HEAT TRANSFER

Introduction

Heat transfer is that science which seeks to predict:

- the energy transfer which may take place between material bodies as a result to a temperature difference,
- how heat energy may be transferred,
- the rate at which heat exchange takes place.

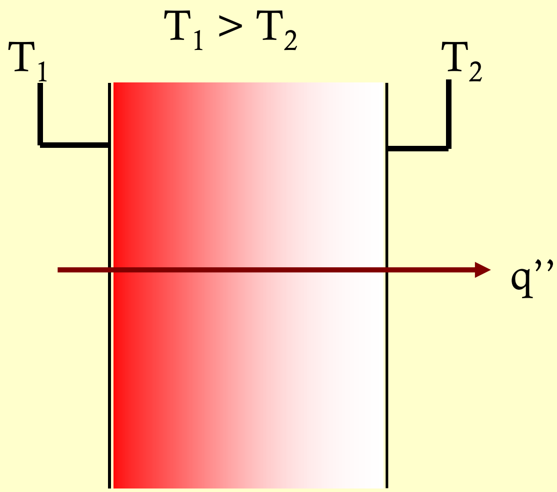
Thermodynamics:

- deals with systems in equilibrium,
- used to predict the amount of energy required to change a system from one equilibrium state to another

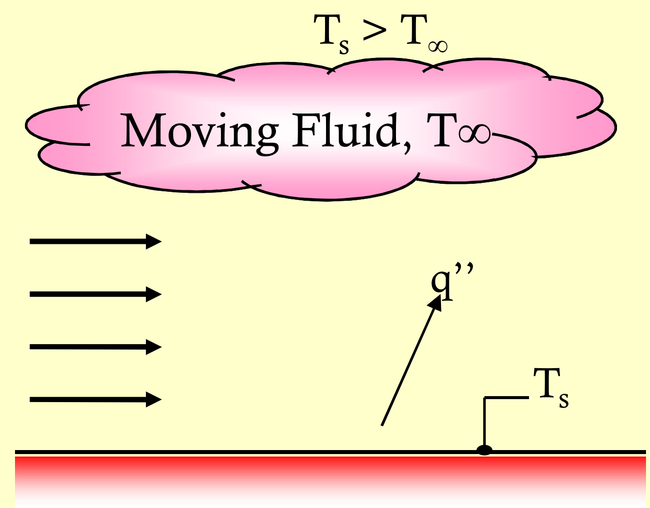
Example: Consider a hot steel bar which is placed in a pail of water.

- Thermodynamics may be used to predict the final temperature of the steel bar-water combination. It will cannot tell how long it takes to reach equilibrium or the temperature of the bar during the process
- Heat transfer may be used to predict the temperature of both the bar and the water as a function of time.

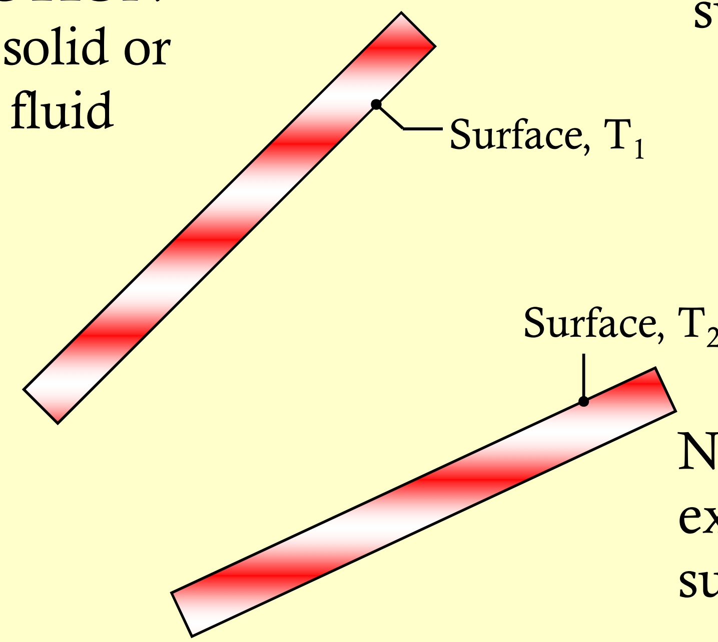
Heat transfer modes



CONDUCTION through a solid or stationary fluid



COVECTION from a surface to a moving fluid

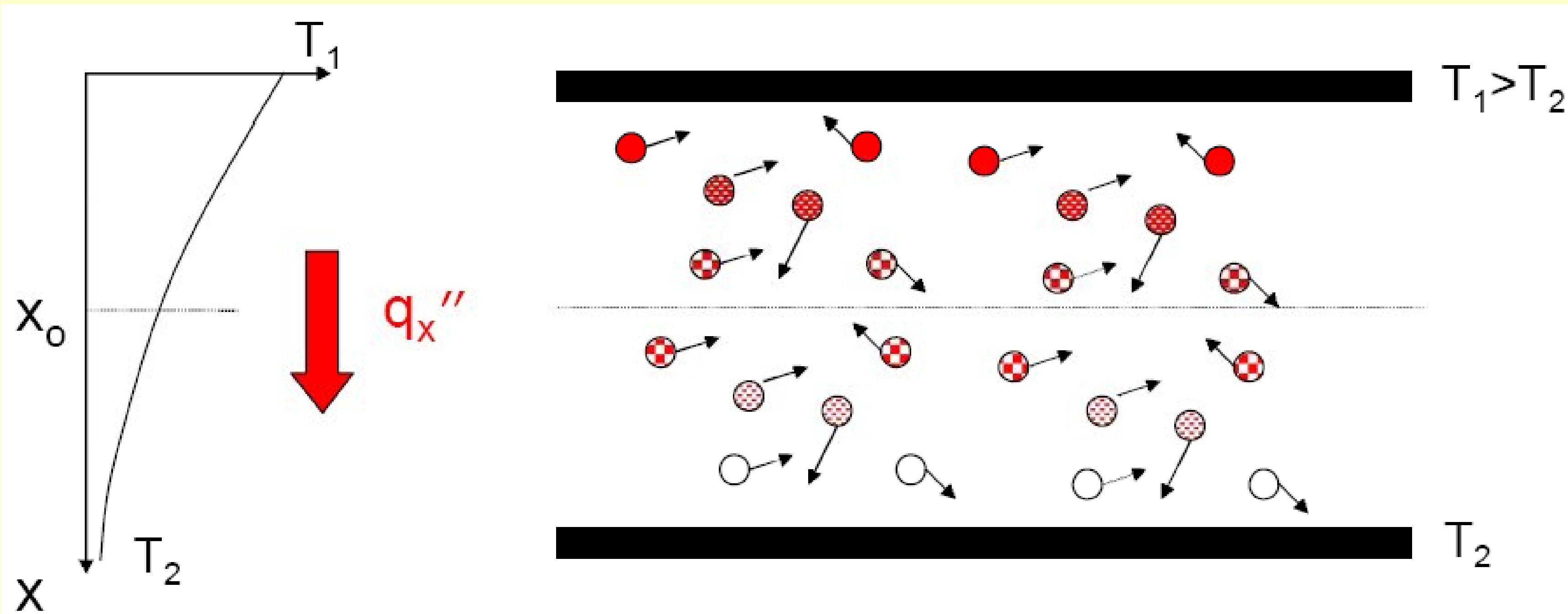


Net **RADIATION** heat exchange between two surface

Conduction

- Conduction heat transfer occurs due to atomic or molecular activity.
- Heat transferred from more energetic to less energetic particles.
- Consider the gas with no *bulk motion* in the next figure.
- The gas occupies the space between two surfaces that are maintained at different temperatures.
- The temperature at any point is associated with the energy of the gas molecules at that point.
- This energy is related to the random translational motion, internal rotation and vibration motions of the molecules.
- Higher temperatures means higher molecular energies (activity).

- When molecules collide, energy is transferred from the high energy molecules to the less energy ones.
- Hence we say that in the presence of a temperature gradient, energy transfer occur in direction of decreasing temperature.



Conduction heat transfer due to molecular activity

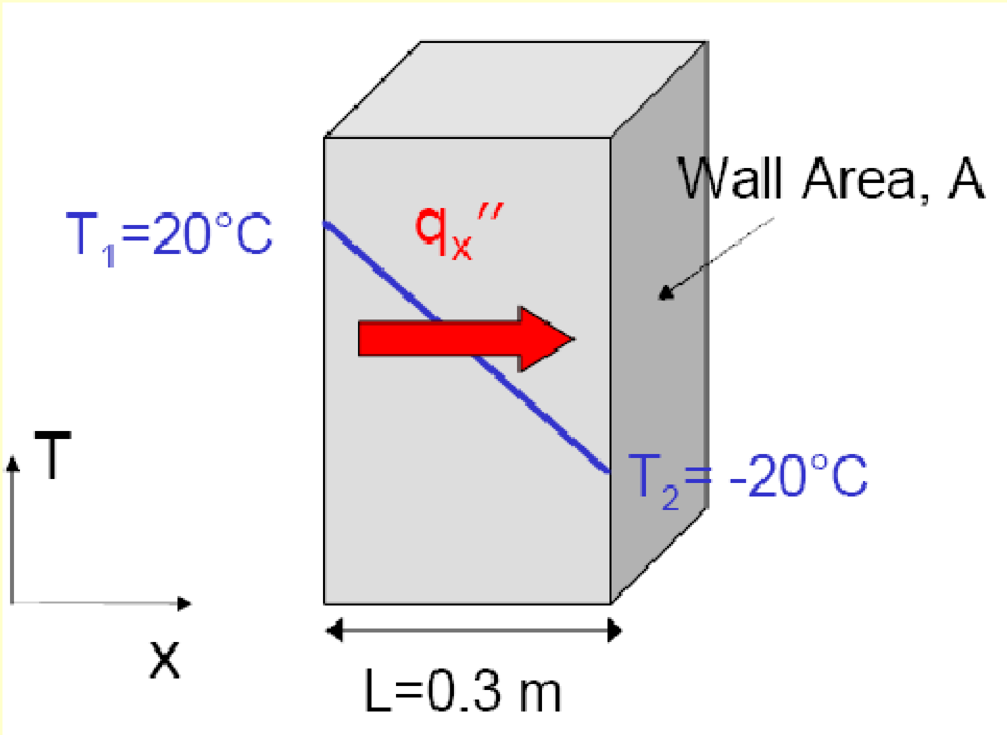
- The situation applies to both liquids and solids however, since the molecules are more closely spaced, the molecular interactions are stronger and more frequent.
- In solids these molecular activity can include lattice vibrations and motion of free electrons.
- The rate equation for heat transfer is given by:

$$q''_x = -k\frac{dT}{dx} \qquad (W/m^2)$$

- This equation is also known as Fourier's law where,

heat flux, q'' (W/m^2) is the heat transfer in the **x direction** per unit **area perpendicular** to the direction of transfer, and it is proportional to the temperature gradient, dT/dx.

- *k* is known as the **thermal conductivity** and is based on the material of the wall. Units for k is W/m.K



- The minus sign in the equation signifies that heat is transferred in the direction of decreasing temperature.

- Under steady state conditions shown in the figure above, the temperature distribution is linear and the heat flux is then

$$q_x'' = k\frac{T_2 - T_1}{L} = k\frac{\Delta T}{L}$$

- Note:

$$q_x = q_x'' \cdot A \quad (W)$$

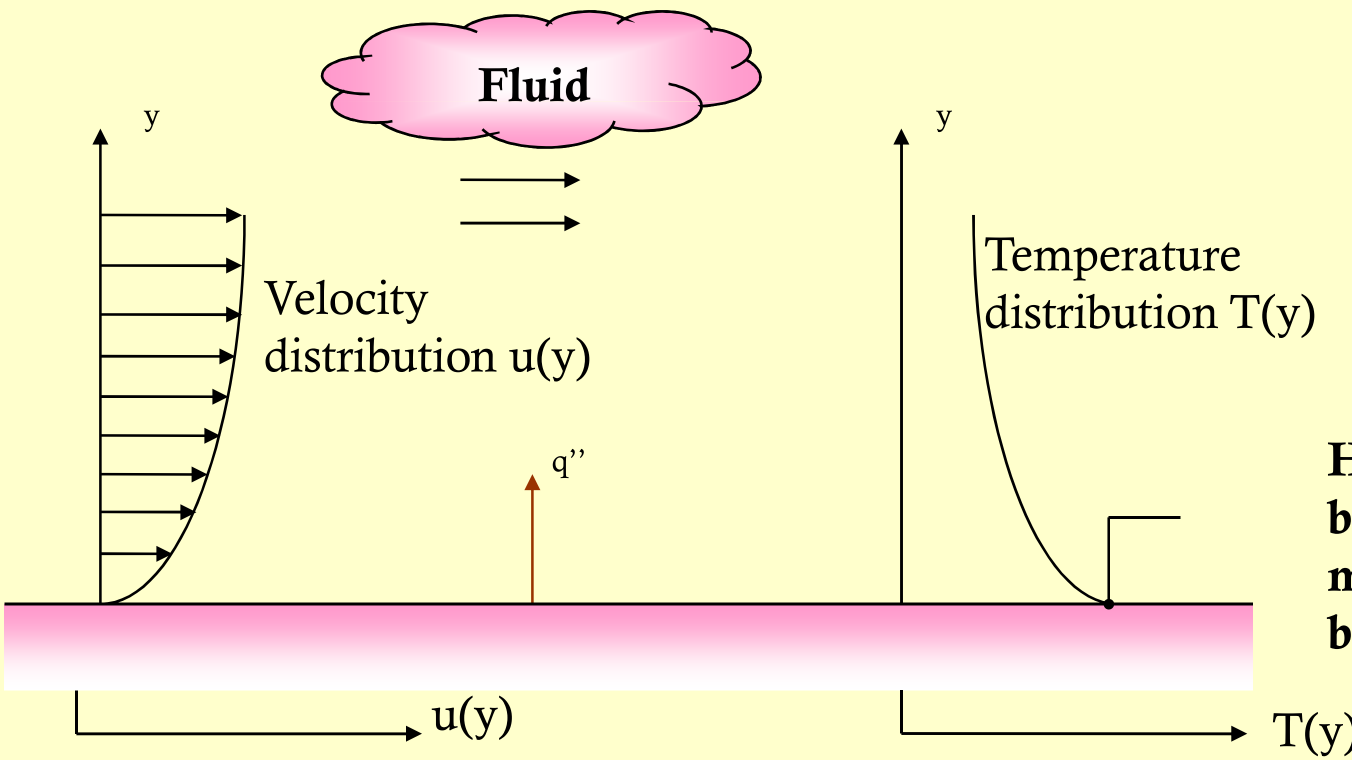
Example:

The wall of an industrial furnace is constructed from 0.15-m-thick fireclay brick having a thermal conductivity of 1.7 W/m.K. Measurements made during steady state operation reveal temperature of 1400 K and 1150 K at the inner and outer surfaces, respectively. What is the rate of heat loss through a wall that is 0.5 m by 1.2 m on a side?

Convection

Convection heat transfer comprises two mechanisms.

1. Energy is transferred due to molecular activity as in the case of conduction and
2. Due to bulk motion of the fluid, together it is called convection heat transfer.



Heat transfer between fluid in motion and an bounding surface

- Considering the diagram above, fluid flow over a heated surface.
- Due to fluid-surface interaction, the velocity varies from zero at the surface to a finite value, u_∞. This region is know as the velocity, boundary layer.
- Thermal boundary layer is the region of the fluid through which the temperature varies from Ts (surface temperature to T_∞.
- Convection heat transfer occurs both by random molecular motion and by the bulk motion of the fluid **within the boundary layer**.
- Heat transfer due to molecular motion dominates neat the bounding surface where fluid velocity is low.

There are two classifications of convection heat transfer:

1. Forced convection external means such as a pump or a fan.
2. Natural convection natural means of bouncy forces

- The rate equation for convection heat transfer:

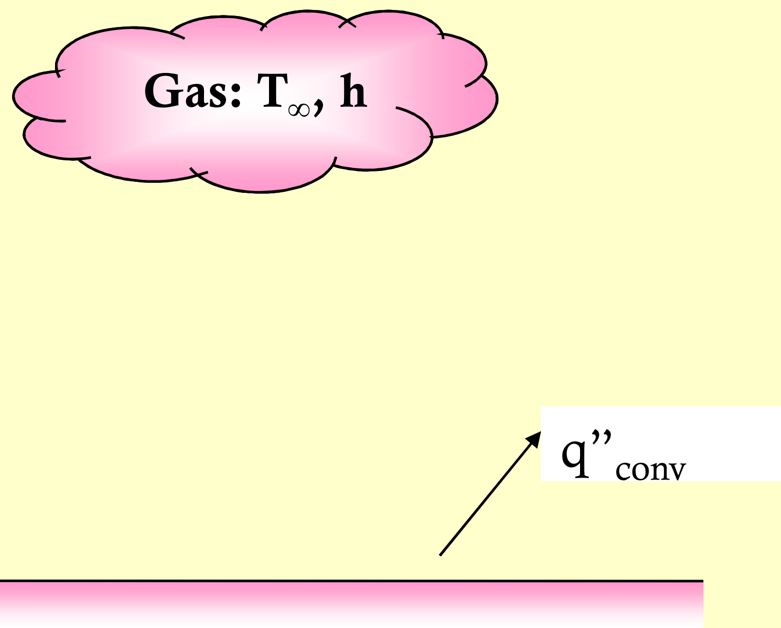
$$q'' = h(T_s - T_\infty) \qquad (W/m^2)$$

- This expression is known as Newton's law of cooling.
- *h* is known as **convection heat transfer coefficient**.
- If $T_\infty > T_s$ then : $q'' = h(T_\infty - T_s)$

Typical values of the convection heat transfer coefficient	
Process	*h* **(W/m²·K)**
Free convection	
Gasses	2 – 25
Liquids	50 – 1,000
Forced convection	
Gasses	25 – 250
Liquids	100 – 20,000
Convection with phase changes	
Boiling or condensation	2,500 – 100,000

Radiation

- Thermal radiation or radiant energy is energy emitted by matter that is at a finite temperature.
- Radiant energy is emitted by solids, liquids and gasses and it is transported by electromagnetic waves.
- Radiation does not require the presence of a medium and occurs most efficiently in vacuum.



Heat from the sun reaches the earth through radiation process…

- Consider the diagram above, the radiation emitted by the surface comes from the thermal energy of matter within the surface.
- The rate at which energy is released per unit area (W/m^2) is called the surface **emissive power, E**.
- There is an upper limit to the emissive power, which is given by the Stefan – Boltzmann law:

$$E_b = \sigma T_s^4 \qquad (W/m^2)$$

- T_s is the **absolute temperature (K)** of the surface and σ is the Stefan-Boltzmann constant ($\sigma = 5.67 \times 10^{-8}\ W/m^2.K^4$)
- Such a surface is called an **ideal radiator** or **blackbody**.

- The heat flux emitted by a real surface is less than that of a blackbody at the same temperature and it is given by:

  $$E = \varepsilon \sigma T_s^4 \qquad (W/m^2)$$

  where ε, is called the emissivity with values in the range of $0 \leq \varepsilon \leq 1$.
- The closer the emissivity to 1 the more efficiently it emits energy relative to a blackbody.
- Emissivity depends strongly on the surface material and finish.
- Radiation may also be incident on a surface from its surroundings and it is designated as irradiation, G.
- Irradiation is the process by which an item is exposed to and absorbs radiation.

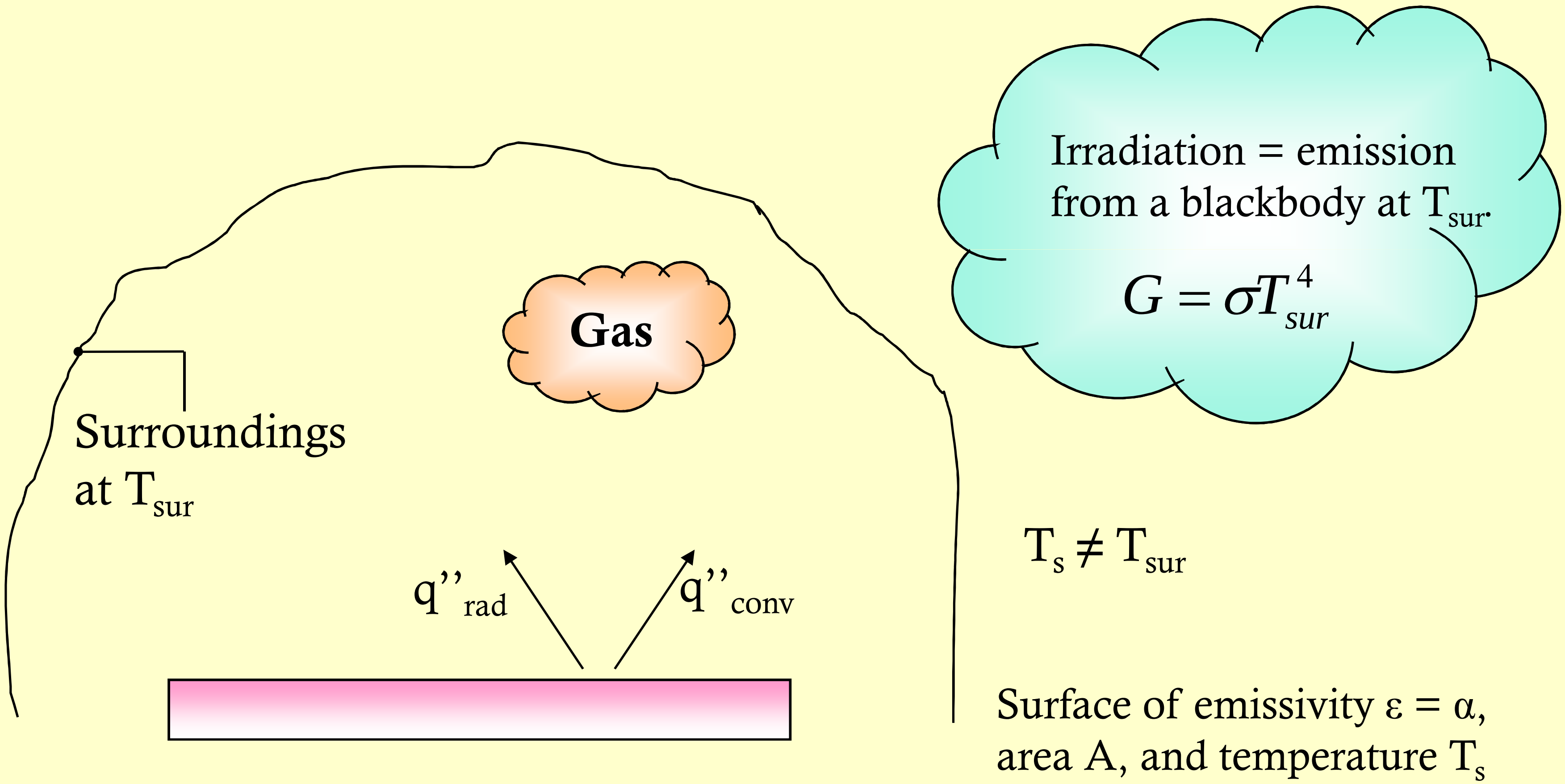
- The rate at which radiant energy is absorbed per unit surface area is given by:

$$G_{abs} = \alpha G \qquad (W/m^2)$$

where α, is called the absorptivity with values in the range of $0 \leq \alpha \leq 1$.

- If the surface is *opaque* (i.e. not clear), portions of the irradiation is **reflected**.
- If the is semitransparent, portions of the irradiation is **transmitted**.
- Absorbed and emitted radiant energy increase and reduce the thermal energy of matter respectively.

- Reflected and transmitted radiation have no effect on this energy.
- At any one time, a surface may be emitting and absorbing radiation energy.



- **Special case, (see diagram above):**
  radiation exchange between a small surface at T_s and a much **larger, isothermal surface** that completely surrounds the smaller one:

- If the surface is a *gray surface*, then the net rate of radiation heat transfer from the surface per unit area is given by:

$$q''_{rad} = \varepsilon E_b(T_s) - \alpha G = \varepsilon\sigma(T_s^4 - T_{sur}^4) \qquad (W/m^2)$$

Example:

An insulated steam pipe passes through a room in which the air and walls are at 25ºC. The outside diameter of the pipe is 70 mm, and its surface temperature and emissivity are 200ºC and 0.8 respectively. What are the surface emissive power and irradiation? If the coefficient associated with free convection heat transfer from the surface to the air is 15 W/m².K, what is the rate of heat loss form the surface per unit length of pipe?

the end