boiling Configurations: Spray Cooling

Visaria & Mudawar (2008)

Nozzle 1 (θ = 55.8°)
PF 5052 (T_{sat} = 50°C)
T_{in} = 24°C
Q = 3.86 \times 10^{-6} \text{ m}^3/\text{s}

Recording speed: 6000 fps
Playback speed: 60 fps

α = 0°

α = 50°

x [cm]

y [cm]

L = 1 cm
θ = 56°
BTPFL Applications
Applications: Very-High-Flux Fusion Reactors, Particle Accelerators & MHD Generators

Fusion Reactor Blanket

- Magnetic containment of plasma in donut-shaped vacuum vessel (tokomak)
- Fusion reactor blanket extracts fusion power to generate electricity
- Highly subcooled water cooling at high pressure and high mass velocity required to guard against CHF

Heat flux in cooling channels can exceed $10^4$ W/cm$^2$

International Thermonuclear Experimental Reactor (ITER)

Particle Accelerator Target

MHD Electrode Walls

Boiling and Two-Phase Flow Laboratory (BTPFL)
Ultra-High-Flux Flow Boiling in Micro-Channels

Low mass velocity
Low subcooling

Dryout
Liquid film evaporation
Saturated boiling
Subcooled boiling
Forced convection heat transfer

High mass velocity
High subcooling

Annular flow
Slug flow
Bubbly flow
Saturated boiling
Subcooled boiling
Forced convection heat transfer

DNB

CHF = 27,600 W/cm²
demonstrated experimentally

G = 120,000 kg/m².s
D = 0.406 mm

Applications: Very-High-Flux Fusion Reactors, Particle Accelerators & MHD Generators

Boiling and Two-Phase Flow Laboratory (BTPFL)
Research Presentation
Fall 2014

Mudawar & Bowers (1999)

\[ \text{CHF} = 27,600 \text{ W/cm}^2 \]
Applications: Avionics

- 40 W cooling capacity for conventional 5.38 x 6.41 x 0.59 in³ edge air-cooled module
- 200 W capacity for equivalent flow-through polyalphaolafin (PAO) module

MTS
12 kW Jet-Impingement Clamshell Module

BTPFL-C2
3 kW Micro-Channel Clamshell Module

Applications: Avionics

Avionics Enclosure

Boiling and Two-Phase Flow Laboratory (BTPFL)

Research Presentation

Fall 2014
Applications: Boiling in Rocket Engines, Turbine Blades

NASA rocket engine with high aspect ratio cooling channels

- Engine life doubled by decreasing wall temperature by 50-100°C
- Cooling performance in wall enhanced by using closely-spaced micro-channels separated by thin walls
- Depending on rocket engine type, boiling may or may not be desirable

Hydrogen/oxygen liquid rocket engine with walls cooled by hydrogen

\[ \frac{H_{\text{ch}}}{W_{\text{ch}}} \approx 2 \]
\[ \frac{H_{\text{ch}}}{W_{\text{ch}}} \approx 8 \]

\[ \varepsilon = \frac{2k_w}{hW_w} \]

Cooling Passage

Combined effects of centrifugal and Coriolis forces help achieve 4500 W/cm² inside blade

M.I.T. Gas Turbine Lab

Research Presentation Fall 2014
Applications: High Mach Turbine Engines, Radar, Laser & Microwave Systems

Nacke, Northcutt & Mudawar (2011)


High-Power Laser, Radar and Microwave Systems

Power Supply
1 MW Total

Diode Array
50% efficient
500 kW Total

Solid State Crystal
20% efficient
100 kW Total

500 kW of Waste Heat

400 kW of Waste Heat

100 kW Laser output

Waste heat from high power diode pumped solid state laser

Mudawar (2001)

Boiling and Two-Phase Flow Laboratory (BTPFL)

Research Presentation Fall 2014
Applications: Nuclear Fission/Rankine Power Cycle for Future Space Missions

Project Prometheus:
Developing means to efficiently power advanced spacecraft for Solar System exploration

- Liquid-Metal Cooled Reactor
- Power Conversion Units
- Deployable Power Conversion Radiators

Applications: Nuclear Fission/Rankine Power Cycle for Future Space Missions

- Primary Lithium Loop
- Secondary Potassium Loop

Boiling and Two-Phase Flow Laboratory (BTPFL)

Research Presentation  Fall 2014

<table>
<thead>
<tr>
<th>Fission 1.0–100 kWe</th>
<th>Present - 2015</th>
<th>2017 - 2022</th>
<th>2023 - 2028</th>
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<tr>
<td>Nuclear System Demo</td>
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<td>kW-Class Science</td>
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</table>

| Fission > 100 kWe |               |             |             |
| Exploration Missions |           |             |             |
| 1 kW-class Components |   |             |             |
| 1 MW-class Integrated |   |             |             |
| MW-class Exploration |   |             |             |
| Flexible Path Robots |   |             |             |

| Science Missions |               |             |             |
| Flagship #1 |               |             |             |
| Flagship #2 |               |             |             |
| Flagship #3 |               |             |             |
Thermal management systems responsible for controlling temperature and humidity using Thermal Control System (TCS) consisting of Heat Acquisition, Heat Transport and Heat Rejection hardware

- Refrigerator/freezer components provide cooling for science experiments and food storage

- Advanced water recovery systems transfer crew and system wastewater into potable water for crew and system reuse
NASA Johnson Space Center (JSC) Ground based Solar Heat Pump (SHP):

- Precursor to R134a vapor compression heat pump for future space vehicles and planetary bases
- Absorbs 5 to 15 kW
- Heat to evaporator provided by single-phase (liquid) Internal Thermal Control Cycle (ITCS)
- Heat from condenser by single-phase (liquid) External Thermal Control Cycle (ETCS)
- Evaporator and Condenser are SWEP Copper Brazed Plate (CBP) heat exchangers

Applications: Vapor Compression Heat Pump for Future Space Vehicles Planetary Bases
Applications: Gravity Effects on Two-phase Flow in Space Missions

- Space Vehicle
- Astronaut Suit
- Martian Base
- Asteroid Landing
- Earth Orbiting Station
- Earth Orbiting Vehicles
- Satellites
- Moon (0.17 $g_e$)
- Mars (0.38 $g_e$)
- $1g_e$
- $10g_e$

Boiling and Two-Phase Flow Laboratory (BTPFL)
Applications: Purdue Microgravity Flow Boiling Apparatus

Flight Rack

Two-Phase Flow Loop

Phase Change Photo Library (Mudawar, 1984 - 2014)

Boiling and Two-Phase Flow Laboratory (BTPFL)

Research Presentation

Fall 2014
KC-135 Tests performed at NASA Glenn Research Center

Flight Trajectory

Phase Change Photo Library
(Mudawar, 1984 - 2014)
Applications: Purdue Microgravity Flow Boiling Apparatus

Predictions of Interfacial Lift-Off Model

CHF (W/cm²) vs. U (m/s)

- One $g_e$
- $\mu g_e$

FC-72
$\Delta T_{sub,o} = 2 - 8°C$

Boiling and Two-Phase Flow Laboratory (BTPFL)
Research Presentation
Fall 2014
Applications: Purdue Flow Boiling & Condensation Experiment (FBCE) for International Space Station (ISS)

Consists of:
- nPFH sub-loop
- Water sub-loop

Contains three test modules:
- Flow Boiling Module (FBM)
- Condensation Module CM-HT for heat transfer measurements
- Condensation Module CM-FV for flow visualization
Applications: Purdue Flow Boiling & Condensation Experiment (FBCE) for International Space Station (ISS)

Parabolic Flight FBCE

Condensation Rig

Water Conditioning Rig

Deaeration Rig

Applications: Purdue Flow Boiling & Condensation Experiment (FBCE) for International Space Station (ISS)
Applications: Purdue Flow Boiling & Condensation Experiment (FBCE) for International Space Station (ISS)

Parabolic Flight FBCE

Condensation Rig

CM-HT: Condensation Module for Heat Transfer Measurements

CM-FV: Condensation Module for Flow Visualization

Boiling and Two-Phase Flow Laboratory (BTPFL)
Applications: Purdue Flow Boiling & Condensation Experiment (FBCE) for International Space Station (ISS)

Flight Campaigns:
- May 2012
- August 2012

Boiling and Two-Phase Flow Laboratory (BTPFL)

Research Presentation

Fall 2014
Applications: Purdue Flow Boiling & Condensation Experiment (FBCE) for International Space Station (ISS)
Predictive Methods
Predictive Methods for Liquid-Vapor Two-Phase Systems

- **Computational methods:** computationally very intensive; predictions very sensitive to numerical and phase change model used
- **Theoretical models:** very few exist!
- **Semi-empirical models:** mechanistic models with specific constants determined from empirical data
- ‘**Universal**’ experimental correlations: based on large databases for many fluids and broad ranges of geometrical or flow parameters; few exist; most desirable in industry
- **Narrow-range experimental correlations:** applicable to one or very few fluids and limited ranges of geometrical or flow parameters; often extrapolated resulting in erroneous predictions
- **Replication:** performance based on specific fluid, geometry, and operating conditions of given device

**Recent Challenges:**

- Reluctance to develop large, complex phase-change facilities
- Studies focused on development of narrow-range correlations or simply data trends
- Findings very incremental
- Avoidance of mechanistic models
Two-Phase Flow and Heat Transfer Regimes

Heat Transfer Regimes

- Liquid forced convection
- Subcooled boiling
- Saturated boiling
- Post-dryout heat transfer
- Vapor forced convection

Flow Constrain and Instabilities

- Compressibility
- Flashing
- Two-phase choking

Heat Transfer Limits and Anomalies

- CHF
- Premature CHF

Boiling and Two-Phase Flow Laboratory (BTPFL)

Research Presentation

Fall 2014
Consolidated World Databases and Correlations for Flow Boiling Critical Heat Flux of Water in Tubes

Boiling and Two-Phase Flow Laboratory (BTPFL)
**Flow Boiling Heat Transfer Transfer Coefficient**

**Universal Heat Transfer Correlation for Saturated Boiling in Small Channel**

Consolidated database:
10,805 saturated boiling heat transfer coefficient data points from 37 sources

- FC72, R11, R113, R123, R1234yf, R1234ze, R134a, R152a, R22, R236fa, R245fa, R32, R404A, R407C, R410A, R417A, CO₂, water

- $0.19 < D_h < 6.5$ mm
- $19 < G < 1608$ kg/m²s
- $57 < Re_\text{fo} = GD_h/\mu_t < 49,820$
- $0 < x < 1$
- $0.005 < \text{Reduced pressure} < 0.69$

\[
Bo = \frac{q_{\text{in}}}{G h_{fg}}
\]

\[
h_{\text{tp}} = (h_{\text{nb}}^5 + h_{\text{cb}}^5)^{0.5}
\]

**For nucleate boiling dominant regime**:

\[
h_{\text{nb}} = 2345 \left( Bo \frac{P_h}{P_f} \right)^{0.70} P_x^{0.38} (1-x)^{-0.51} \left[ 0.023 R_{ef}^{0.8} P_{rf}^{0.4} \frac{k_f}{D_h} \right]
\]

**For convective boiling dominant regime**:

\[
h_{\text{cb}} = 5.2 \left( Bo \frac{P_h}{P_f} \right)^{0.08} We_{fo}^{-0.54} + 3.5 \left( \frac{1}{X_f} \right)^{0.94} \left( \frac{\rho_g}{\rho_f} \right)^{0.25} \left[ 0.023 R_{ef}^{0.8} P_{rf}^{0.4} \frac{k_f}{D_h} \right]
\]


Boiling and Two-Phase Flow Laboratory (BTPFL)
Condensation

Air Cooled Condensers for Refrigerant

Shell-and-Tube Condensers
Different flow regimes: pure vapor, annular, slug, bubbly and pure liquid

Annular regime most prevalent … separated two-phase flow consisting of thin shear-driven liquid film along tube wall and central vapor core

Thin annular film responsible for high condensation heat transfer coefficients

Condensation in Tubes

Mudawar (2008)
**Fundamental Challenges to Modeling Annular Condensation**

**Common perception:**

Separated flows presumed convenient to model because they can be represented by two predominantly single-phase flows

**Complicating Influences (Fluid Physics):**

1. Circumferential variations of mean film thickness due to transverse body force
2. Complex transitional characteristics of condensation films
3. Turbulence dampening near film interface
4. Interfacial waves
5. Droplet entrainment and deposition

**Challenges:**

1. Develop fundamental understanding of all above
2. Incorporate all above influences into robust predictive model
Complicating Influences: Turbulence Dampening near Film Interface

- Near-wall region: Most use Van Driest (1956) function
- Mudawar & El-Masri: Ueda et al. (1977) experimental profile in middle, and a function of Kapitza number near interface:
  \[ Ka = \frac{\mu^4 g}{\rho \sigma^3} \]

\[ \varepsilon_m / \nu_f = Ky^* \]

\[ -q'' = k_f \left( 1 + \frac{Pr_f \varepsilon_m}{Pr_{f,*} \nu_f} \right) \frac{dT}{dy} \]

Failure to account for interfacial dampening of turbulence near the interface and large interfacial temperature gradient has been shown to produce significant errors in predicting heat transfer across films!!
Complicating Influences: Interfacial Waves

'Small' sinusoidal surface disturbances (ripples)  
'Large' mass-carrying waves  
'Rogue' solitary waves

Vertical test section situated above pump and reservoir

Mudawar & Houpt (1993a,b)

Beam crossing viewed from bottom of sampling channel

Vertical cylinder and film thickness probe

LDV Optics
Condensation Measurements

**Boiling and Two-Phase Flow Laboratory (BTPFL)**

**Purdue High Capacity Condensation Facility**

- **Condensation Module for Flow Visualization**
  - Borosilicate Glass Tube: 10.16 mm ID x 1.8 mm Wall x 1219 mm Long
  - Polycarbonate Plastic Tube: 19.05 mm ID x 25.40 mm OD
  - Latex Rubber Tube

**High-Speed Video Motion Analysis System:**
- Photron FASTCAM-Ultima camera with shutter speeds up to 1/120,000 s
- Infinity K-2 high magnification lenses
- PerkinElmer Xenon source fitted with Olympus fiber optic cable

**Research Presentation**

Fall 2014
Condensation Measurements – Large Tubes

Flow

\[ \dot{m}_{FC-72} = 19.5 – 19.6 \text{ g/s} \]

Inlet

\[ Re_{f, FC-72, exit} = 179 – 181 \]
\[ q_{out} [W] = 77.5 – 78.3 \]

Middle

\[ Re_{f, FC-72, exit} = 927 – 960 \]
\[ q_{out} [W] = 392 – 406 \]

Outlet

\[ Re_{f, FC-72, exit} < 200 \]
- Smooth Laminar in inlet
- Wavy Laminar in middle and outlet

\[ Re_{f, FC-72, exit} > 200 \]
- Flow appears to turn turbulent
- Wave structure more complex

Purdue High Capacity Condensation Facility

For \( Re_{f, FC-72, exit} \) < 200
- Smooth Laminar in inlet
- Wavy Laminar in middle and outlet

For \( Re_{f, FC-72, exit} \) > 200
- Flow appears to turn turbulent
- Wave structure more complex

Boiling and Two-Phase Flow Laboratory (BTPFL)
Condensation Measurements – Small Channels

### Flow Regimes

- **Annular**
- **Wavy-Annular**
- **Slug**
- **Bubbly**

### Regime Table

<table>
<thead>
<tr>
<th>Regime</th>
<th>FC-72 (g/s)</th>
<th>Water (g/s)</th>
<th>Video Rate</th>
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</thead>
<tbody>
<tr>
<td>Annular</td>
<td>1.51</td>
<td>5.06</td>
<td>1/66.6</td>
</tr>
<tr>
<td>Wavy-Annular</td>
<td>2.97</td>
<td>1/66.4</td>
<td>1/66.4</td>
</tr>
<tr>
<td>Slug</td>
<td>0.55</td>
<td>2.97</td>
<td>1/66.4</td>
</tr>
<tr>
<td>Bubbly</td>
<td>0.55</td>
<td>5.06</td>
<td>1/66.4</td>
</tr>
</tbody>
</table>

### Purdue Small Channel Condensation Facility

- FC-72
- Water

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Boiling and Two-Phase Flow Laboratory (BTPFL) - Purdue
In Pursuit of More Efficient, Renewable and Cleaner Energy …

1. Hydrogen Fuel Cells

2. Hybrid Vehicles

3. Solar Receivers

4. Intelligent Heat Treating of Metal Alloys
1. Heat Exchanger for Hydrogen Storage Fuel Cell Systems

- Developed for high-pressure metal hydride (e.g., Ti$_{1.1}$CrMn) storage systems
- Used to remove large amount of heat dissipated from hydriding reaction when H$_2$ is charged into storage vessel

![Diagram of heat exchanger system]
1. Thermally-Optimized Heat Exchanger

Assembled Heat Exchanger

US Patent 8,636,836 B2
January 28, 2014
1. Transient Contours of Temperature, Fraction of Reaction Completion and Volumetric Heat Generation Rate during Hydriding

- P = 100 bar
- P = 200 bar
- P = 300 bar
- P = 300 bar
- P = 300 bar
- P = 300 bar
- P = 300 bar
- P = 300 bar
1. Coiled and Micro-Channel Heat Exchangers

**Coiled Heat Exchanger Design**

US Patent 8,778,063 B2
July 15, 2014

**Micro-Channel Heat Exchanger Design**

- Single micro-channel heat exchanger module
- Cooling tube
- Base plate with serpentine micro-channel for coolant flow
- Underside identical in construction to top plate

Mudawar (2009)

**Boiling and Two-Phase Flow Laboratory (BTPFL)**

Research Presentation

Fall 2014
2. Hybrid Vehicle Power Electronics

- **Direct liquid cooling** of chip to:
  1. Eliminate conductive resistances of intermediate layers
  2. Allow closer packaging of high-flux chips
  3. Greatly decrease weight and volume of cooling system

- **Indirect liquid cooling**

- **Alternative direct liquid cooling** of chip to:
  1. Eliminate conductive resistances of intermediate layers
  2. Allow closer packaging of high-flux chips
  3. Greatly decrease weight and volume of cooling system

- **Goal**: dissipate over 250 W/cm² while maintaining device temperature below 125°C for silicon devices

- **Two-phase cooling options**: R134a loop that taps into vehicle’s refrigeration loop, or separate HFE 7100 cooling loop
2. NREL Hybrid Vehicle Power Electronics Thermal Test Laboratory

Mudawar, Bharathan, Kelly & Narumanchi (2009)
2. Coolant/Refrigerant Thermal/Environmental Study

Refrigerants

Chlorofluorocarbons (CFCs) (e.g., R11, R12, R113 and R114) composed of chlorine, fluorine and carbon; they are nontoxic and inert, but highly ozone-depleting and contribute to global warming.

Hydrochlorofluorocarbons (HCFCs) (e.g., R123, R124 and R141b) constitute a more recent alternative to CFCs, given their somewhat similar inertness and cooling characteristics but less than 10% of the ozone-depleting effects of CFCs.

Hydrofluorocarbons (HFCs) (e.g., R134a and R143a) provide essentially zero ozone depletion and reduced global warming effects; R134a has good ratings in most performance categories.

Liquid Coolants

3M perfluorocarbons (PFCs) (e.g., Fluorinerts FC-72, FC-87 and FC-84, and Performance Fluids PF-5050, PF-5052, PF-5060 and PF-5070) have average environmental ratings because of their relatively high GWP.

3M HFCs (e.g., Novec fluids HFE-7100 and HFE-7200). HFE-7100 has good ratings in all performance categories but HFE-7200 carries a low LEL. HFE-7100 has a freezing point of -135°C, which is well below any expected automobile application range of temperatures.

Most promising: R134a and HFE-7100
2. Cooling Loop Options for Hybrid Vehicle Power Electronics

- **Modified R134a Air-Conditioning Refrigeration Loop**
  - Pump
  - Flow Control Valve
  - Spray Chamber
  - Primary Vehicle Condenser
  - Expansion Valve
  - Outside Air
  - Vehicle Evaporator
  - Compressor
  - Spray Chamber
  - Condenser
  - Heat Exchanger
  - Pump

- **Separate Cooling Loop with Appropriate Coolant**

**Heat Flux, $q''_s$ (W/cm²) vs. Surface Temperature, $T_s$ (°C)**

- **R134a** can yield high CHF values, but cannot maintain low device temperatures.
- **HFE-7100** can yield CHF values in excess of 200 W/cm² at surface temperatures below 125°C.
- Two-phase HFE-7100 spray cooling is effective at meeting thermal management requirements of hybrid vehicle electronics.
Ivanpah Solar Power Facility
- World’s largest solar thermal project
- California Mojave Desert
- 3,600 acres (3 units)
- 370 MW power output
- 173,500 heliostats
- Serves 140,000 homes

Evaporator heats subcooled water to boiling temperature to produce steam-water mixture at high pressure and temperature

Heat flux one-sided and much higher than in fossil boilers
3. Single-Sided versus Double-Sided Heating

0.9 m/s

114.6 mm

5.0 mm

Flow

Heater Wall H₁

Heat Flux

CHF

77%
(CHF = 29.9 W/cm²)

5.0 mm

Flow

Heater Wall H₂

Heat Flux

CHF

69%
(H₂ CHF: 34.0 W/cm²)

114.6 mm

Heater Wall H₁

Boiling and Two-Phase Flow Laboratory (BTPFL)
3. Measurement of effects of Waves on Wavy Heated Liquid layers

Temperature fluctuations across wavy, turbulent water film falling on vertical heated cylinder at Re = 5700 (Lyu & Mudawar, 1991)
3. Computed Nitrogen Velocity Vector and Contour Plots along Stationary Wavy Interface

\[ \text{Re}_g = 3450 \quad \rightarrow \quad 24 \text{ m/s} \quad \text{Re}_g = 6100 \quad \rightarrow \quad 40 \text{ m/s} \]

Nitrogen velocity vector plots at \( z = 0 \)

Nitrogen velocity contour plot at \( z = 0 \)

FLUENT, \( k - \omega \) model

Research Presentation  
Boiling and Two-Phase Flow Laboratory (BTPFL)  
Fall 2014
4. Intelligent Heat Treating of Aluminum Alloy Parts

U.S. Aluminum Industry Profile

- Energy Consumption: 200,000 Trillion BTU
- 23.0 B lbs Annual Production Volume
- Generates $65 Billion (plus $87 B indirect)
- 155,000 Employees (plus 517,000 Indirect)

Source: Aluminum Assoc.

Enormous Energy Consumption
High Scrap Rate
High Water Consumption
High Emissions & Greenhouse Gases
Up to 50% of Cost of Aluminum Production associated with Post-Processing of Poorly Produced Parts

Large Residual Stresses
Warping
Cracking
Soft Spots
Poor Corrosion Resistance
Poor Hardness
Poor Strength

Boiling and Two-Phase Flow Laboratory (BTPFL)

Research Presentation
Fall 2014

Heat treating of Al-Cu (4.4 wt %) alloy (Hall & Mudawar, 1996)
4. Cooling Curve for Liquid Bath Quenching versus Spray Quenching

- **Critical Temperature Range**: \( \Delta T \approx 100 \, ^\circ C \)
- **Critical Heat Flux Point**
- **Leidenfrost Point**
- **Onset of Liquid Cooling**

**Distortion induced by Poor Quenching**

**Spray Quenching**

**Bath Quenching**

\( \Delta t = 7 \, s \)
\( \Delta t = 30 \, s \)
4. Fundamental Physics of Spray Cooling

Spray Heat Transfer Facility

Mudawar & Valentine (1989)

Surface Analysis Facility

Krüss Tensiometer

Research Presentation

Fall 2014
4. Fundamental Physics of Spray Cooling

Nozzle Region: Droplet Breakup Physics

Surface Region: Local Impact Physics

Individual Droplet Impact:
- Weber number
- Surface temperature

Surface Region: Global Impact Physics

Light Spray

Dense Spray

Liquid Film Formation, Evaporation & Boiling:
- Volumetric flux

Phase Change Photo Library (Mudawar, 1984 - 2014)
4. Purdue Quenching Facility

- Spray Initiation
- Film Boiling
- Transition/Nucleate Boiling
- Single-Phase Liquid Cooling

Quenching of Aluminum L-Shape

Testbed Control Console

Spray Control System

Quench Chamber
4. Determination of Quench Factor and Hardness

Quench factor:
\[ \tau = \int_{t_1}^{t_2} \frac{dt}{C} = \frac{\Delta t_1}{C_{t,1}} + \frac{\Delta t_2}{C_{t,2}} + \ldots + \frac{\Delta t_n}{C_{t,n}} = \sum_{i=1}^{n} \frac{\Delta t_i}{C_{t,i}} \]
where \( C_i = -k_1 k_2 \exp\left( \frac{k_3 k_4^2}{RT(k_1 - T)^2} \right) \exp\left( \frac{k_4}{RT} \right) T \) in Kelvin

Hardness:
\[ H = H_{\text{min}} + (H_{\text{max}} - H_{\text{min}}) \exp(k_1 \tau) \]

Rockwell B hardness (average of three measurements near thermocouple plane rounded to nearest 0.5 HRB, all three measurements were within ±1 HRB)
Rockwell B hardness contours predicted using quench factor technique with predicted temperature-time history

Hall & Mudawar (1995)