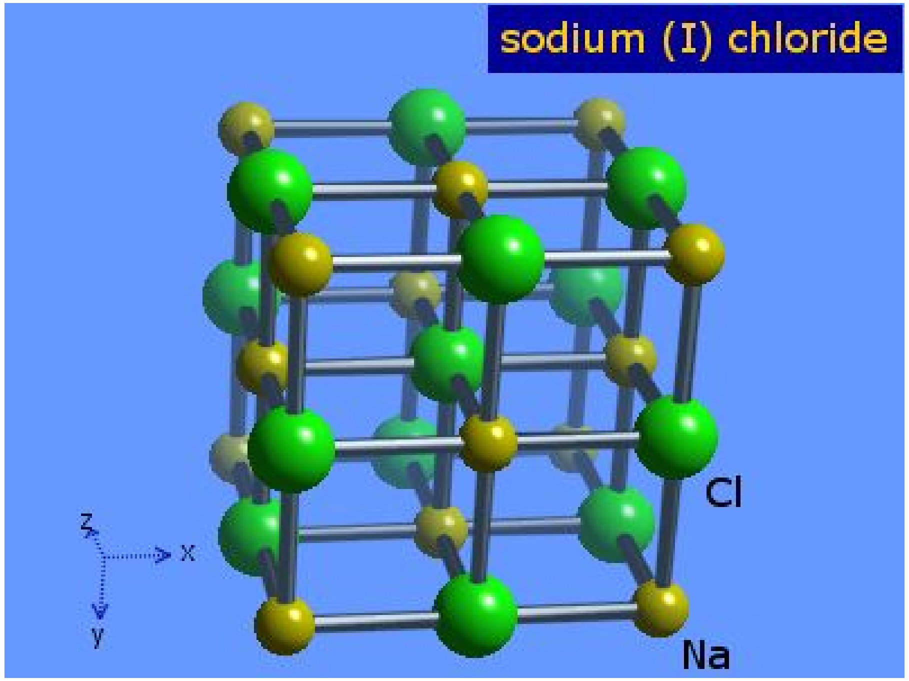
INTRODUCTION

- What is Heat Transfer ?
- Continuum Hypothesis
- Local Thermodynamic Equilibrium
- Conduction
- Radiation
- Convection
- Energy Conservation

WHAT IS HEAT ?

In a solid body

Crystal : a three-dimensional periodic array of atoms

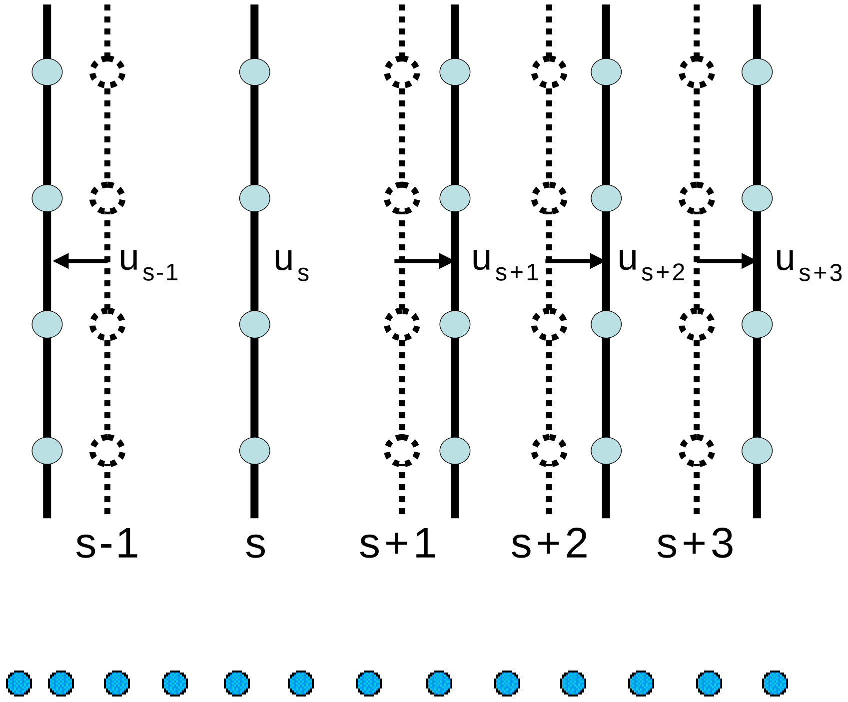


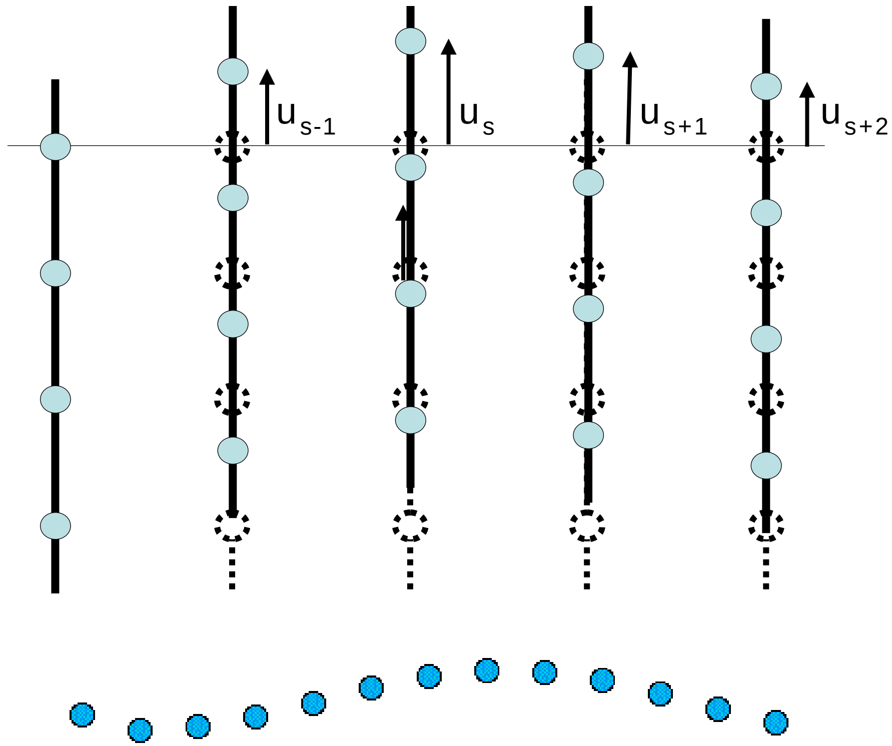
Oscillation of atoms about their various positions of equilibrium (lattice vibration): The body possesses heat.

Conductors: free electrons $\leftrightarrow$ Dielectics

Vibration of crystals with an atom

Longitudinal polarization vs. Transverse polarization





The energy of the oscillatory motions:

the heat-energy of the body

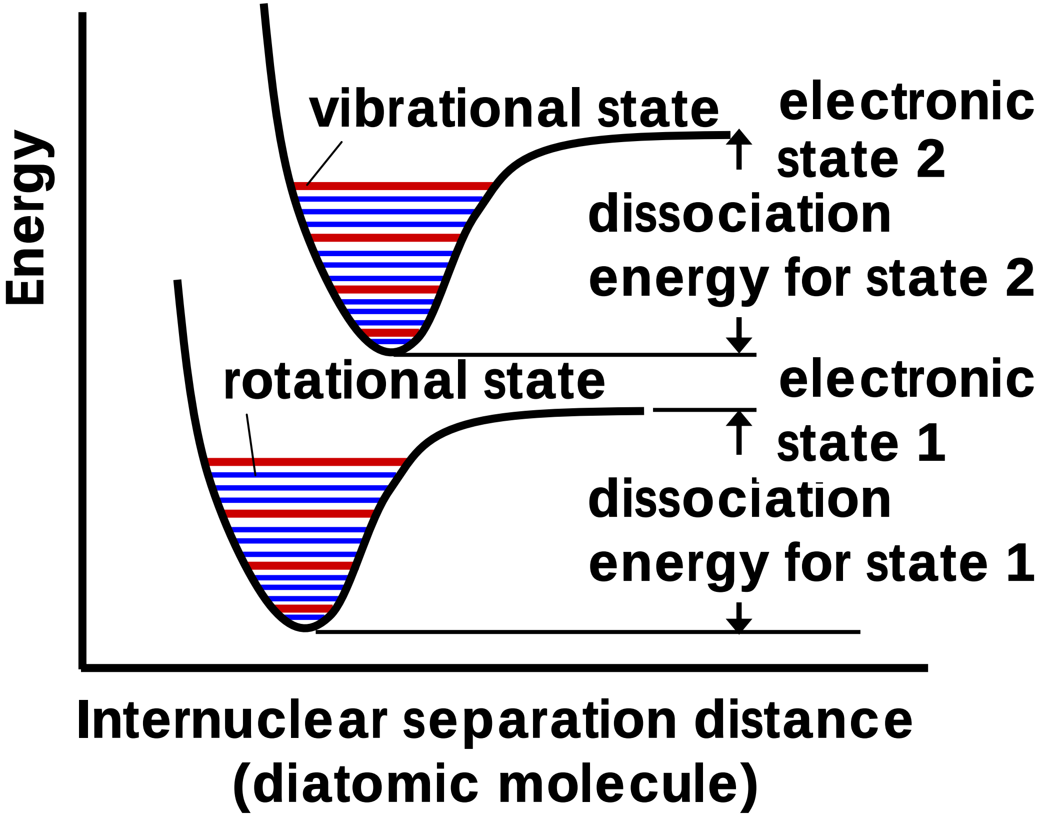
More vigorous oscillations:

the increase in temperature of the body

In a gas

The storage of thermal energy:

- molecular translation, vibration and rotation
- change in the electronic state
- intermolecular bond energy



average kinetic energy

$$E_u = \frac{1}{2} m \overline{u_m^2} \equiv \frac{3}{2} k_B T$$

$$k_B = 1.3807 \times 10^{-23}\ \mathrm{J/K}$$

at $T = 300$ K,

air $M = 28.97$ kg/kmol

$$\left\langle u_m^2 \right\rangle^{1/2} = 468.0\ \mathrm{m/s}$$

HEAT TRANSFER

Heat transfer is the study of thermal energy transport within a medium or among neighboring media by

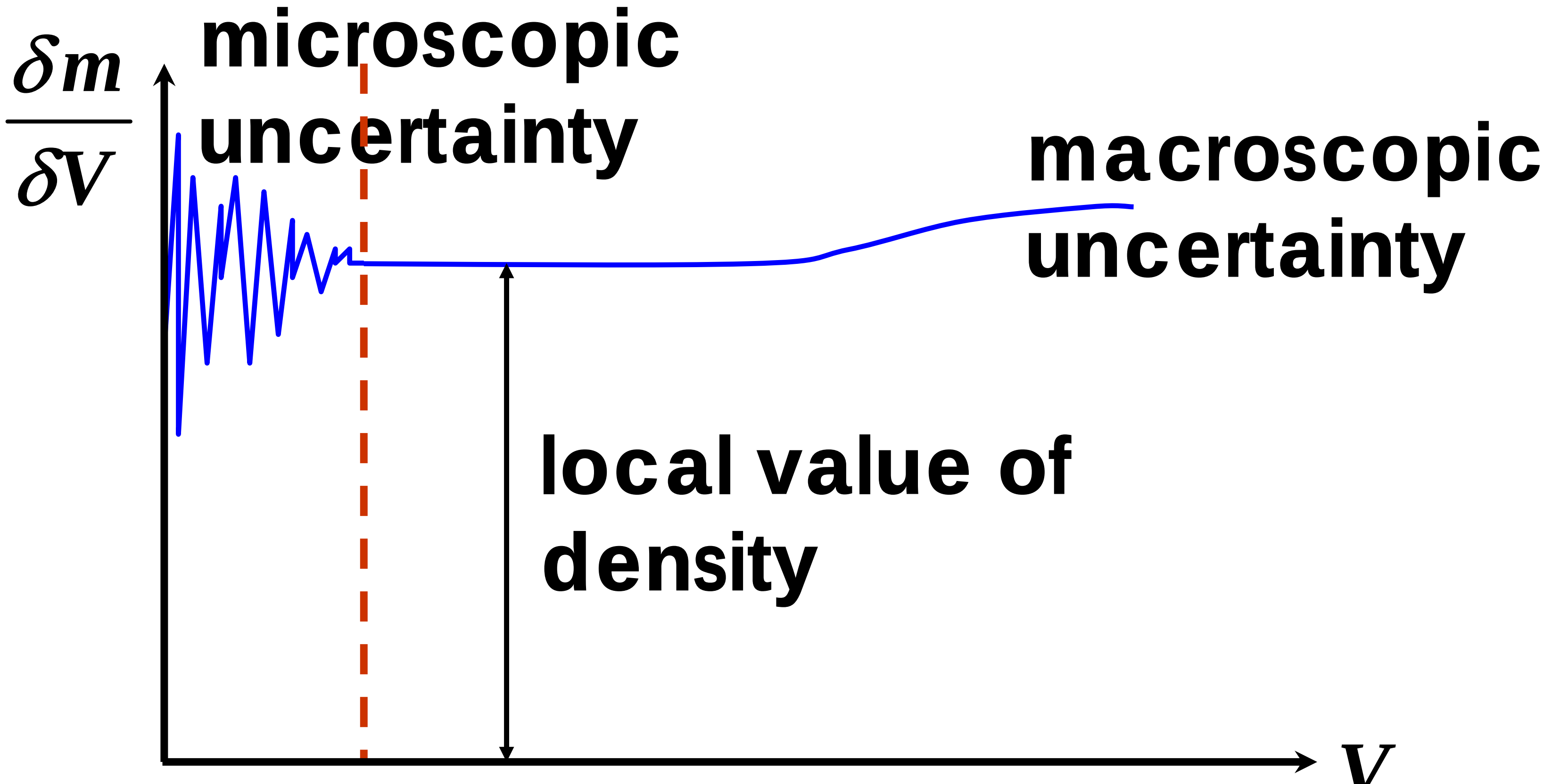
- Molecular interaction: conduction
- Fluid motion: convection
- Electromagnetic wave: radiation

resulting from a spatial variation in temperature

Energy carriers: molecule, atom, electron, ion, phonon (lattice vibration), photon (electro-magnetic wave)

CONTINUUM HYPOTHESIS

Ex) density $\rho = \lim_{\delta V \to \delta V_0} \dfrac{\delta m}{\delta V}$



$$\delta V_0 \approx 10^{-9}\ \text{mm}^3$$

(3×10^7 molecules at sea level, 15°C, 1atm)

- **microscopic uncertainty**

  due to molecular random motion

- **macroscopic uncertainty**

  due to the variation associated with spatial distribution of density

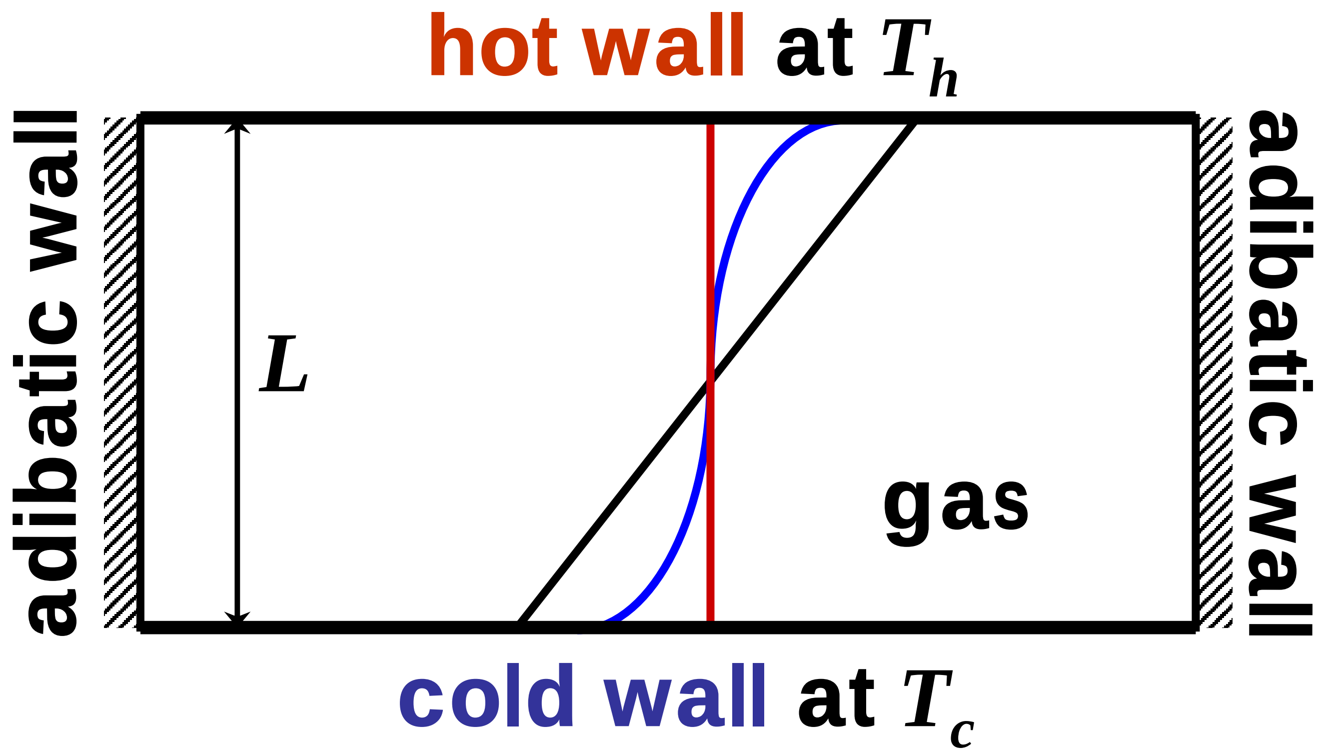
In continuum, velocity and temperature vary smoothly. → differentiable

Mean free path of air at STP (20°C, 1atm)

$$\lambda_{\mathrm{m}} = 66\ \mathrm{nm},\ \left\langle u_m^2 \right\rangle^{1/2} = 468.0\ \mathrm{m/s}$$

bulk motion vs molecular random motion

LOCAL THERMODYNAMIC EQUILIBRIUM



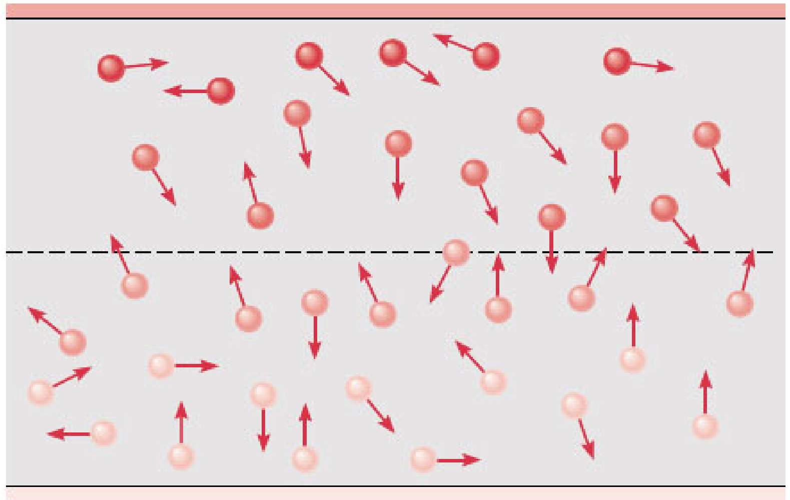
a) $\lambda_m << L$: normal pressure

b) $\lambda_m \sim L$: rarefied pressure

c) $\lambda_m >> L$

CONDUCTION

Gases and Liquids

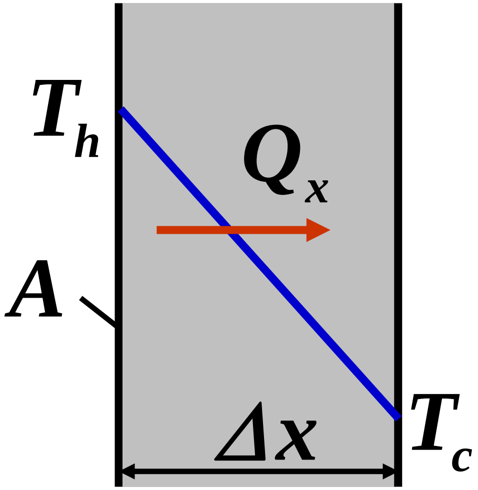


- Due to interactions of atomic or molecular activities
- Net transfer of energy by random molecular motion
- Molecular random motion→ diffusion
- Transfer by collision of random molecular motion

Solids

- **Due to lattice waves induced by atomic motion**
- **In non-conductors (dielectrics): exclusively by lattice waves**
- **In conductors:**
  translational motion of free electrons as well

Fourier's Law



$$\Delta T = T_h - T_c$$

$$Q_x \propto \frac{\Delta T}{\Delta x} \cdot \Delta t \cdot A \quad [\mathrm{J}]$$

heat flux $$q''_x = \frac{Q_x}{A \cdot \Delta t} \propto \frac{\Delta T}{\Delta x} = -k \frac{\Delta T}{\Delta x}$$

$$[\mathrm{J/(m^2 s) = W/m^2}]$$

k: thermal conductivity [W/m·K]

As $\Delta x \to 0, \quad q''_x = -k \dfrac{\partial T}{\partial x}$

Notation

Q : **amount of heat transfer [J]**

q : **heat transfer rate [W],** $q' = \dfrac{Q}{\Delta t}$

q'' : **heat transfer rate per unit area [W/m^2]**

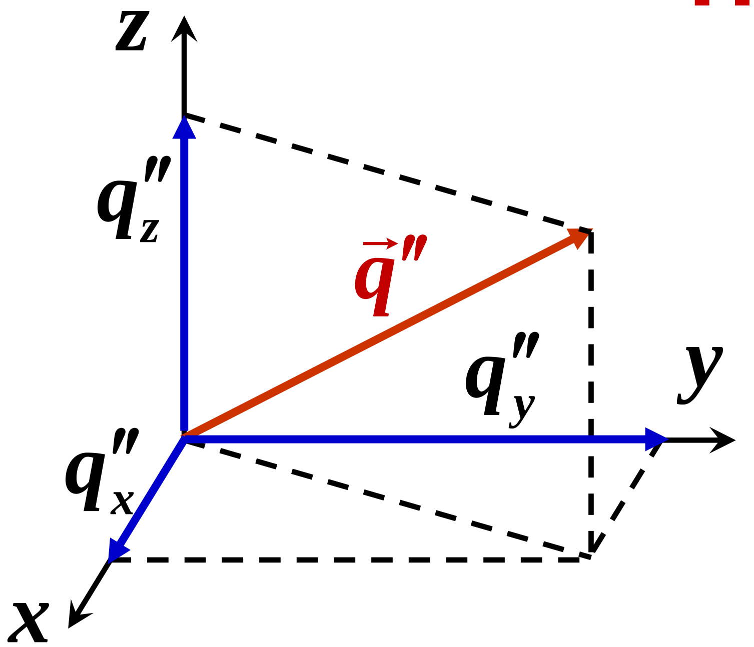
$$q'' = \frac{Q}{A \cdot \Delta t}$$

q' : **heat transfer rate per unit length [W/m]**

$$q' = \frac{Q}{L \cdot \Delta t}$$

$$q = q''A = q'L$$

Heat Flux



vector quantity

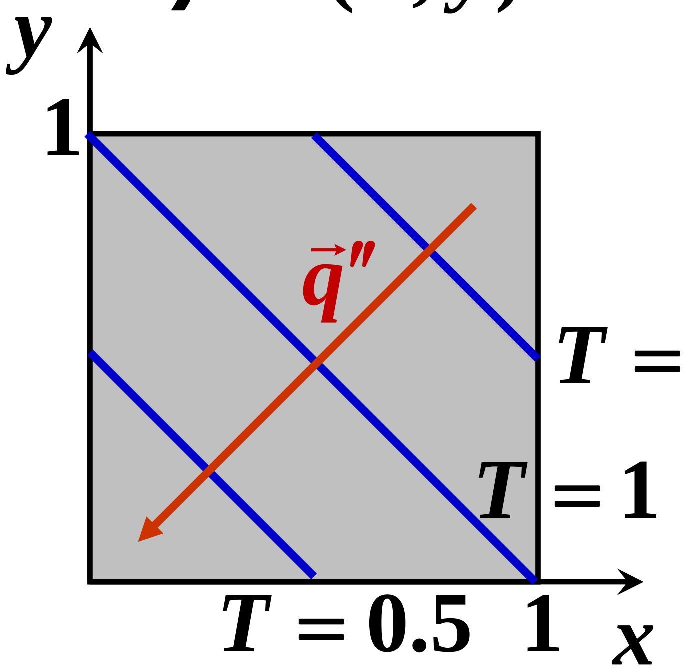
$$\vec{q}'' = q''_x \hat{i} + q''_y \hat{j} + q''_z \hat{k}$$

$$q''_x = \vec{q}'' \cdot \hat{i} = -k \frac{\partial T}{\partial x}$$

$$q''_y = \vec{q}'' \cdot \hat{j} = -k \frac{\partial T}{\partial y}, \qquad q''_z = \vec{q}'' \cdot \hat{k} = -k \frac{\partial T}{\partial z}$$

$$\vec{q}'' = -k \left(\frac{\partial T}{\partial x} \hat{i} + \frac{\partial T}{\partial y} \hat{j} + \frac{\partial T}{\partial z} \hat{k} \right) = -k \nabla T$$

Ex) $T(x,y) = x + y \quad (0 \le x \le 1,\ 0 \le y \le 1)$



$T =$ constant line or surface: isothermal lines or surfaces (isotherms)

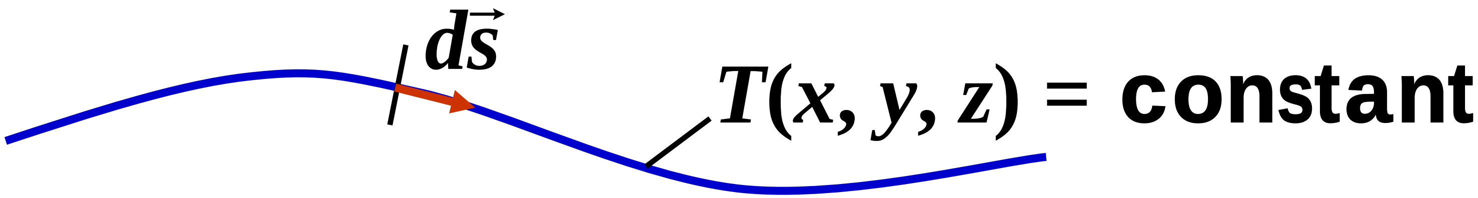
$$\vec{q}'' = -k\nabla T = -k\left(\frac{\partial T}{\partial x}\hat{i} + \frac{\partial T}{\partial y}\hat{j}\right) = -k\left(\hat{i} + \hat{j}\right)$$

$$= q''_x\hat{i} + q''_y\hat{j} = -k\hat{i} - k\hat{j}$$

$$q''_x = -k,\quad q''_y = -k$$

- **temperature : driving potential of heat flow**
- **heat flux : normal to isotherms**

along the surface of $T(x, y, z)$ **= constant**

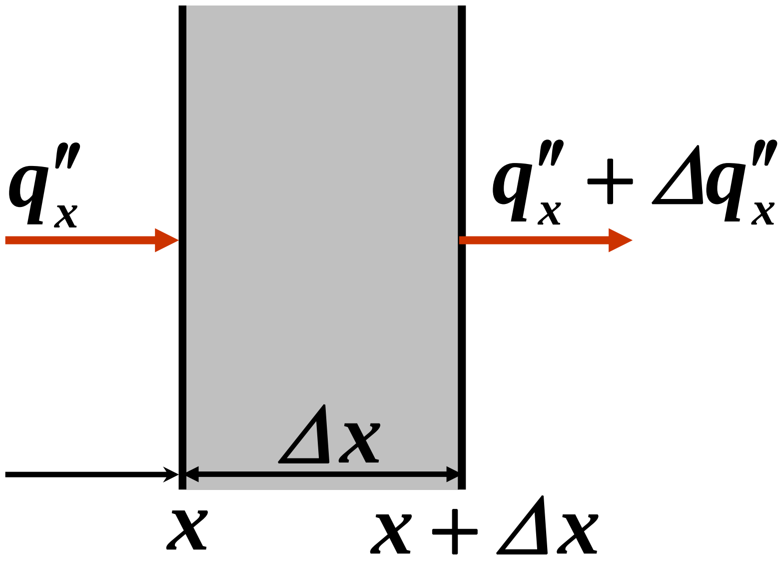


$$d\vec{s} = dx\hat{i} + dy\hat{j} + dz\hat{k}$$

$$dT = \frac{\partial T}{\partial x}dx + \frac{\partial T}{\partial y}dy + \frac{\partial T}{\partial z}dz = 0$$

$$= \nabla T \cdot d\vec{s} = 0 \;\rightarrow \vec{q}'' \cdot d\vec{s} = 0$$

Steady-State One Dimensional Conduction



$T = T(x)$ **only**

steady-state

$$q''_x = q''_x + \Delta q''_x \rightarrow \Delta q''_x = 0$$

$$q''_x = -k\frac{dT}{dx}$$

$$q''_x + \Delta q''_x = q''_x + \frac{dq''_x}{dx}\Delta x + O\left[(\Delta x)^2\right]$$

$$= -k\frac{dT}{dx} + \frac{d}{dx}\left(-k\frac{dT}{dx}\right)\Delta x + O\left[(\Delta x)^2\right]$$

$$\Delta q''_x = \frac{d}{dx}\left(-k\frac{dT}{dx}\right)\Delta x + O\left[(\Delta x)^2\right] = 0$$

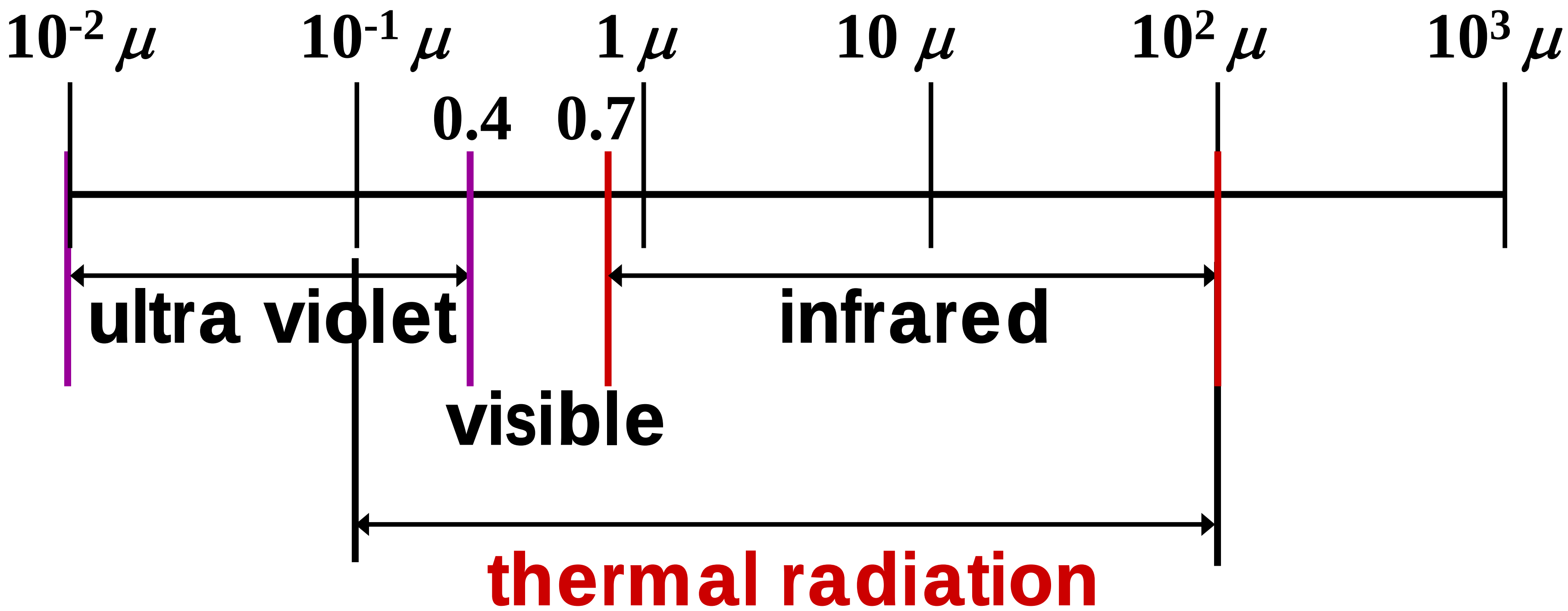
or $$\frac{d}{dx}\left(-k\frac{dT}{dx}\right) + O(\Delta x) = 0$$

As $\Delta x \rightarrow 0$, $$\frac{d}{dx}\left(k\frac{dT}{dx}\right) = 0$$

When k = const., $$\frac{d^2T}{dx^2} = 0$$

RADIATION

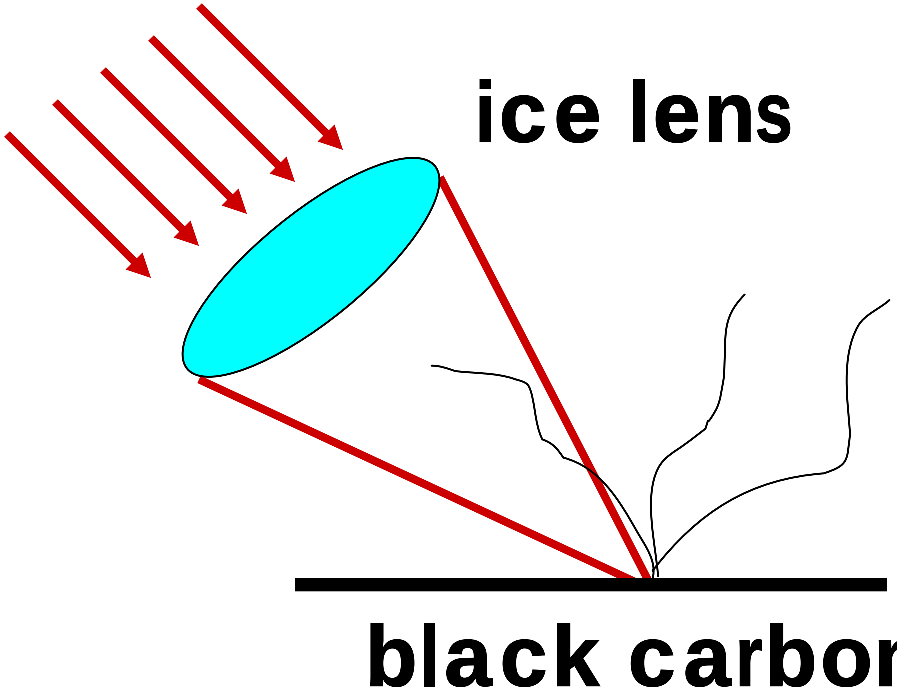
Thermal Radiation



Characteristics of Thermal Radiation

1. Independence of existence and temperature of medium

Ex) ice lens



2. Acting at a distance

Ex) sky radiation

- electromagnetic wave or photon
- photon mean free path
- ballistic transport $\longleftrightarrow$ diffusion
- volume or integral phenomena

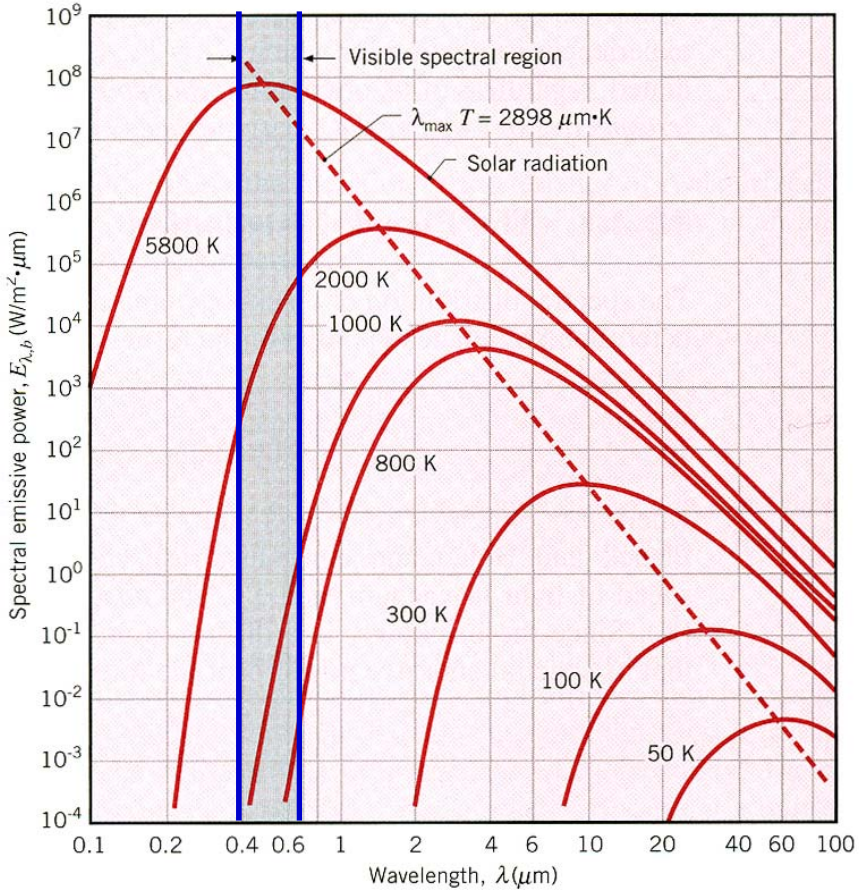
conduction

- fluid: molecular random motion
- solid: lattice vibration (phonon)
  free electron

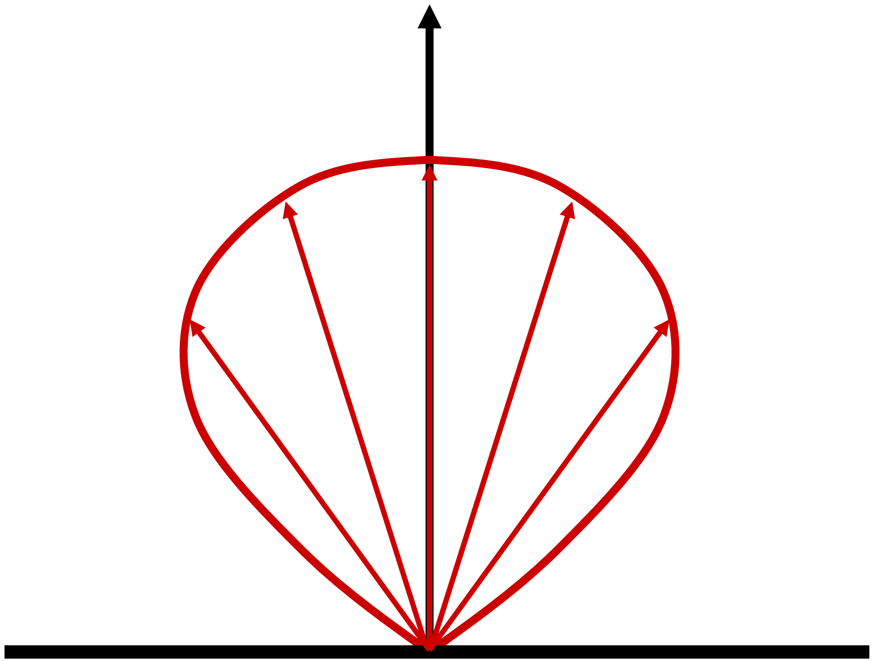
diffusion or differential phenomena
as long as continuum holds

3. Spectral and Directional Dependence

- quanta
- history of path



Blackbody spectral emissive power



surface emission

Two Points of View

1. Electromagnetic wave

- **Maxwell's electromagnetic theory**
- **Useful for interaction between radiation and matter**

2. Photons

- **Planck's quantum theory**
- **Useful for the prediction of spectral properties of absorbing, emitting medium**

Radiating Medium

- Transparent medium
  ex: air
- Participating medium
  emitting, absorbing and scattering
  ex: CO_2, H_2O
- Opaque material

Stefan-Boltzmann's law

- **Blackbody emissive power**

$$E_b = q''_{b,e} = \sigma T^4 \ \ [\mathrm{W/m^2}]$$

blackbody: a perfect absorber

$$\sigma = 5.6696 \times 10^{-8} \ \mathrm{W/m^2 \cdot K^4}$$

Stefan by experiment (1879): $E_b \sim T^4$

Boltzmann by theory (1884): $E_b = \sigma T^4$

Planck's law

(The Theory of Heat Radiation, Max Planck, 1901)

spectral distribution of hemispherical emissive power of a blackbody in vacuum

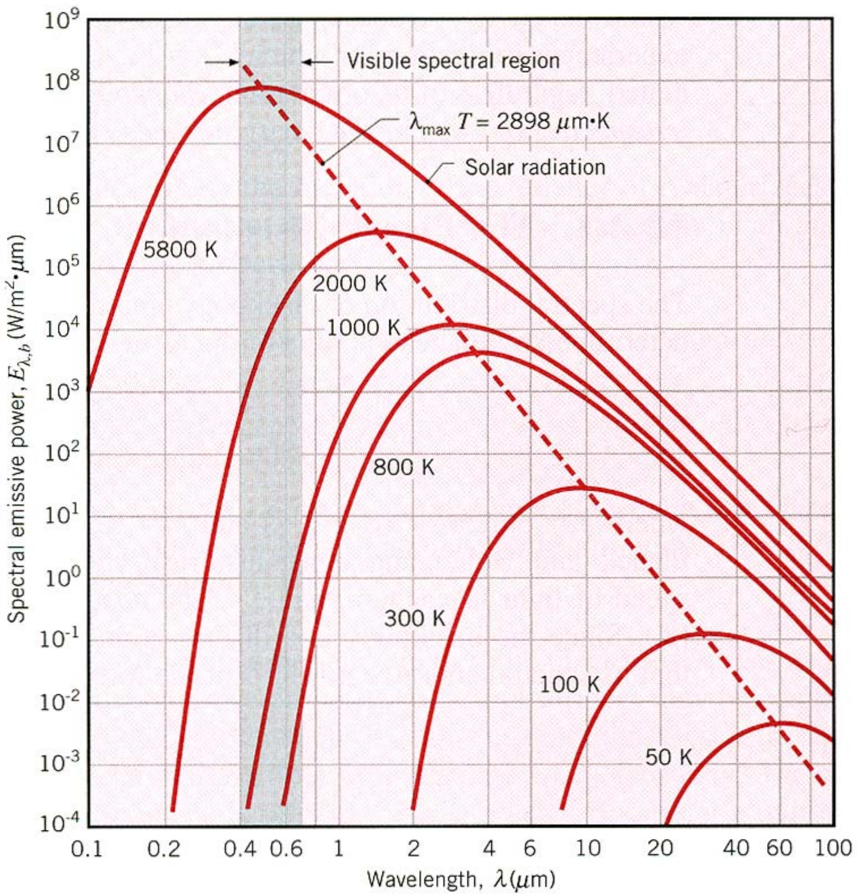
$$E_{\lambda b} = \frac{2\pi C_1}{\lambda^5\left(e^{C_2/\lambda T} - 1\right)}$$

$$C_1 = hC_0^2,\ C_2 = hC_0/k$$

C_0: speed of light in vacuum

h: Planck constant

k: Boltzmann constant



Blackbody spectral emissive power

$$E_b = \int_0^\infty \frac{2\pi C_1}{\lambda^5 \left(e^{C_2/\lambda T} - 1\right)} d\lambda$$

$$= \sigma T^4$$

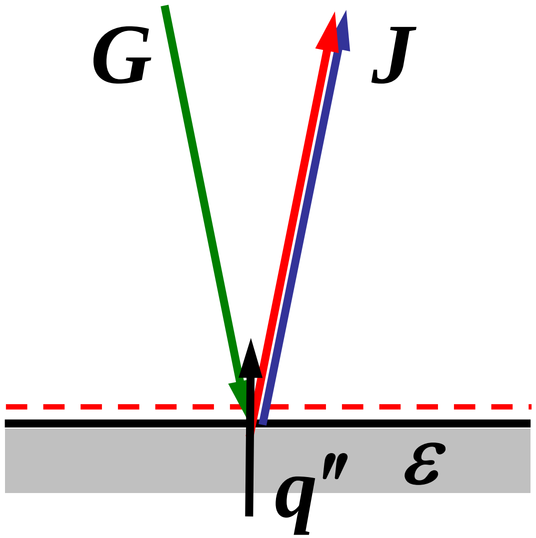
For a real surface,

$$E = \varepsilon \sigma T^4$$

ε **: emissivity**

Surface Radiation

Ray-tracing method vs Net-radiation method



diffuse-gray surface at T

G: irradiation [W/m²]

J: radiosity [W/m²]

$$J = \varepsilon\sigma T^4 + \rho G,\quad \rho: \text{reflectivity}$$

$$q'' = J - G$$

$$q'' = \varepsilon\sigma T^4 + \rho G - G$$

$$= \varepsilon\sigma T^4 - (1-\rho)G$$

$$\alpha + \rho = 1, \quad \alpha: \text{absorptivity}$$

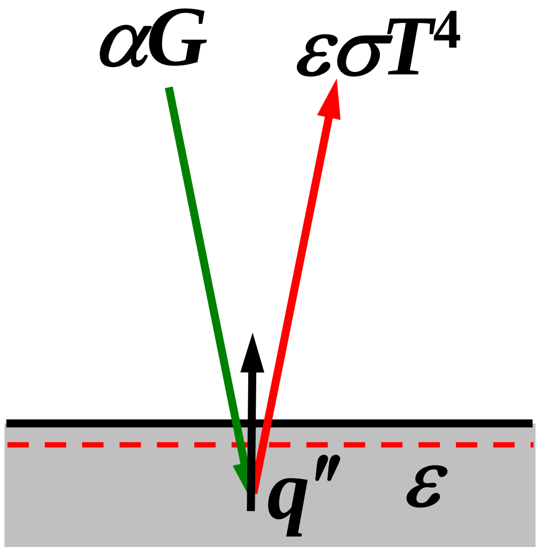
Kirchihoff's law $\alpha = \varepsilon \quad \rightarrow q'' = \varepsilon\left(\sigma T^4 - G\right)$

$$q'' = J - G$$

$$J = \varepsilon\sigma T^4 + \rho G$$

$$q'' = J - \frac{1}{\rho}\left(J - \varepsilon\sigma T^4\right) = \frac{1}{\rho}\left(\rho J - J + \varepsilon\sigma T^4\right)$$

$$= \frac{1}{\rho}\left(\varepsilon\sigma T^4 - \varepsilon J\right) = \frac{\varepsilon}{1-\varepsilon}\left(\sigma T^4 - J\right)$$



diffuse-gray surface at T

$$q'' = \varepsilon\sigma T^4 - \alpha G$$

$$= \varepsilon\sigma T^4 - \varepsilon G$$

$$= \varepsilon\left(\sigma T^4 - G\right)$$

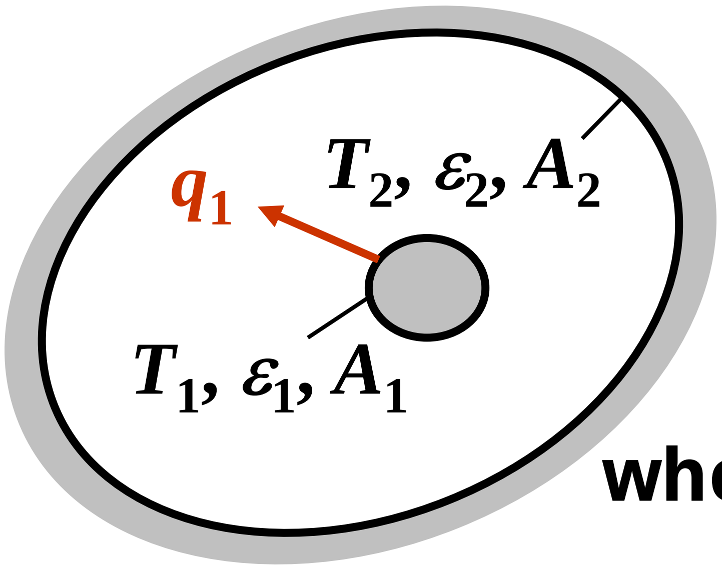
$$J = \varepsilon\sigma T^4 + \rho G$$

$$G = \frac{1}{\rho}\left(J - \varepsilon\sigma T^4\right)$$

$$q'' = \varepsilon\sigma T^4 - \frac{\alpha}{\rho}\left(J - \varepsilon\sigma T^4\right)$$

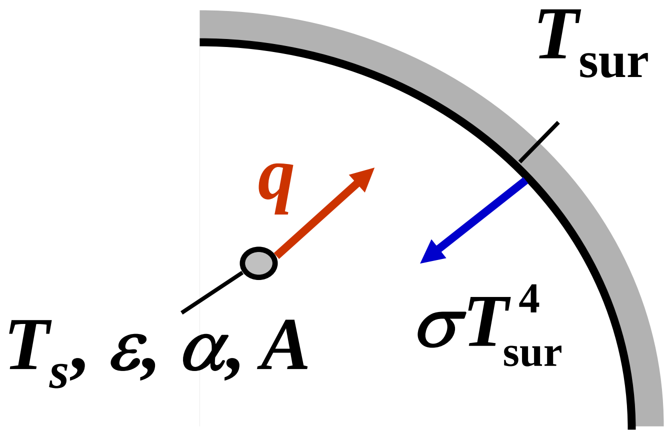
$$= \varepsilon\sigma T^4 - \frac{\varepsilon}{1-\varepsilon}\left(J - \varepsilon\sigma T^4\right) = \frac{\varepsilon}{1-\varepsilon}\left(\sigma T^4 - J\right)$$

Ex) a body in an enclosure



$$q_1 = \frac{A_1\sigma\left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1} + \cancel{\frac{A_1}{A_2}\left(\frac{1}{\varepsilon_2} - 1\right)}} \quad \text{[W]}$$

when $\frac{A_1}{A_2} << 1, \quad q_1 = \varepsilon_1 \sigma A_1\left(T_1^4 - T_2^4\right)$



$$q = \varepsilon\sigma A T_s^4 - \alpha\sigma A T_{\text{sur}}^4$$

$$\varepsilon = \alpha$$

$$q = \varepsilon\sigma A\left(T_s^4 - T_{\text{sur}}^4\right)$$

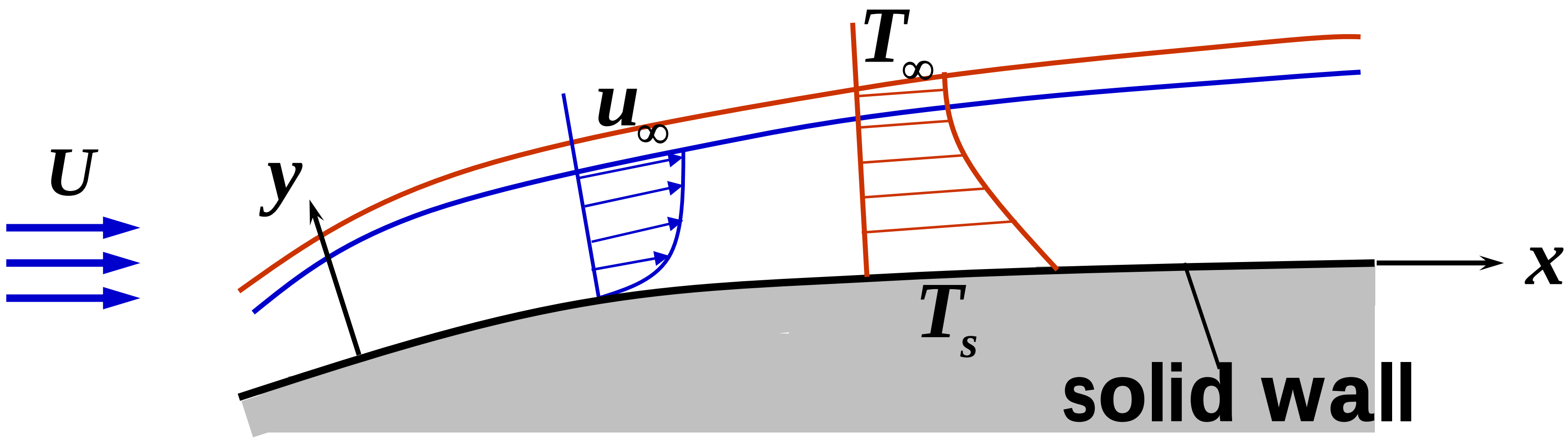
Surrounding can be regarded as a blackbody.

CONVECTION

energy transfer due to bulk or macro-scopic motion of fluid

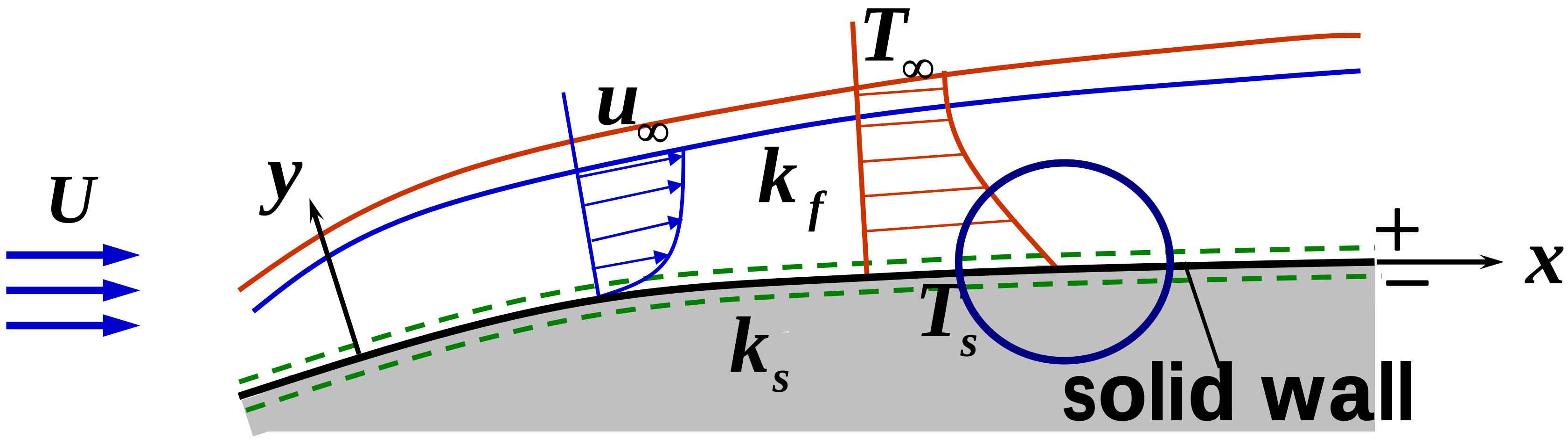
bulk motion: large number of molecules moving collectively

- convection: random molecular motion + bulk motion
- advection: bulk motion only

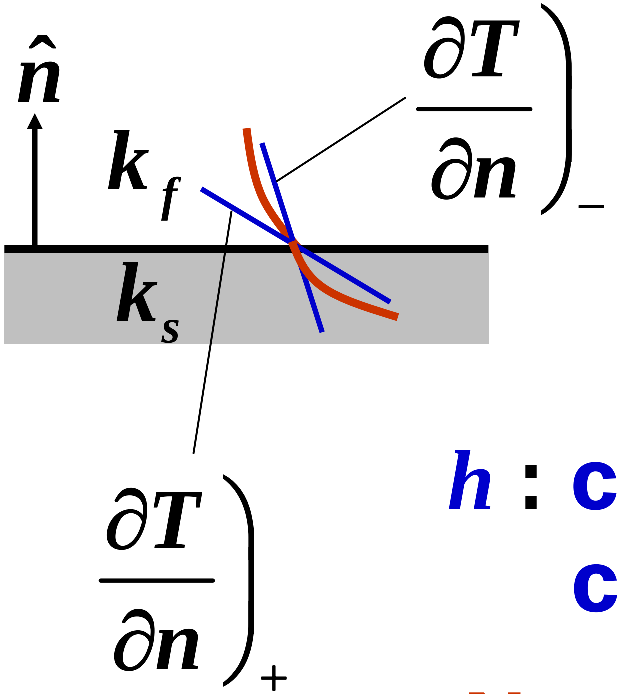


- **hydrodynamic (or velocity) boundary layer**
- **thermal (or temperature) boundary layer**

at $y = 0$, velocity is zero: heat transfer only by molecular random motion



When radiation is negligible,



$$q_s'' = -k_f \left.\frac{\partial T}{\partial n}\right)_+ = -k_s \left.\frac{\partial T}{\partial n}\right)_-$$

$$\equiv h\left(T_s - T_\infty\right)$$

h **: convection heat transfer coefficient [W/m²·K]**

Newton's Law of Cooling

Convection Heat Transfer Coefficient

$$h = -\frac{k_f}{(T_s - T_\infty)} \frac{\partial T}{\partial n}\bigg)_+ = -\frac{k_s}{(T_s - T_\infty)} \frac{\partial T}{\partial n}\bigg)_-$$

not a property: depends on geometry and fluid dynamics

- **forced convection**
- **free (natural) convection**

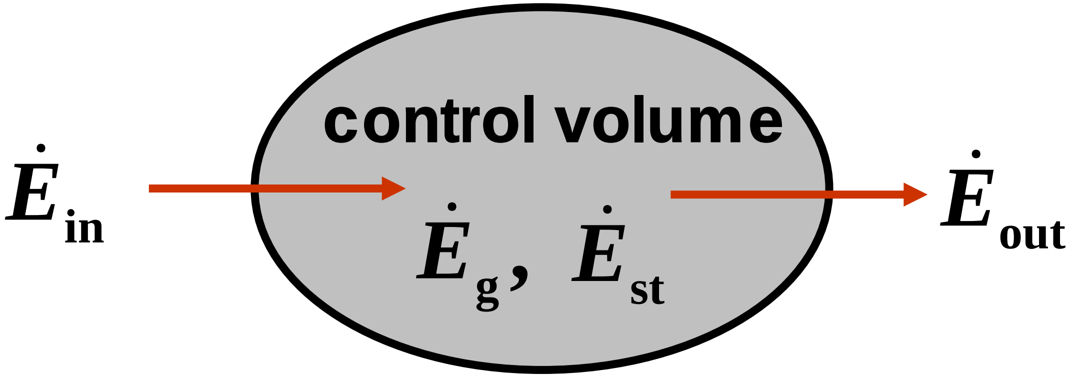
- **external flow**
- **Internal flow**

- **laminar flow**
- **turbulent flow**

ENERGY CONSERVATION

First law of thermodynamics

- control volume (open system)
- material volume (closed system)

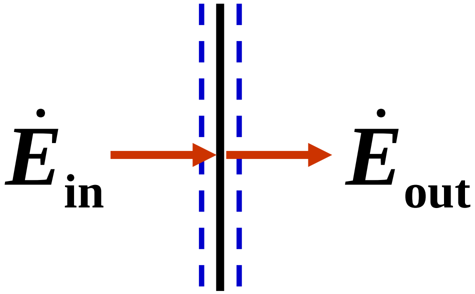


$$\dot{E}_{in} + \dot{E}_g - \dot{E}_{out} = \dot{E}_{st}$$

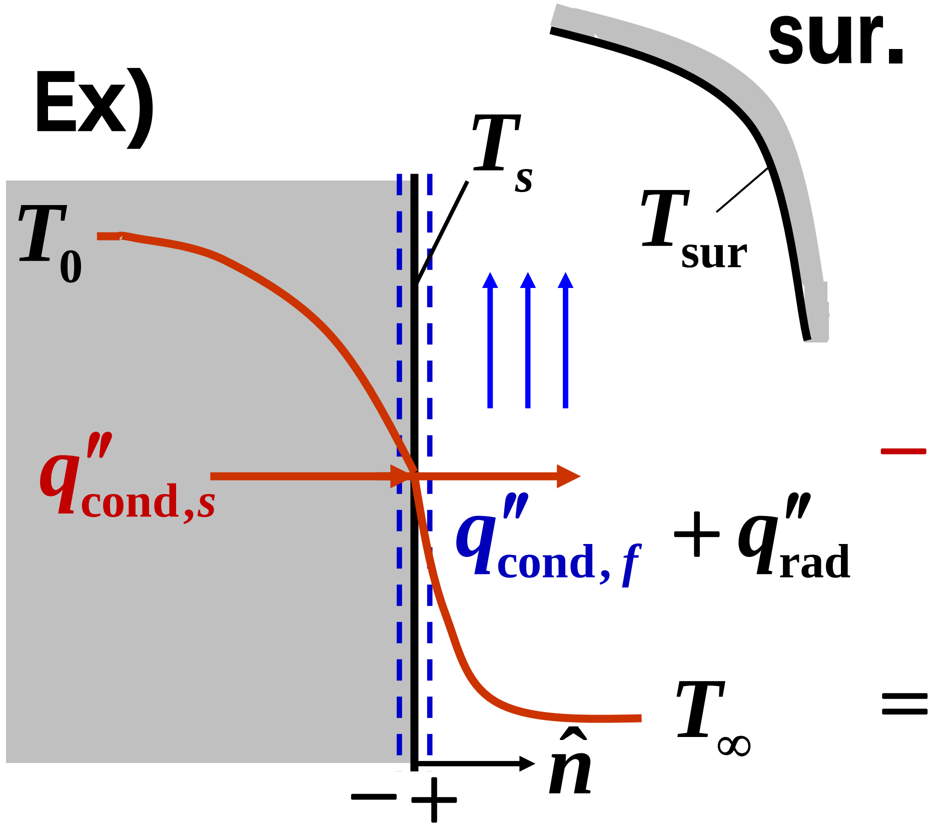
In a time interval Δt: $E_{in} + E_g - E_{out} = \Delta E_{st}$

steady-state: $\dot{E}_{st} = 0 \rightarrow \dot{E}_{in} + \dot{E}_g - \dot{E}_{out} = 0$

Surface Energy Balance



$$\dot{E}_{in} = \dot{E}_{out}$$



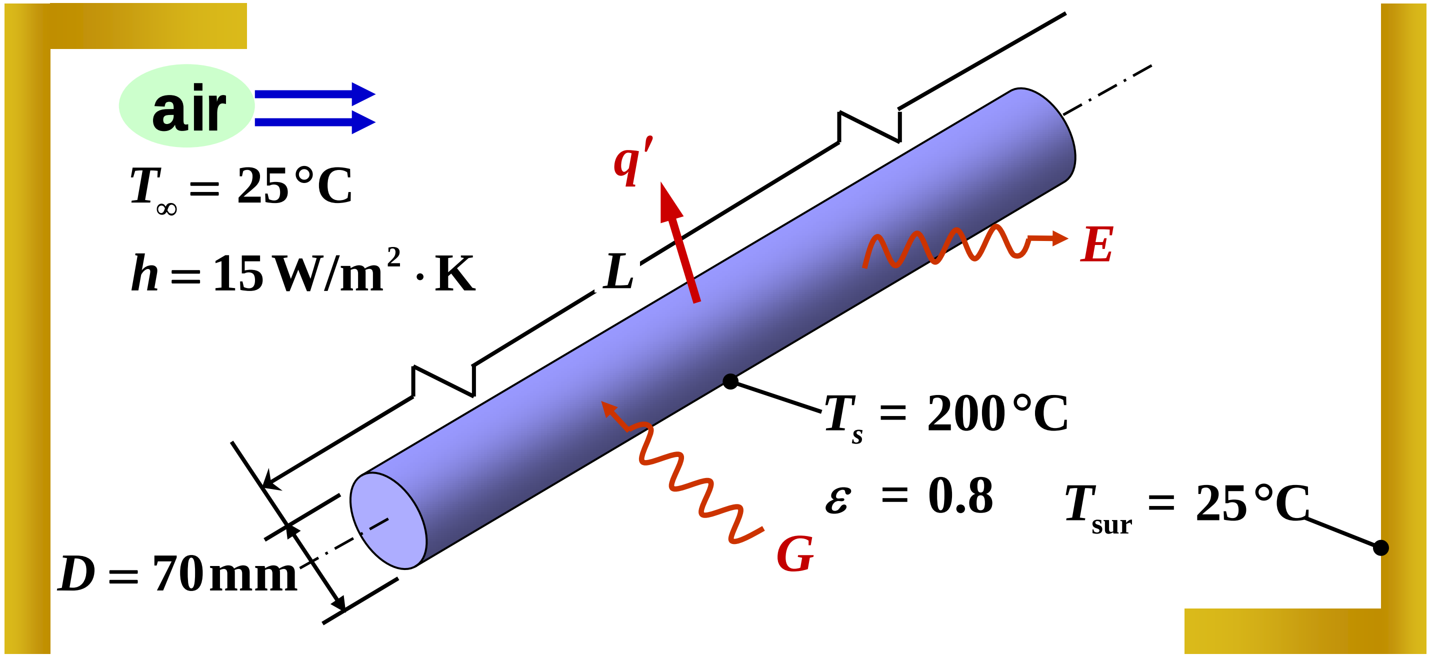
$$q''_{cond,s} = q''_{cond,f} + q''_{rad}$$

$$= q''_{conv} + q''_{rad}$$

$$-k_s \left.\frac{\partial T}{\partial n}\right)_{-} = -k_f \left.\frac{\partial T}{\partial n}\right)_{+} + q''_{rad}$$

$$= h\left(T_s - T_\infty\right) + \varepsilon\sigma\left(T_s^4 - T_{sur}^4\right)$$

Example 1.2

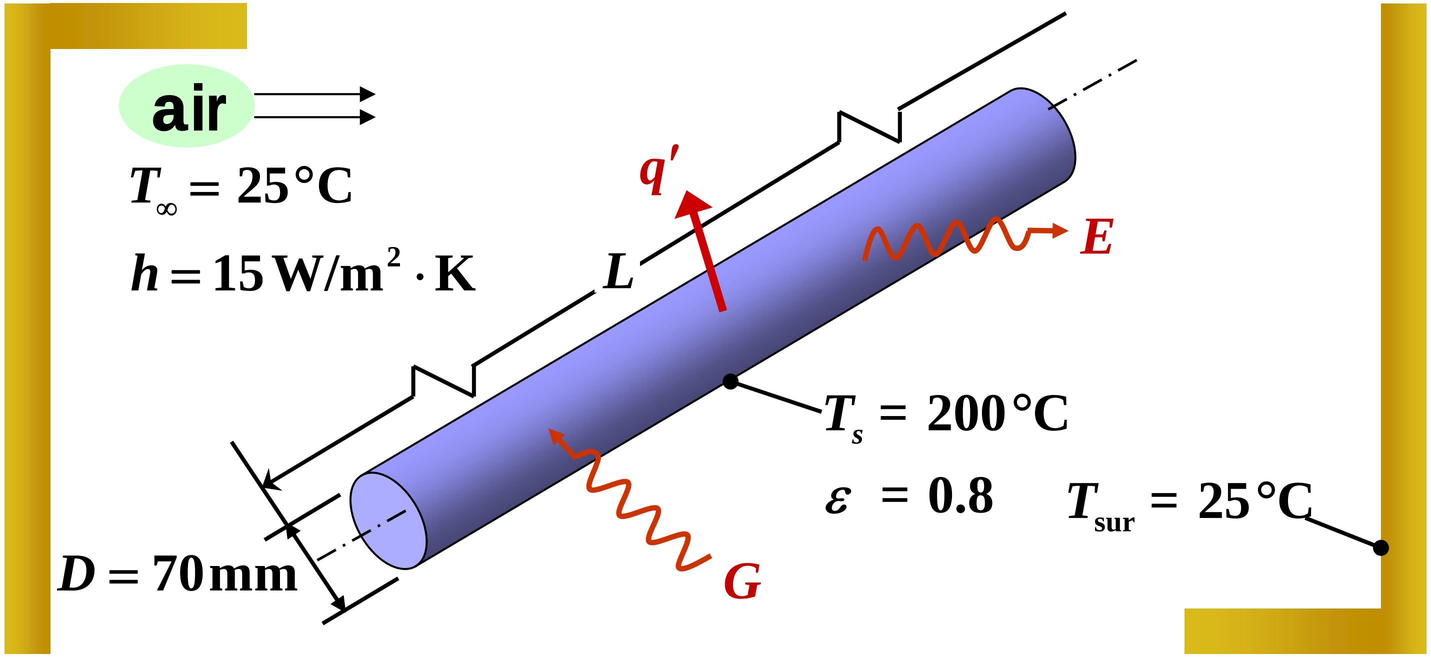


Find:

1) Surface emissive power E and irradiation G
2) Pipe heat loss per unit length, q'

Assumptions:

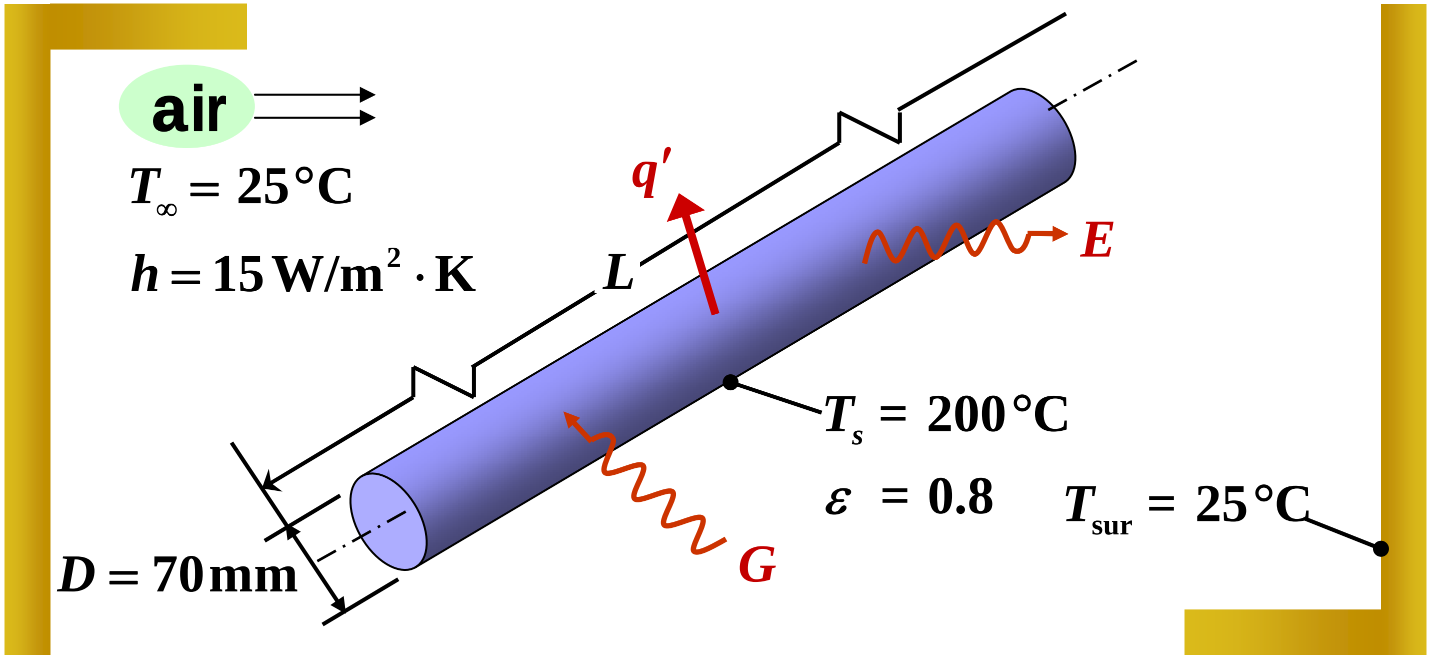
1) Steady-state conditions
2) Radiation exchange between the pipe and the room is between a small surface in a much larger enclosure.
3) Surface emissivity = absorptivity



1. Surface emissive power and irradiation

$$E = \varepsilon \sigma T_s^4 = 0.8(5.67 \times 10^{-8}\ \mathrm{W/m^2 \cdot K^4})(473\ \mathrm{K})^4 = 2,270\ \mathrm{W/m^2}$$

$$G = \sigma T_{sur}^4 = 5.67 \times 10^{-8}\ \mathrm{W/m^2 \cdot K^4}(298\ \mathrm{K})^4 = 447\ \mathrm{W/m^2}$$



2. Heat loss from the pipe

$$q_{loss} = q_{conv} + q_{rad} = hA\left(T_s - T_\infty\right) + \varepsilon\sigma A\left(T_s^4 - T_{sur}^4\right) \qquad A = \pi DL$$

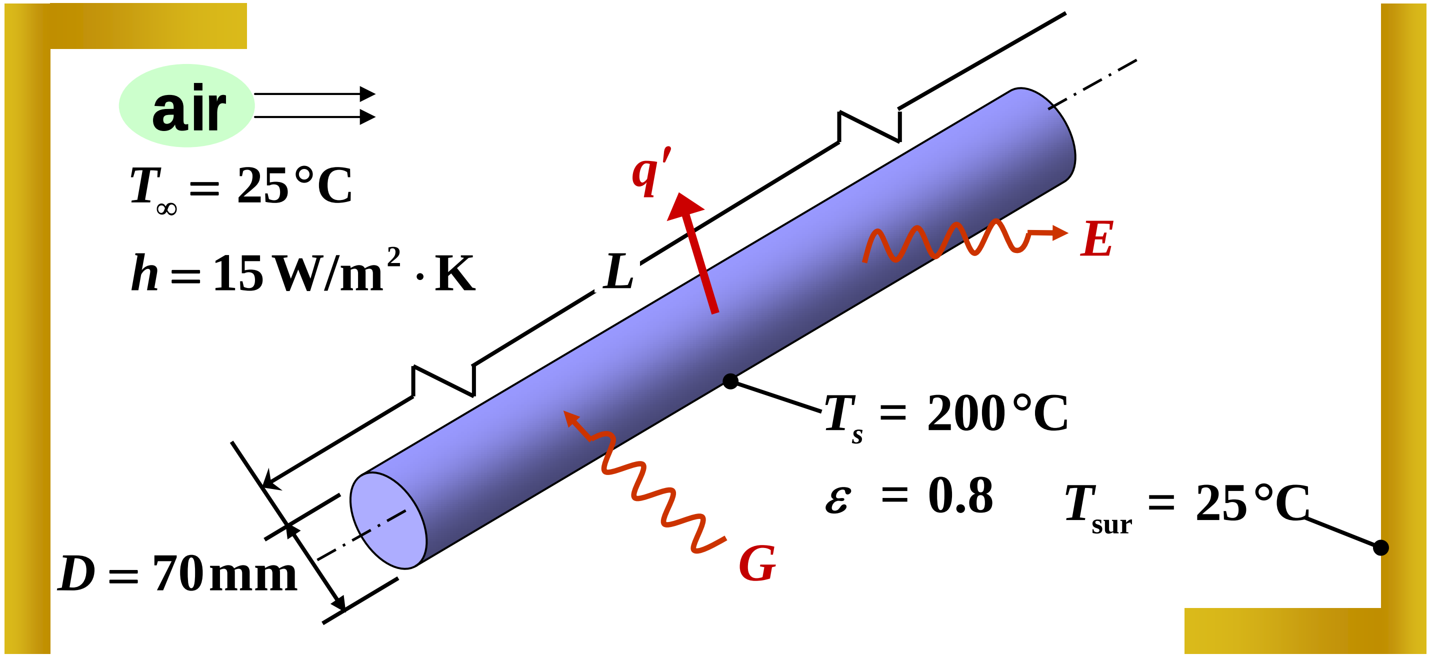
$$= h(\pi DL)\left(T_s - T_\infty\right) + \varepsilon(\pi DL)\sigma\left(T_s^4 - T_{sur}^4\right)$$

$$q' = \frac{q_{loss}}{L} = 15\ W/m^2 \cdot K\left(\pi \times 0.07\ m\right)\left(200 - 25\right)°C$$

$$+\ 0.8\left(\pi \times 0.07m\right)5.67 \times 10^{-8}\ W/m^2 \cdot K^4\left(473^4 - 298^4\right)\ K^4$$

$$= 577\ W/m + 421\ W/m = 998\ W/m$$

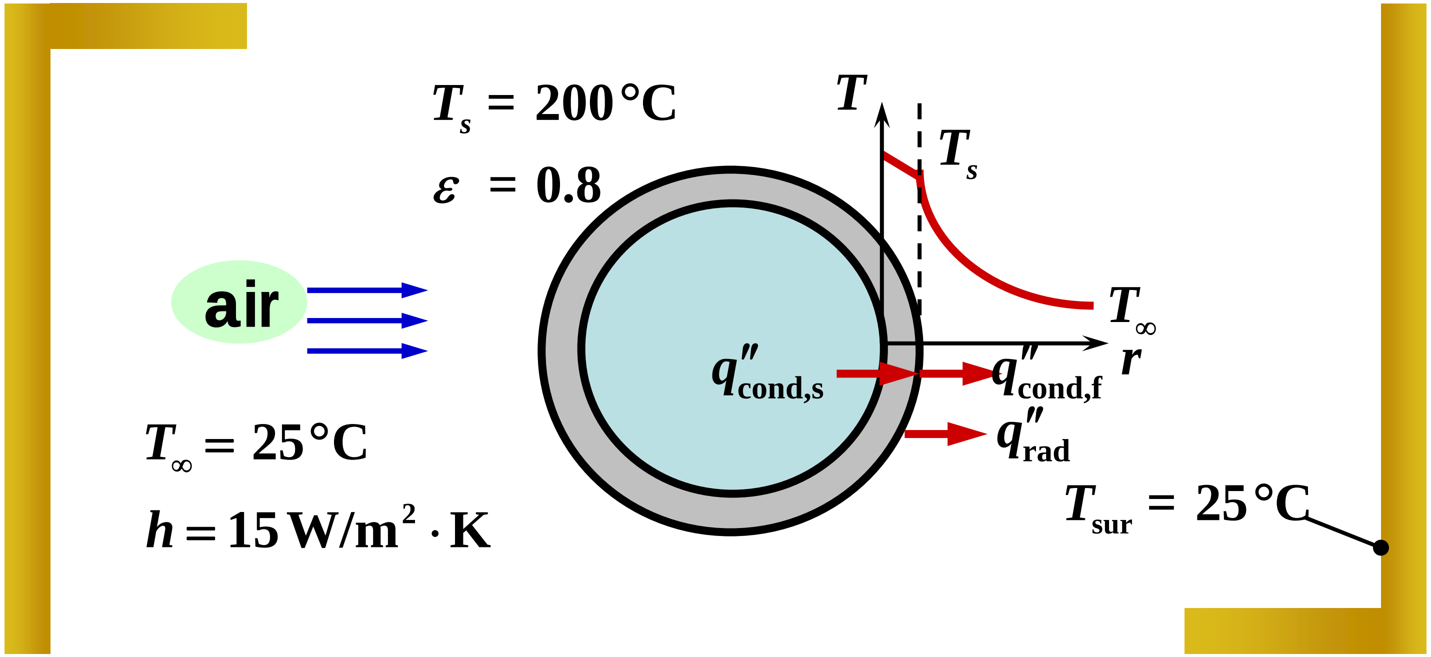
Example 1.2



$$q_{\text{loss}} = q_{\text{conv}} + q_{\text{rad}}$$

Q: Why not $q_{\text{loss}} = q_{\text{conv}} + q_{\text{rad}} + q_{\text{cond}}$ **?**

Conduction does not take place ?



$$q''_{loss} = q''_{cond,s} = q''_{cond,f} + q''_{rad}$$

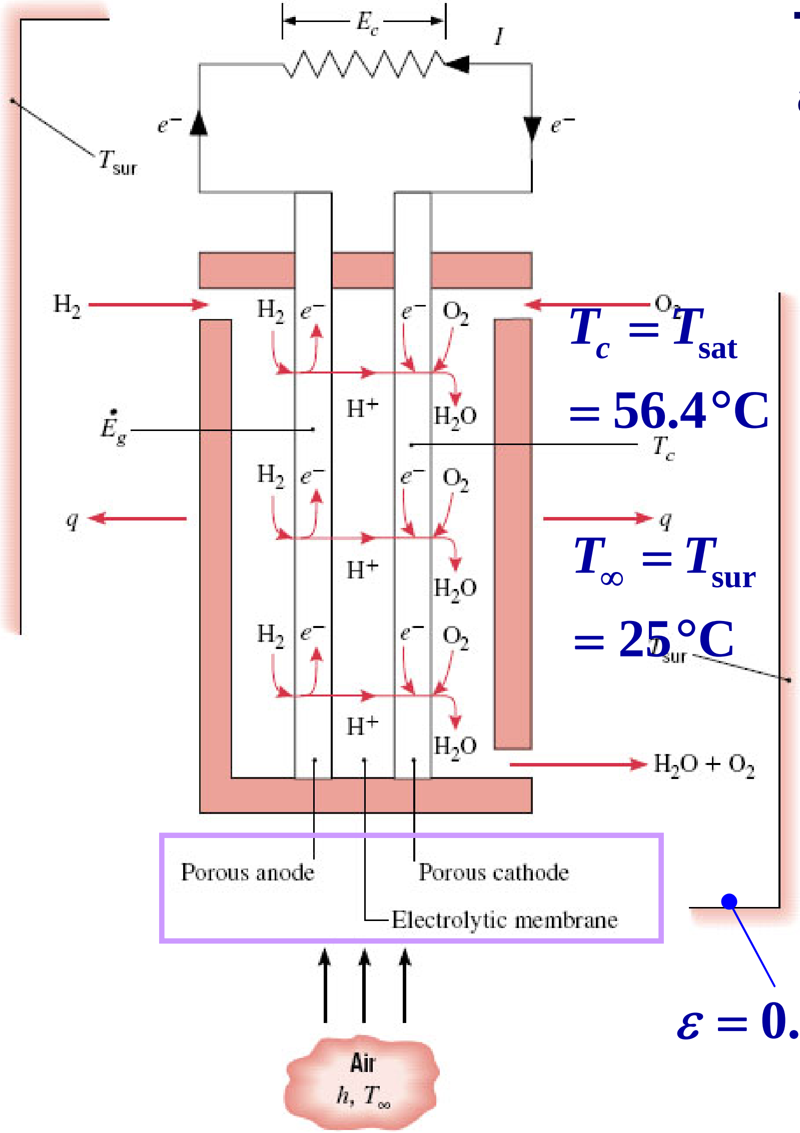
$$-k_s \left.\frac{dT}{dr}\right)_s = -k_f \left.\frac{dT}{dr}\right)_f + \varepsilon\sigma\left(T_s^4 - T_{sur}^4\right)$$

$$\equiv h\left(T_s - T_\infty\right) + \varepsilon\sigma\left(T_s^4 - T_{sur}^4\right)$$

$$q''_{loss} = q''_{conv} + q''_{rad}, \qquad q''_{cond,f} \equiv q''_{conv}$$

Example 1.4

Hydrogen-air Proton Exchange Membrane (PEM) fuel cell



$T_c = T_{sat} = 56.4°C$

$T_\infty = T_{sur} = 25°C$

$\varepsilon = 0.88$

$P = I \cdot E_c = 15\ [A] \times 0.6\ [V] = 9\ [W]$

Three-layer membrane electrode assembly (MEA)

Anode: (exothermic) $2H_2 \rightarrow 4H^+ + 4e^-$

Cathode: $O_2 + 4e^- + 4H^+ \rightarrow 2H_2O$

$$2H_2 + O_2 \rightarrow 2H_2O$$

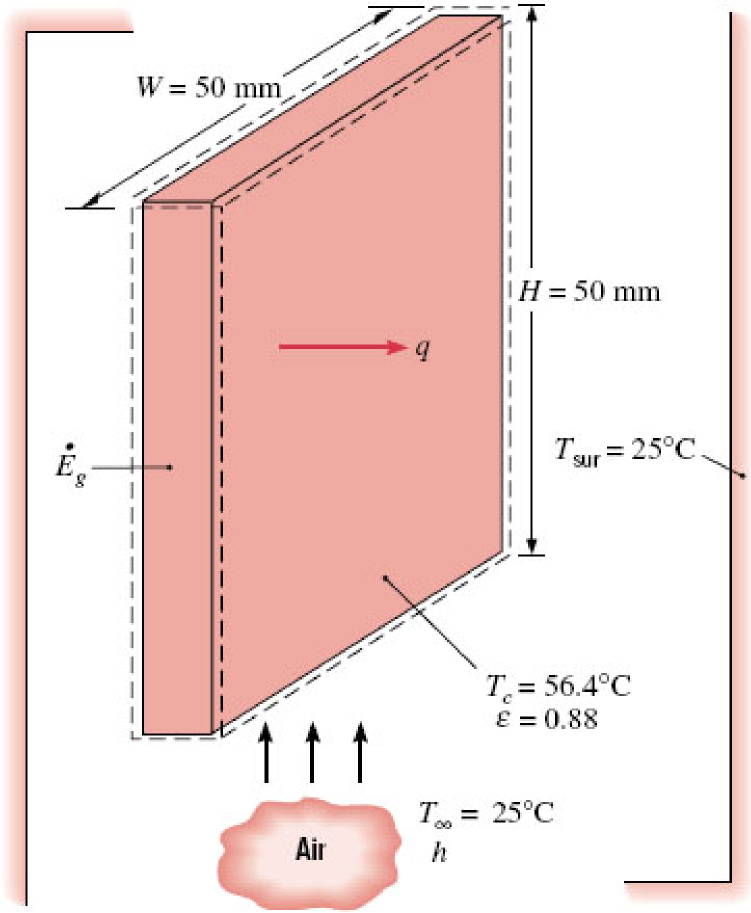
Role of Electrolytic membrane

1. transfer hydrogen ions
2. serve as a barrier to electron transfer

Membrane needs a moist state to conduct ions.
Liquid water in cathode: block oxygen from reaching cathode reaction site → need to control T_c

The convection heat coefficient, h

$$h = 10.9\ \mathrm{W \cdot s^{0.8} / m^{2.8} \cdot K} \times V^{0.8}$$



Find: The required cooling air velocity, V, needed to maintain steady state operation at T_c=56.4ºC.

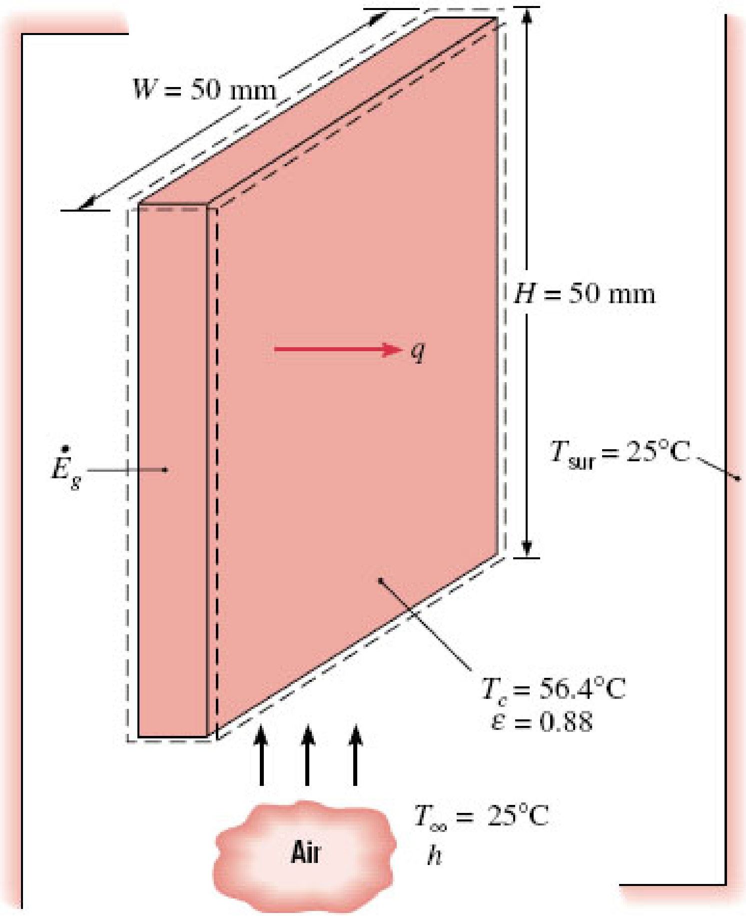
$$h = 10.9\ \mathrm{W \cdot s^{0.8} / m^{2.8} \cdot K} \times V^{0.8}$$

$$\dot{E}_g = 11.25\ \mathrm{W}$$

Assumptions:

1) Steady-state conditions
2) Negligible temperature variations within the fuel cell
3) Large surroundings
4) Insulated edge of fuel cell
5) Negligible energy flux by the gas or liquid flows

Energy balance on the fuel cell



$$\cancel{E}_{\text{in}} + E_{\text{g}} - E_{\text{out}} = \Delta \cancel{E}_{\text{st}}$$

$$\dot{E}_{\text{g}} = \dot{E}_{\text{out}} = q_{\text{conv}} + q_{\text{rad}}$$

$$\dot{E}_{\text{g}} = 11.25\,\text{W} = q_{\text{conv}} + q_{\text{rad}}$$

$$q_{\text{conv}} = hA\left(T_c - T_\infty\right)$$

$$q_{\text{conv}} = \dot{E}_{\text{g}} - q_{\text{rad}}$$

$$q_{\text{rad}} = \varepsilon A \sigma\left(T_c^4 - T_{\text{sur}}^4\right)$$

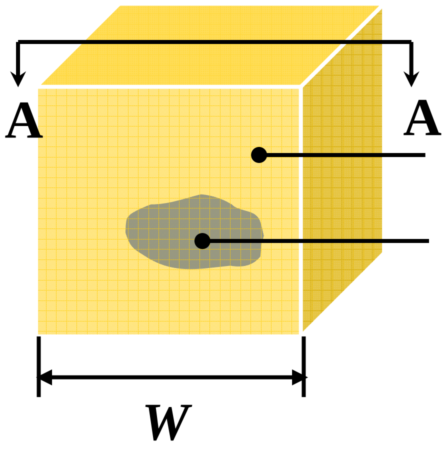
$$hA\left(T_c - T_\infty\right) = \dot{E}_g - \varepsilon A \sigma\left(T_c^4 - T_{\text{sur}}^4\right)$$

$$h = 10.9\ \text{W}\cdot\text{s}^{0.8}/\text{m}^{2.8}\cdot\text{K} \times V^{0.8}$$

$$= \frac{\dot{E}_{\text{g}} - \varepsilon A \sigma\left(T_c^4 - T_{\text{sur}}^4\right)}{A\left(T_c - T_\infty\right)}$$

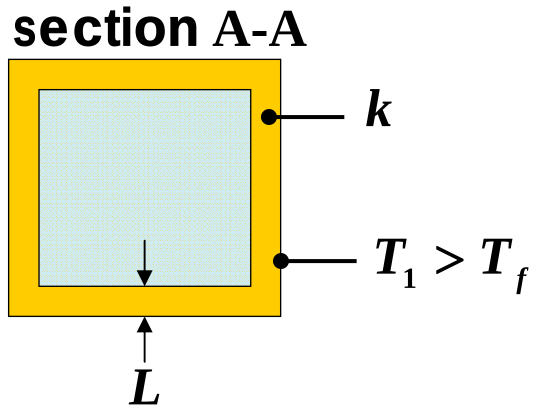
$$V = 9.4\ \text{m/s}$$

Example 1.5



cubical cavity

ice of mass M at the fusion temperature $T_f = 0°\mathrm{C}$

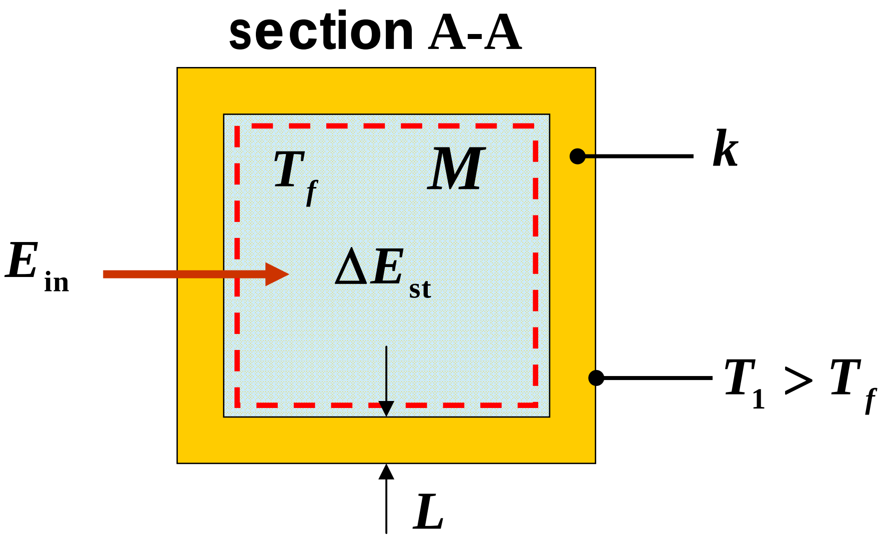


Find:

Expression for time needed to melt the ice, t_m

Assumptions:

1) Inner surface of wall is at T_f through the process.
2) Constant properties
3) Steady-states, 1-D conduction through each wall
4) Conduction area of one wall = $W^2 (L << W)$



$$E_{\text{in}} + \cancel{E_{\text{g}}} - \cancel{E_{\text{out}}} = \Delta E_{\text{st}}$$

$$E_{\text{in}} = \Delta E_{\text{st}}$$

$$E_{\text{in}} = q_{\text{cond}} \cdot t_m$$

$$\Delta E_{\text{st}} = M h_{sf}$$

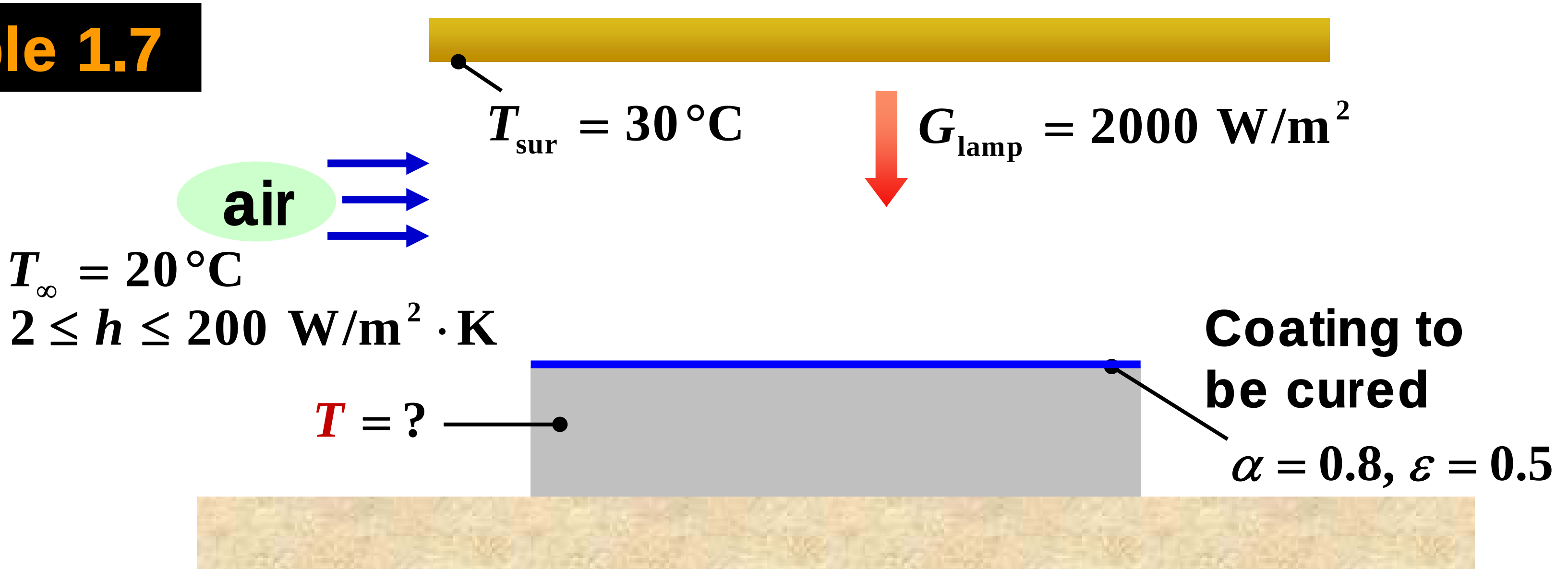
h_{sf} : latent heat of fusion

$$q_{\text{cond}} = kA\frac{T_1 - T_f}{L} = k\left(6W^2\right)\frac{T_1 - T_f}{L}$$

$$\left[6kW^2\frac{T_1 - T_f}{L}\right] t_m = M h_{sf}$$

$$t_m = \frac{M h_{sf} L}{6kW^2\left(T_1 - T_f\right)}$$

Example 1.7

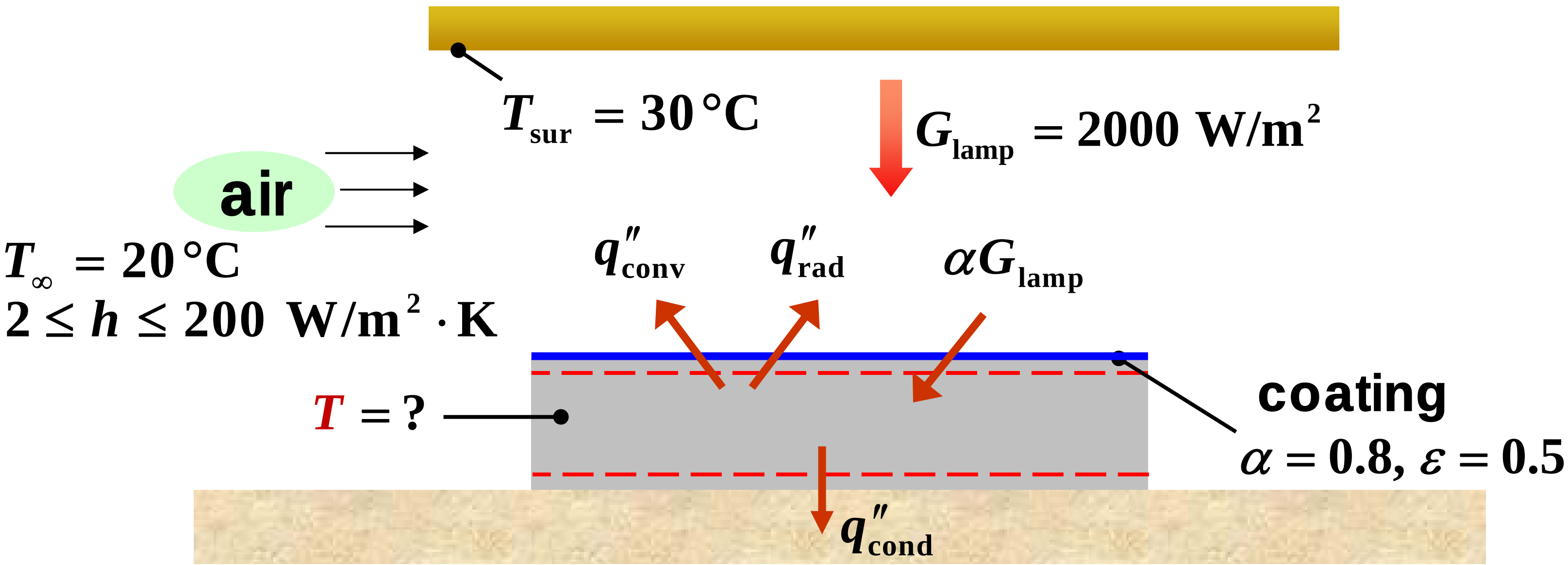


Find:

1) Cure temperature T for $h = 15\,W/m^2 \cdot K$
2) Effect of air flow on the cure temperature for $2 \le h \le 200\ W/m^2 \cdot K$
   Value of h for which the cure temperature is $50°C$.

Assumptions:

1) Steady-state conditions
2) Negligible heat loss from back surface of plate
3) Plate is very thin and a small object in large surroundings, coating absorptivity $\alpha = \varepsilon = 0.5$ w.r.t. irradiation from the surroundings



$$\dot{E}_{in} + \cancel{\dot{E}_g} - \dot{E}_{out} = \cancel{\dot{E}_{st}} \;\rightarrow\; \dot{E}_{in} = \dot{E}_{out}$$

$$\dot{E}_{in} = \alpha G_{lamp}$$

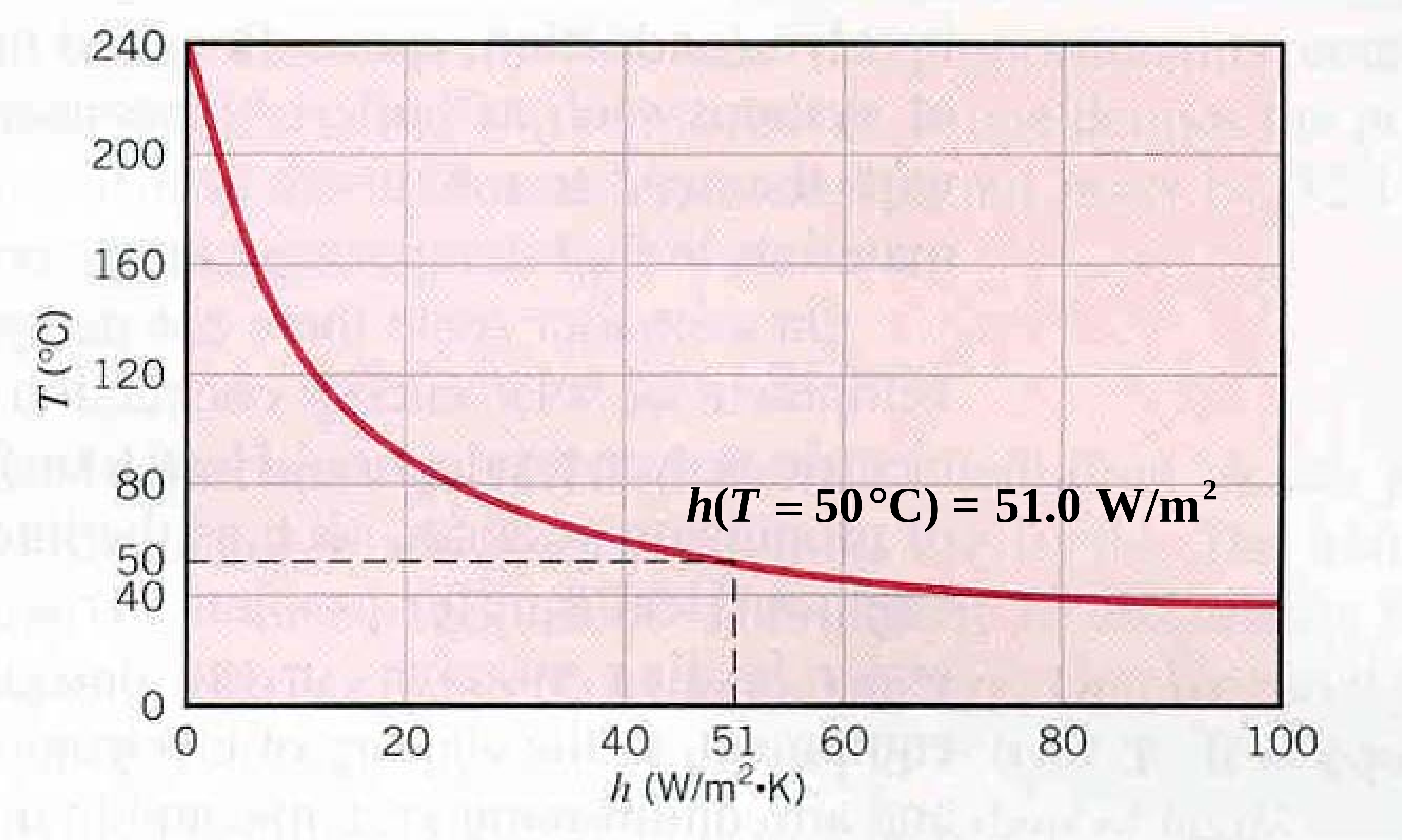
$$\dot{E}_{out} = q''_{conv} + q''_{rad} + \cancel{q''_{cond}} = h\left(T - T_\infty\right) + \varepsilon\sigma\left(T^4 - T_{sur}^4\right)$$

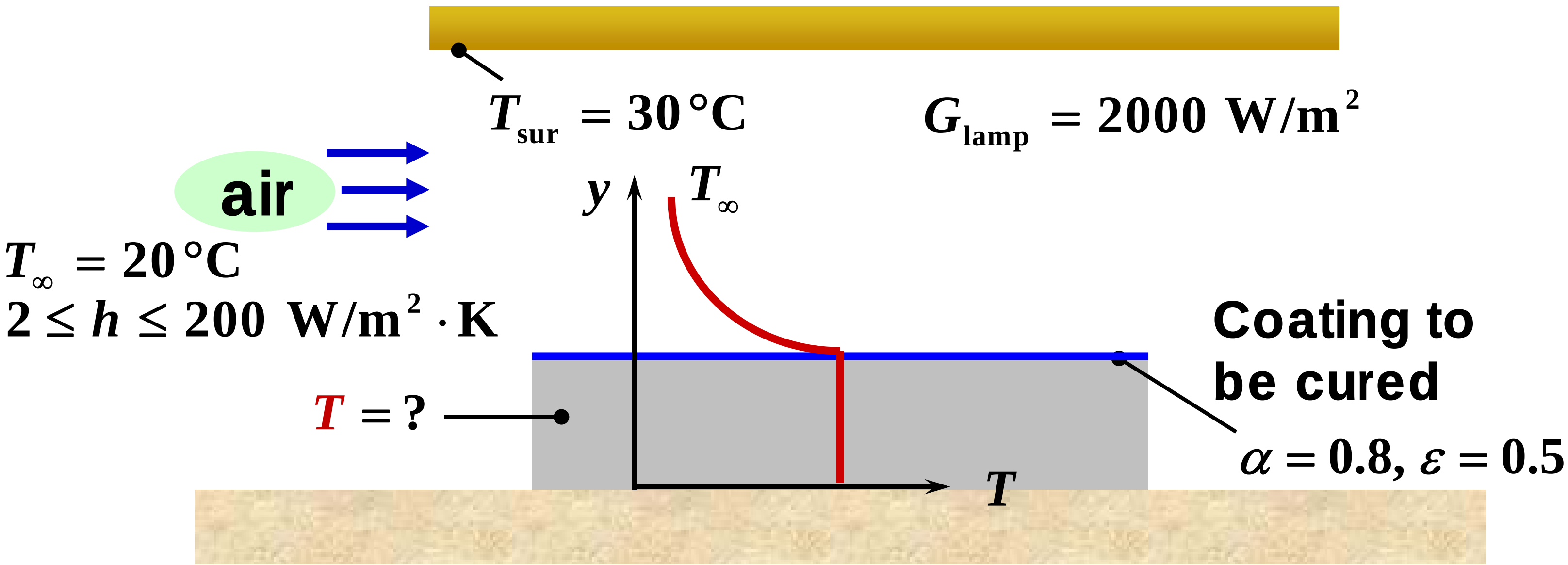
$$\alpha G_{lamp} = h\left(T - T_\infty\right) + \varepsilon\sigma\left(T^4 - T_{sur}^4\right)$$

$$h = 15\,\mathrm{W/m^2 \cdot K}$$

$$T = 377\ \mathrm{K} = 104\ °\mathrm{C}$$

$$2 \le h \le 200\ \mathrm{W/m^2 \cdot K}$$





$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}, \quad \dot{E}_{\text{in}} = \alpha G_{\text{lamp}}$$

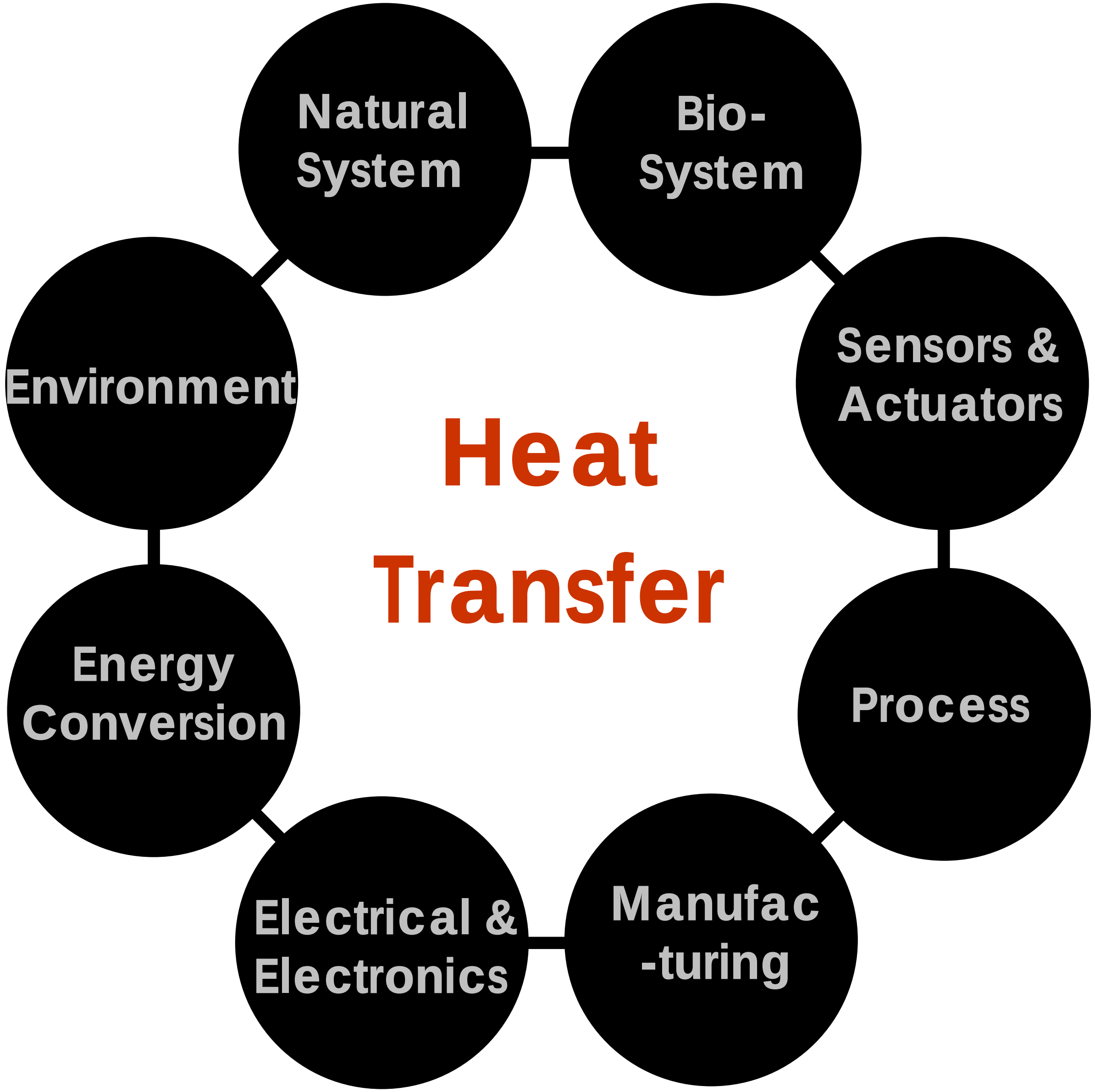
$$\dot{E}_{\text{out}} = q''_{\text{cond,f}} + q''_{\text{rad}} = -k_f \left.\frac{dT}{dr}\right)_f + \varepsilon\sigma\left(T^4 - T_{\text{sur}}^4\right)$$

$$q''_{\text{cond,s}} = 0$$

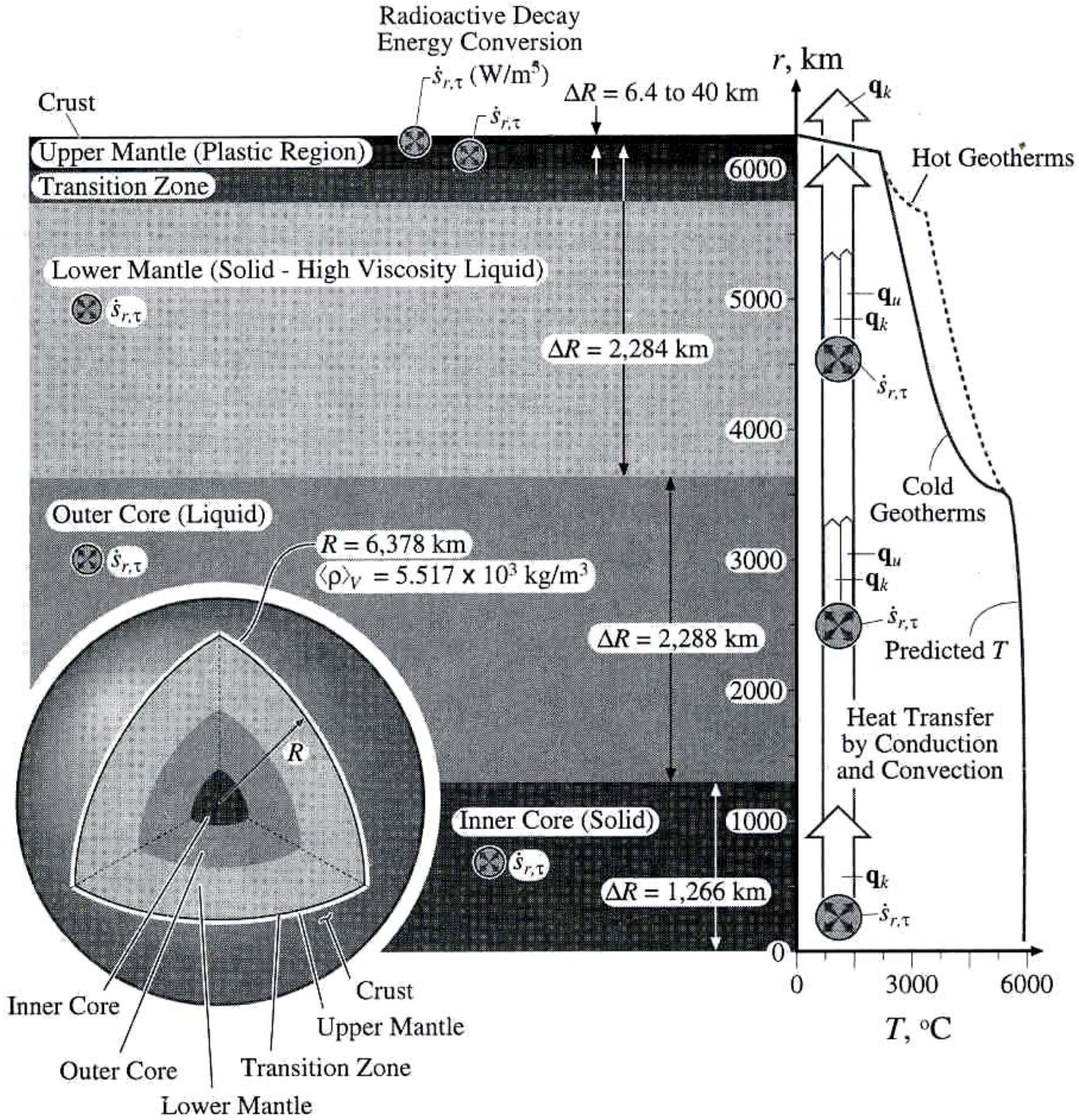
$$\equiv h\left(T - T_\infty\right) + \varepsilon\sigma\left(T^4 - T_{\text{sur}}^4\right)$$

$$= q''_{\text{conv}} + q''_{\text{rad}}$$

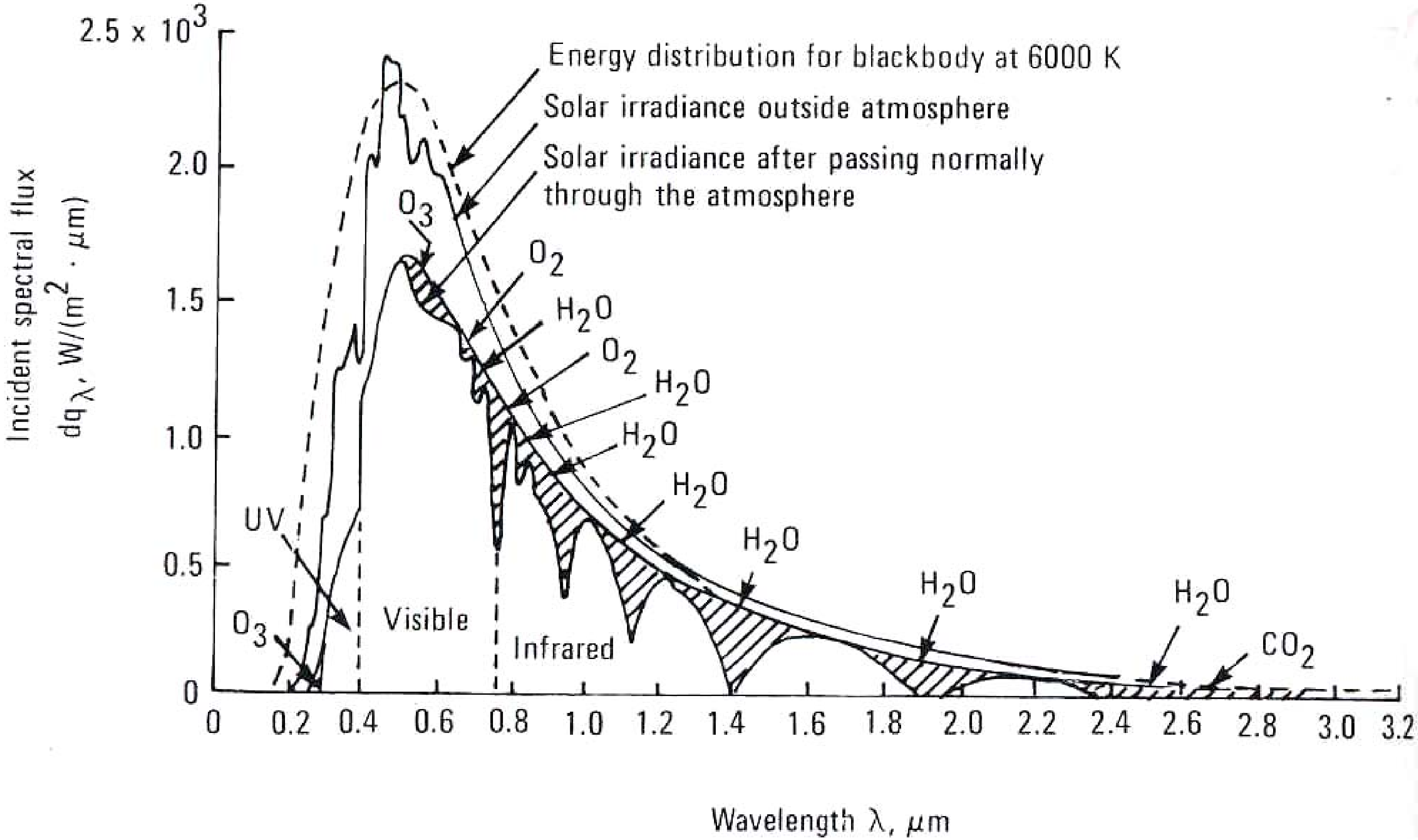
WHY HEAT TRANSFER ?



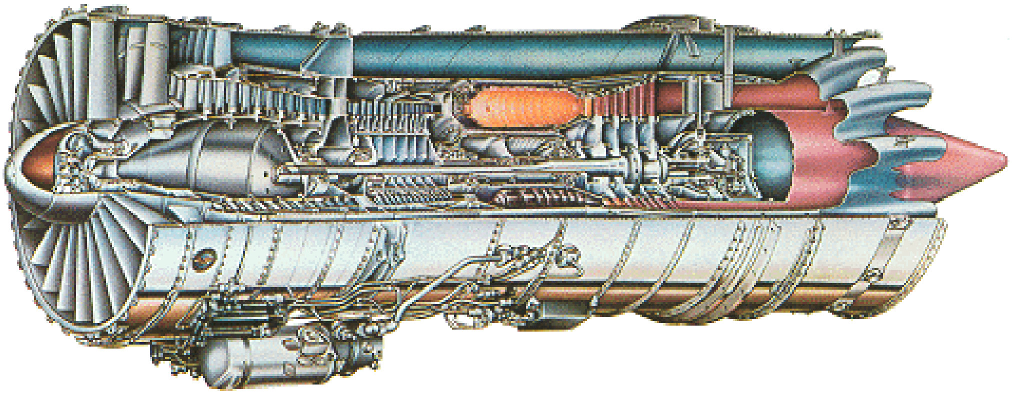
Natural System / Temperature Distribution in the Earth



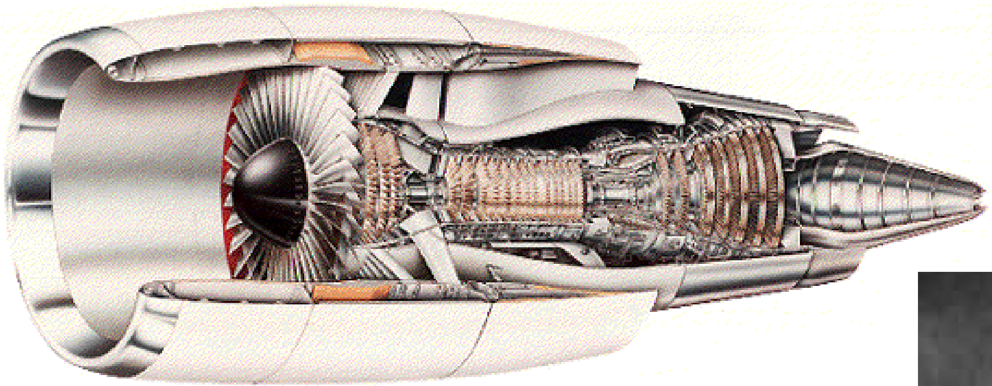
Environment / Solar Radiation



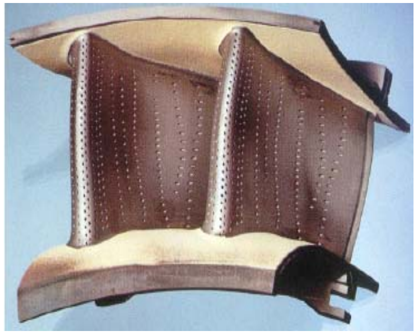
Energy Conversion / Gas Turbine Engine



JT8D

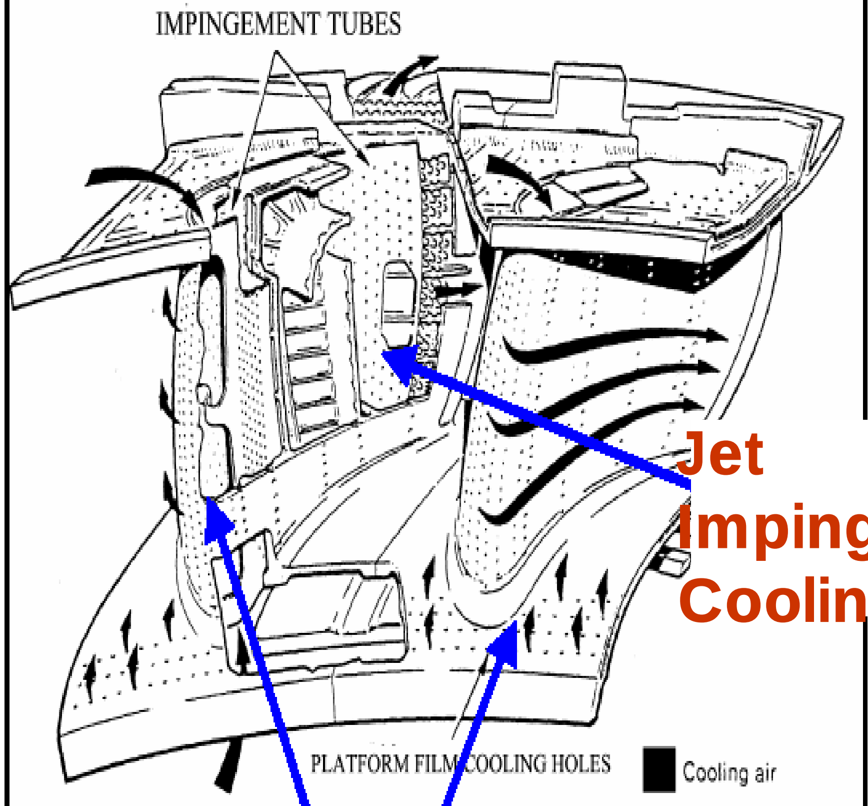


CF6

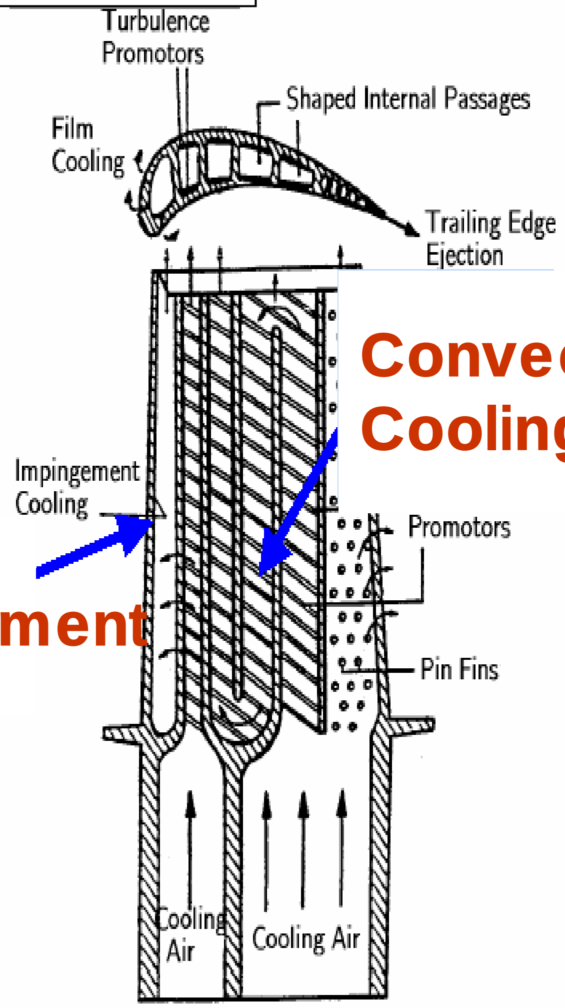


Energy Conversion / Gas Turbine Blade Cooling

Stator



Rotor



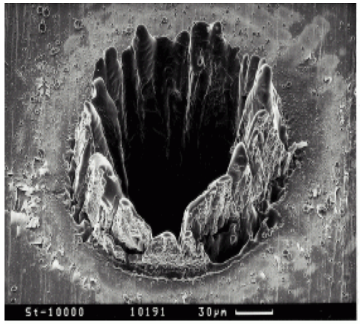
Jet Impingement Cooling

Convection Cooling

Film Cooling

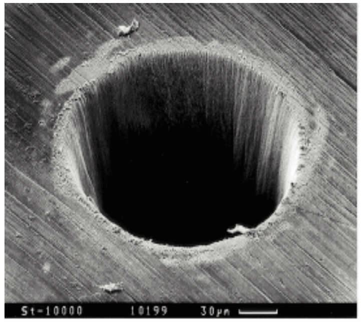
Manufacturing / Ultra-Short Pulse Laser Material Processing

ns Machining Process



4.2 J/cm^2 @ 3.3 ns

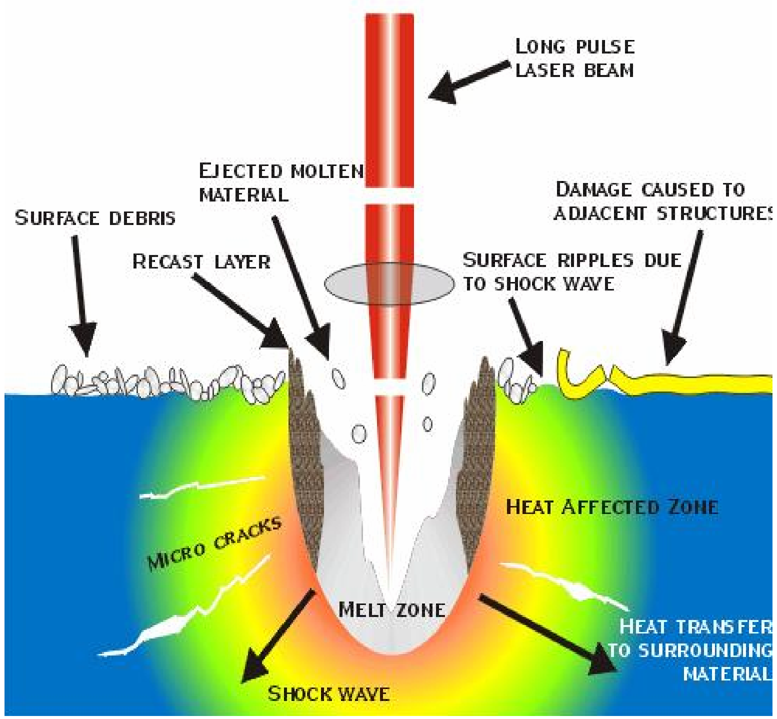
fs Machining Process

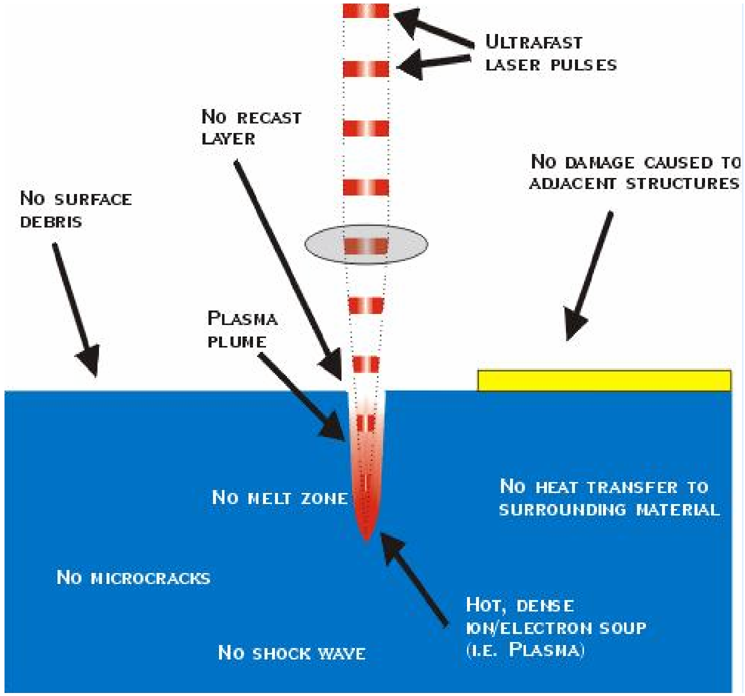


0.5 J/cm^2 @ 200 fs

Steel foil

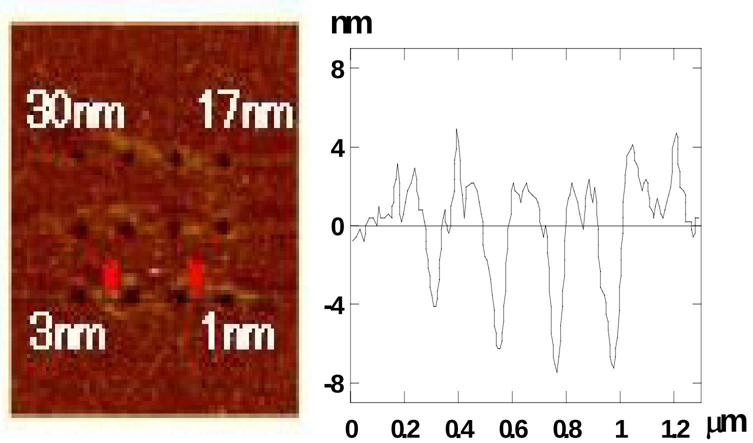
100μm in thickness



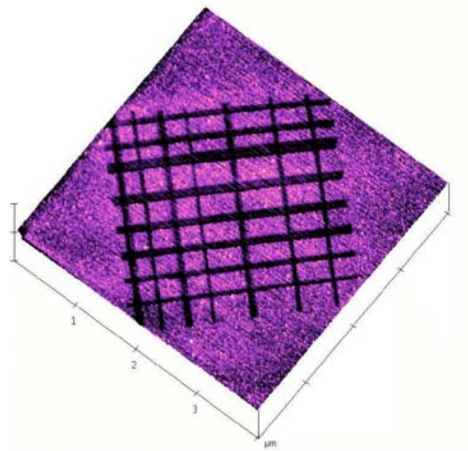


Manufacturing / Nano-Machining

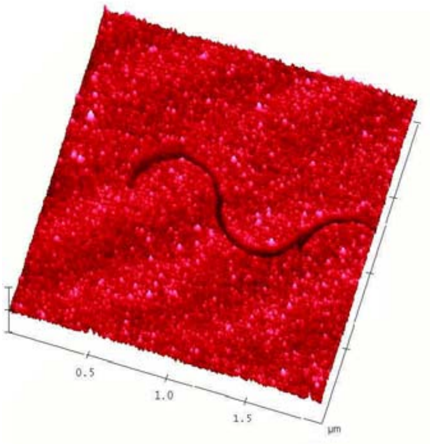
Atomic Force Microscope + Near Field Optics (Grigoroporos, UC Berkeley)



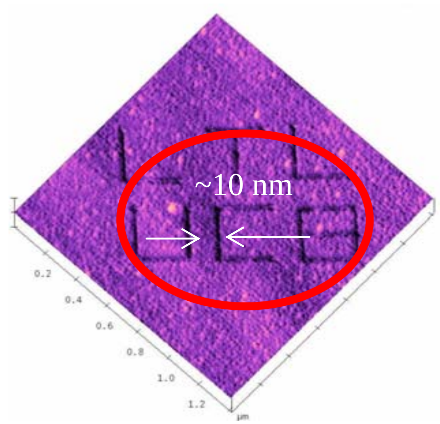
Nanodots



Nanogrids



Nanocurves



Nano-lithography/machining

Bio-System

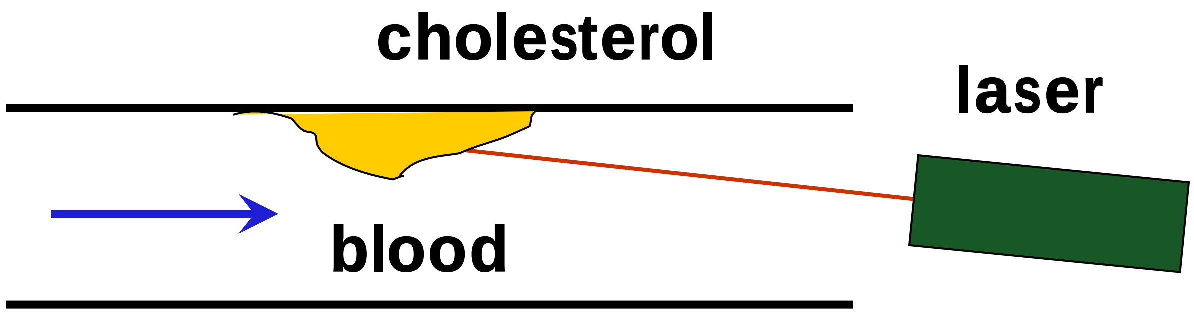
Cryo-Preservation

Adiabatic demagnetization technique

Paramagnetic salt

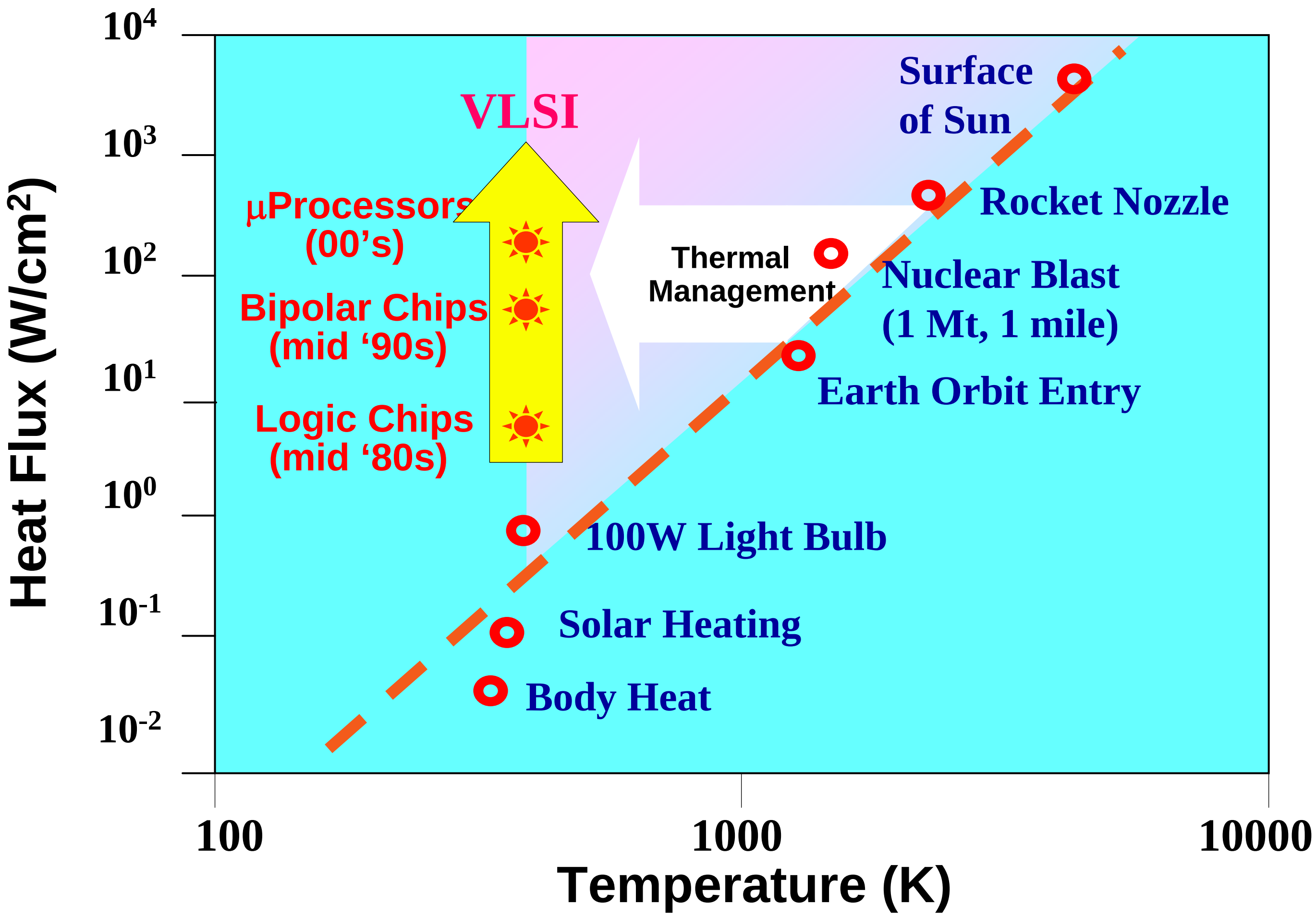
$T = 10^{-5}$ K

Laser Surgery



Blood vessel

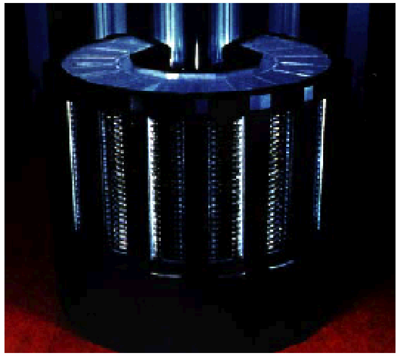
Electrical & Electronics / Thermal Management



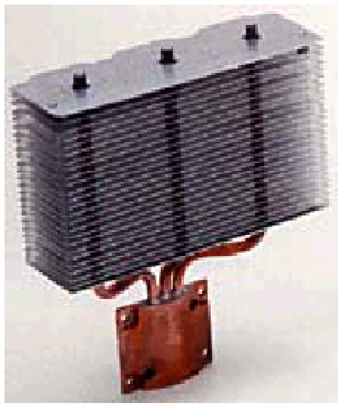
- local heat flux of 200-300 W/cm^2, today
- equivalent to that of 1 Mt nuclear blast at 1 mile from ground zero
- only one order of magnitude less than the sun

Electrical & Electronics / Cooling Techniques

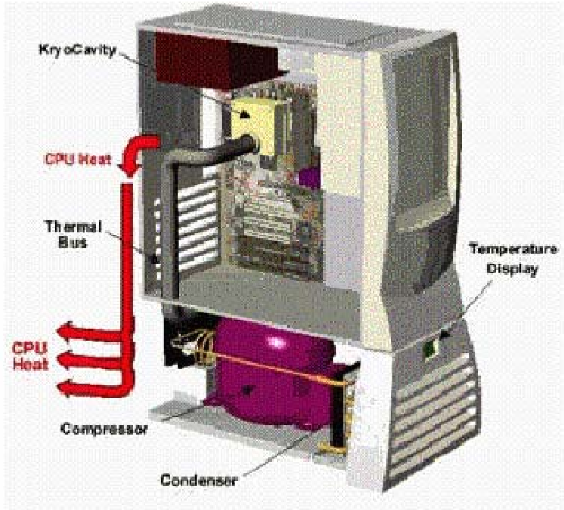
Direct Immersion



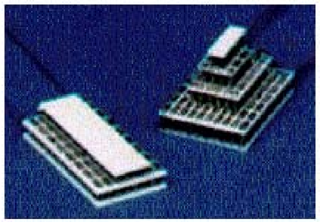
Heat Pipes



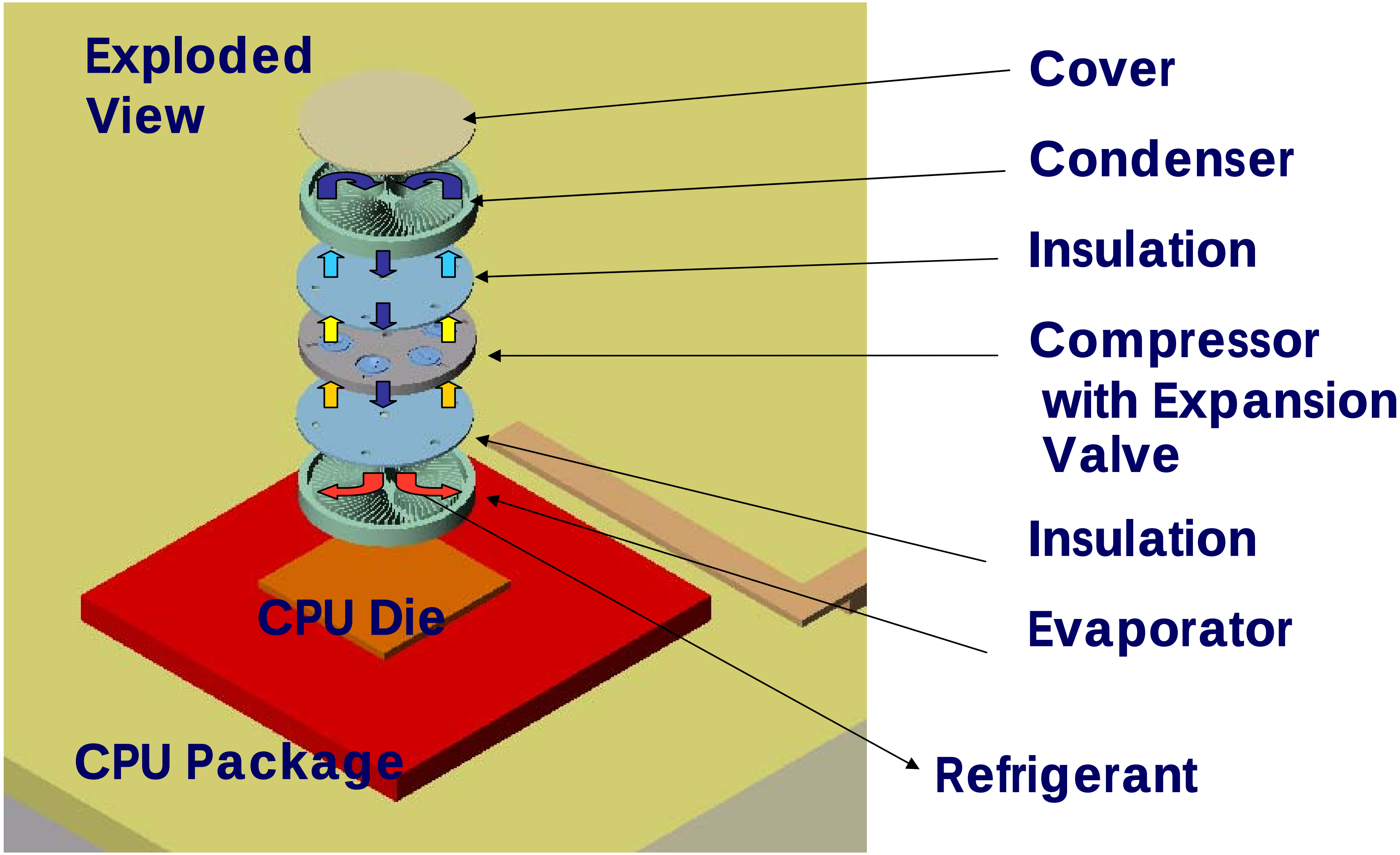
Refrigeration Cooling



Thermoelectric Coolers (TEC)

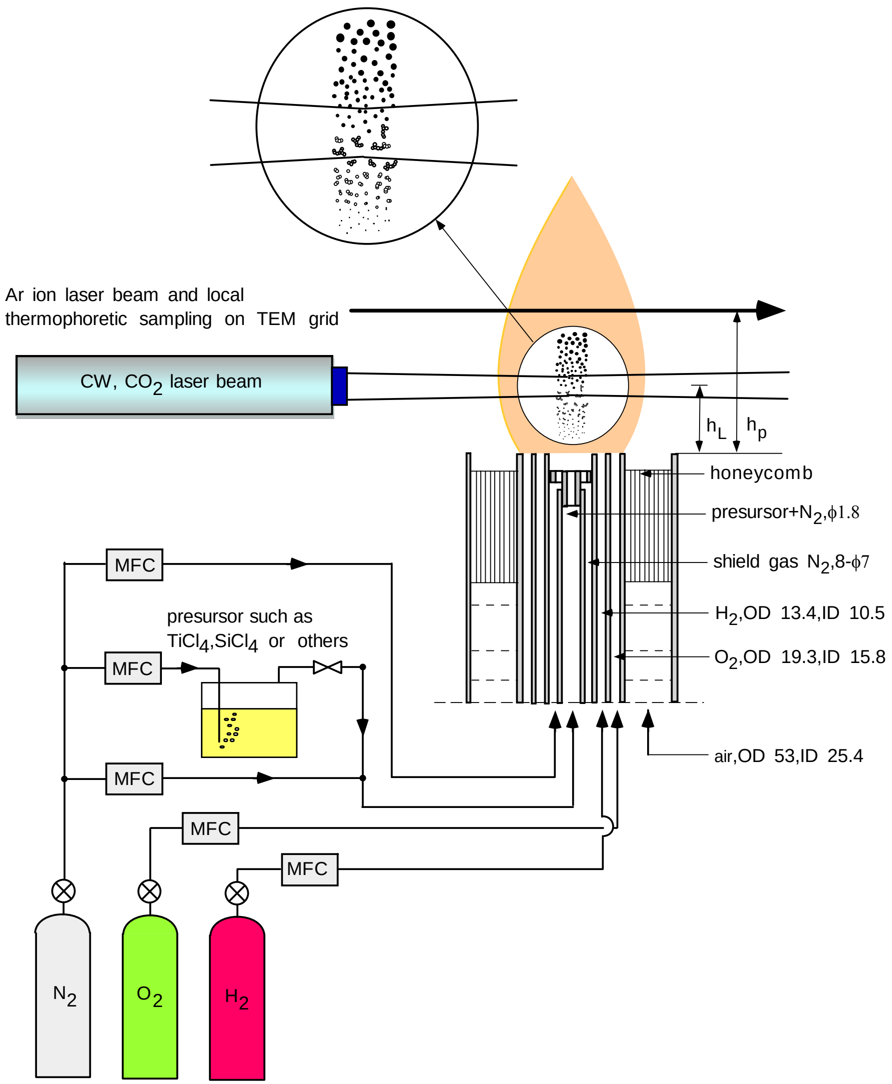


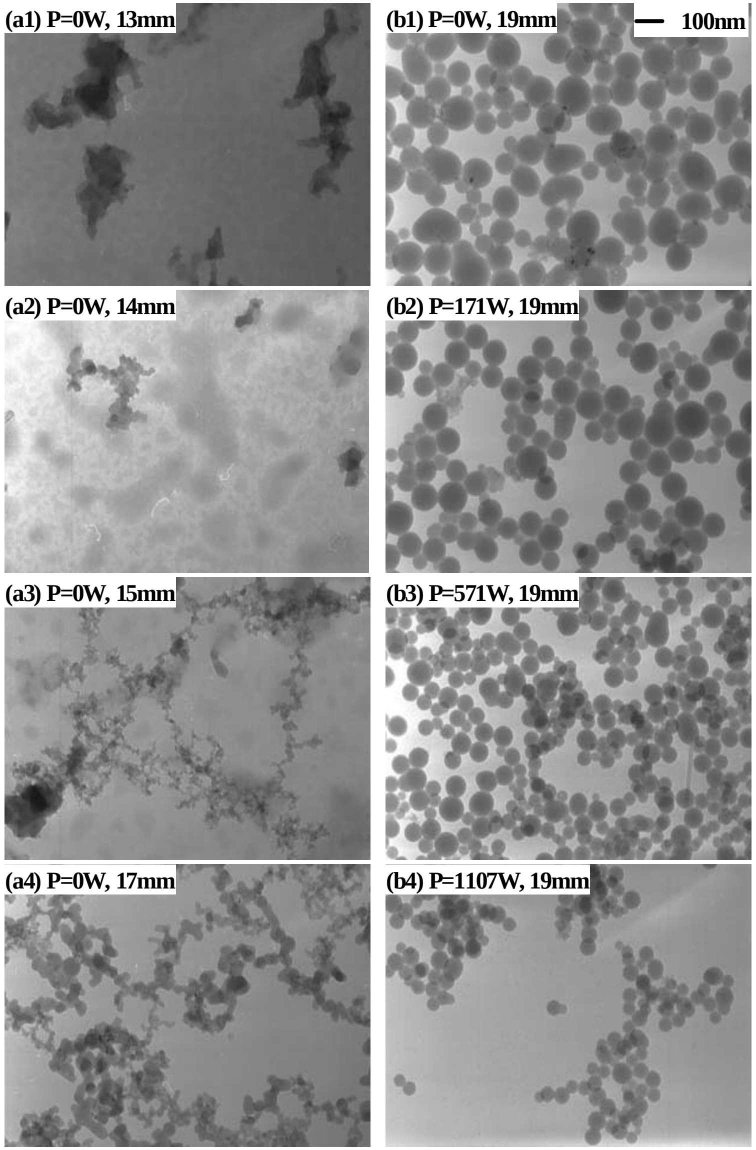
Electrical & Electronics / Micro Cooler



Process / Nanoparticle Control Principle

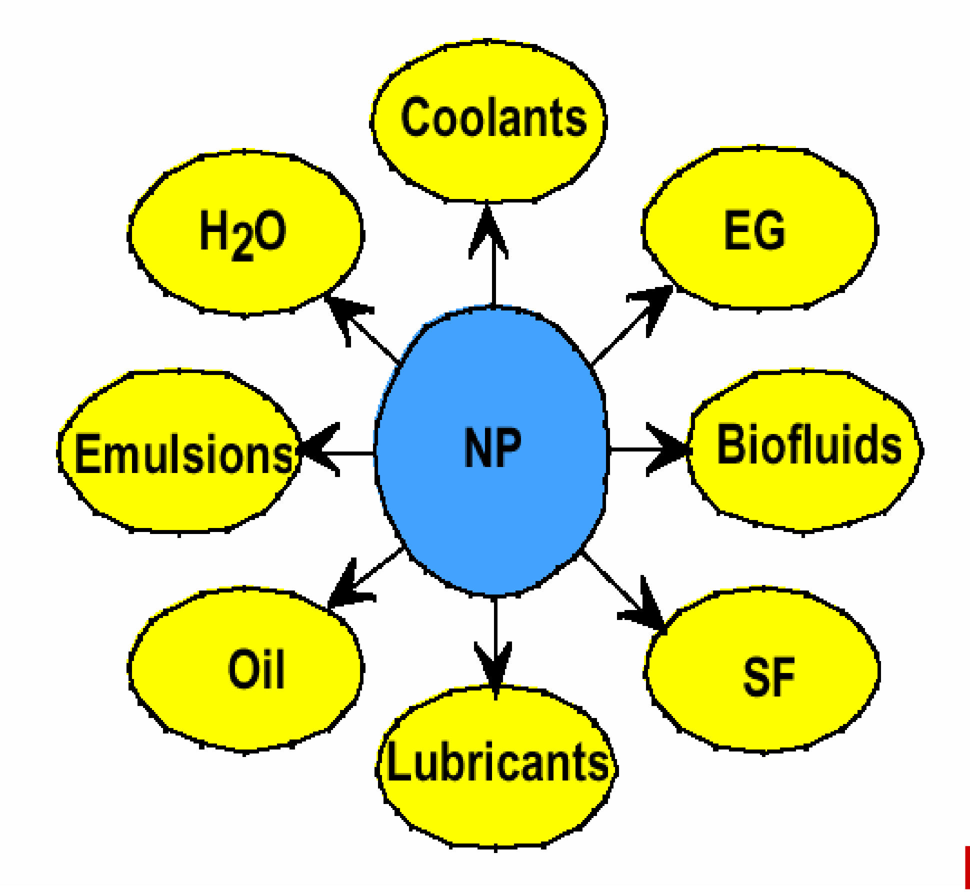
(M. Choi, SNU)





Process / Nanofluids

(Argonne National Lab., USA)



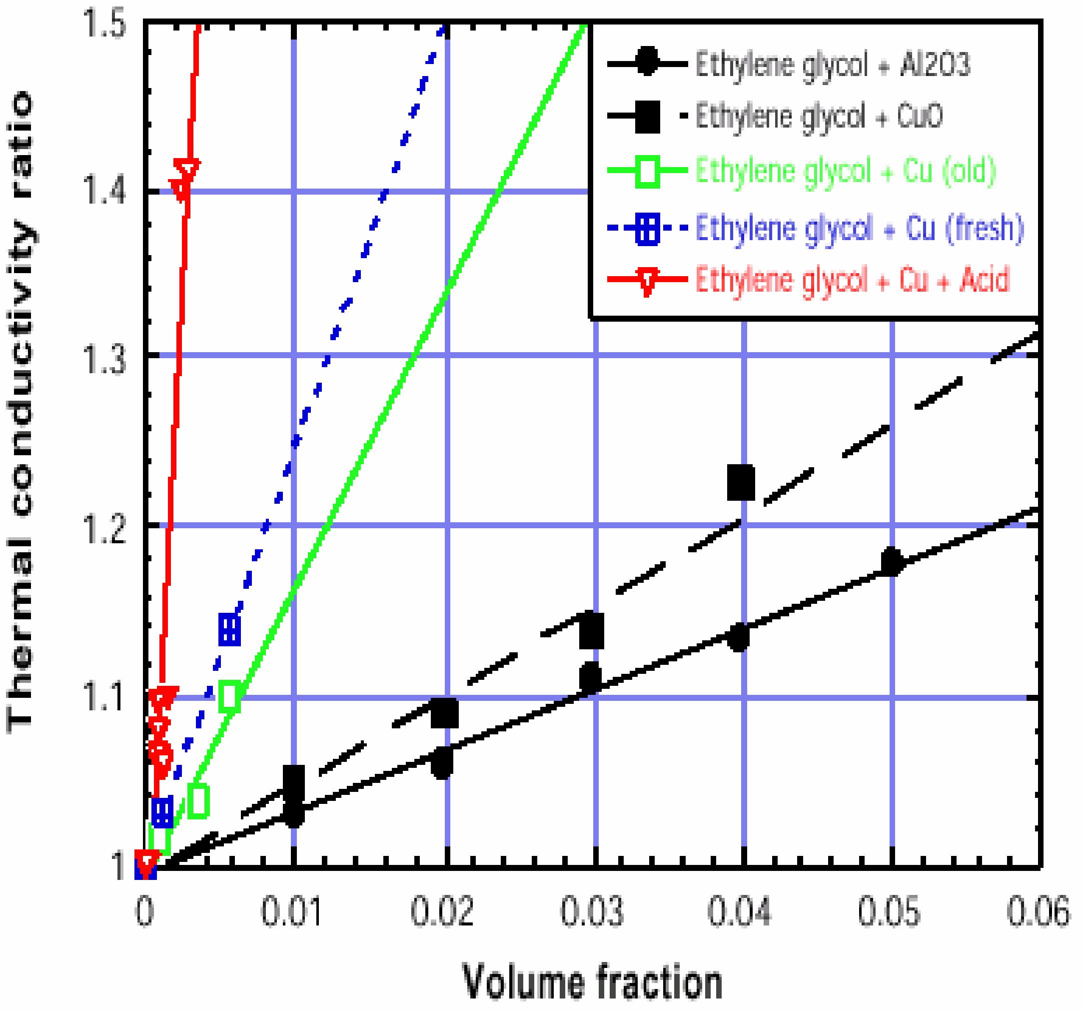
- Size dependent physical properties: color, conductivity
- Large surface area: 3 orders of magnitude greater than microfluids
- Surface structure: ~20% of atoms near the surface

Problem:

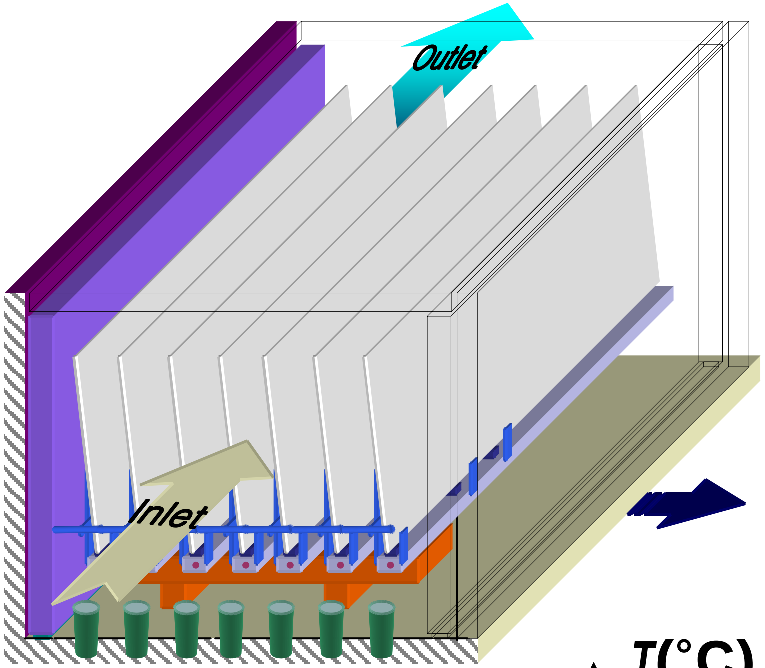
rapid setting

agglomeration

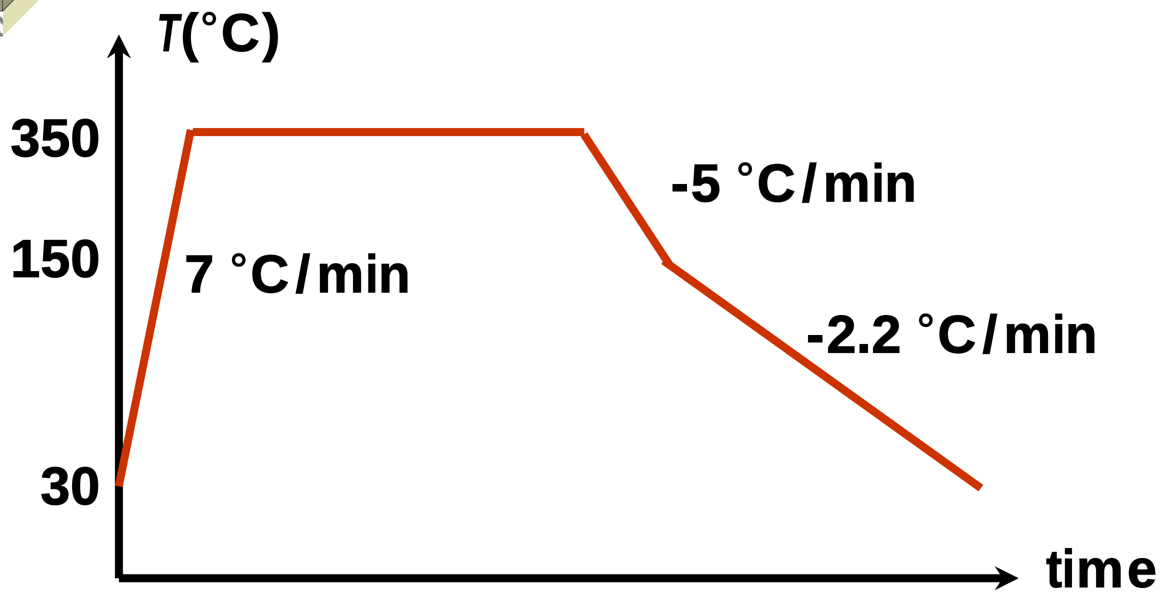
Process / Thermal Conductivity of Nanofluids



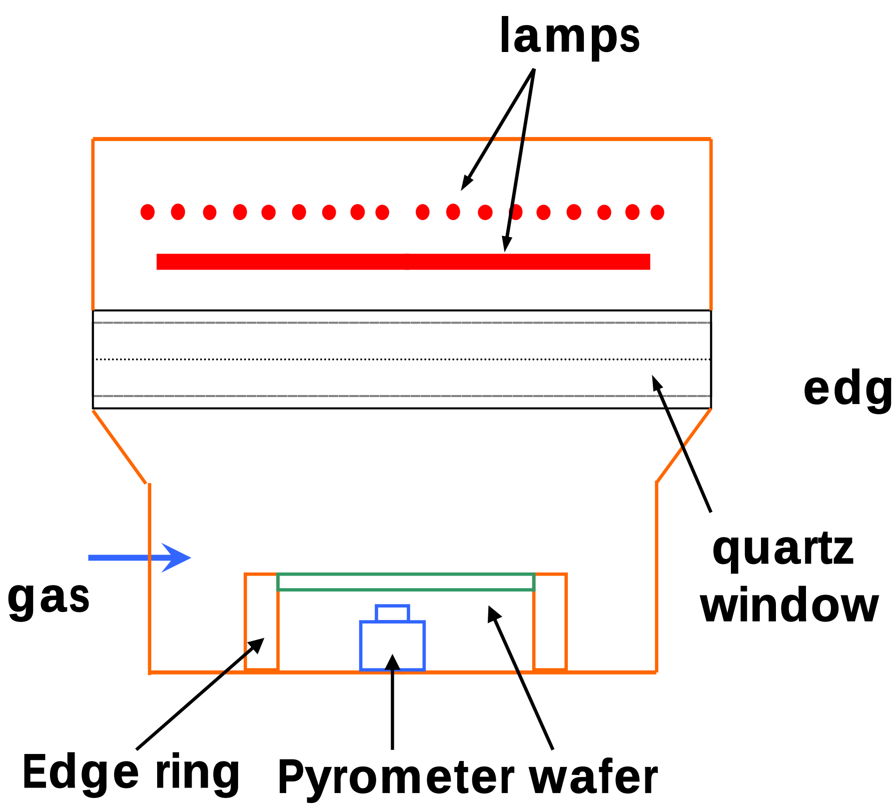
Process / PDP Thermal Process

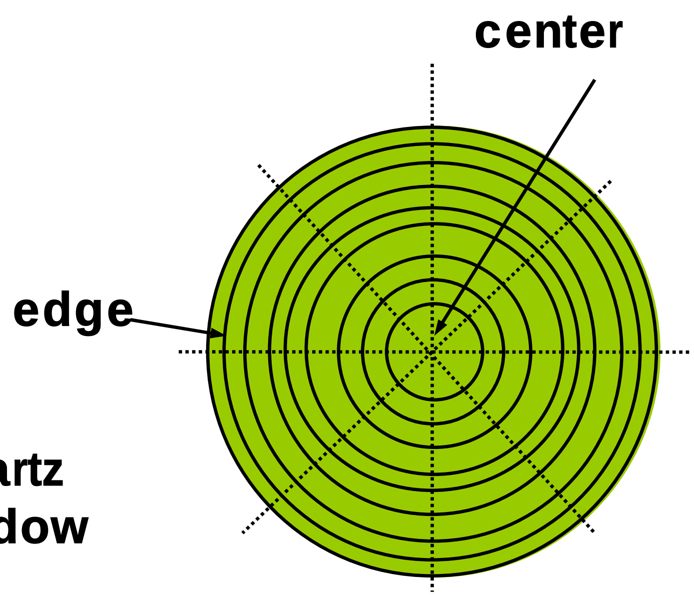


Process Propagation



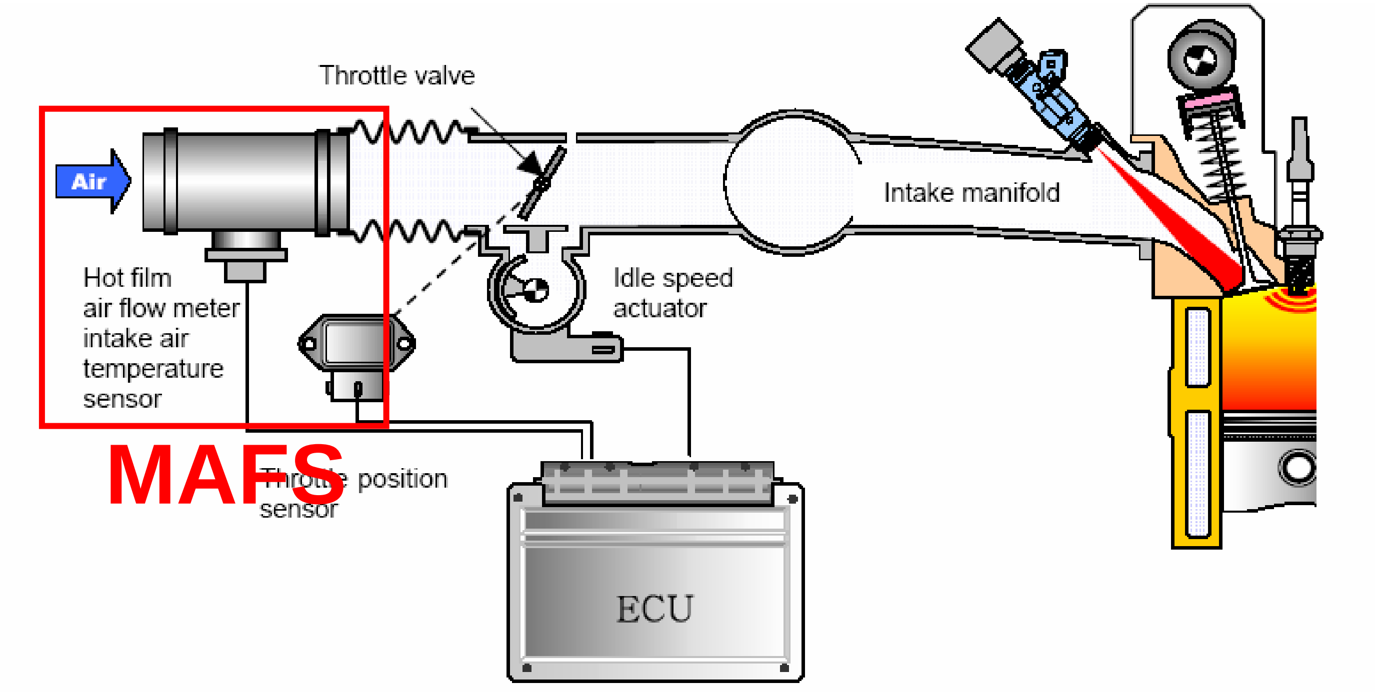
Process / Rapid Thermal Processing (RTP) System



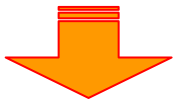


wafer grid & sensor point

Sensors & Actuators / Micro Thermal Flow Sensor

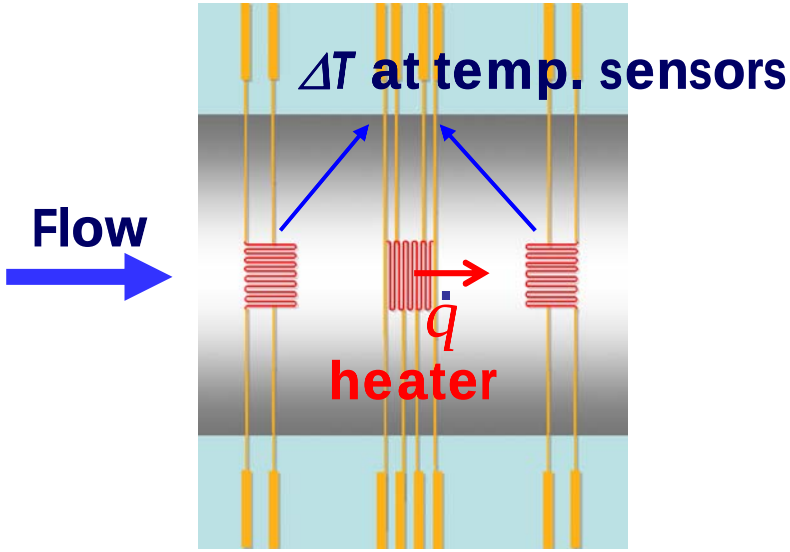


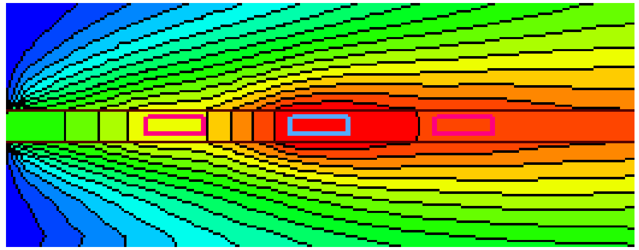
Low emission, High performance
Electronic gasoline injection control



Need precise A/F ratio control
Better Air flow sensor

Sensors & Actuators / Micro Thermal Flow Sensor





$$\dot{q} = \dot{m} c_p \Delta T$$

Mass flow rate

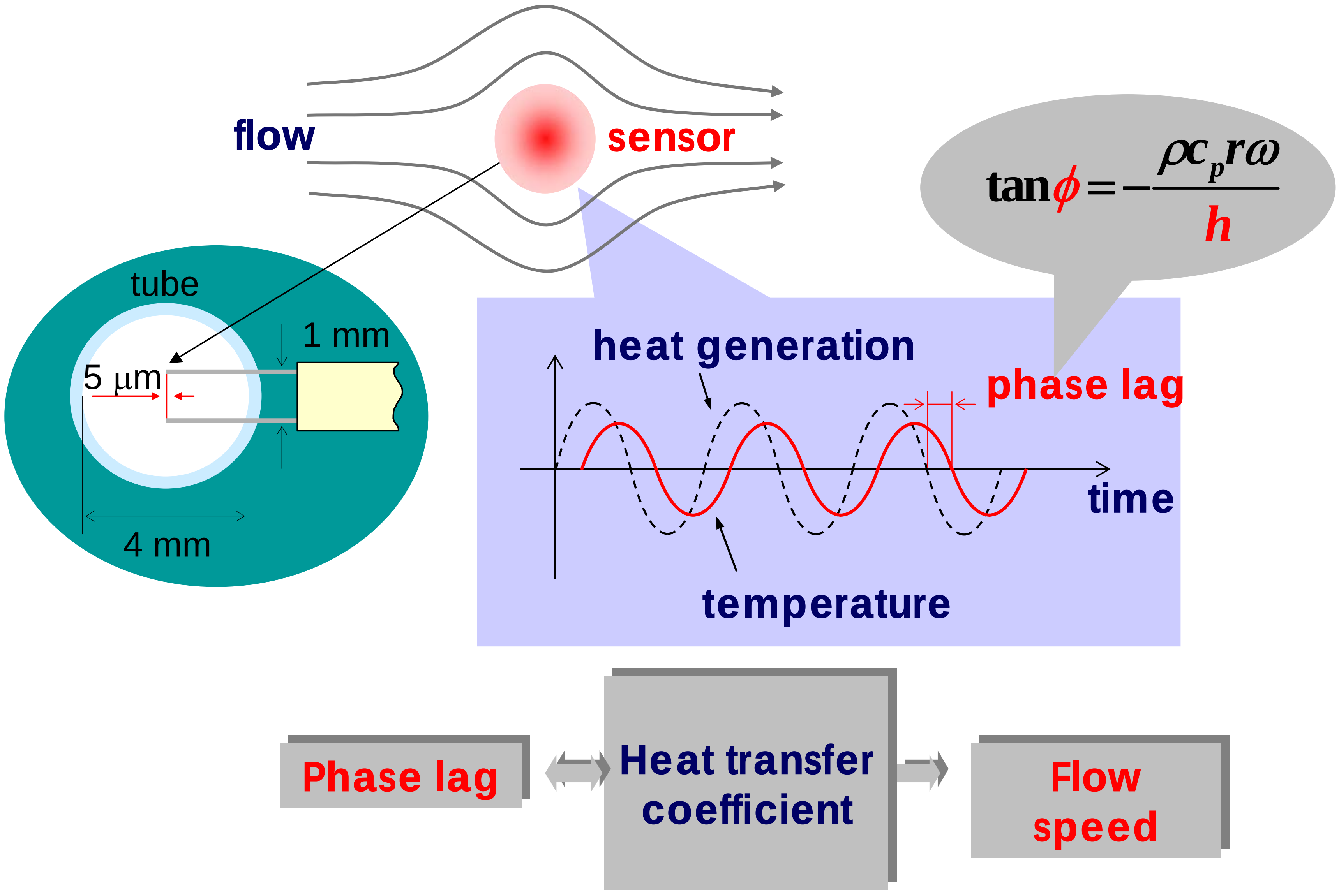
Characteristics

- Independent to inlet pressure, temperature variations
- Sensitive, precise, low power consuming…

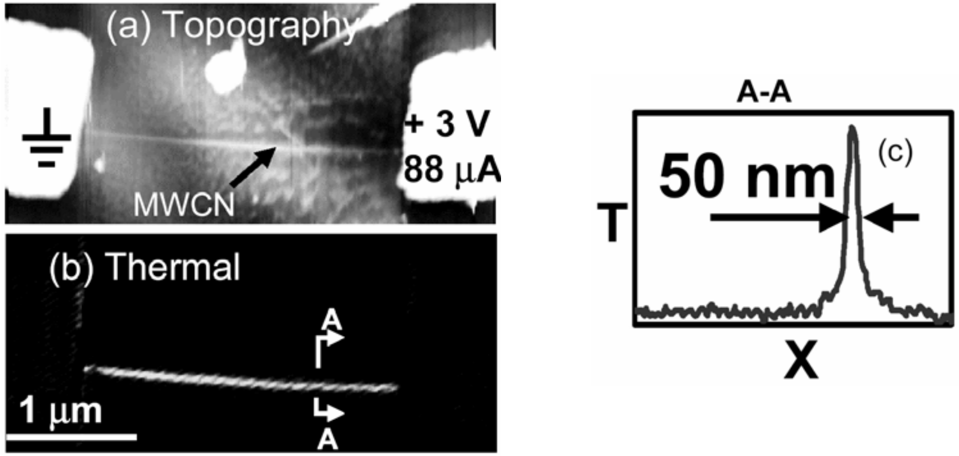
Considerations

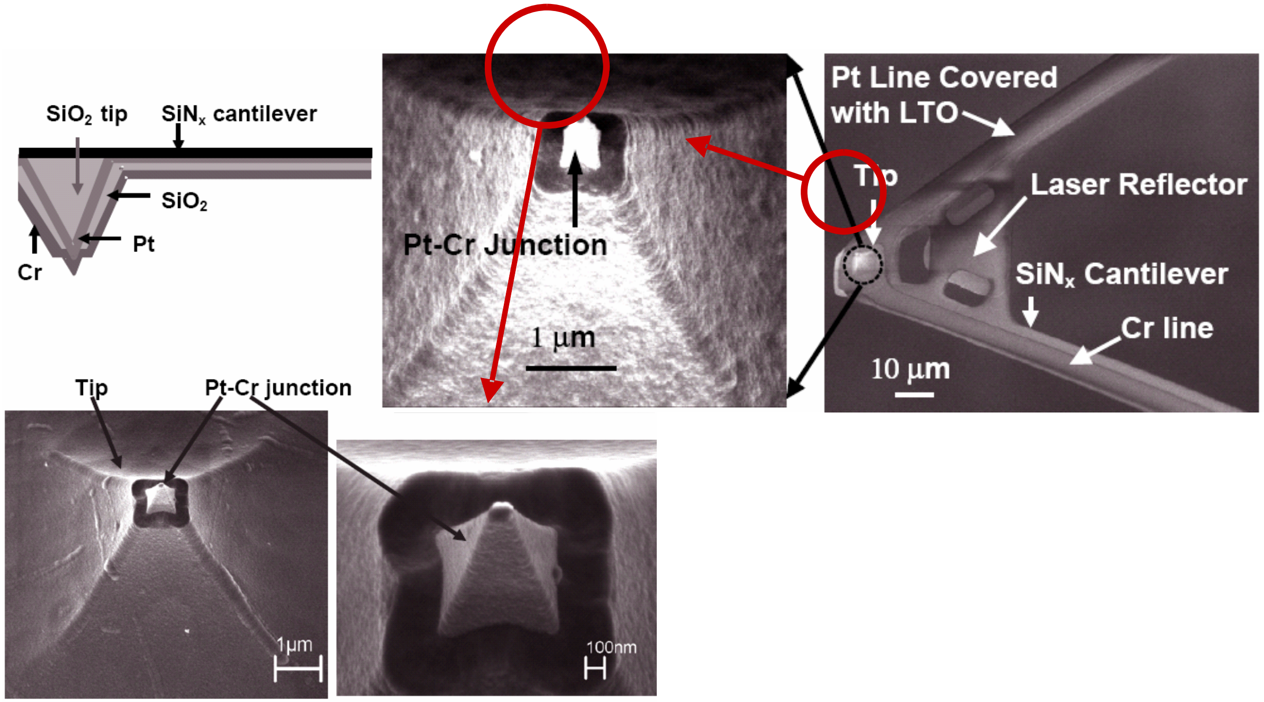
- Conduction, convection heat transfer between substrate and fluid
- Sensor / heater array shape and material
- Transient heating

Sensors & Actuators / Tunable AC Thermal Anemometry



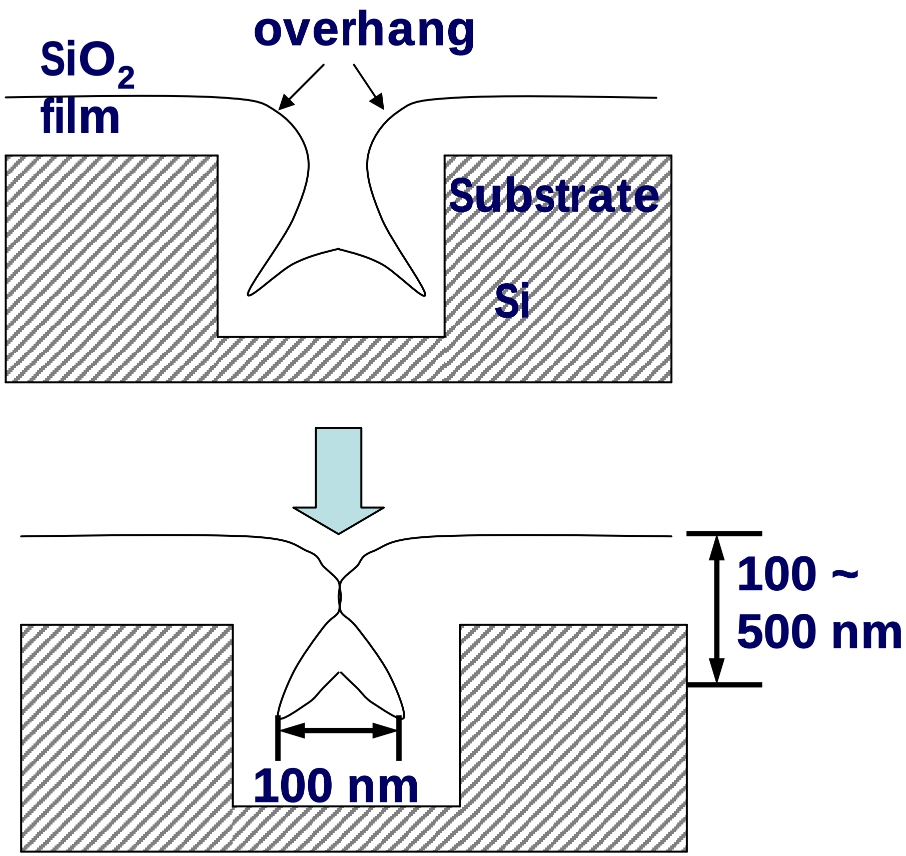
Sensors & Actuators / Scanning Thermal Microscope

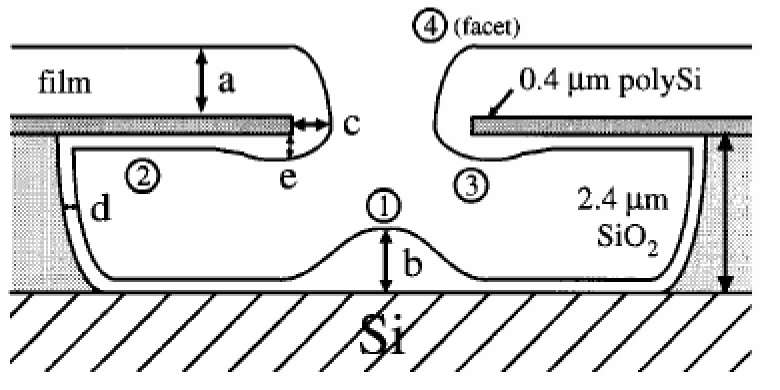


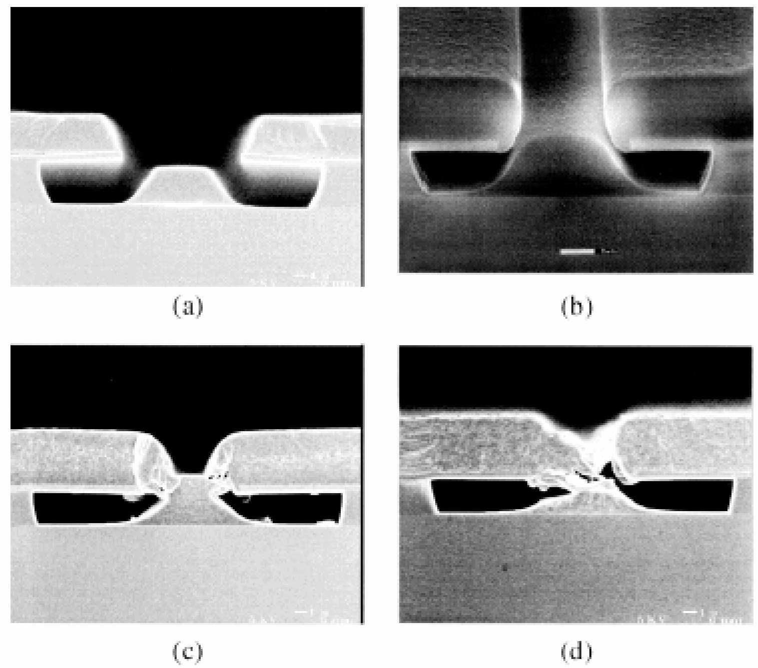


Sub-surface Thermal Image – Overhang

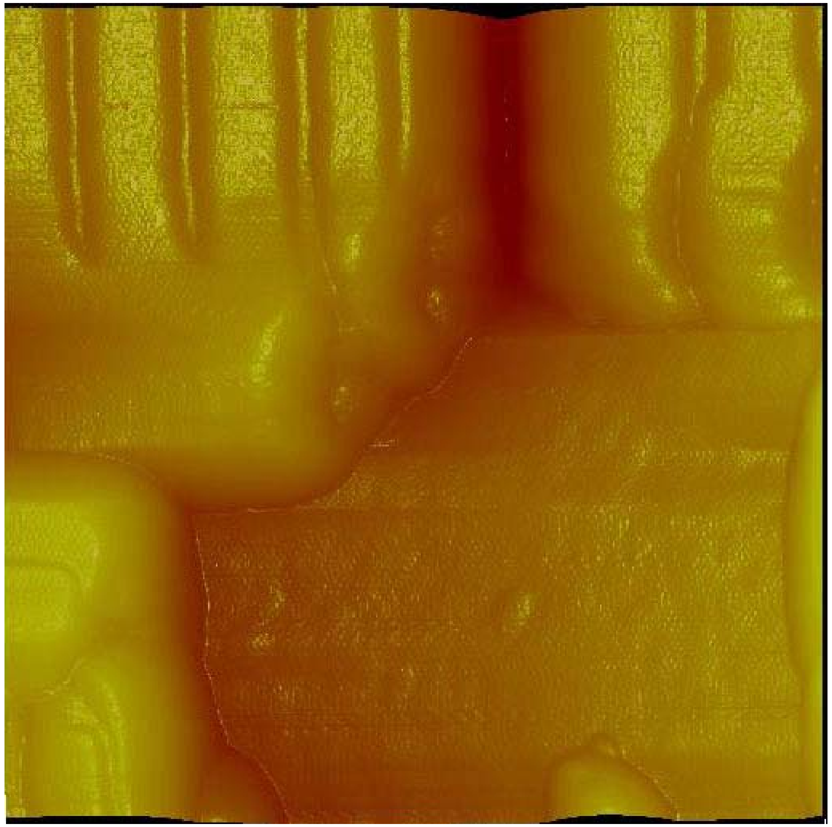
80 nano DRAM



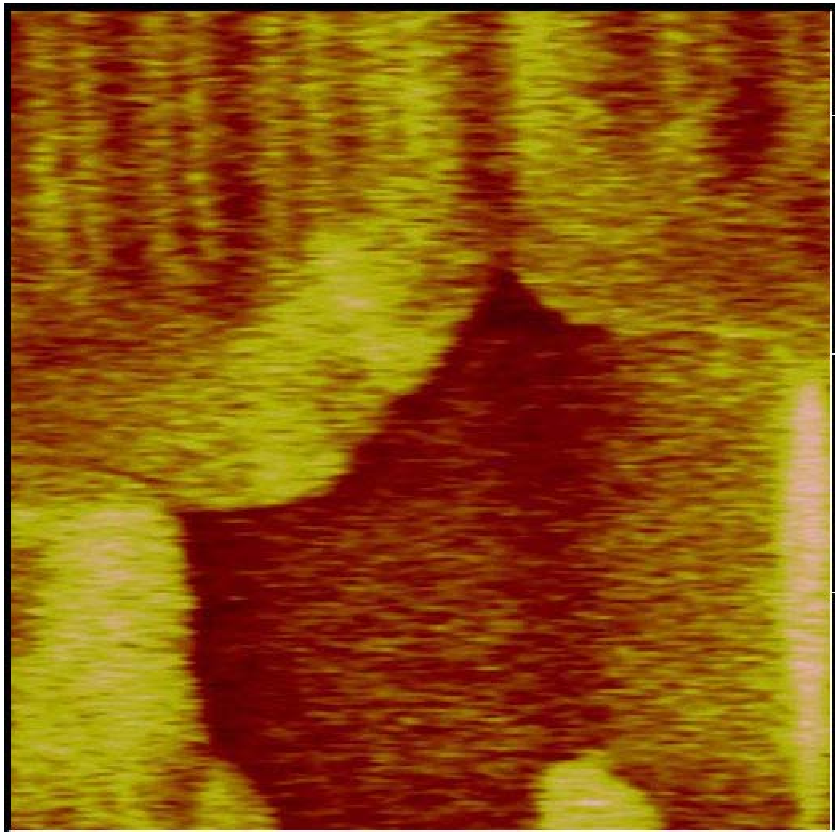




Sub-surface Thermal Image – Result



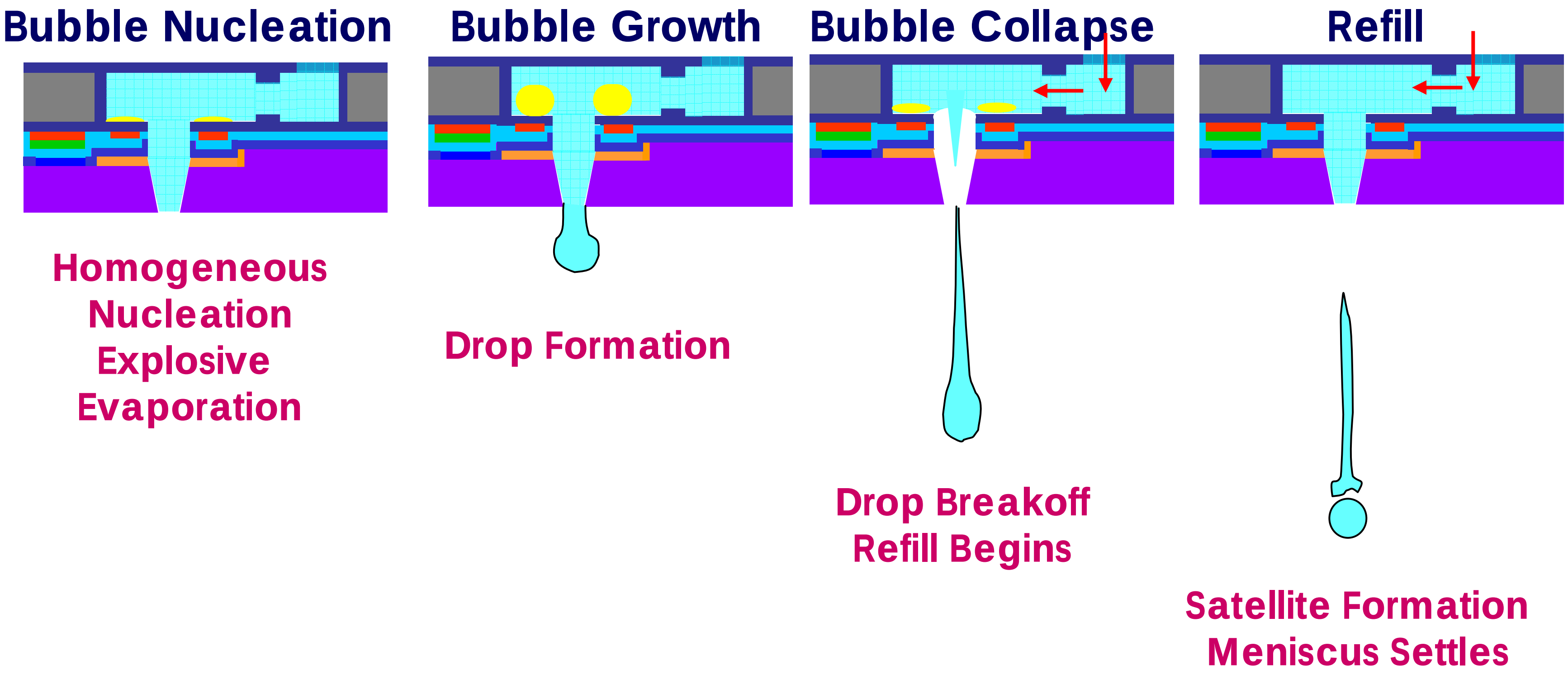
Topography



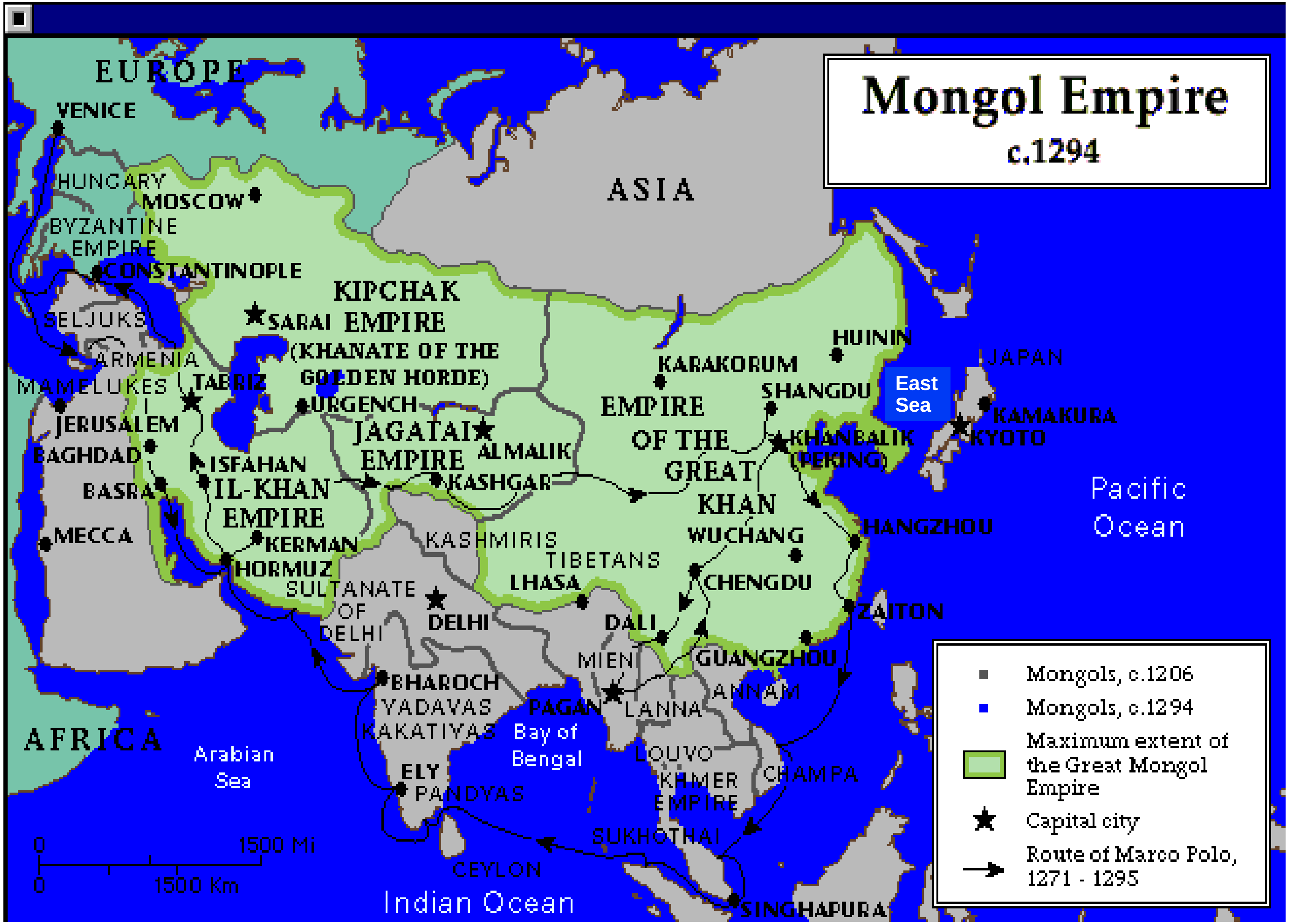
2ω signal

Sensors & Actuators / Thermal Ink Jet

- **Facts about Ink Jet**
  - **heating rate >10^8 K/s**
  - **heat flux > 5×10^8 W/m^2**



Real Estate to Patent



Paradigm Shift