


Fundamentals of Liquid Cooling

Thermal Management of Electronics

San José State University
Mechanical Engineering Department



Air as a Coolant

PROS:

- Simplicity
- Low Cost
- Easy to Maintain
- Reliable

CONS:

- Inefficient at heat removal
(low k and Pr)
- Low thermal capacitance (low ρ and C_p)
- Large thermal resistance

Using Alternate Coolants

- As electronic components get smaller and heat transfer requirements increase air becomes a less efficient coolant
- Liquid cooling provides a means in which thermal resistance can be reduced dramatically



Types of Liquid Cooling

- Indirect –

The coolant does not come into contact with the electronics.

- Direct (Immersion) –

The coolant is in direct contact with the electronics.

The bottom right portion of the slide features a decorative graphic of several concentric, light blue circles that resemble ripples on water, set against the dark blue background.

Fluid Selection

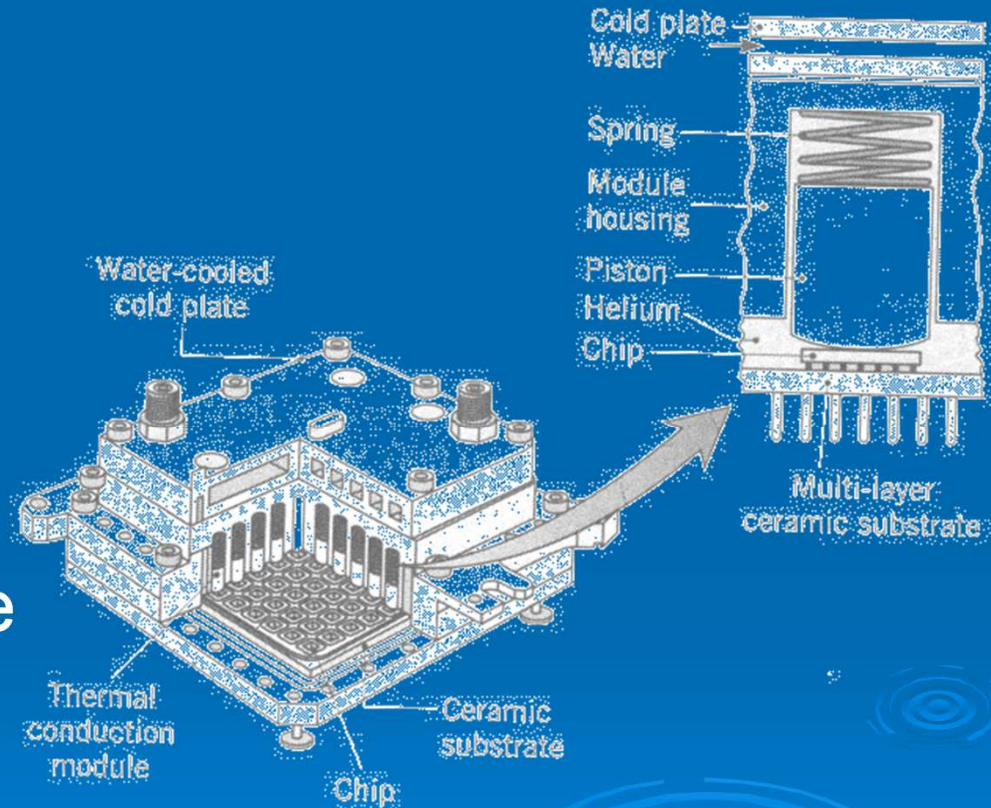
- Is the fluid in direct contact with the electronics?
 - No. Water will normally be used due to the fact that it is cheap and has superior thermal properties.
 - Yes. A dielectric must be used. Consideration must be given to the thermal properties of different dielectric fluids.

Microchannels

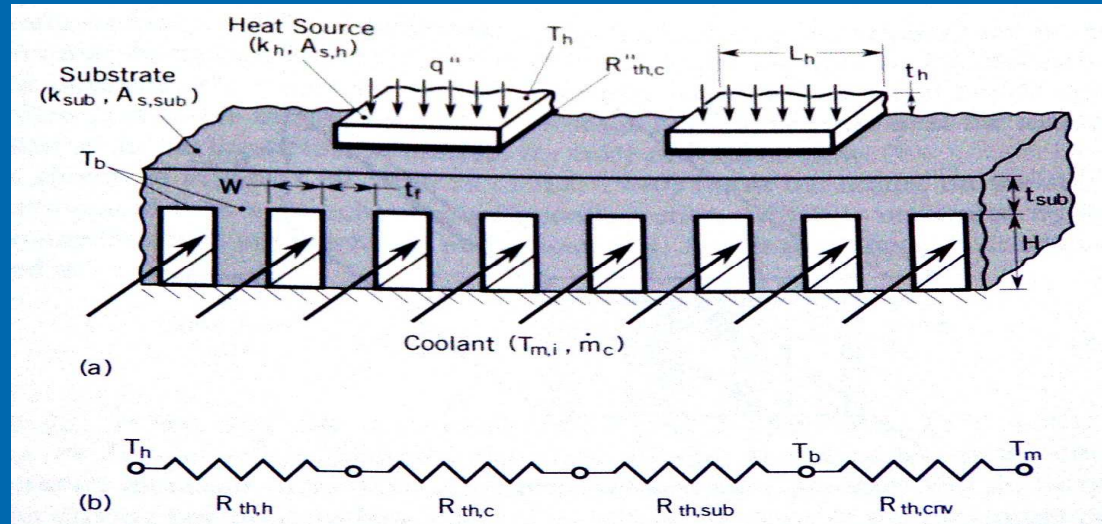
- Microchannels are most commonly used for indirect liquid cooling of IC's and may be:
 - Machined into the chip itself.
 - Machined into a substrate or a heat sink and then attached to a chip or array of chips.

Microchannels

- *Example:* Thermal Conduction Module used on IBM 3080X/3090 series
- Heat is transmitted through an intermediate structure to a cold plate through which a coolant is pumped



Microchannels



Incropera, pg. 155

- $R_{th,h}$ – Conduction Resistance through the chip
- $R_{th,c}$ – Contact Resistance at the Chip/Substrate Interface
- $R_{th,sub}$ – 3-D Conduction Resistance in the substrate (spreading resistance)
- $R_{th,cnv}$ – Convection Resistance from the substrate to the coolant

Note that this network ends with the mean fluid temperature. If we use the inlet fluid temperature, we also need to include $R_{caloric}$

Motivating Example

Laminar flow through a rectangular channel:

$$D_h = \frac{4 g w}{2(g + w)}$$

$$\alpha = g/w$$

$$\text{Nu} = 8.235(1 - 2.0421\alpha + 3.0853\alpha^2 - 2.4765\alpha^3 + 1.0578\alpha^4 - 0.1861\alpha^5)$$

$$h = \text{Nu } k/D_h$$

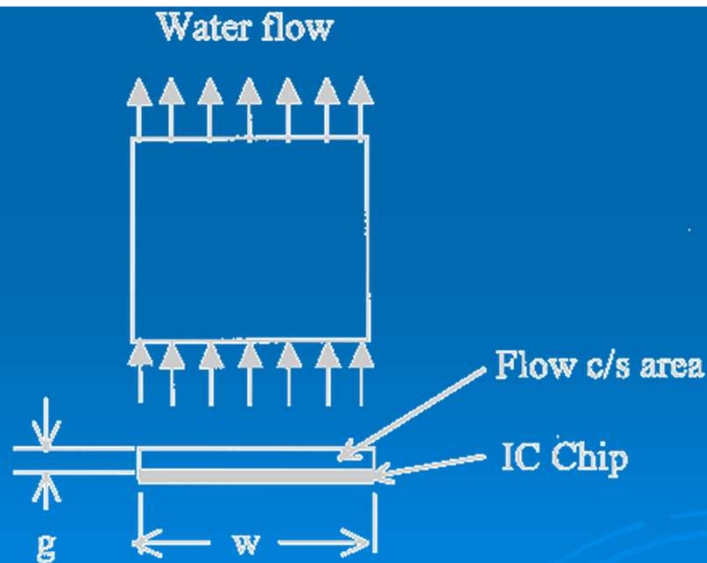


Figure 2 Top and cross-sectional views of the flow channel for water utilizing the back surface of the chip for cooling.

Kandlikar and Grande, pg. 7

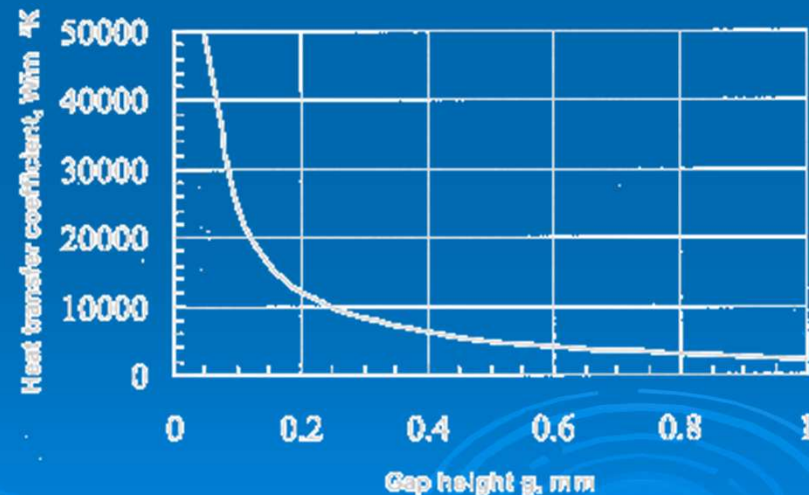


Figure 4 The variation of the heat transfer coefficient with a gap size g for laminar flow of water in a 25 mm-wide rectangular channel.

Kandlikar and Grande, pg. 8

Pressure Drop in Microchannels

- The pressure drop due to forcing a fluid through a small channel may produce design limitations.

$$\Delta p = \frac{2fL\rho V^2}{D_h}$$

V is the mean flow velocity

L is the flow length

ρ is the fluid density

f is the friction factor, depends on the aspect ratio.

Limitations may include:

1) Pumping Power

2) Mechanical Stress

Limitation of the Chip
Material

Pressure Drop Example

$$\dot{m} = \frac{q}{c_p(T_{w,o} - T_{w,i})}$$

- If chip power increases mass flow rate must increase
- If mass flow rate increases pressure drop increases

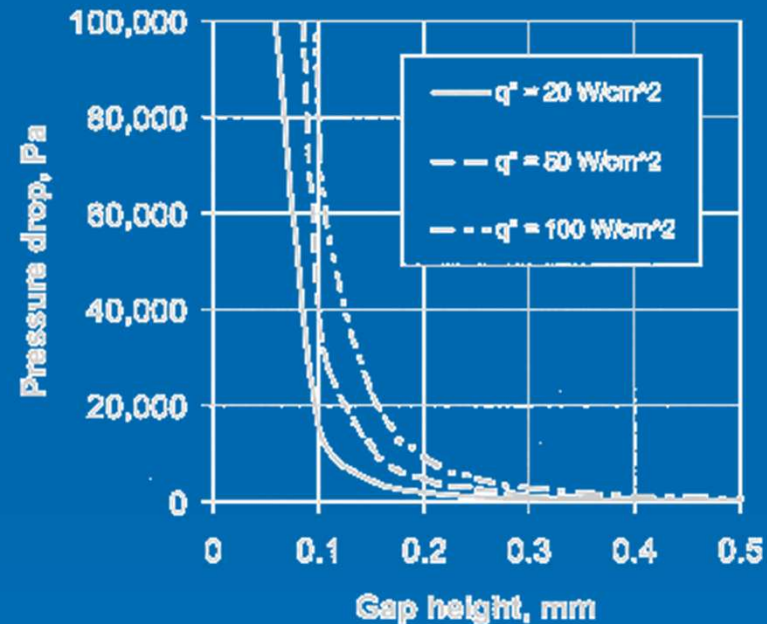
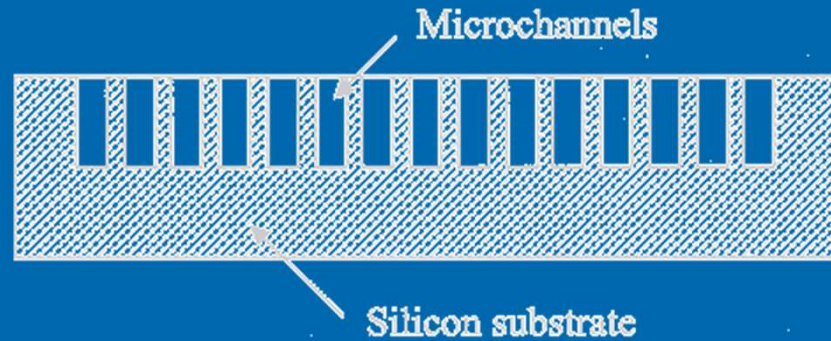


Figure 5 The variation of pressure drop with a gap height for water flow in a 25 mm-wide rectangular channel.

Kandlikar and Grande, pg. 9

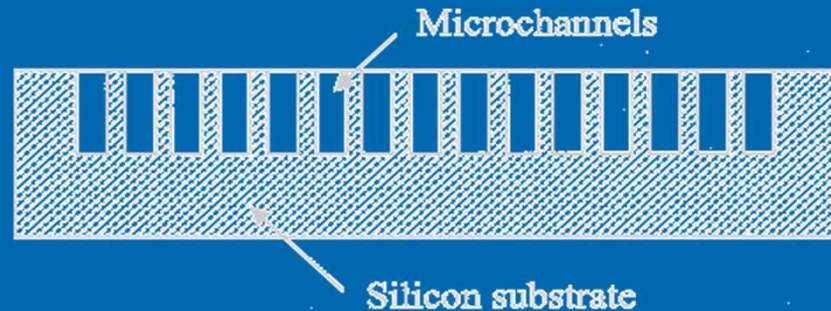
Optimization of Microchannels



Kandlikar and Grande, pg. 9

- How should the channels in the silicon substrate be designed for optimal heat transfer? Should the channel be deep or shallow? Make sure to give a valid reason.

Optimization of Microchannels



Kandlikar and Grande, pg. 9


- The channels should be deep so that the hydraulic diameter is small but the channel surface area is large.
- *Caution:* Making the channels too small may result in unreasonable pressure drop.

Microchannel Issues

➤ Liquids + Electronics

- Self-explanatory

➤ Fouling Leading to Clogging

- Clogging prevents flow of liquids through a channel
 - Local areas where heat is not pulled away from components at a high enough rate are developed
- 
- The bottom right corner of the slide features a decorative graphic of several concentric, light blue ripples, resembling water droplets hitting a surface, set against the dark blue background.

Microchannel Issues

➤ Mini-Pumps

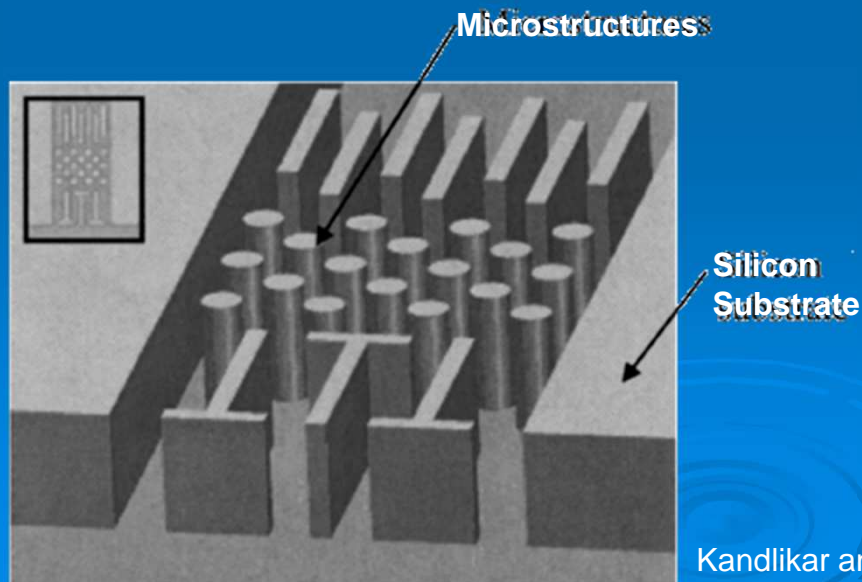
- Able to move liquid through the channel at a required rate
- Able to produce large pressure heads to overcome the large pressure drop associated with the small channels
- Tradition rotary pumps can not be used due to their large size and power consumption
- For information on some current solutions refer to

http://www.electronics-cooling.com/html/2006_may_a3.html

Current Research for Single Phase Convection in Microchannels

➤ Surface Area

- Adding protrusions to the channels to increase surface area.
- Adding and arranging fins in a manner that is similar to a compact heat exchanger.



Examples of different geometries:

- Staggered Fins
- Posts
- T-Shaped Fins

Current Research for Single Phase Convection in Microchannels

➤ Manufacturing Technology

- Reducing cost of manufacturing
- Producing enhanced geometries
- For further information refer to article by Kandlikar and Grange

Current Research for Single Phase Convection in Microchannels

- Justifying deviation from classical theory for friction and heat transfer coefficients when microchannel diameters become small
 - Lack of a good analytical model
 - Surface Roughness
 - Accurate measurements of system parameters
 - Ect.

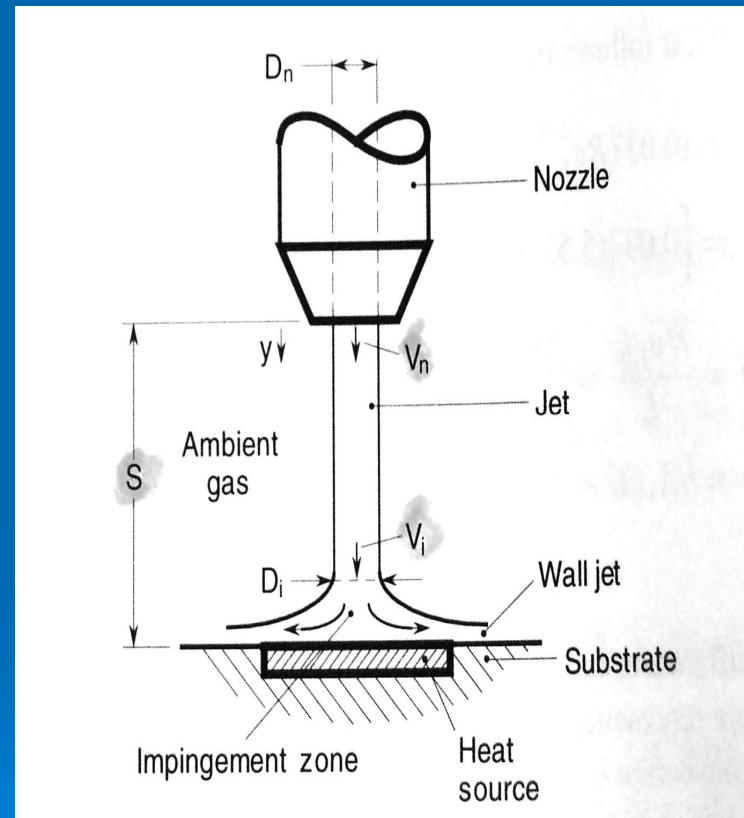
***If you are interested in this take a look at:

Palm, B. "*Heat Transfer in Microchannels*". *Microscale Thermophysical Engineering* 5:155-175, 2001. Taylor Francis, 2001.

Jet Impingement

➤ Benefits of using a jet in thermal management of a surface:

- A thin hydrodynamic boundary layer is formed
- A thin thermal boundary layer is formed



Incropera, pg. 56

Classifying Impinging Jets

➤ Jets can be:

- Free-Surface – discharged into an ambient gas
- Submerged – discharged into a liquid of the same type

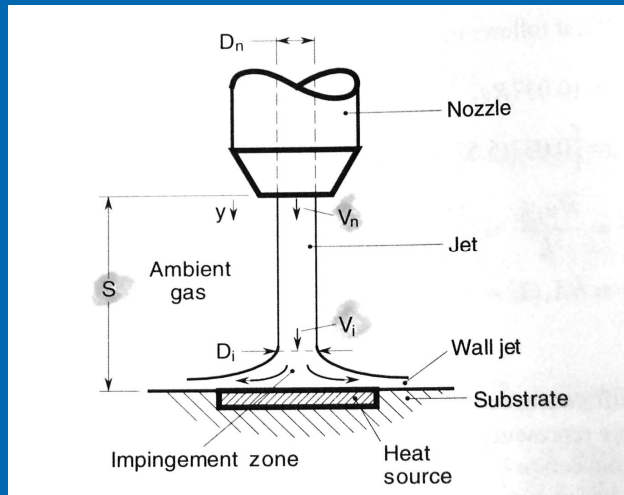
➤ Cross Sections:

- Circular
- Rectangular

➤ Confinement:

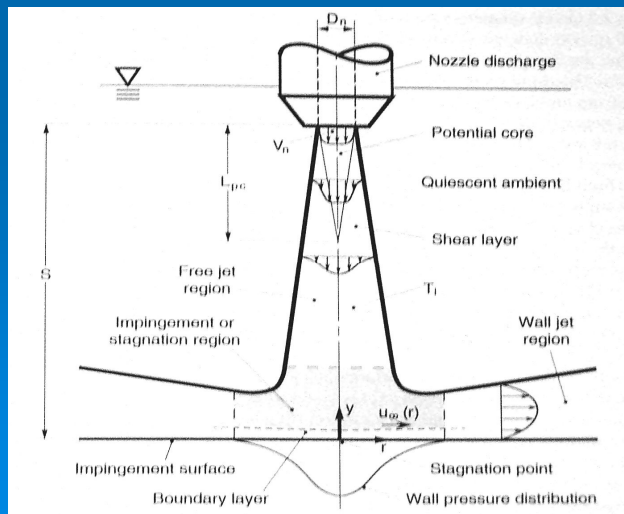
- Confined – Flow is confined to a region after impingement
- Unconfined – Flow is unconfined after impingement

Classify the Following Jets



Incropera, pg. 56

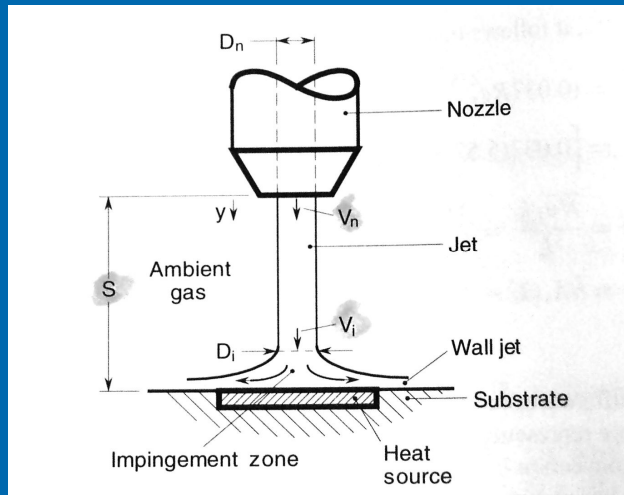
- Liquid jet released into ambient gas



Incropera, pg. 65

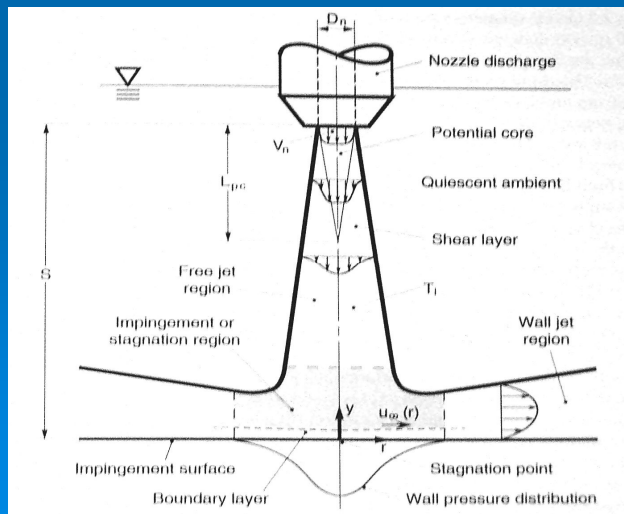
- Liquid release into liquid of the same type

Classify the Following Jets



Incropera, pg. 56

- Unconfined, circular, free-surface jet

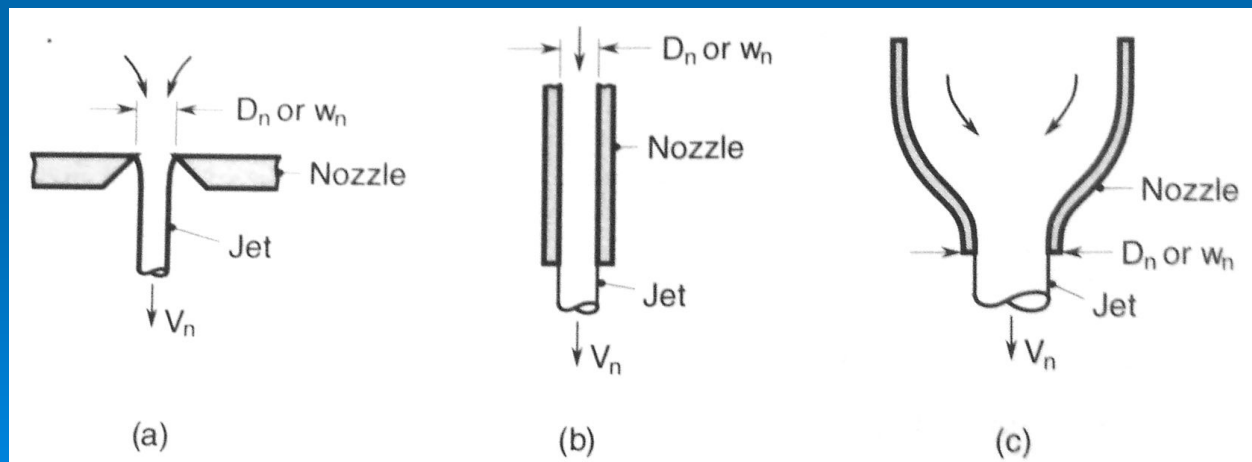


Incropera, pg. 65

- Unconfined, circular, submerged jet

Nozzle Design

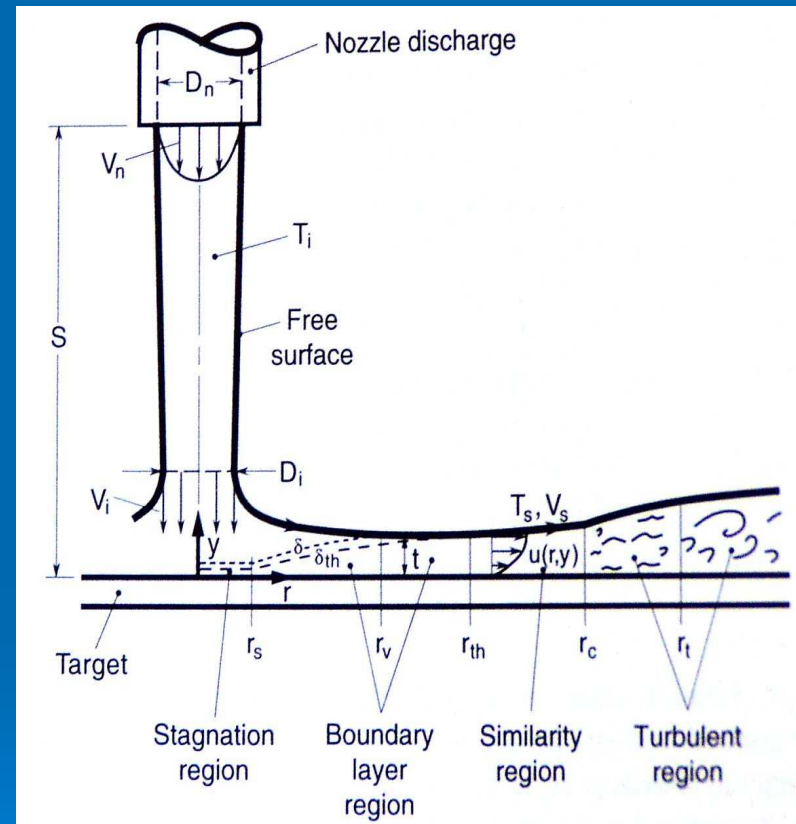
- Nozzles are designed to create different jet characteristics
 - Example: Sufficiently long nozzles will produce both fully developed laminar or turbulent jets (Shown in b)



Flow Regions

➤ Stagnation Region – Jet flow is decelerated normal to the impingement surface and accelerated parallel to it. Hydrodynamic and thermal boundary layers are uniform.

➤ Wall Jet Region – Boundary layers begin to grow

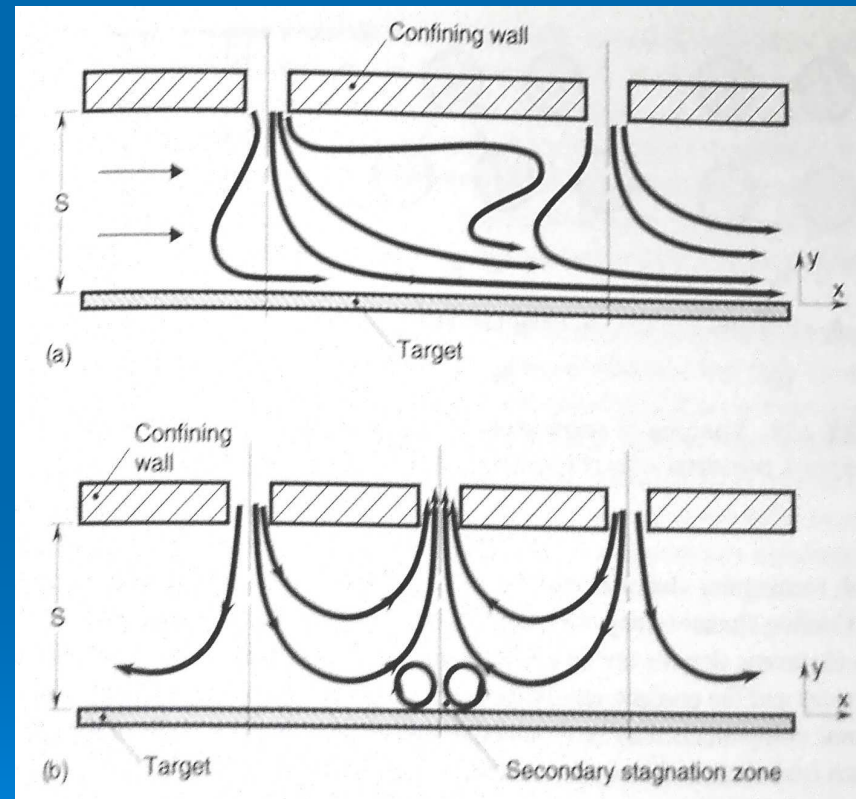


Degradation of Heat Transfer During Jet Impingement

- Splattering – Droplets are ejected from the wall jet region due to the distance the nozzle is from the heat source and the surface tension of the jet fluid
- Hydraulic Jump – An abrupt increase in film thickness and reduction in film velocity occurring in the wall jet region

Confining Fluid Flow




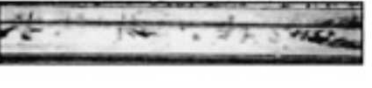










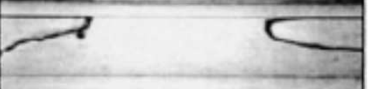

- Adding a confining wall:
 - Adds low and high pressure regions
 - Sometimes adds secondary stagnation regions
 - Degrades convection heat transfer
 - Decreases space needed to use jet impingement




Two-Phase Boiling in Microchannels

- Fluid entering microchannels is heated to the point where it boils
- Flow in microchannels is highly unpredictable and can produce large voids and multiple flow regimes inside of tubes
- No accurate analytical models currently exist; many analytical models have errors ranging from 10% to well over 100%

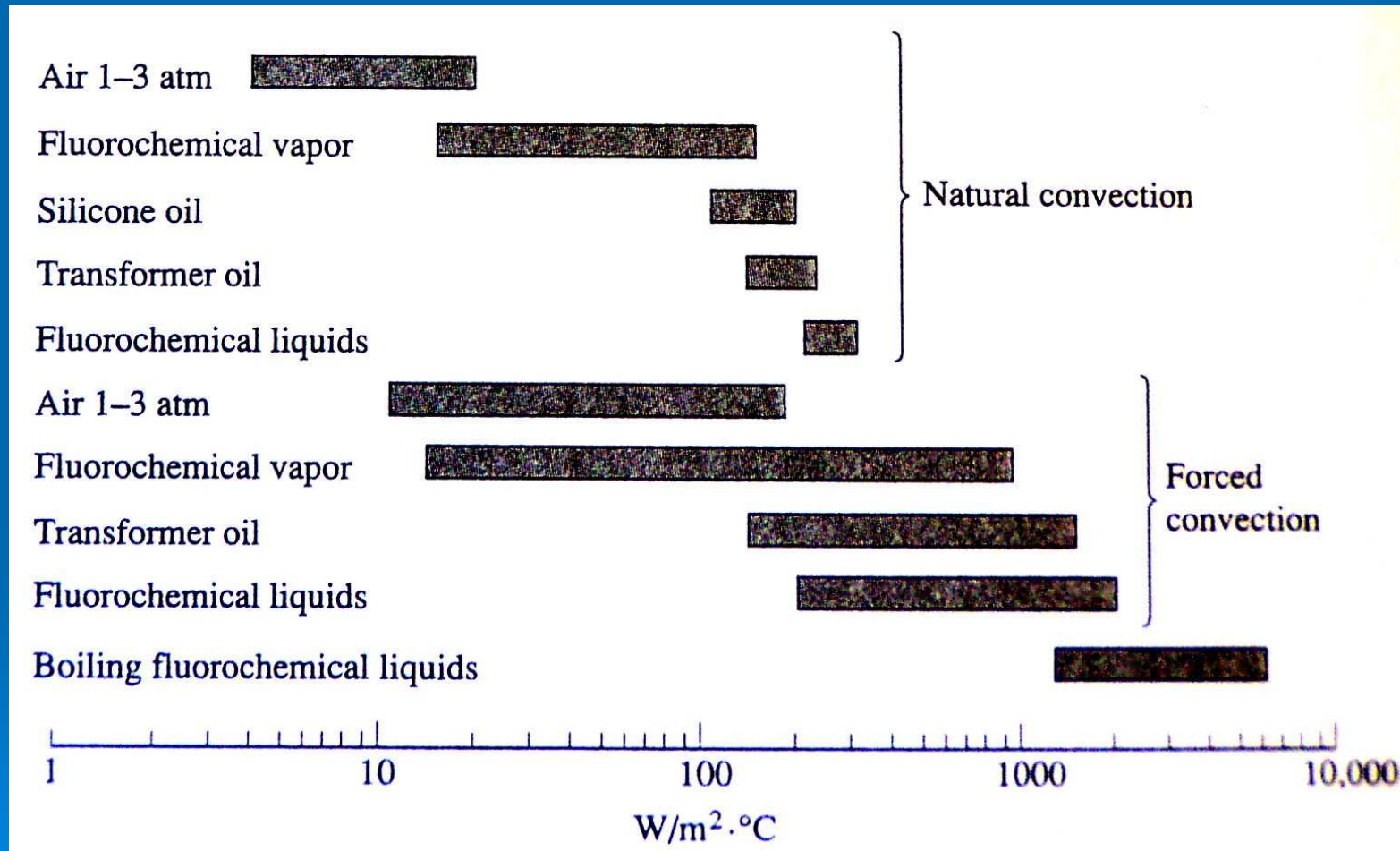
Flow Regimes in Two-Phase Applications

		FLOW REGIMES			
		Annular	Wavy	Intermittent	Dispersed
Flow Patterns					
	Mist Flow	Discrete Wave (0)	Slug Flow	Bubbly Flow	
					
	Annular Ring	Discrete Wave (1)	Slug Flow	Bubbly Flow	
					
Wave Ring	Discrete Wave (2)	Plug Flow	Bubbly Flow		
					
Wave Packet	Disperse Wave (3)	Plug Flow			
					
Annular Film					

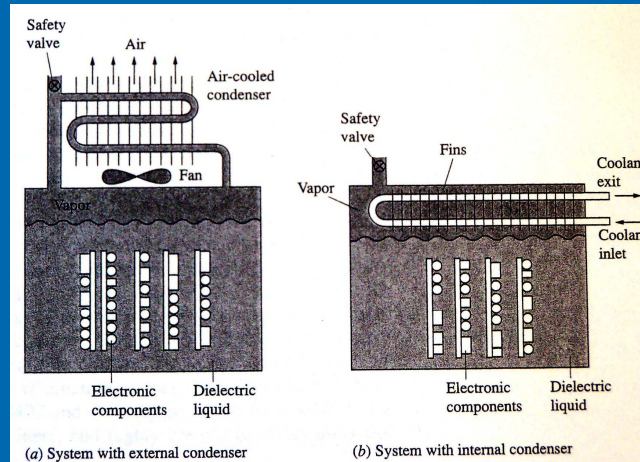
Immersion (Direct) Cooling

- In direct cooling electronics are immersed into a dielectric liquid
 - Closed loop systems are normally used due to both the cost of the liquids used and the environmental issues associated with the liquids escaping into the atmosphere
- 
- The bottom right corner of the slide features a decorative graphic of several concentric, light blue circles that resemble ripples on water, set against the dark blue background.

Typical Liquids Used in Immersion



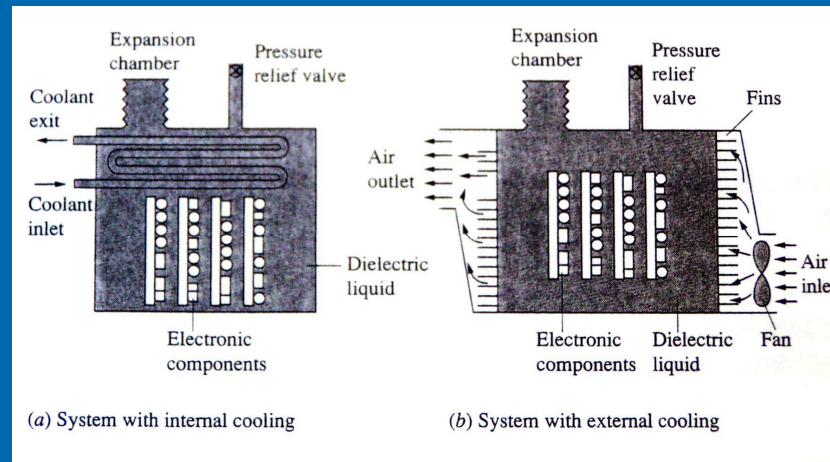
Boiling Used in Immersion



Cengel, pg. 918

- Electronics expel heat into the liquid
- Vapor bubbles are formed in the liquid
- The vapor is collected at the top of the enclosure where it comes in contact with some sort of heat exchanger
- The vapor condenses and returns to the liquid portion of the reservoir

Boiling Used in Immersion

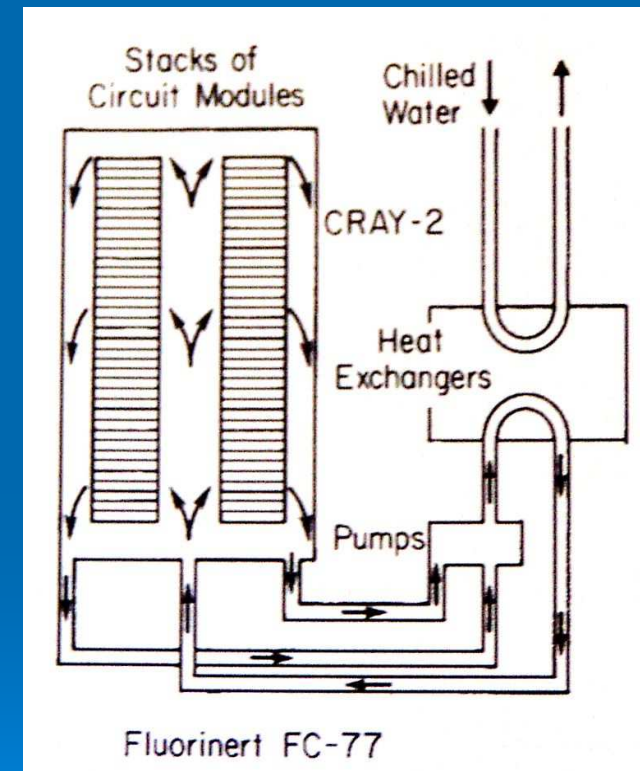


Cengel, pg. 919

- Electronics dissipate heat through the liquid
 - Vapor bubbles are generated
 - As vapor bubbles rise they come in contact with the cooler liquid produced by an immersed heat exchange and they implode
- *The prior example is more efficient due to the heat transfer coefficient associated with condensation

Cray-2 Supercomputer

- Cold fluid enters between the circuit modules
- Convection occurs, pulling heat from the electronics to the liquid
- The heated fluid is pumped to a heat exchanger
- Heat is transfer from the immersion liquid to chilled water in the heat exchanger



Concerns with Immersion

- Introduction of incompressible gasses into a vapor space
 - This will limit the amount of condensation that is allowed to occur and degrade heat transfer
- Leakage
 - Environmental Concerns
 - Reliability

Sources

- Cengel, Yunus A. Heat Transfer: A Practical Approach. 1st edition. New York, NY: McGraw Hill. 1998
- Incropera, Frank P. Liquid Cooling of Electronic Devices by Single Phase Convection. Danvers, MA: John Wiley & Son. 1999
- Kandlikar, Satish G. and Grande, William J. *“Evaluation of Single Phase Flow in Microchannels for High Heat Flux Chip Cooling – Thermohydrolic Performance Enhancement and Fabrication Technology”*. *Heat Transfer Engineering*. Taylor Francis Inc. 25(8). 2004
- Palm, Bjorn. *“Heat Transfer in Microchannels”*. *Microscale Thermophysical Engineering* 5:155-175, 2001. Taylor Francis, 2001.
- Kandlikar, Satish G. and Grande, William J. *“Condensation Flow Mechanisms in Microchannels: Basis for Pressure Drop and Heat Transfer Models”*. *Heat Transfer Engineering*. Taylor Francis Inc. 25(3). 2004