MEDICAL UNIVERSITY – PLEVEN
FACULTY OF MEDICINE

DIVISION OF PHYSICS AND BIOPHYSICS

LECTURE 6

THE EFFECTS OF HEAT

Changes of phase. Applications of phase changes. Evaporation and vapor pressure. Relative humidity. Heat transfer. Physiological applications of heat transfer

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CHANGES OF PHASE

Giving internal energy to a solid body that is not at its melting T:

1. increases E_k of molecules (more agitated vibrations about the equilibrium positions);
2. has the effect of stretching and weakening the bonds, resulting in thermal expansion.

If enough U is added, the molecular activity will become great enough to break the solid bonding forces and free the molecules from their rather rigid relative positions.

Melting – breakdown of the rigid structure. It is an example of a "change of phase" or "phase transition ", from the solid to the liquid phase.

The change of phase requires a large amount of internal energy compared to the process of raising the temperature of the solid. $\boxed{h_f = 80\ cal/g}$ is required to change ice to water at 0°C.

Continuously adding Q to a liquid after the solid-liquid phase change will gradually raise its temperature up to the boiling point, which is the point where the liquid-to gas phase change occurs rapidly.

When the solid-to-liquid phase change occurs, the intermolecular attraction is reduced, but it still remains very strong.

The liquid-to-gas phase change requires enough U to completely overcome the attractive forces and free the molecules almost completely from any mutual attraction.

This transition takes considerably more internal energy than the solid-liquid transition. It requires $\boxed{h_r = 540\ \text{cal/g}}$ to convert water to steam at 100°C. This is almost seven times as much energy as that required to change ice to liquid water.

The temperature does not change during a phase transition, even though the amount of energy added is quite large.

You can have water and ice at equilibrium at 0°C and water and steam at 100°C. How can this be? The internal energy of a substance involves both E_p of intermolecular forces and E_k of random molecular motion.

The temperature only reflects the kinetic part. The main event during a phase change is the breaking or forming of intermolecular attachments – i.e. the change in potential energy.

Def. The energy required to melt one gram of a solid once it has reached its melting temperature is referred to as the *latent heat of fusion* or *latent heat of melting* for that substance (**h_f=80 cal/g** - water)

$$\boxed{Q = mh_{f.}}$$

Def. The energy required to vaporize one gram of a liquid at its boiling temperature is called the *latent heat of vaporization.*

$$\boxed{Q = mh_r}$$

For one gram of water at 100°C it would be 540 cal;

h_r=540 cal/g

The internal energies involved in the phase transitions are enormous.

E.g. Consider the process of taking a very cold 1 g piece of ice at t=-50°C and adding Q to it at the rate of 1 cal/s.

The rate of temperature rise can be calculated using the energy equation $Q=cm\Delta T$ (c_w=1 cal/g°C, c_{ice} =c_{steam} = 0.5 cal/g°C at a constant P).

One calorie is seen to raise the temperature of the ice by 2°C, the ice will then rise in T up to the melting point, 0°C, in 25 s with the addition of 25 cal.

At 0°C it must absorb 80 cal in order to change into water, *without raising its T*.

With heat added at $\frac{dQ}{dt} = 1 \text{cal/s}$, it will take 80 s to convert the ice to water, during which time its T will remain constant at 0°C.

The fact that we can have ice at 0°C or water at 0°C is a good illustration of the statement in that two objects which are at the same temperature can have drastically different amounts of U.

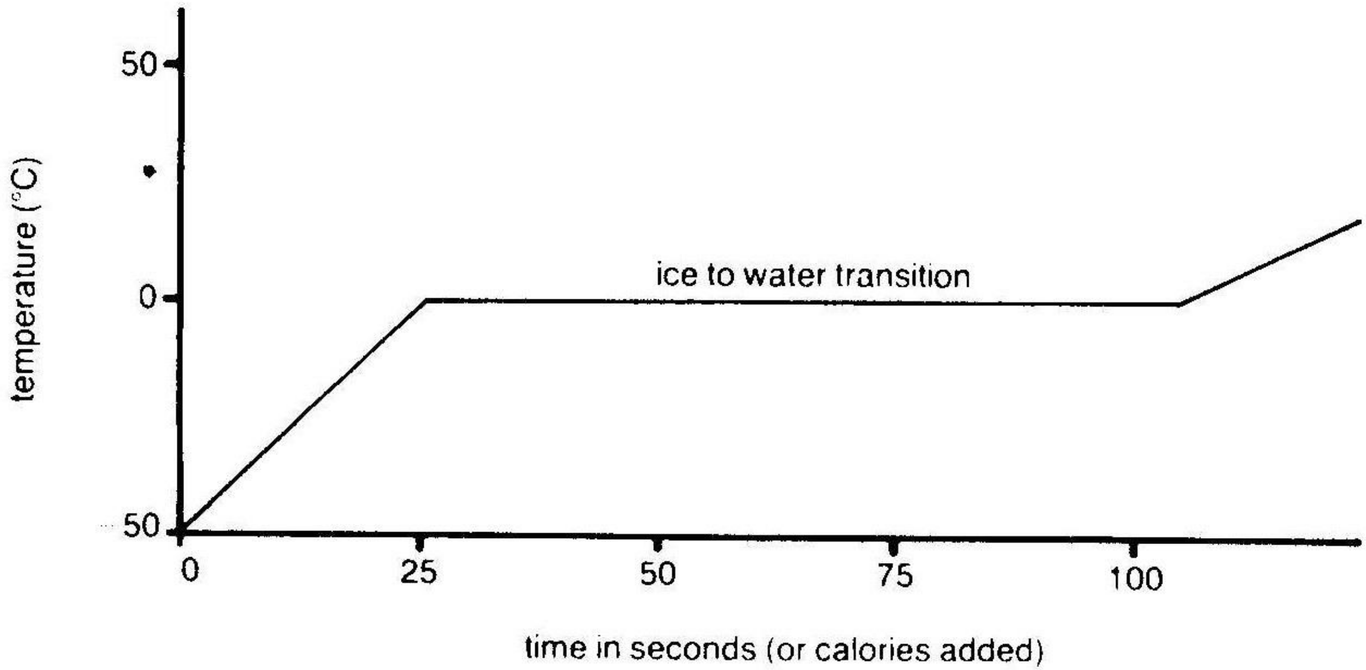
Since it takes 1 cal to raise the temperature of water by 1°C, the water temperature will rise at the rate of 1°C/s after all the ice has melted. It will then take 100 s for the temperature to rise to 100°C, the boiling point.

The whole process of changing from ice at t=-50°C to water at t=100°C will have taken

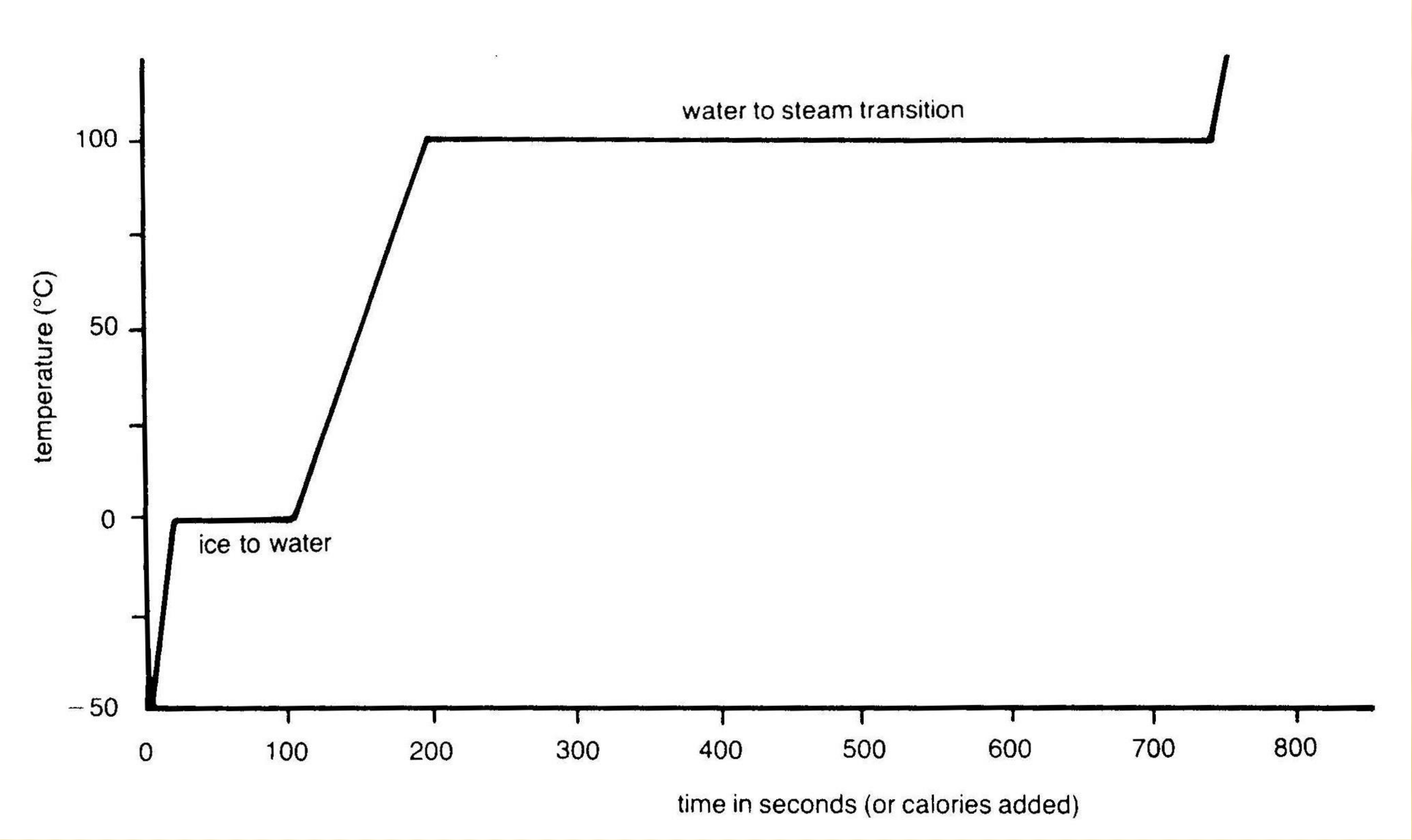
25 + 80 + 100 = 205 s.

1 gram of 100°C water must absorb 540 cal to break the attractive bonds and free the molecules in the form of steam at 100°C. This will require 540 s, during which the temperature remains constant at 100°C. This gives the long constant-temperature plateau.

Only after all the water is converted to steam will T of the steam start to rise at the rate of 2°C/s.



The ice-to-water phase transition when heat is added to 1 g of ice at $\frac{dQ}{dt} = 1\,\mathrm{cal/s}$



The temperature as a function of time for 1 g of water to which heat is added at the rate of 1 cal/s.

Why are boiling points and freezing points particularly suitable as calibration temperatures for thermometers ?

Ans: Because of the temperature plateaus.

If a vessel contains a well stirred mixture of ice and water at thermal equilibrium, then one can be confident that T=0°C.

If a vessel of water which is open to the atmosphere at 760 mm Hg is brought to a vigorous boil and stirred, T=100°C. The stirring is important in both cases, since otherwise sizable temperature gradients can exist.

APPLICATIONS OF PHASE CHANGES

There are numerous ways in which the large internal energies involved in phase changes can be utilized.

If a liquid can be forced to evaporate, then it will extract the heat of vaporization from its surroundings and act as a cooling agent.

If a vapor is forced to condense, it will release h_r to its environment.

Similarly, melting solids extract U, and freezing liquids give up U to their environments. This energy is the latent *heat of fusion*, h_f.

REFRIGERATION. A refrigerator must extract heat from a cold area and exhaust it in an area of higher T. This is opposite to the normal flow of heat and requires work to "pump" the internal energy out of the interior of the refrigerator.

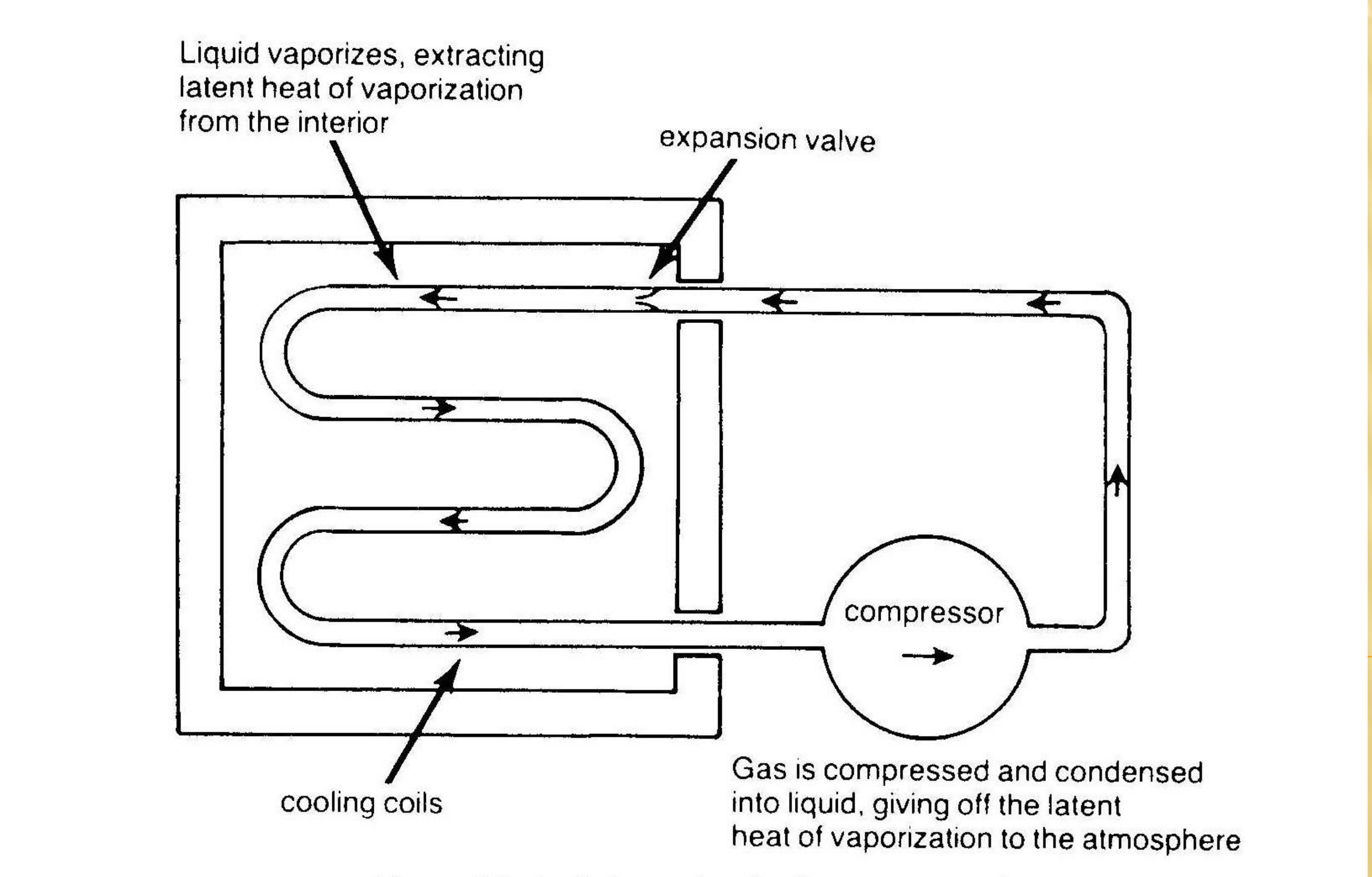
The process can be accomplished by making use of the large h_r of some substance. A refrigerant fluid is circulated in a closed system of coils.

By means of an expansion valve at the beginning of the cooling coils, the refrigerant liquid can be forced to evaporate. This expansion valve is basically a nozzle, which uses the Bernoulli effect to lower the pressure in a region of the flow.

The liquid will boil at a lower T in this lower pressure region and will begin to make the liquid-to-gas phase change. But it cannot vaporize without extracting the necessary heat of vaporization from its surroundings, in this case the cooling coils of the refrigerator. Energy is taken from the cold interior of the refrigerator, cooling it further.

This energy is carried out to the compressor, where increased pressure forces the condensation of the refrigerant. In the process of condensation, the refrigerant gives off the latent heat of vaporization to the surrounding air.

The fact that the latent heat of vaporization represents a large amount of internal energy makes this an efficient method for cooling.



Cooling by Perspiration. When perspiration evaporates, it extracts the latent heat of vaporization from the skin. This latent heat of vaporization is about 580 cal/g at normal body temperature. Since the specific heat of the body is somewhat less than 1 cal/g°C, the evaporation of one gram of perspiration could cool over 600 grams of the body material by 1°C.

E.g. Show that the evaporation of 250 cm^3 of perspiration would cool the entire body of a 54 kg person by about 3°C. Circulating air helps to cool the body because it speeds the evaporation process. ($\rho_p = 10^3 kg/m^3$)

It is difficult to keep cool on a humid day because the level of moisture in the air inhibits the evaporation of perspiration.

Alcohol sponges are used to cool feverish patients because alcohol evaporates much more quickly.

APPLICATION OF THE MELTING TRANSITION.

Why is a quantity of ice at 0 °C a more effective coolant than the same quantity of water at 0 °C?

ANS. Ice is much more effective in cooling a solution than just cold water because of the internal energy required to melt the ice.

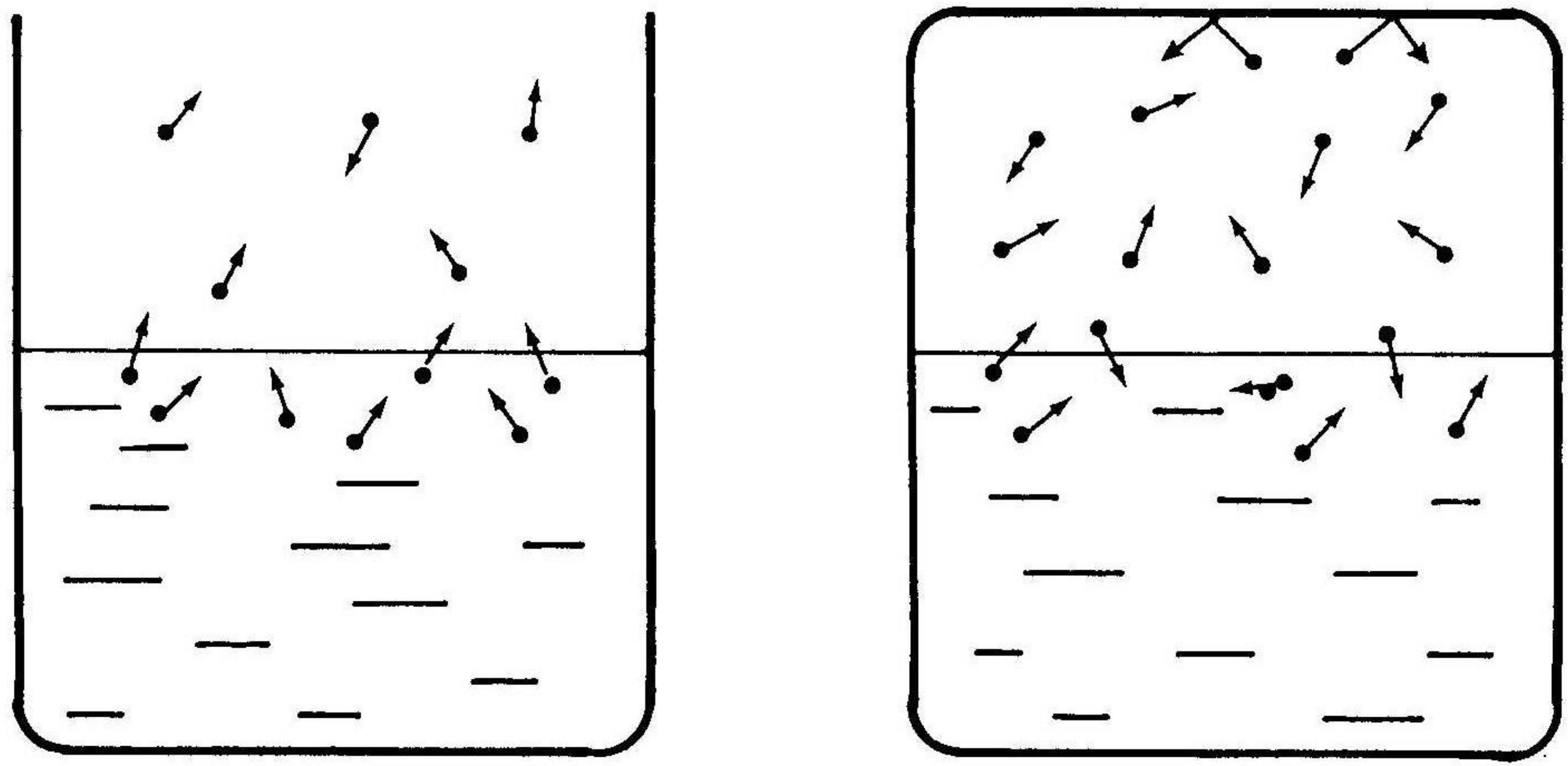
EVAPORATION AND VAPOR PRESSURE

Evaporation occurs at all T > 0°C. Because of higher than average kinetic energy, some of the molecules will escape from the liquid into the air.

If T of the liquid is increased, more molecules will have the energy necessary to escape and the evaporation rate will therefore be greater.

If the container is closed, an equilibrium will be reached when the number of molecules bouncing back into the surface is equal to the number leaving.

The vapor is then said to be saturated and the pressure exerted on the container walls is the *saturation vapor pressure.*



(a) evaporation from an open liquid surface

(b) saturation of a vapor in a closed volume

Def. The mass of water vapor per unit volume under saturation condition is the ***saturation vapor density.***

The saturation vapor density and pressure increase with temperature. When the temperature reaches 100°C, the vapor pressure is equal to atmospheric pressure, 760 mm Hg.

Def. *Boiling point* of any liquid is the temperature at which the vapor pressure equals atmospheric pressure.

What is the main advantage of a high pressure steam sterilizer (autoclave) over simple boiling water for sterilizing instruments?

Ans. An increase in pressure raises the boiling point above 100°C and allows the water to be superheated, as in a pressure cooker or instrument sterilizer (autoclave).

Why must instrument sterilizers be constructed of sturdy material ?

When water is boiled in a container, the vapor pressure of the water exceeds atmospheric pressure and can therefore push the air out of the container. The effect can be demonstrated by boiling water in a can and then sealing the can as it cools.

The water vapor which replaces the air in the can will condense as the can cools. Since the vapor pressure of the cooled liquid is much less than atmospheric pressure, the unbalanced P will crush the can.

That is why, sterilizers must withstand the unequal P when they are cooled.

RELATIVE HUMIDITY

The amount of water in the air is usually less than the saturation density. The percentage of saturation humidity at the given temperature is referred to as the *relative humidity*. It can be calculated from the relationship

$$r = \frac{e}{e_o} .100\%$$

Since the saturation vapor density increases with the temperature, the same actual vapor density will represent a smaller relative humidity if T of the air is increased.

The membranes of the body tend to be sensitive to the relative humidity rather than the absolute humidity.

The air will seem dryer if it is heated without increasing the actual vapor pressure in the air. Central heating systems which heat and circulate a closed volume of air will reduce the relative humidity in the process unless water is added to the air by means of a humidifier.

If the air is gradually cooled while maintaining the moisture content constant, the relative humidity will rise until it reaches 100%.

Def. The temperature, at which the moisture content present in the air will saturate the air, is called the *dew point.*

What will happen to the relative humidity in a closed house at night when the air is heated? Explain.

Why does a cool basement tend to be damp?

Why does the saturation vapor pressure of water increase with temperature?

HEAT TRANSFER

Heat transfer may occur by one of the following three mechanisms:
(1) conduction, (2) convection, and (3) radiation of heat. It can also occur by (4) the transfer of the latent heat of fusion or vaporization.

Conduction - the primary method of heat transfer in solids.

E.g. If a silver spoon is placed in a hot cup of coffee, the other end of the spoon will quickly become hot because of the conduction of internal energy through the handle of the spoon.

Conduction is the transfer of heat by the direct interaction of molecules in a hot area with molecules in a cooler area.

Microscopically, this interaction is in the form of collisions between molecules. The efficiency of heat conduction depends upon:

1. the number of collisions and
2. the amount of energy transferred during each collision.

Metals are generally much better heat conductors than nonmetals. Why? Some of the electrons in metals are essentially free to move about in the material, in contrast to the more tightly bound electrons in nonmetals.

These electrons move at high speeds, transferring energy by collisions with other electrons and with atoms in the metal lattice.

In addition, these mobile electrons cause the metals to act as much better electrical conductors than the nonmetals. Gases are generally poorer heat conductors than solids because of the smaller number of molecular collisions that occur in the gaseous state.

The difference in thermal conductivity between metals and nonmetals like wood explains the results of the example in which metal and wood blocks at 0°C and 100°C were touched.

$$\frac{\Delta Q}{\Delta t} = -k\,A\,\frac{\Delta T}{\Delta x}$$

Fourier's law

Doubling the thickness of a garment will halve the rate of heat loss from the body.

Wearing a garment with the same thickness but with one-half the thermal conductivity *k*, would have the same result and perhaps be more comfortable.

Show that keeping the inside of a house at 20°C when the outside temperature is 10°C will require the same amount of energy as keeping the house at 30°C when the outside temperature is 20°C. Why ?

Since the heat loss depends upon ΔT rather than upon the actual T involved.

In applying heat to the body, the rubber hot water bottle serves as an insulator which slows the rate of heat transfer from the water to the body to prevent burns and to allow the available internal energy from the hot water to be used over a longer period of time.

A flannel cloth can further insulate the water to slow the heat transfer, but its insulating properties are destroyed if it is wet, since water is a conductor of heat.

Def. *Convection* refers to heat transfer by the movement of the fluid.

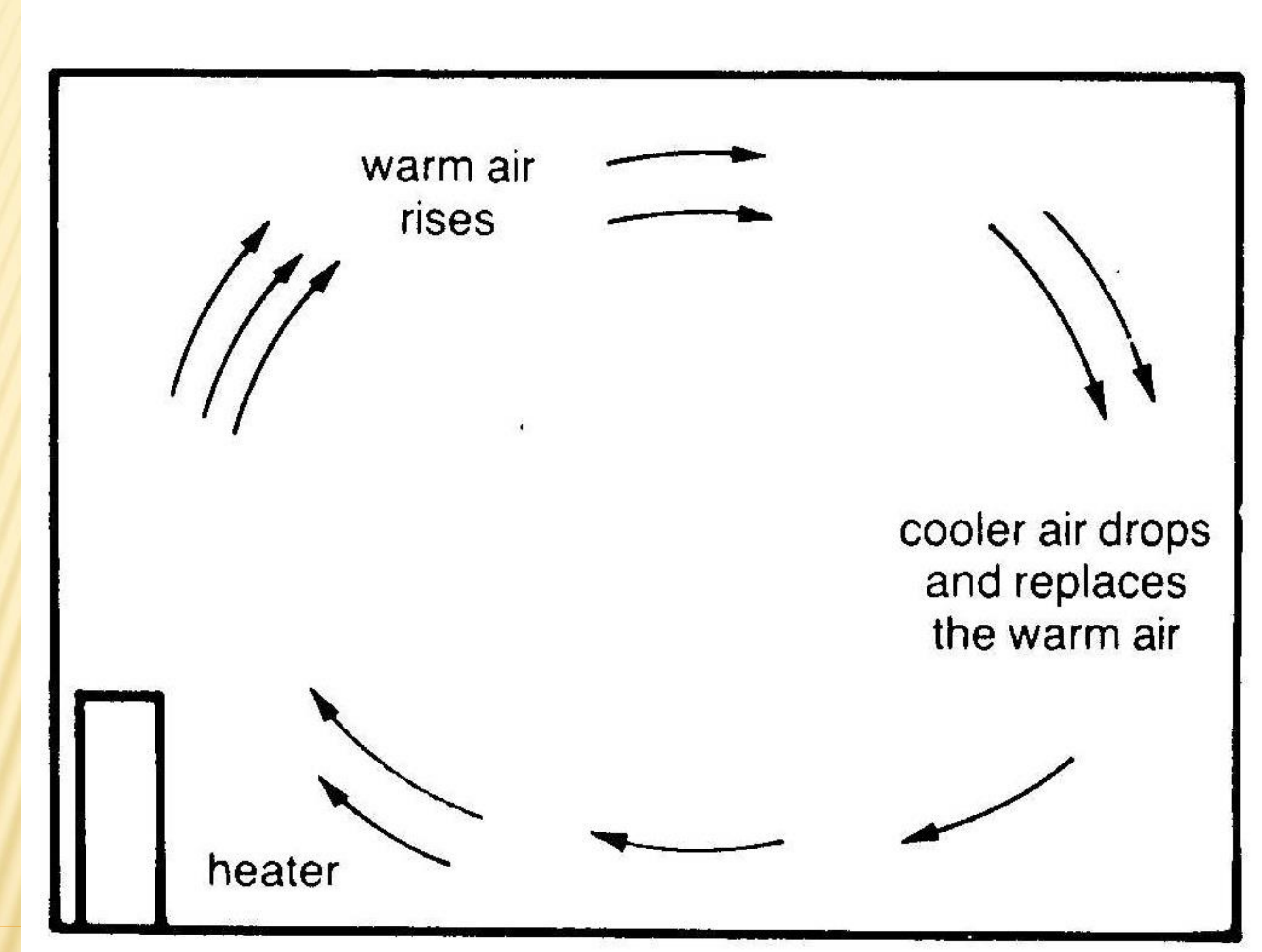
Air is a poor conductor, but it can efficiently transfer heat by convection.

Def. The movements of fluids which carry heat are called convection currents.

The origin of convection currents in gases can be understood from the relationship between T, V, and P of gases. As air rises in temperature, it expands and therefore becomes less dense than the surrounding air. The resulting buoyant forces cause it to rise; the more dense cool air will tend to move down to replace it.

In a room heated by a radiator, these influences will set up a continuous cyclic convection current.

- Heat-generated convection currents are major factors in atmospheric air movements.
- Any hot object exposed to air will generate such currents, and a considerable part of the cooling process of such objects can be attributed to convection.
- Clothing helps to prevent such currents of air from touching the skin and therefore minimizes convection loss.


warm air
rises
cooler air drops
and replaces
the warm air
heater

Radiation is fundamentally different from the other two types of heat transfer.

Both conduction and convection require material of some kind to transport the energy.

Radiant energy is of the same nature as light and can travel through a vacuum.

The earth receives all of its energy from the sun by the process of radiation. The radiant energy given off by objects near room T is in the infrared range, but when an object becomes "red hot," it is radiating some of its energy in the form of visible light.

Heat loss by radiation from a hot object of temperature T_2 when surrounded by an environment with uniform temperature T_1, is given by

$$\boxed{\frac{\Delta Q}{\Delta t} = -\sigma e A(T_2^4 - T_1^4)}$$

The symbol **e** is the "emissivity" of the object, a measure of its effectiveness as a radiator.

For a perfect radiator e = 1 and for a perfect reflector e = 0. This ideal radiator is also an ideal absorber, it absorbs 100% of the incident radiant energy.

Def. A body that absorbs all of the light incident on it would appear completely black. Hence, the ideal emitter-absorber is called a black body.

The emittance of visible light is strongly correlated with the color of the object.

A light-colored object is both a poor absorber and a poor emitter in the visible spectrum. Hence a person with white clothing will stay cooler than a person with dark clothing, if they are in direct sunlight.

However, the color does not have much effect upon the emittance or absorption in the infrared region of the spectrum where most of the energy transfer takes place.

PHYSIOLOGICAL APPLICATIONS OF HEAT TRANSFER

The body obtains energy by the oxidation of foods. A large fraction of this energy must ultimately be given off to the environment as heat, so heat transfer from the body is very important.

By what methods is heat given off by the body? In addition to conduction, convection, and radiation from the skin, **the process of evaporation** from the skin carries off a significant amount of heat.

A large amount of water vapor is added to the expired air, and the latent heat of vaporization of this water is lost from the body.

Example: For an adult male the heat loss from the body associated with the basal metabolism is about 40 kcal/h m^2. Show that this rate of energy loss is equivalent to 46.5 watts, so for a person with a surface area of about 2 m^2, the basic rate of energy loss is about 90 watts.

Energy expenditure during strenuous exercise may be 600 kcal/h (700 watts) for a short time. The body temperature would rise very rapidly if there were no efficient means of transferring the excess energy away from the body as heat.

Radiation is an effective mechanism for the transfer of energy from the body. This is in contrast with room radiators, which actually transfer most of their energy by conduction and convection.

But the skin is apparently an almost ideal absorber and radiator in the infrared region, absorbing approximately 97% of the infrared radiation which strikes it. The radiation efficiency is equal to the absorption efficiency and this leads to an emission coefficient e = 0.97.

The skin T is controlled by the blood flow to it, and this blood supply can be controlled by vasoconstriction and vasodilation.

60% of the body's energy loss may occur by radiation. Clothing which is highly reflective of infrared radiation could help prevent this loss by reflecting the energy back to the body.

As mechanisms for removing body heat, conduction and convection are closely related. Without air movement, heat loss by conduction would be quite inefficient because of the low thermal conductivity of air, but heat must be conducted to the layer of air immediately surrounding the body before it can be carried away by convection currents.

Undersea experimenters living in a helium and oxygen atmosphere.

Helium is a much better heat conductor than the nitrogen which is replaced in the air.

The experimenters feel chilled even in an ambient temperature of 26°C.

Conduction is the main mechanism by which heat is transferred from the core of the body to the skin. To facilitate this transfer, the skin temperature is normally maintained at 4 to 5°C below internal temperatures, depending upon the blood supply to the skin.

Cooling the body by evaporation of perspiration is an efficient process because during evaporation the large latent heat of vaporization, h_r = 580 cal/g at 37 °C, is extracted from the skin.

A fact of major significance about perspiration heat loss is that it will remove heat from the body even when the ambient temperature is higher than body temperature.

It is the body's only major heat loss mechanism under this condition since radiation, conduction, and convection can transfer heat only from high temperature areas to lower temperature areas. They transfer energy into the body rather than out of it at ambient temperatures above body temperature.