Thermal Management of Electronics with Mechanically Pumped Two-Phase Flow Loops.

G. Zummo

ENEA, Rome, Italy

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HEAT TRANSFER AND FLUID FLOW IN MULTIPHASE SYSTEMS
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Directors: Prof. Luisa Rossetto, Prof. Davide Del Col – Università di Padova

UIT - Unione Italiana di Termofluidodinamica
Outline of the Presentation

- Introduction
- Electronics cooling introduction.
- Electronics Cooling Techniques
- Two-phase Mechanically Pumped Loops
- Analysis of the components: fluid, evaporator, expansion tank, condenser, pump.
- Multichannel Evaporator
- Two-Phase Phenomena influencing two-phase cooling loop
- Effect of gravity on Two-Phase Flow.
- Conclusion and references
Introduction

- All electronic equipment requires power for their use.
- Typically, a CPU of today uses about 100 - 140 watts with an increasing trend for future applications.
- This is an enormous power density that, if not properly managed, can result in equipment failure.
- This presentation addresses an overview of Two-Phase Mechanically Pumped Loop, a potential new cooling technology for the next generation of electronic components.
An **integrated circuit** (IC, chip, or microchip) is a set of electronic circuits on one small flat piece (or "chip") of semiconductor material, normally silicon.

The IC is housed in a chip carrier (package) or substrate made of ceramic, plastic, or glass in order to protect its delicate circuitry from the environment.

An **integrated circuit** is composed of individual electronic components, such as resistors, transistors, capacitors, inductors and diodes, connected by conductive wires or traces through which electric current can flow.

The **electronic components** and interconnections are formed on the same substrate (die of silicon wafer), typically a semiconductor such as silicon.

A **printed circuit board** (PCB) mechanically supports and electrically connects electronic components using conductive tracks, pads and other features etched from copper sheets laminated onto a non-conductive substrate. Components (e.g. capacitors, resistors or active devices) are generally soldered on the PCB.
The narrow band where two different regions of a semiconductor (such as the p-type and n-type regions) come in contact is called a junction.

A transistor, for example, involves two such junctions, and a diode, which is the simplest semiconductor device, is based on a single p-n junction.

In heat transfer analysis, the circuitry of an electronic component through which electrons flow and thus heat is generated is also referred to as the junction.

Junctions are the sites of heat generation and thus the hottest spots in a component.

In silicon-based semiconductor devices, the junction temperature is limited to 125°C for safe operation.
DEFINITIONS

Power is required to operate integrated circuits (ICs). This power is provided to the IC in the form of voltage, V, and current, I, through power supply pins.

The consumption of power creates heat dissipation and results in rise of junction temperature.

\[ Q = VI = I^2R \]

The first law of thermodynamics requires that in steady operation the energy input into a system be equal to the energy output from the system. Considering that the only form of energy leaving the electronic device is heat generated as the current flows through resistive elements, we conclude that the heat dissipation or cooling load of an electronic device is equal to its power consumption.
DEFINITIONS

Higher junction temperatures may result in data transmission bit errors and/or a decrease in a system’s life expectancy.

A successful thermal design requires that the junction temperatures of all critical devices in a system be sufficiently below their critical level in the worst-case ambient temperature.

The objective of the Thermal Management of an electronic device is to ensure that the junction temperature is maintained below a set limit.
THERMAL RESISTANCE

The most important parameter in electronics cooling is the Thermal Resistance.

The form of integrated Fourier Equation for conduction suggests an analogy between conductive heat transfer and the flow of an electric current through a conductor as expressed in Ohm’s Law:

\[ \Delta T = \frac{Q}{L} \quad \Delta V = IR \]

- Q is analogous to current I
- \( \Delta T \) is analogous to voltage drop \( \Delta V \)

Thermal resistance, \( R_{th} \), can be defined as:

\[ R_{th} = \frac{\Delta T}{Q} \]

Thermal resistance measures the resistance to heat flow between two specified points of an object.

Although the electrical analogy applies only to conduction heat transfer, it is possible to generalize this definition to cover all forms of heat transport.

\( R_{th} \) can be determined experimentally, based on measured values of \( \Delta T \) and heat flow and analytically, based on correlations or models for these two quantities.

In convective heat transfer (\( Q = hA(T_s - T_f) \)), the thermal resistance is:

\[ R_{th} = \frac{1}{hA} \]

A similar expression can be derived for radiation heat transfer with an approximation.
CALCULATION OF THERMAL RESISTANCE FOR AN ELECTRONIC DEVICE WITH A HEAT SINK

\[ R_{Th} = \frac{\Delta T}{Q} \]

\[ \Delta T = T_x - T_y \]

\( \Delta T \) [K] is the temperature difference between two points

\( Q \) [W] is heat to be dissipated

\( R_{Th} \) [K/W] is the thermal resistance

The most used resistances in electronics cooling are:

- \( R_{Th,j,a} \) \( \rightarrow \) junction-to-case
- \( R_{Th,c,a} \) \( \rightarrow \) case-to-heat sink
- \( R_{Th,s,a} \) \( \rightarrow \) heat sink-to-ambient
CALCULATION OF THERMAL RESISTANCE FOR AN ELECTRONIC DEVICE

A heat sink is a heat exchanger that transfers the heat generated by an electronic device to a fluid medium (air or liquid).

The air temperature \( T_A \) set the minimum temperature at which the device operates. No matter how much heat sinking or airflow is supplied, the device will not get colder than the surrounding air. Once the IC begins to dissipate power the junction temperature \( T_J \) increases above the ambient temperature. You can reduce the junction temperature by adding airflow or heat sinks, but as long as the power is dissipated, the junction rises to a temperature above \( T_A \).

\[
T_J = T_A + P_D \cdot R_{Th,j,a}
\]

\[
R_{j,a} = \sum_i R_{Th,i} = R_{Th,j,c} + R_{Th,c,s} + R_{Th,s,a}
\]
Permissible Power Dissipation

\[ Q_D = \frac{T_{j,max} - T_a}{R_{Th,j,c} + R_{Th,c,s} + R_{Th,s,a}} \]

**Thermal resistance from junction to environment**

1. \( R_{Th,j,c} \) transports the heat from the small die area of the device to the case
2. \( R_{Th,c,s} \) transports the heat from the case to the sink. It is the resistance of the external interface (Thermal Interface Material, TIM).
3. \( R_{Th,c,a} \) transports the heat from the case to the ambient.

Thermal resistance is the ability for a given device to dissipate the internally generated heat, expressed in units of °C/W. Basically, the thermal resistance is derived to show how much the \( T_J \) increases based on the power dissipated by the device.
**Electronics Cooling - Introduction**

**HEAT GENERATION IN ELECTRONICS**

Heat is generated in active and passive components: $Q = Q_A + Q_P$

*Active components (MOSFET, typically)*

$Q_A \propto NCV^2f$

$N \rightarrow$ number of transistors (can be very high!)

$C \rightarrow$ Capacitance

$V \rightarrow$ Operating Voltage

$f \rightarrow$ Operating Frequency (high)

*Passive components (resistors, interconnections etc.)*

$Q_P = I^2R$

$I \rightarrow$ Operating Current

$R \rightarrow$ Resistance
HEAT GENERATION IN ELECTRONICS

What is the effect of high temperature on an electronic device?

High temperatures affect speed (performance), reliability, and power.

**PERFORMANCE**

The effect of temperature on performance is usually weak, in general an increase in temperature will lower the performance of an electronic device.

**POWER**

A rise in temperature is able to generate an increase of dissipated power with a possible thermal runaway and catastrophic failure of the device.

**RELIABILITY**

Carrier mobility is degraded at higher temperatures, resulting in slower devices.

The resistance of the interconnects increases with temperature. This leads to higher voltage drops and longer delays and causes performance degradation.

<table>
<thead>
<tr>
<th>Environmental factor</th>
<th>Failure percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand and dust</td>
<td>6</td>
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<tr>
<td>Moisture</td>
<td>19</td>
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<td>Shock</td>
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<td>Salt</td>
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<td>Altitude</td>
<td>2</td>
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<tr>
<td>Vibration</td>
<td>27</td>
</tr>
</tbody>
</table>

Distribution of environmentally related failures in an airborne electronic system.
EFFECT OF HIGH TEMPERATURES ON ELECTRONICS

High temperatures affect the failure rate of electronic devices. Arrhenius equation is an adequate way to model this failure mechanism.

\[ f_r = A_r e^{\frac{-E_a}{k_b T}} \]

**ARRHENIUS EQUATION**

- \( f_r \): failure rate
- \( A_r \): empirical constant
- \( E_a \): activation energy [eV]
- \( k_b \): Boltzmann’s Constant [8.63 \times 10^{-5} \text{ eV/K}]
- \( T \): junction temperature [K]

Thermal acceleration factor: the increase of failure rate with temperature, for a typical electronic device.
Electronics Cooling - Introduction

EFFECT OF HIGH TEMPERATURES ON ELECTRONICS

Thermal management is important to guarantee an adequate lifespan of the electronics.
TREND IN ELECTRONICS

MOORE’S LAW

Moore’s law is based on the observation that the number of transistors in a dense integrated circuit doubles approximately every two years.

Moore’s law is expected to at least hold until 2021, according to the ITRS (International Technology Roadmap for Semiconductors) predictions.

High power densities, typically encountered in nuclear reactors.

Multi-core processors (parallel computing).

Large quantity of transistors \( \rightarrow \) High power densities

Corresponding power loss densities on these microprocessor chips.
SUMMARY OF TREND IN ELECTRONICS

- Moore’s law is expected to at least hold until 2021
- High-performance processors will dissipate higher heat fluxes
  - Increase of non-uniformity of heat flux
- Increase number of transistors means higher power dissipation
- High frequency operation means higher power dissipation
  - Smaller size means higher power dissipation

Thermal management is important for the performance and reliability of high power and high density electronics systems.

Thermal management will be critical for the future design of electronic devices.
Applications of Power Electronics in Various Fields

• Aerospace (Satellite power supplies, electronics, Aircraft power system, avionic)
• Transportation (Battery chargers, traction control of electric vehicles, electric locomotives, automotive electronics, etc.)
• Computer (laptop, desktop)
  • HPC (High Performance Computing)
  • DataCenter
Electronics Cooling - Introduction

**Electronics Cooling Techniques**

Typical convective thermal resistances for a heat source of 10 cm² and a fluid velocity range of 2 – 8 m/s, from Tummala (2000).

\[
R_{Th,c,s} + R_{Th,s,a} = \frac{T_{c,max} - T_a}{Q_D}
\]

**Heat Transfer Mode**  
- **h [W/m²-K]**
  - Natural convection in gasses: 5 - 15
  - Natural convection in liquids: 50 - 100
  - Forced convection in gasses: 15 - 250
  - Forced convection in liquids: 100 - 2000
  - Boiling liquids or condensing vapors: 2000 - 25000
Electronics Cooling - Introduction

Given the rate of heat dissipation and the maximum allowable component temperature, the graph helps to determine the appropriate cooling technology.

Temperature difference is the difference between the case surface temperature (max. allowable value) and the ambient temperature.

Surface heat flux is determined by dividing the power dissipation rate to the exposed surface of the device.

Temperature difference versus heat flux for some heat transfer mechanisms

Kraus and Bar-Cohen, 1983
Electronics Cooling Techniques

EXAMPLE – Intel i7

Model: i7-5960X

Thermal Design Power (TDP): 140 W

$T_{\text{case}}$: 67.1 °C

Available Cooling Area: 40.5 mm x 36.74 mm

Data for Thermal Analysis

Liquid Cooling

$q'' = 9.41 \text{ W/cm}^2 (A = 14.87 \text{ cm}^2)$

$\Delta T = T_{\text{case}} - T_a = 42.1 \text{ °C} (T_a = 35\text{°C})$

Two-Phase Cooling

$q'' = 9.41 \text{ W/cm}^2 (A = 14.87 \text{ cm}^2)$

$\Delta T = T_{\text{case}} - T_a = 17.1 \text{ °C} (T_a = 50\text{°C})$

Temperature difference versus heat flux for some heat transfer mechanisms

Kraus and Bar-Cohen, 1983
Electronics Cooling Techniques

PASSIVE AND ACTIVE AIR COOLING

Passive air cooling ➔ Natural Convection
The advantages of this cooling method is its simplicity, reliability, noiseless and costless operation.
Low performance ➔ convective heat transfer associated with this cooling method is low, due to the low flow rates and the poor heat transfer properties of air.
Large surfaces.

Active air cooling ➔ Forced Convection
Improved performance.
Thermal capacity and conductivity of the medium are poor, therefore high fan speed for better heat removal (noise, moving parts).
Most liquids are much better heat transfer media than air, with water being a prime example of this having a thermal conductivity that is 23 times higher (0.596 W/(mK)), a density that is 828 times higher (998 kg/m³) and a specific heat capacity that is 4 times higher than air (4182 J/(kgK)) at 20°C and atmospheric pressure.
The definition of the dimensionless Nusselt number can be used to understand how the convective heat transfer coefficient scales with the hydraulic diameter of the flow channel for a constant mass flow rate:

\[ h = \frac{Nu \cdot K}{D_h} \propto \frac{1}{D_h} \]

where \( h \) is the convective heat transfer coefficient, \( Nu \) is Nusselt number, \( D_h \) is the hydraulic diameter of the channel (for non-circular channels: \( D_h = 4A/P \) with \( A \) the cross-sectional area of the channel and \( P \) the channel perimeter) and \( k \) the thermal conductivity of the coolant.

For laminar flow, the Nusselt number is independent of the channel size, therefore \( h \) is inversely proportional to \( D_h \).
MICROCHANNEL LIQUID COOLING

For Turbulent Flow, Nusselt number depends on $D_h$. This relation can be estimated considering the Dittus-Boelter correlation:

$$Nu = 0.023 \cdot Re^{0.8} \cdot Pr^{0.4} \Rightarrow Nu \propto \frac{1}{D_h^{0.8}} \Rightarrow h \propto \frac{1}{D_h^{1.8}}$$

For turbulent flow, heat transfer coefficient is inversely proportional to $D_h^{1.8}$.

Heat sink with microchannels ($D_h = 200 – 300 \, \mu m$) are very effective way to remove high heat fluxes.

The major drawback of using this method is the high pressure losses associated with microchannels. For a constant mass flow rate, the frictional pressure losses are inversely proportional to $D_h^4$.

This heat sink was proposed by Tuckerman and Pease in 1981.
A heat pipe consists of a closed two-phase cycle contained in a single container under vacuum, partially filled by a liquid.

This completely passive device operates by evaporating the liquid from a capillary wick structure at one end of the device, and condensing vapor back into the wick structure at the other end of the device.

The capillary force is what drives the liquid through the wick structure, resulting in a vapor flow at the center of the device.
Electronics Cooling Techniques

PASSIVE AND ACTIVE TWO-PHASE COOLING – LOOP HEAT PIPE (LHP)

The operating principle of a LHP is the same as that of a regular heat pipe, except for the fact that the wick structure is only present in the evaporator, and the liquid and vapor flows are separated into two different sections.

In a regular heat pipe, the liquid has to flow through the wick for the entire heat pipe length, undergoing large pressure losses, while it is only at the evaporator that the capillary force is generated. Additionally, the vapor and liquid move in opposite directions. This too generates extra pressure losses. Both these problems have been improved with a LHP. Consequently, a LHP can effectively transport heat over longer distances than a regular heat pipe and the capillary limit is reduced.
PASSIVE AND ACTIVE TWO-PHASE COOLING – IMMERSION COOLING AND POOL BOILING

With immersion cooling, the entire electronic device is immersed in a liquid coolant (dielectric fluid). At local high heat fluxes, pool boiling will occur. Thus enhanced cooling automatically occurs at high heat generation locations ensuring an overall uniform temperature. The generated vapor will either condense on the sides of the container, or at an actively cooled condenser.

Immersion Cooled Electronics by Extoll

Electronic device: Xeon Phi (for supercomputing)
Fluid: 3M Novec 649
Cooling water: $T_{in} = 35^\circ C - T_{out} = 50^\circ C$

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Electronics Cooling Techniques

MECHANICALLY PUMPED LOOPS

TWO-PHASE MECHANICALLY PUMPED LOOP

Working Principle

Single Phase System
Heat is transported by sensible heat. \[ Q_{in} = \dot{m} \cdot c_p \cdot \Delta T \]
Heat input results in increase of fluid exit temperature and of mass flow.

Two-Phase System
Heat is transported by latent heat. \[ Q_{in} = \dot{m} \cdot h_{lv} \cdot \Delta x \]
Heat input results in an increase of vapor mass fraction, while the fluid temperature is the same in the entire system (only for low pressure drops). Mass flow can be smaller than that of the single phase system, because the heat of vaporization \( h_{lv} \) (2257 kJ/kg) is larger than \( c_p \) (4.180 kJ/kg-K) of the single phase coolant (water).
Electronics Cooling Techniques

MECHANICALLY PUMPED LOOPS

TWO-PHASE

Pros

• High heat flux
• Low mass flow
• Uniform temperature
• Large amount of energy ($h_{lv} > c_p$)
• Heat input results in a change of vapor mass fraction
• Small volume

Cons

• Higher Complexity
• Design tools not available completely
• Higher system mass
• Not easy to implement

SINGLE PHASE

Pros

• Good heat removal capability
• Easy to implement
• Easy to design
• Simple
• Small volume

Cons

• Temperature gradients
• High mass flow
• High pressure loss
• Pumping energy could be an issue
TWO-PHASE MECHANICALLY PUMPED LOOPS

By combining the excellent properties of two-phase cooling with the small volume and high cooling capabilities of microchannels, two-phase microchannel cooling could be a promising cooling method. The next section is dedicated to analyse the components of a Two-Phase Loop and the related Boiling Phenomena that influence the performance and operation of such a cooling system.
COMPONENTS - MULTICHANNEL EVAPORATOR HEAT SINK

One of the major advantages of microchannels is the extremely low volume required at the backside of the chip.

The main barriers and challenges encountered by engineers in trying to implement two-phase cooling technology are liquid maldistribution, coolant leaks, and large pressure drop in flow direction, which increases the coolant pumping power requirement.
TWO-PHASE MECHANICALLY PUMPED LOOPS

COMPONENTS

- Plate Heat Exchanger
- Centrifugal pump
- Microchannel Condenser
- Fluid accumulator / Expansion Tank

Schematic of a two-phase loop
FLUID ACCUMULATOR – EXPANSION TANK

Accumulator controls the system pressure (Saturation Temperature) variation in a small range.

Accumulator allows the vapor expansion.

Solutions: Active control or Passive
COMPONENTS - FLUID

The selection of a suitable fluid is an important steps for the design of a two-phase thermal management system.

How to select the most suitable fluid for an application?

General Requirements for a Liquid Coolant for Electronics

1. Good thermo-physical properties (high thermal conductivity and specific heat; low viscosity; high latent heat of evaporation)
2. Low freezing point
3. Low boiling point (high boiling point for a single-phase system)
4. Good chemical and thermal stability for the life of the electronics system
5. High flash point and auto-ignition temperature (sometimes non-combustibility is a requirement)
6. Non-corrosive to materials of construction
6. Regulatory constraints: environmentally friendly, nontoxic, and possibly biodegradable
7. Economical
Different coolants are ideally suited for different electronics cooling applications because the boiling temperature needs to be matched with maximum case temperature.

As an example consider the strong vacuum needed to lower the boiling temperature of water below the typical maximum junction temperatures of regular electronic devices (very difficult).

FC-72 has a boiling point of 52°C at 1atm, but low latent heat of vaporization (low power dissipation).
How to select the most suitable fluid for an application?

1. Definition of Selection criteria (‘low power consumption’).

2. From the selection criterion it is possible to write an equation. This equation is called the ‘figure of Merit’.

3. Figure of Merit is then plotted for a group of fluids.

4. The fluids with the highest figure of Merit are good candidates.

5. Further analysis on toxicity, flammability, material compatibility, radiation hardness etc.

\[
\Delta P_{fr} = f \frac{L}{D_h} \frac{\rho_l u_l^2}{2}
\]

\[
f = \frac{64}{Re_l}
\]

\[
\Delta P_{fr} = \frac{128}{\pi} \frac{L}{D_h} \frac{\rho_l}{\mu} \left(\frac{\mu}{\rho_l}\right)\dot{m}
\]

\[
M = \frac{\mu}{\rho_l}
\]

Figure of merit based on low pressure drop
## COMPONENTS - FLUID

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<th>649</th>
<th>7500</th>
<th>774</th>
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<td>90</td>
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<td>Liquid Density</td>
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<td>1600</td>
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<td>cSt</td>
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<td>1103</td>
<td>1183</td>
<td>1130</td>
<td>1220</td>
<td>1400</td>
<td>1128</td>
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<td>Surface Tension</td>
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<td>Solubility of Water in Fluid</td>
<td>ppm by weight</td>
<td>&lt;60</td>
<td>20</td>
<td>95</td>
<td>20</td>
<td>92</td>
<td>97</td>
<td>45</td>
<td>14</td>
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<td>Solubility of Fluid in Water</td>
<td>ppm or ppb by weight</td>
<td>&lt;5 ppm</td>
<td>-</td>
<td>12 ppm</td>
<td>-</td>
<td>&lt;5 ppm</td>
<td>&lt;255 ppb</td>
<td>&lt;4 ppb</td>
<td>&lt;1 ppb</td>
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<td>Dielctric Strength Range, O.1 gap</td>
<td>kV</td>
<td>&gt;25</td>
<td>&gt;40</td>
<td>&gt;25</td>
<td>&gt;40</td>
<td>&gt;25</td>
<td>&gt;25</td>
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<tr>
<td>Dielctric Constant @ kHz</td>
<td>-</td>
<td>7.4</td>
<td>1.8</td>
<td>7.4</td>
<td>1.0</td>
<td>7.3</td>
<td>6.1</td>
<td>5.8</td>
<td>6.7</td>
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<td>Volume Resistivity</td>
<td>Ohm·cm</td>
<td>10⁸</td>
<td>10⁸</td>
<td>10⁸</td>
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<td>Global Warming Potential</td>
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<td>530</td>
<td>&lt;1</td>
<td>297</td>
<td>&lt;1</td>
<td>57</td>
<td>310</td>
<td>100</td>
<td>436</td>
</tr>
</tbody>
</table>

Selection of fluids for thermal management proposed by 3M.
MULTICHANNEL EVAPORATOR

Geometry of Multichannel Evaporator

Inlet/outlet manifold

Cover plate

Multichannel evaporator (ENEA)

Typical two-phase flow patterns in a microchannel

Typical two-phase flow patterns in a multichannel evaporator with 3M Novec 7100 (ENEA)
Characteristics of a multichannel evaporator

- $d = 1.0\text{mm} - 3.0\text{mm}$
- $W = 0.1\text{mm} - 1.0\text{mm}$
- $W_f = 0.2\text{mm} - 0.3\text{mm}$
- $D_h = 4S/p$
- $L = 30\text{mm} - 40\text{mm}$

Material: cooper, aluminium, silicon

Heat Fluxes

- $S_b = L \times L$ Base area
- $S_w = \text{wetted area}$

Base area heat flux $\Rightarrow$ 

$$q_b = \frac{Q_{in}}{S_b}$$

Wetted area heat flux $\Rightarrow$ 

$$q_w = \frac{Q_{in}}{S_w}$$
Flow boiling tests in multichannel heat sink

L = 12.7 mm

Material: silicon

Fluid: FC-77, a 3M perfluorocarbon fluid (specific heat 1.1 kJ/kg-K, latent heat of vaporization 89 kJ/kg, boiling point 98°C)

MULTICHANNEL EVAPORATOR

EFFECT OF MASS FLUX ON HEAT TRANSFER

Flow boiling tests in multichannel heat sink

\[ L = 12.7 \text{ mm} \]

Material: silicon

Fluid: FC-77, a 3M perfluorocarbon fluid (specific heat 1.1 kJ/kg-K, latent heat of vaporization 89 kJ/kg, boiling point 98°C)

Flow boiling tests in multichannel heat sink

L = 12.7 mm

Material: silicon

Fluid: FC-77, a 3M perfluorocarbon fluid (specific heat 1.1 kJ/kg-K, latent heat of vaporization 89 kJ/kg, boiling point 98°C)

MULTICHANNEL EVAPORATOR

EFFECT OF MASS FLUX ON PRESSURE DROP

Flow boiling tests in multichannel heat sink

L = 12.7 mm

Material: silicon

Fluid: FC-77, a 3M perfluorocarbon fluid (specific heat 1.1 kJ/kg-K, latent heat of vaporization 89 kJ/kg, boiling point 98°C)

Flow boiling tests in multichannel heat sink

L = 12.7 mm

Material: silicon

Fluid: FC-77, a 3M perfluorocarbon fluid (specific heat 1.1 kJ/kg-K, latent heat of vaporization 89 kJ/kg, boiling point 98°C)

Flow boiling tests in multichannel heat sink

L = 12.7 mm

Material: silicon

Fluid: FC-77, a 3M perfluorocarbon fluid (specific heat 1.1 kJ/kg-K, latent heat of vaporization 89 kJ/kg, boiling point 98°C)

List of heat transfer correlations

[12] Liu and Garimella
[27] Cooper
[28] Gorenflo
[29] Chen
[30] Shah
[31] Gungor and Winterton
[32] Tran et al.
[33] Warrier et al.
[34] Zhang et al.
[35] Peters and Kandlikar

Cooper, valid for Water, refrigerant, organic fluids in Pool boiling (Nucleate Boiling)

\[ h_{nb} = 55 \left( \frac{\rho}{\rho_{crit}} \right)^{0.12-0.091\ln\left(\frac{R_p}{R_{po}}\right)} \left( -0.4343\ln\frac{\rho}{\rho_{crit}} \right)^{-0.55} M^{-0.5} q^{0.67} \]

- \( R_p \) surface roughness, \( R_{po} = 1.0 \) mm
- \( M \) fluid molecular weight [kg/kmol]
- \( h_{nb} \) [W/m²K], \( q'' \) [W/m²]
SURFACE STRUCTURE

The modification of surface micro/nano-structure has a significant influence on boiling phenomena.

The use of micro/nano geometries results in enhancement of Nucleate Boiling Heat Transfer and CHF and a reduction of superheat required for bubble nucleation.

Surface modification methods: mechanical machining, chemical process (oxidation, chemical etching, etc.)

SEM images of silicon chips with micro-pin–fins (Kim et al. 2015)

SEM image of Cu macroporous structures after electrolyte deposition (Kim et al. 2015)
MULTICHANNEL EVAPORATOR

SURFACE STRUCTURE

Boiling curves for surface roughness modification

Photographs of boiling process in pool boiling of water for varying heat flux and surface roughness values

Benefits of surface structure treatment

- Lower $\Delta T_{ONB}$
- Lower $\Delta T$ ➔ Lower case temperature
- Increase of density of active nucleation sites
- Increase of HTC (Heat Transfer Coefficient)
- Increase of CHF

➔ Enhancements depend strongly on fluid and material!
FLOW PATTERNS

A particular type of geometric distribution of the liquid and vapor phases in a two-phase flow is called a **flow pattern or flow regime** and many of the names given to these flow patterns are (now) quite standard.

Flow patterns are displayed on maps that show flow pattern dependence on several parameters (mass flux and vapor quality). These maps identify the boundary between different flow patterns.

Heat transfer physical mechanisms in a multiphase system depend on flow pattern. Therefore, models and correlations are flow regime dependent.

The knowledge of the flow pattern enables the use of the correct model for the calculation of heat transfer coefficient.
Evolution of flow patterns in a vertical tube for increasing values of heat flux.

\[ D = 4 \text{ mm}, \quad p = 1.81 \text{ bar}, \quad \Delta T_{\text{sub}} = 24 \text{ K}, \quad G = 173 \text{ kg/m}^2\text{-s}, \quad 600 \text{ fps} \quad (q''[\text{ kW/m}^2]) \]

*ENEA, MICROBO Experiment*
FLOW PATTERNS IN MICROCHANNELS

In microchannel the observed flow patterns are mainly: Bubbly Flow, Slug/Intermittent Flow and Annular Flow.

Each flow pattern is associated to a heat transfer mechanism:

- **Bubbly Flow** ➔ Nucleate Boiling
- **Slug Flow** ➔ Evaporation of liquid film and strong turbulence in the liquid slug
- **Annular Flow** ➔ Evaporation of liquid film

![Bubbly Flow Images](image1)

- (a) Bubbly flow at $x = 0.038$
- (b) Bubbly/slug flow at $x = 0.04$
- (c) Slug flow at $x = 0.043$
- (d) Slug/semi-annular flow at $x = 0.076$
- (e) Semi-annular flow at $x = 0.15$
- (f) Wavy annular flow at $x = 0.23$
- (g) Smooth annular flow at $x = 0.23$
FLOW PATTERNS IN MICROCHANNELS

Very few flow pattern maps are proposed for microtubes.

Flow pattern map for a microchannel (Ong, Thome 2011)
Two-Phase Flows can be affected by gravity (in intensity and in direction).

Tests of flow boiling at hyper- and microgravity conditions.

Transparent test section for flow boiling tests

MICROBO experimental loop for flow boiling experiment on-board of ZERO-G
TWO-PHASE PHENOMENA – EFFECT OF GRAVITY

\[ G = 215 \text{ kg/m}^2 \cdot \text{s} \]

\[ P = 1.58 \text{ bar} \]

\[ T_{\text{sat}} = 70.2 \degree \text{C} \]

\[ \Delta T_{\text{sub,in}} = 20 \text{K} \]

\[ D = 4.0 \text{ mm} \]

\[ U_{\text{liq}} = 131 \text{ mm/s} \]

\[ \text{Re} = 1920 \]

\[ q'' = 10.3 \text{ kW/m}^2 \]
TWO-PHASE PHENOMENA – EFFECT OF GRAVITY

G = 215 kg/m²-s
P = 1.58 bar
T_{sat} = 70.2 °C
ΔT_{sub,in} = 20K
D = 4.0 mm
U_{liq} = 131 mm/s
Re = 1920
q^{"} = 28.9 kW/m²
Summary

Further research is needed to develop reliable design tools:

• Heat transfer correlation/model valid for multichannels

• Flow pattern map

• Effect of gravity acceleration on flow boiling (heat transfer and flow pattern)
Conclusions

- Moore’s law predicts an increase of electronics density (increase number of transistors) with the consequent increase of power density to be dissipated.
- It is expected that the trend will continue (2021)
- Classical methods of cooling (air, heat pipes, liquid cooling) will not be adequate for high power electronics thermal management (due to high heat fluxes to be removed).
- Two-phase Mechanically Pumped Loop is a promising cooling technology with small volume and high cooling capabilities of microchannels.
- Components must be selected according to the objectives of the thermal management.
- Coolant selection can be made on the maximum case temperature.
- Coolant can be selected according to Figures of Merit.
- Multichannel Evaporator is very a complex component.
- Dimensions of the channels have significant influence on heat transfer, pressure drop, CHF
- Surface microgeometry (roughness or nanostructures) can increase heat transfer and reduce the ONB. These geometries must be matched with the fluid.
- Gravity acceleration (intensity and direction) can have a significant influence on Two-Phase Flow heat transfer.
- Further research is needed to develop reliable design tools for flow boiling in multichannels: heat transfer correlation/model and flow pattern maps.
THANK YOU FOR YOUR ATTENTION!
REFERENCES-1


Intel® Core™ i7 Processor Family for the LGA2011-3 Socket, Thermal/Mechanical Specification and Design Guide (TMSDG), August 2014


REFERENCES-2


THERMAL RESISTANCE FOR RADIATION HEAT TRANSFER

In convective heat transfer \( Q = hA(T_s - T_f) \), the thermal resistance is:

\[
R_{th} = \frac{1}{hA}
\]

The same relation can be used for any thermal transport process that can be described with the Fourier Equation:

\[
Q = h \cdot A \cdot (T_s - T_f)
\]

Radiative heat transfer between two surfaces or a surface and its surroundings, is governed by the following equation:

\[
Q = \varepsilon \cdot \sigma \cdot A \cdot (T_1^4 - T_2^4) \cdot F_{12}
\]

where \( \varepsilon \) is the emissivity, \( \sigma \) is the Stefan-Boltzmann constant \( \sigma = 5.67 \times 10^{-8} \text{ W/m}^2\text{-K}^4 \), and \( F_{12} \) is the “view factor” between surfaces 1 and 2.

For small temperature differences, this equation can be linearized to the following equation:

\[
Q = h_r \cdot A \cdot (T_1 - T_2)
\]

Where \( h_r \) is the radiation heat transfer coefficient given by:

\[
h_r = 4 \cdot \varepsilon \cdot \sigma \cdot F_{12} \cdot (T_1 \cdot T_2)^{3/2}
\]