Chapter 5: Energy

In the living body, the conversion of the energy operates the life activity, maintains the body temperature, and controls the movement of the material. In this chapter, we learn the basic technology of the energy with examples: the movement of substances through the biological membranes, and the work rate of the heart.

5.1 State of substance

5.1.1 Temperature

The temperature [K] is used to represent the energy state (see Chapter 2). The state of the object changes with the increase of the temperature. The volume of the solid increases. A solid melts to a liquid at the “**melting point**”. The volume of the liquid increases. The liquid changes to the gas at the “**boiling point**”. The volume of the gas increases.

The gas, in which the molecules have zero volume and no interaction among them, is called an “**ideal gas**”. The equation 5.1 represents the relation among the temperature (T), the volume (V), and the pressure (P) in the n moles of ideal gas.

$$P = (n / V) R T \tag{5.1}$$

In the Eq. 5.1, R is the “**gas constant**” of 8.3 J K^{-1} mol^{-1}.

The pressure of the gas is caused by the molecular motion. The **absolute zero** temperature (0 K) is defined, when the pressure is zero without the molecular motion.

The point, where the water vapor, the water and the ice coexist, is called the “**triple point**” of water: 273.16 K, 611.73 Pa (**Fig. 5.1**). The standard scale of the temperature is defined by the triple point of water.

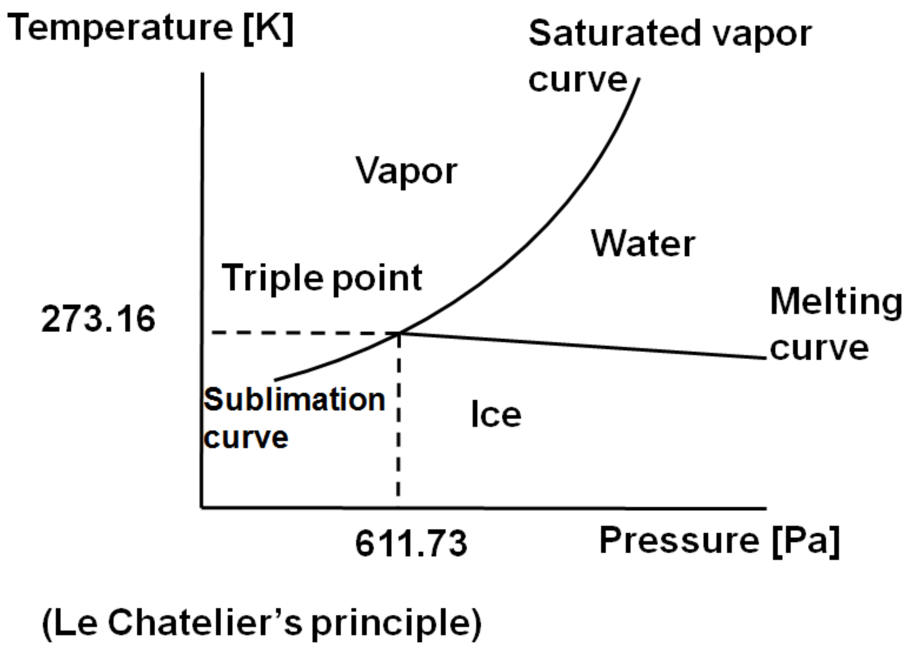


Fig. 5.1: Triple point of water.

The melting point (the freezing point) and the boiling point are used for the reference of the temperature scale, as a stable temperature. At the standard atmospheric pressure 101325 Pa, the freezing point of tin and gold are 505.078 K and 1337.33 K, respectively [22].

The volume varies, when the phase of substance changes among the solid, the liquid, and the gas. The pressure affects the change of the volume.

When the reaction system has equilibrium, the balance moves to the direction to reduce the change. It is called "**Le Chatelier's principle**".

The volume of the substance increases with the change of the phase from liquid to gas. Therefore, the boiling point is lowered under the low pressure, and is raised under the high pressure.

The volume increases, when the phase of substance changes from solid to liquid. Therefore, the melting point rises under the high pressure. In the case of water, on the other hand, the volume decreases, when the phase of substance changes from solid (the ice) to liquid (see 5.1.4). Therefore, under the high pressure, the melting point of the ice is lowered.

In the diluted solution, the boiling point is raised and the freezing point is lowered in proportion to the increase of the molar concentration of the non-volatile solutes. The **boiling point elevation** and the **freezing point depression** are applied to measure the concentration of the solution. The **osmotic pressure** can be calculated by the concentration of the solution (see 5.3.2).

5.1.2 Hydrogen ion concentration index

Three-dimensional structure of biological macromolecules in the aqueous solution varies with the hydrogen ion concentration of the surrounding. The hydrogen ion concentration is represented by pH (**power of hydrogen**).

In the diluted solution,

$$pH = -\log_{10}[H^+] \tag{5.2}$$

$[H^+]$ is the hydrogen ion concentration [mol dm^{-3}] (dm = 0.1 m, $dm^3 = 0.001\ m^{-3}$). The value of pH = 7 in the neutral solution.

The control of pH is important, because the three-dimensional structure of biological macromolecules affects the chemical reaction in the body. Because the concentration of carbon dioxide is higher *in vivo* than that in the atmosphere, pH of the physiological solution is biased to alkaline *in vivo*. The pH of the blood is controlled at 7.40. The chemical equilibrium controls carbon dioxide and hydrogen ion through carbonate.

$$H^+ + HCO_3^- \Leftrightarrow H_2CO_3 \Leftrightarrow H_2O + CO_2 \tag{5.3}$$

5.1.3 Heat

The heat is transferred according to the difference of the temperature: from the higher to the lower. The unit of the heat is J (Joule). The transfer of the heat is categorized to three kinds of paths: the **conduction** through the contact, the **convection** through the flow of fluid, and the **radiation** via the electromagnetic wave.

The heat is not transferred at the **thermal equilibrium**. The amount of the heat required for 1 K rise of the temperature of the object is called the **heat capacity**. The unit is J K^{-1}.

The amount of heat required for 1 K raise of the temperature of a substance of 1 kg is called the **specific heat capacity**. The unit is J kg^{-1} K^{-1}. The amount of heat required for 1 K raise of the temperature of a substance of 1 kg under the constant pressure is called the **specific heat at constant pressure**. The amount of heat required for 1 K raise of the temperature of a substance of 1 kg under the constant volume is called the **specific heat at constant volume**.

The **enthalpy** (*H*) is used to represent the energy state change associated with exothermic and endothermic reactions. The unit is J.

$$H = U + PV \qquad (5.4)$$

In equation (5.4), *U* is the internal energy, *P* is pressure, and *V* is the volume. The heat to the outside (exothermic) or the work to the outside lowers the enthalpy. Conversely, the heat received from the outside (endothermic) or the work received from the outside raises the enthalpy.

In a system, **entropy** dS [J K^{-1}] increases, when the system has received amount of heat δQ [J] from the heat source at temperature T [K]. The entropy dS is the quotient of the quantity of heat δQ divided by temperature T [K] of the system (Eq. 5.5).

$$dS = \delta Q / T \qquad (5.5)$$

The entropy represents disorder in a system. In an **irreversible process**, the entropy increases. Thermal vibration of atoms and molecules tends to be **random**. In the biological activity, each function is realized by being controlled based on the regularity. Against the **law of entropy increase**, **homeostasis** is maintained.

The thermal insulation material serves to impede the movement of heat. The thermal conductivity of the gas is low, since the gas has the low density of molecules. The gas is used for insulation: fibers to impede the convection of the gas, and small foams of the gas trapped in the solid (**Fig. 5.2**).

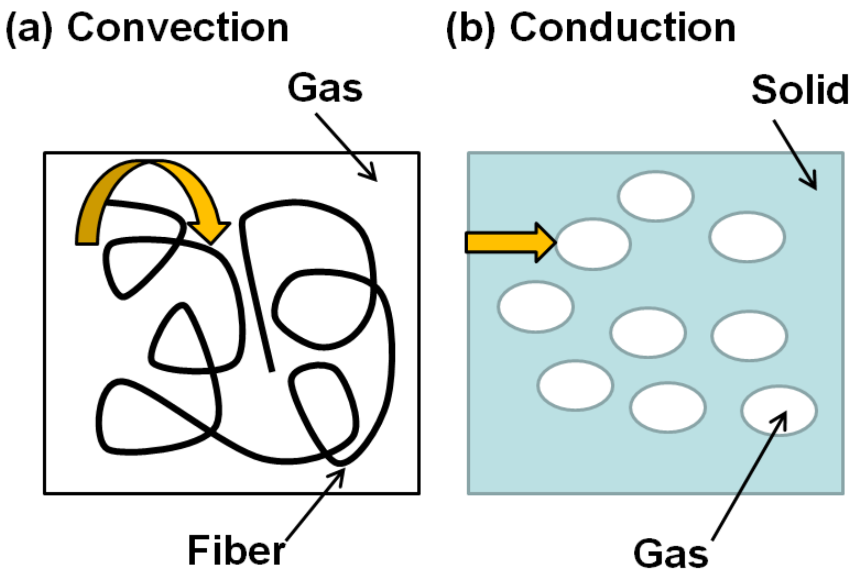


Fig. 5.2: Insulation material.

The internal energy increases and the temperature rises at the **adiabatic compression** by the external pressure, because the system receives the external work. Conversely, the internal energy decreases and the temperature falls at the **adiabatic expansion** by the internal pressure, because the system produces the work to the outside (**Fig. 5.3**).

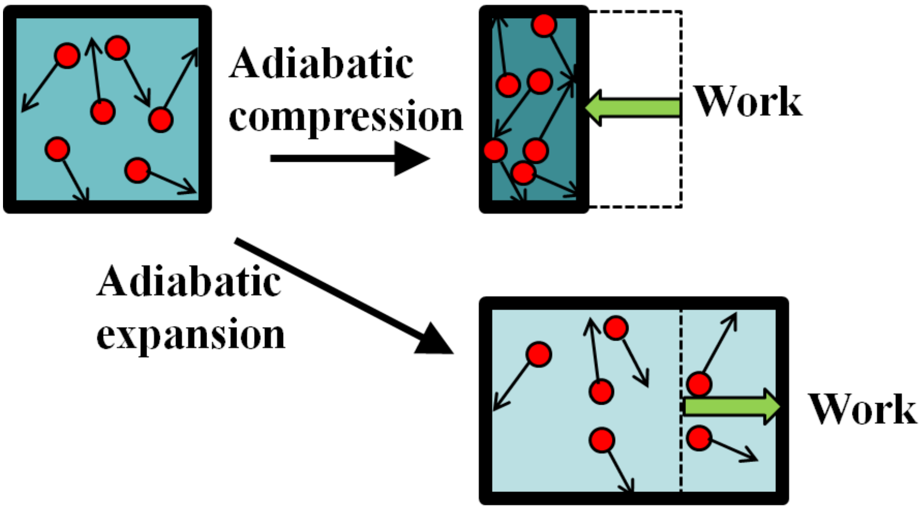


Fig. 5.3: Adiabatic compression and expansion.

The physical quantity, which varies with temperature, is used to measure the temperature: the pressure of the gas (e.g., the vapor pressure), the density of the liquid (e.g., mercury), the deformation of the solid (e.g., bimetal), the electrical resistance (e.g., platinum resistors, thermistors), the thermal electromotive force (e.g., thermocouple), the infrared radiation, the viscosity coefficient, and the propagation speed of the elastic wave.

When the temperature of the sensor element itself should be same as that of the object, it is necessary to pay attention to the heat transfer phenomena. The amount of heat transfer per unit parameters (area, time, and temperature difference) is called the **heat transfer coefficient** *Hc*. The unit is J m^{-2} s^{-1} K^{-1} or W m^{-2} K^{-1}. The heat transfer Q [J] is proportional to the area A [m^2], the time t [s], and the temperature difference ΔT [K].

$$Q = Hc\, A\, t \Delta T \qquad (5.6)$$

It takes time to measure temperature, when the heat capacity of the sensor element is large. It also takes time, when the heat transfer rate to the sensor element is small. The temperature of the object might change by the heat transfer during the measurement.

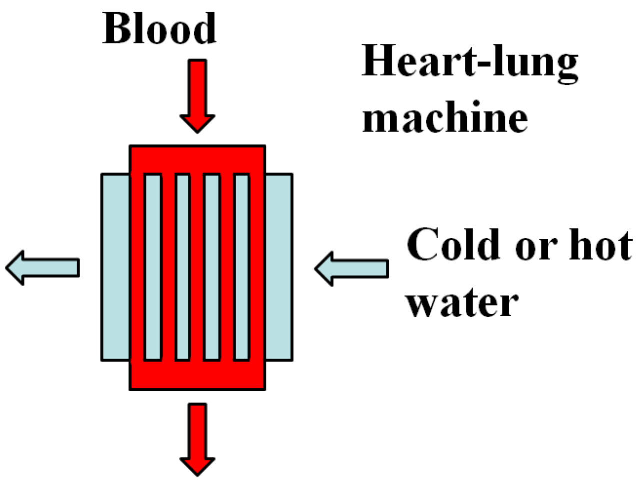
The thermal energy [J s^{-1} m^{-2}], which passes through unit area in unit time, divided by the temperature gradient [K m^{-1}] is called the **thermal conductivity**. The unit is J s^{-1} m^{-1} K^{-1} or W m^{-1} K^{-1}. The thermal conductivity is high in the solid of metal. It is lower in the liquid than in the solid. It is lower in the gas than in the liquid.

Human body temperature is maintained at around 310 K. With the change of the temperature, the three-dimensional structure of biological macromolecules changes, which change the function. In maintaining biological activity, the temperature control plays an important role. For example, through changes in chemical bonding, such as phosphoric acid binding, the heat (exothermic, endothermic) occurs. The body temperature is maintained by several effects: the insulating effect by the skin and by the fat layer, and the heat transfer effect of the blood flow.

The water absorbs the heat during the phase transition from the water to the vapor. The **heat of vaporization** of water is 40.8 kJ mol^{-1}. The heat of vaporization of water is larger than that of other substances, because of the hydrogen bonds between molecules of the water. The vaporization in sweating makes radiation of the heat through the skin in the body.

The phase transition from ice to water absorbs heat. The **heat of fusion** of the ice is 6.01 kJ mol^{-1}. Conversely, the phase transition from water to ice generates heat. Both the heat of vaporization and the heat of fusion are referred to **latent heat**.

In some warm-blooded animals, the body temperature is lowered during hibernation [12]. In the **hypothermia** therapy, the metabolism is suppressed by lowering the body temperature. In the **heart-lung machine**, the blood temperature is lowered during cardiac surgery by the **heat exchanger** (**Fig. 5.4**).



$$Q = Hc\,A\,t\Delta T \qquad (5.6)$$

Fig. 5.4: Heat exchanger.

A fluctuating magnetic field produces an alternating electric current. The electric current generates heat through the resistance. The electric current also generates heat through the living tissue. Cells are destroyed at high temperature. In some cases, on the other hand, the high body temperature is applied to medical treatment (**hyperthermia**). In hyperthermia, cancer cells are selectively killed by slightly elevated temperature. In the treatment, heat generated by the local current is applied.

The effect of the magnetic field on the living body has been investigated [32-34]. The effect of the temperature rise due to local currents induced by the magnetic field should be distinguished from the effect of the magnetic field itself. The effect of temperature rise by a heater can be compared with that by the magnetic field (**Fig. 5.5**). The effect of the magnetic field, on the other hand, can be eliminated, when cells are cultured in the space shielded by a metal sheet of magnetic material (**Fig. 5.6**).

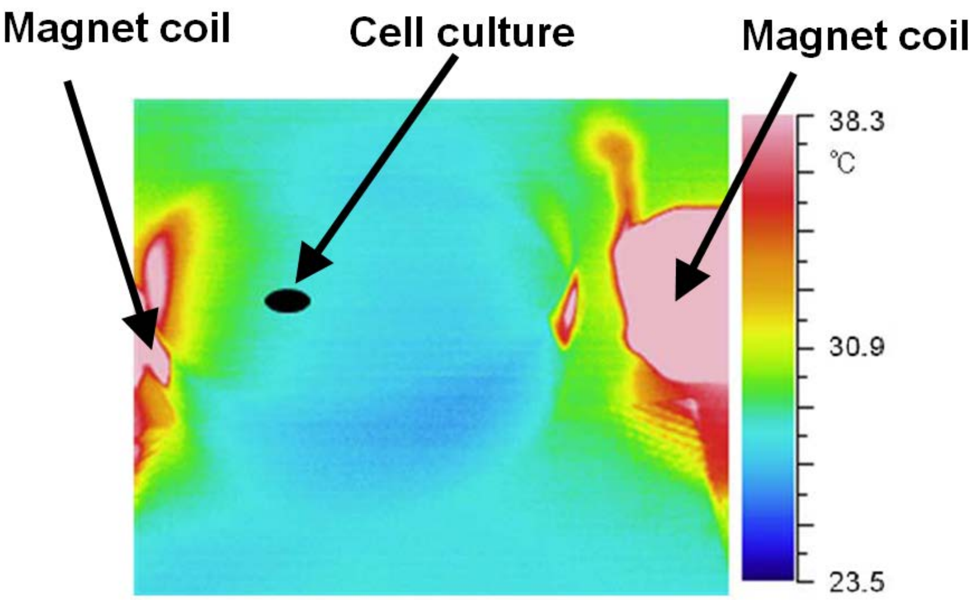


Fig. 5.5: Thermography.

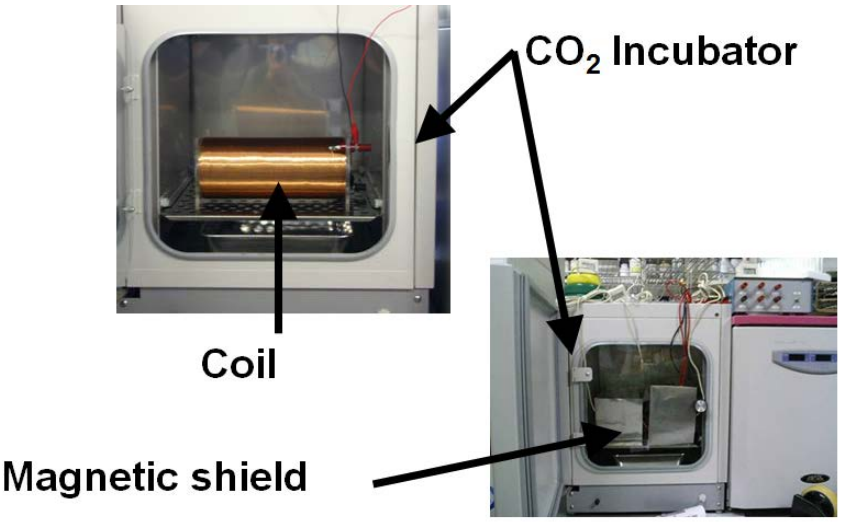


Fig. 5.6: Cell culture in magnetic field.

Thermography is used to measure the surface temperature distribution [32]. The thermography detects the amount of infrared rays radiated from a substance in proportion to the fourth power of absolute temperature.

Electrical pulses also give a variety of effects on the organism (see 7.2.1) [35].

5.1.4 Phase transformation

Substances changes own phase with the lowering of temperature: from a gas to a liquid, or from a liquid to a solid. In most of substances, the density increases with these phase change. The density of the water, on the other hand, decreases (the volume increases) with the phase change from a liquid to a solid. At freezing by cooling the bottle containing the water, the container may burst. The burst occurs because of the increase of the volume of the water against the decrease of the capacity of the bottle.

A biological cell contains a large amount of water. At the rapid freezing, the membrane of the cell might be broken (**Fig. 5.7**). The water should penetrate through the membrane fast enough to inhibit the rupture of the membrane. For the cryopreservation of red blood cells, the rupture of the membrane accompanied by freezing of water should be controlled. Several methods have been proposed: regulation of cooling speed, or replacement of the water with other solvents.

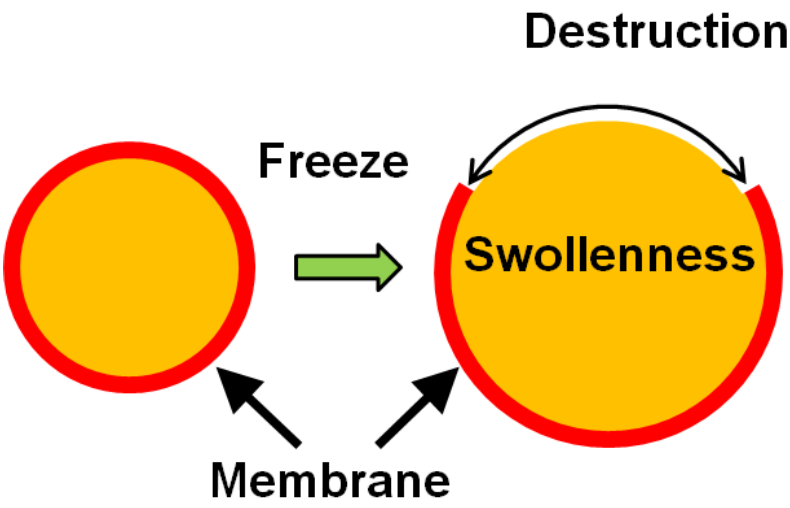


Fig. 5.7: Membrane destruction during freeze.

A state, in which atoms are arranged regularly, is called "**crystal**". A state, in which sequences are not developed, on the other hand, is called "**amorphous**". When you heat the synthetic resin or the natural rubber, fluidity is rapidly increased above a certain temperature. The temperature is called the "**glass transition temperature**". The amorphous state below the glass transition temperature is called the glass state. At the higher temperature above the glass transition point, the solid becomes a liquid or rubbery state.

At the aggregation of molecules of polymer, both conformation of each molecule and arrangement of the molecules vary with temperature. A state, which has regularity as crystal and fluidity as liquid, is called "**liquid crystal**". The liquid crystal shows an optical anisotropy. Biopolymers also form the regular structure, such as a lipid bilayer (**Fig. 5.8**) in biological membranes.

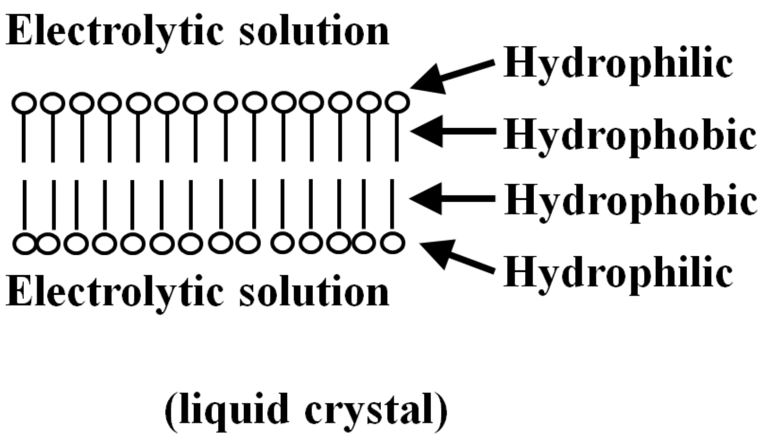


Fig. 5.8: Lipid bi-layer.

5.2 Energy conversion

5.2.1 Form of energy

A machine works. The machine not only transmits the motion to the motion, but also converts gravitational field, heat, electricity to the motion. The conversion can be calculated by a common physical quantity of "energy": "**kinetic energy**", "**potential**

energy”, “**thermal energy**”, and “**electrical energy**”. The energy is described by a common quantity with a unit of J (joule) as the quantity conserved during the conversion (**law of conservation of energy**).

The friction between the skins increases the temperature of the surface of the skin. In this case, the kinetic energy is converted into heat energy through the friction. In the falling motion in a gravitational field, the velocity increases during falling. In this case, the potential energy is converted into the kinetic energy. The electric motor converts the electrical energy to the kinetic energy.

In the gravitational field, an object falls from a higher position to a lower position. The potential energy is higher at the higher position. In the shunt for hydrocephalus, the change of the attitude of an individual varies the head of fluid between the two positions, which are connected with the shunt. The flow rate through the shunt depends on the head of fluid (see 4.1.1) [20].

The flow rate can be measured by temperature change. A catheter is inserted into the pulmonary artery through the right atrium. The temperature of the blood flow, which is warmed by hot wire upstream in the right atrium, is measured downstream of the pulmonary artery. The blood flow is calculated by the equation, in which the received energy at the blood is equal to the added energy at the heat wire (see Question 5.2). A certain volume of cooled physiological saline can be injected to the right atrium instead of using the hot wire (**Fig. 5.9**).

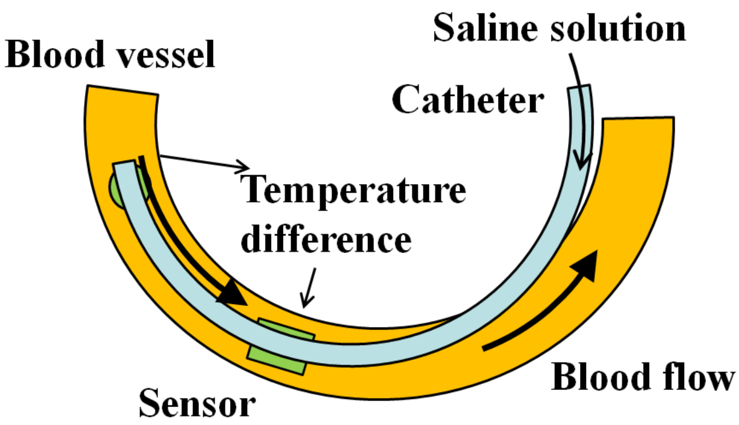


Fig. 5.9: Flow measurement with catheter.

5.2.2 Conversion efficiency

In the energy conversion, the ratio converted into the targeted energy is called **efficiency**. For example, the muscle is heated, when you move the muscle. In the muscle, 100% of chemical energy cannot be converted into the kinetic energy. The rest of energy becomes heat energy, which raise the temperature of the surroundings.

Through friction, "work" is converted to heat. A "**heat engine**" is necessary, on the other hand, to convert heat into work. A "**Carnot cycle**" a heat engine, which utilizes the energy flow from the high-temperature heat source to the low temperature heat source. In the Carnot cycle, four processes repeat: the adiabatic compression process (see Fig. 5.3), the isothermal heat absorption expansion process, the adiabatic expansion process, and the isothermal heat dissipation compression process. It is not possible to make the efficiency of conversion from heat to work 100%.

At the implanted machine, such as artificial organs, the low efficiency generates excess heat. For example, the low efficiency of the implanted artificial heart generates heat to be dissipated. If the heat cannot be dissipated through the blood of circulation and the air of respiration, the temperature of the surrounding tissue is elevated.

At transmitting the energy from outside into the body, the low efficiency generates the excess heat. When the implanted battery is charged through the skin from the outside, the low efficiency raises the temperature of surrounding tissue.

The left ventricle ejects the cardiac output against the pressure difference between the left atrium and the aorta. The power of the pumping is equivalent to 1 W at the left ventricle of an adult at rest. Consider a blood pump driven by an electric motor. When the conversion efficiency from the electrical energy into mechanical energy is 25%, the required electrical energy is 4 W, which corresponds to the product of the voltage of 4 V and the current of 1 A.

5.3 Substance transportation

5.3.1 Permeability through membrane

In the living body, transportation is realized by the pressure gradient, the concentration gradient, the temperature gradient, the electric gradient, and the flow. As a result, the state tends to uniform state.

According to the law of entropy increase (see 5.1.3), the state of nature tends to become disorder. Consider how to counter the "direction to the chaotic state". For example, separation by a wall can control the movement of the material. Several partitions control the movement of the material *in vivo*: the vessel wall, the tissue membrane, and the cell membrane.

In the **lung**, oxygen is taken up in the blood and carbon dioxide is discharged from the blood. The gases are exchanged between the air and blood through the membrane of the **alveolus**. The permeate flow rate of the gas (Q) through the membrane is proportional to the partial pressure difference (ΔP) of the gas and to the area of the membrane (S). The flow rate is inversely proportional to the thickness of the membrane d (**Fig. 5.10**).

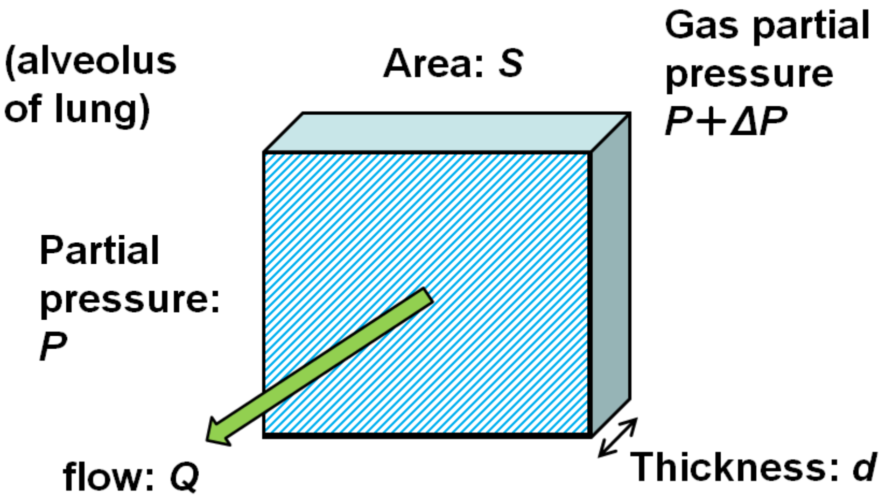


Fig. 5.10: Transport through membrane.

$$Q \propto S \Delta P / d \tag{5.7}$$

The volume percentages of nitrogen and oxygen in the air are 80% and 20%, respectively. Water vapor is saturated in the trachea. The partial pressure of the water vapor in the air is 6.2 kPa at 310 K. In the trachea, the volume percentage of the carbon dioxide is 5%. The wall thickness of alveolus is about 1 μm, which corresponds to the blood vessel wall thickness of the capillary. From the average diameter and the number of alveoli, the sum of the lung membrane area of adults is estimated to be 100 m^2.

The membrane area at the membrane oxygenator of the heart-lung machine used during the cardiac surgery, on the other hand, is about 1 m^2. The **membrane oxygenator** consists of hollow fibers. The wall thicknesses of hollow fibers are 200 μm in case of silicone and 25 μm in case of polypropylene, respectively. Compared to the adult lung, the oxygenator has smaller membrane area, and thicker membrane.

The gas partial pressure in the vicinity of the membrane depends on the fluid flow in the vicinity of the membrane. The agitation of the fluid prevents the accumulation of gas content in the **boundary layer** near the membrane (see 4.2.3). Both the pulsatile blood flow and the vibration of the membrane produce a stirring effect (**Fig. 5.11**). Turbulence also exerts the stirring effect as a non-steady flow.

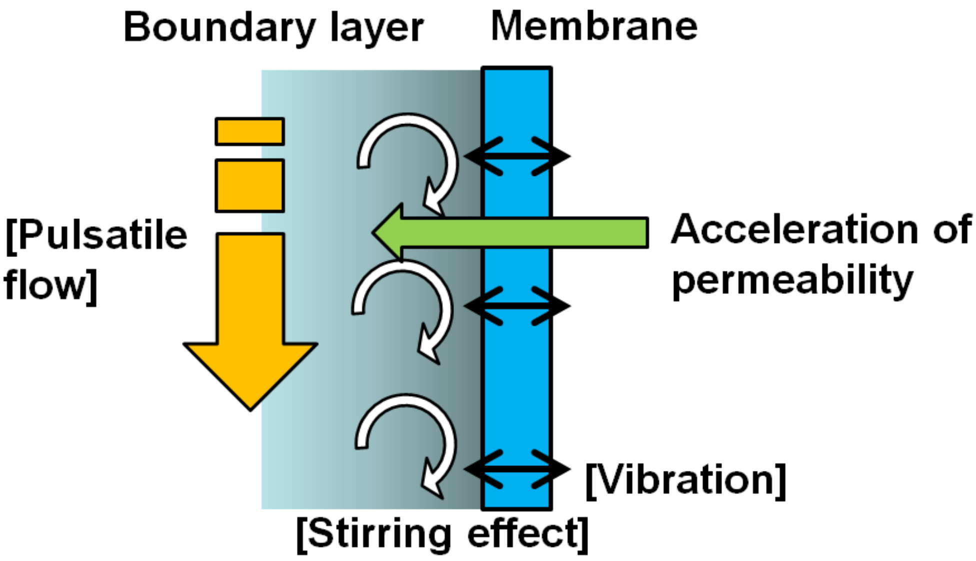


Fig. 5.11: Acceleration of permeability.

For example, agitation of the fluid by the pulsatile flow or membrane vibration improves the gas exchange efficiency of the oxygenator. At the silicone tubes bundled in the gas exchanger, the gas exchange efficiency is improved by several methods: the pulsatile blood flow, the pulsatile gas flow, and the vibration of the membrane by adding cyclic pressure to the membrane. When the blood flow path contains one-way valve, the blood can be pumped by the cyclic pressure. The method realizes the device, which integrates the pump and the gas exchanger (**Fig. 5.12**) [36].

The lung of a living body, on the other hand, has the huge total membrane area. The lung can exchange enough gases even in a non-pulsatile flow [37].

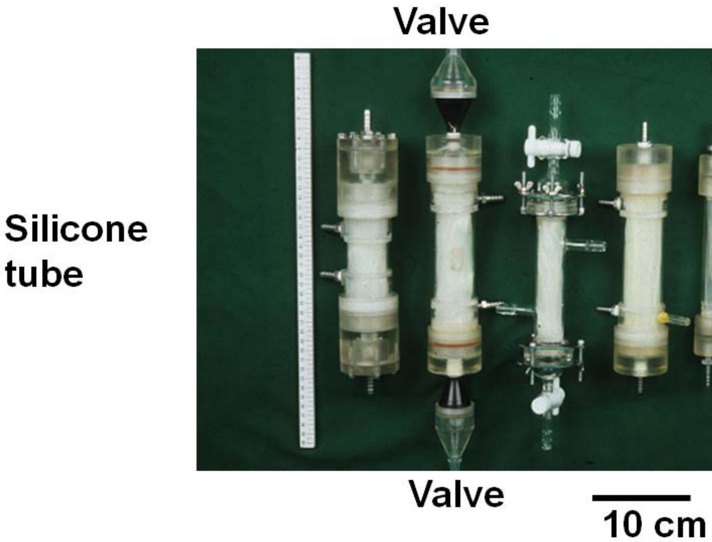


Fig. 5.12: Vibrating membrane oxygenator.

5.3.2 Osmotic pressure

At the capillary wall, substances are transported by the pressure difference and by the osmotic pressure difference. When the solution is divided by the semi-permeable membrane, through which a particular solute cannot pass, the solvent moves to balance the concentration of the solute at both sides of the membrane. The driving force is expressed by the **osmotic pressure** *P*.

$$P = (n / V)\, R\, T \qquad (5.8)$$

In the equation (5.8), (see equation (5.1)) n / V is the molar concentration of the solution [mol m^{-3}], R is the gas constant, and T is the temperature [K].

The solution, which has the higher osmotic pressure, is called "**hypertonic solution**". The solution, which has the equal osmotic pressure, is called "**isotonic solution**". The solution, which has the lower osmotic pressure, is called "**hypotonic solution**".

The unit of the osmotic pressure is Pa, which is the same unit as the pressure. The serum, which is the supernatant of blood, includes the constant concentration of ions (Na^+, Ca^{2+}, K^+, Cl^-, etc.). The solution, which contains the equal concentration of ions, is called the **isotonic solution**. The NaCl aqua solution of 0.9% mass concentration has the osmotic pressure of 7.7×10^5 Pa at 310 K, which is isotonic to the serum. The isotonic solution for serum is called the **saline solution**.

At the movement of substances *in vivo,* the attractive force between molecules works effectively. The osmotic pressure of the polymer is estimated smaller. Because the number of molecules of polymers is smaller than that of ions *in vivo,* the osmotic pressure of polymers is estimated smaller, which may play a major role in the movement of a solvent. Polymers such as carbohydrate in plasma have the attract function to the water. This is called a **colloid osmotic pressure** (**oncotic pressure**). In a transfusion during the circulatory assist, it is important to regulate not only the osmotic pressure by smaller molecules, but also the colloid osmotic pressure by larger molecules [38].

At the red blood cells, the transportation of the solvent occurs across the membrane. In hypertonic solution, the water comes out to the outside, which makes the **crenated cell**. Conversely, in hypotonic solution, the water comes into the inside, which makes the **swollen cell** (**Fig. 5.13**).

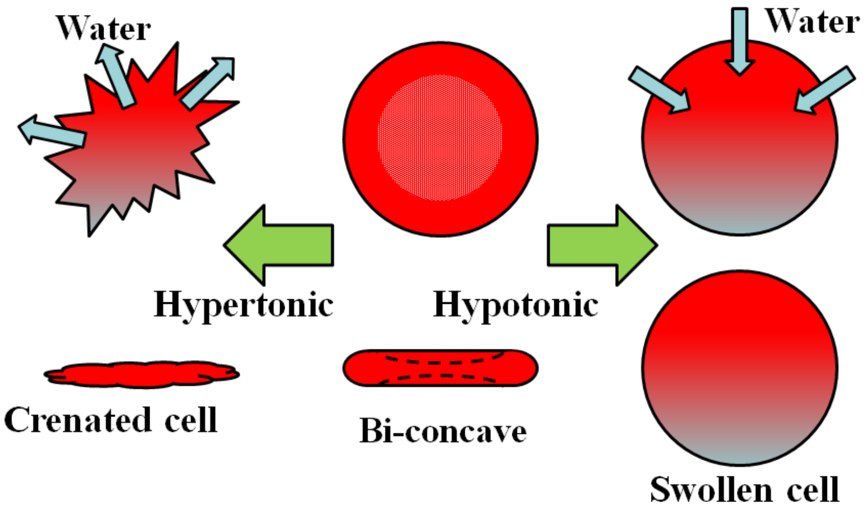


Fig. 5.13: Erythrocyte deformation with osmotic pressure.

The hemolysis owing to the rupture of the membrane of erythrocyte by swelling is applied to the **erythrocyte osmotic fragility test**. Osmotic pressure is measured, when the red blood cells causing hemolysis: “start of hemolysis”, and “hemolysis at every erythrocyte” (**Fig. 5.14**). Measurement value detects variations due to individuality and timing. The method is applied to compare hemolysis in artificial hearts, and to distinguish the cause of the hemolysis [39].

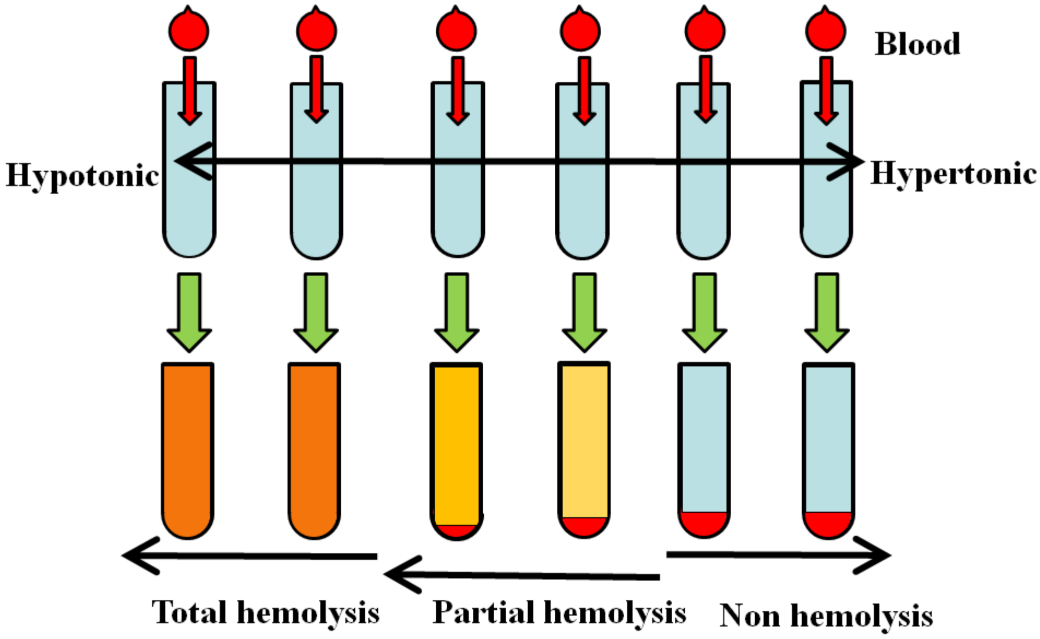


Fig. 5.14: Erythrocyte osmotic fragility test.

The **kidney** discharges the unnecessary components in the blood. The **hemodialyzer** moves the substances into the dialysate from the blood through the dialysis membrane. Both emissions of carbon dioxide at the lungs and the discharge of hydrogen ions at the kidney maintain pH in the blood (see Eq. 5.3).

The difference of the concentration of each ion between both sides of biological membranes generates the **membrane potential** (**Fig. 5.15**). The selective channel of potassium at the biological membrane is equivalent to an electromotive force, which is a battery directed to the extracellular. When the selective channel of sodium at the biological membrane opens, the transmembrane potential changes by the opposite electromotive force. Signals are transmitted by variations of membrane potential at neurons [24]. Electrical pulses, on the other hand, promote mass transfer in the electrolyte gel [19].

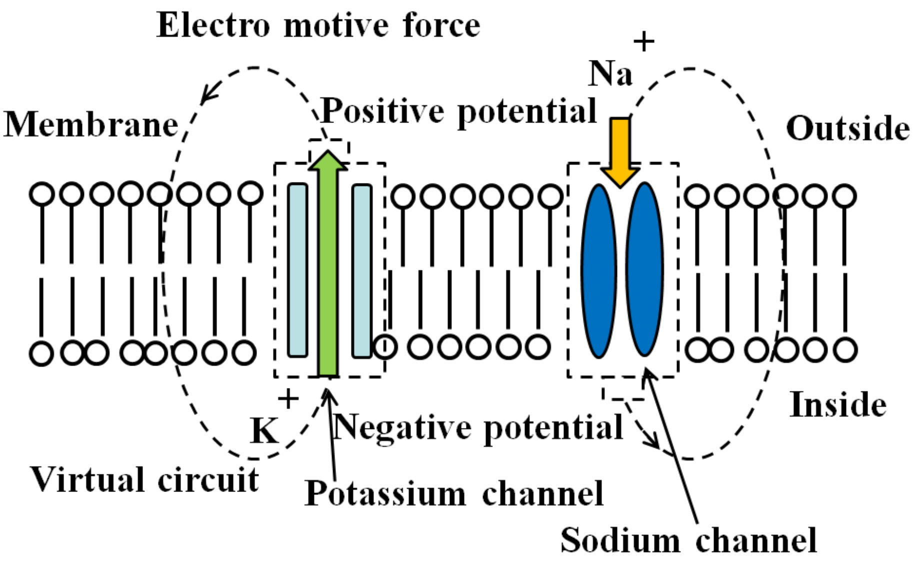


Fig. 5.15: Membrane potential.

Questions (Exercises)

Q 5.1: How much is the heat of vaporization of water of 10 cm^3.

Q 5.2: Calculates the rise of the temperature of the water downstream, when the flowing water at the flow rate of 10 ml per second is heated through electrical resistance of 1 kΩ at the electric current of 0.1 A in the following condition: the specific heat of water is 4.2×10^3 J kg^{-1} K^{-1}, the density of water is 1×10^3 kg m^{-3}, and all of the electrical energy is converted to a temperature rise of the water.

Q 5.3: Find the work rate of the pump to send the blood in place of the right ventricle by an electric motor, when the parameters are as follows: the cardiac output is 1.0×10^{-4} m^3 s^{-1}, the pressure difference between the pulmonary artery and the right atrial is 2×10^3 Pa, and the energy conversion efficiency from electrical energy to work to send the blood is 25%.

Q 5.4: Find the temperature rise rate of the surrounding water 1×10^{-4} m^3, when the rest of the energy is converted into heat in the case of the question 5.3. Specific heat of the water is 4.2×10^3 J kg^{-1} K^{-1}, and the density of water is 1×10^3 kg m^{-3}.

Q 5.5: A solvent is passing through a semipermeable membrane. How many times more of solvent pass through the membrane when the parameter changes as follows: the membrane area becomes four times more, the film thickness becomes 2-fold more, the osmotic pressure difference becomes doubled?

Q 5.6: Calculate osmolarity of plasma, as an aqueous solution containing cations and anions: each molar concentration of 1.5×10^2 mol m^{-3}.