CONTENT MODULE 2. Fundamentals of Applied Biophysics

TOPIC 6A. Physical Properties of Liquids. Basics of Hemorheology and Hemodynamics

Hydrostatics and Hydrodynamics

The liquids (blood, lymph, interstitial and cellular fluids) flow in biological systems play an important role, providing conditions for normal vital activity of various physiological systems. Liquids have a number of properties that are determined by the characteristics of their molecular structure.

Exercise 6.1a. Define the following terms:

The perfect fluid is ____

____

____

Real fluid is ____

____

____

Exercise 6.2a. The perfect fluid flow obeys the Bernoulli`s equation (write down the equation, fill in the names with its components and answer questions):

(6.1a)

ρ is ____

υ is ____

h is ____

p is ____

The physical sense of the Bernoulli equation is ______________________________

____

____

P is ____

$\rho\upsilon^2/2$ is ____

$\rho g h$ is ____

Exercise 6.3a. The fluid flow obeys the continuity equation of flow (please write down this equation, name physical quantities and their units of measurement):

(6.2a)

A is ____

Q is ____

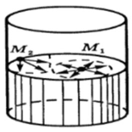
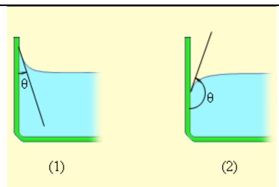
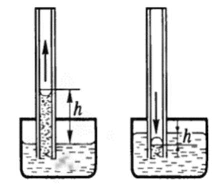
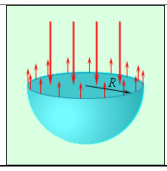
Problem 6.4a. Find the volumetric flow rate of blood in the aorta if the inner diameter of aorta is 1.8 cm, and the mean linear speed of the blood in it is 0.5 $m \cdot s^{-1}$.

Data:	***Solution:***

Answer: ____

Exercise 6.5a. Fill in the table with the descriptions of physical properties of fluids:

Table 6.1.a.

Properties of fluids	Equation	Unit of measurement	Picture
Density	(6.3a)		
Surface tension	(6.4a)		
Viscosity	(6.5a)		
Wetting / non-wetting	(6.6a)		
The capillary effect (a) Juren's formula	(6.7a)		
The capillary effect (b) Laplace's formula	(6.8a)		

Problem 6.6a. One hundred droplets of liquid with a total mass m = 5.1 g dosing from a dropper with internal diameter d = 2 mm. Determine the surface tension of the liquid.

Data: | ***Solution:***

Answer: ____

Exercise 6.7a. *Newton's low* of fluid friction has the form (please write down this equation, name physical quantities and their units of measurement):

(6.9a)

η is ____

$\frac{\Delta \upsilon}{\Delta x}$ is ____

Exercise 6.8a. Underline correct answer.

1. Newtonian fluids are (choose):

a) water; b) suspensions; c) polymer solutions and melts; d) any organic solvents; e) blood.

2. Non-Newtonian fluid are (choose):

a) water; b) blood; c) emulsions; d) suspensions; e) organic solvents.

On the body, which is moving in a viscous medium acts the drag force. The magnitude of this force depends on many factors, for small spherical bodies at low speeds the drag force determined by the Stokes`s low: (6.10a)

Problem 6.9a. Suspension of liver cells with radius of cell equal to 0.12 mm and density equal to 1100 $kg \cdot m^{-3}$bring in a cylinder with buffer liquid with density ρ = 1050 $kg \cdot m^{-3}$. At what distance will sediment liver cells per 10 seconds, if they fall uniformly (buffer liquid viscosity η=1012 $\mu Pa \cdot s$)?

Data: | ***Solution:***

Answer: ____

Example of problem solution

The erythrocytes in the solution with a specific density $\rho_{sol} = 1070\ kg \cdot m^{-3}$ and viscosity $\eta = 1012\ \mu Pa \cdot s$ change their shape to a spherical, i.e. become spherocytes. Spherocytes uniformly sediment for each $t = 5\ s$ at a distance $h = 20\ \mu m$. Find the radius of spherocytes if their density $\rho_{sph} = 1100\ kg \cdot m^{-3}$.

Data:

$\rho_{sol} = 1070\ kg \cdot m^{-3}$

$t = 5\ s$

$\eta = 1012\ \mu Pa \cdot s = 1012 \times 10^{-6}\ Pa \cdot s$

$h = 20\ \mu m = 20 \times 10^{-6} m$

$\rho_{sph} = 1100\ kg \cdot m^{-3}$

R-?

Solution:

According to the definition, mean sediment speed is: $\upsilon = \frac{h}{t}$.

Spherocytes sediment (move) in a viscous fluid and undergone the action of three forces:

1) gravity force (down): $mg = \frac{4}{3}\pi R^3 \rho_{sph} g$;

2) buoyancy force (up): $F_b = \rho_{sol} V g = \frac{4}{3}\rho_{sol}\pi R^3 g$;

3) fluid friction force (up): $F = 6\pi\eta R\upsilon$.

In uniform motion the algebraic sum of these forces must be zero:

$$mg - F_b - F_{ff} = 0, \text{ or } \frac{4}{3}\pi R^3 \rho_{sph} g - \frac{4}{3}\pi R^3 \rho_{sol} g - 6\pi\eta R\upsilon = 0.$$

After simple conversion: $\eta = \frac{2gR^2\left(\rho_{sph} - \rho_{sol}\right)}{9\upsilon}$.

From here: $\upsilon = \frac{2g\left(\rho_{sph} - \rho_{sol}\right) \cdot R^2}{9 \cdot \eta} \Rightarrow$

$$R = \sqrt{\frac{\upsilon \cdot 9 \cdot \eta}{2g\left(\rho_{sph} - \rho_{sol}\right)}} = \sqrt{\frac{h \cdot 9 \cdot \eta}{2g\left(\rho_{sph} - \rho_{sol}\right) \cdot t}} =$$

$$= \sqrt{\frac{20 \times 10^{-6} \times 9 \times 1012 \times 10^{-6}}{2 \times 9.81 \times (1100 - 1070) \times 5}} = 7.87 \times 10^{-6}\ m.$$

***Answer*:** Radius of spherocytes is equal to 7.9 × 10^{-6} m.

The basic formula that determines the amount of fluid that flowing through any cross-section of tube per time t (Poiseuille`s equation) is:

(6.11a)

where *X*– called *hydraulic* or hydrodynamic resistance:

$X =$ (6.12a)

We can draw an analogy between hydrodynamics laws and laws that determine the electrical current in the circuit.

Exercise 6.10a. Specify arrows the accordance between the physical quantity and the formula for its calculation:

1) Total hydraulic resistance X_Σ of two series-connected tubes	a) $X_\Sigma = (X_1 + X_2)$ (6.13a)
2) Total hydraulic resistance X_Σ of two parallel-connected tubes	b) $X_\Sigma = \dfrac{X_1 \cdot X_2}{X_1 + X_2}$ (6.14a)

Problem 6.11a. Calculate the hydraulic resistance *X* of aorta if its diameter is *d*= 2.35 cm, length is *l* = 4 cm, blood viscosity is 5.5 mPa·s.

Data: | ***Solution:***

Answer: ____

There are two modes of flow of viscous liquid - laminar and turbulent.

The transition from one mode to another depending on the value of the Reynolds number:

$$\text{Re} = \qquad (6.15a)$$

ρ – ____

υ - ____

D - ____

$\text{Re}_{cr} = 2300$ - critical Reynolds number.

$\text{Re} < \text{Re}_{cr}$ - the flow is _______________

$\text{Re} > \text{Re}_{cr}$ - the flow is _______________

Problem 6.12a. Determine the Reynolds number for rabbit artery with diameter *d* = 0.3 cm, if the linear speed of blood in it is $\upsilon = 0.6\ \text{m}\cdot\text{s}^{-1}$, and the viscosity is $\eta = 4.5\cdot 10^{-3}$ Pa·s. Which mode of flow corresponds obtained number? Blood density is $\rho = 1050\ \text{kg}\cdot\text{m}^{-3}$.

Data: | ***Solution:***

Answer: ____

Biophysics of the Blood Circulatory System

Blood plays the leading role in the distribution of medicines in the body. The action of many medications is aimed to change rheological (e.g., viscosity) and hemodynamical (e.g., blood pressure) blood parameters.

Blood is a liquid with pronounced non-Newtonian properties, but they are expressed much weaker in plasma than in whole blood. It follows that the non-Newtonian properties of blood related, primarily, with blood cells.

Exercise 6.13a. Which mode has blood flow in the vascular system normally (underline):
a) laminar; b) turbulent; c) slow; d) pulse; e) the other answer.

In capillary network at a slow speed of movement an exchange of substances between blood and tissues takes place. The dependence of the viscosity of blood on hematocrit can be described by an exponential function:

$$\eta = \eta_0 \, e^{2c} \qquad (6.16a)$$

η_0 is ____

c is ____

Exercise 6.14a. List the basics of the Frank`s model:

____

____

____

____

____

Exercise 6.15a. Define the pulse wave:

____

____

____

The rate of transmission of pulse wave depends on the properties of the blood vessels and described by the equation:

$$\upsilon = \qquad (6.17a)$$

E is ____

h is ____

ρ is ____

d is ____

Experimental determination the rate of transmission of pulse wave is a basis of diagnostics of the blood vessels.

Problem 6.16a. The rate of transmission of pulse wave in an artery is $\upsilon = 10\ m\cdot s^{-1}$. Determine the modulus of elasticity E of artery walls if its thickness is h = 0.7 mm, internal diameter of artery is d = 8 mm, the density of blood is $\rho = 1050\ kg\cdot m^{-3}$.

Data:	***Solution:***

Answer: ____

Control questions

1. What is the velocity gradient? In what units it is measured.
2. Under what conditions Stokes`s equation is applicable?
3. List the basic hemodynamic parameters.
4. Describe the Frank`s model.
5. What is hematocrit?
6. What mode of blood flow we can observe in aorta? In veins?

Individual assignments

1. Using Stokes' law, determine after what time in the room with height *h* = 3 m will completely fall out the dust. Particles of dust assume globular with a diameter of 1 μm and density $\rho = 2.5 g \cdot cm^{-3}$.
2. One hundred droplets of alcohol with a total mass *m* = 0.71 g were dosed from a dropper. Determine the diameter of the drop waist at the time moment of drop separation if the surface tension of alcohol is $0.0222\ N\cdot m^{-1}$.
3. Calculate the diameter of the drop waist at the time moment of drop separation. The mass of a drop of distilled water is *m* = 50 mg.
4. In sandy soils capillary water rises to a height of 1.5 m. The water temperature is 20 °C, and its density is $1000\ kg\cdot m^{-3}$. Determine the diameter of soil capillaries. Wetting is considered as complete.
5. ESR (erythrocyte sedimentation rate) in cattle's blood plasma with the addition of an anticoagulant normally is $0.9\ mm\cdot h^{-1}$. Calculate the diameter of red blood cells; consider their shape to be spherical and their movement obeys Stokes' law. The density of erythrocytes is 1250 $kg\cdot m^{-3}$, density of blood plasma is $1080\ kg\cdot m^{-3}$. The coefficient of viscosity of plasma with anticoagulant is 9.5 mPa·s.
6. Calculate the maximum minute volume Q_{max} of blood, at which the blood flow in the aorta remains laminar. The diameter of aorta is d = 2 cm, the blood viscosity is η = 5 mPa·s, the blood density is $\rho = 1050\ kg\cdot m^{-3}$, the critical value of Reynolds number is $Re_{cr} = 2000$.
7. The rate of transmission of pulse wave in an artery is $\upsilon = 12\ m\cdot s^{-1}$. Determine the modulus of elasticity E of artery walls if its thickness is h = 0.8 mm, internal diameter of artery is d=10 mm, the density of blood is $\rho = 1250\ kg\cdot m^{-3}$.

TOPIC 6.B. Electrostatics. Electric Current. The Motion of Charged Particles in the Electric Field

The most spread phenomena that a person has to deal with are connected to *electromagnetic interaction*. To receive substantial knowledge in the field of chemicals interaction with alive organisms is possible only with a deep leaning of *electromagnetism*.

Electrostatics

Exercise 6.1b. Define the following terms:

Electrostatics is ____

____

Electric charge is ____

Electric field is ____

____

Formulate and write down the charge conservation law. ______________________

____

____

The force of interaction between two point charges is determined by the *Coulomb`s law*:

$$\left|\vec{F}_{12}\right| = \frac{q_1 q_2}{4\pi\varepsilon_0\varepsilon r_{12}^2} \qquad (6.1b)$$

Exercise 6.2b. Write down the parameters definitions, their measurement units and the constants numerical values in the Coulomb`s law:

$\vec{F}_{12}$ is ____

q_1, q_2 are ____

r_{12} is ____

ε_0 is ____

ε is ____

The quantitative electric field characteristic is its *strength* E ($V \cdot m^{-1}$), which is given at each point of space as a force that acts on a unit positive point charge at that point:

$$\vec{E}_{(x,y,z)} = \frac{\vec{F}_{(x,y,z)}}{q} \qquad (6.2b)$$

In the scalar form, the field strength, which is created with a point charge q at the distance r, is:

$$E = \frac{q}{4\pi\varepsilon_0\varepsilon r^2} \qquad (6.3b)$$

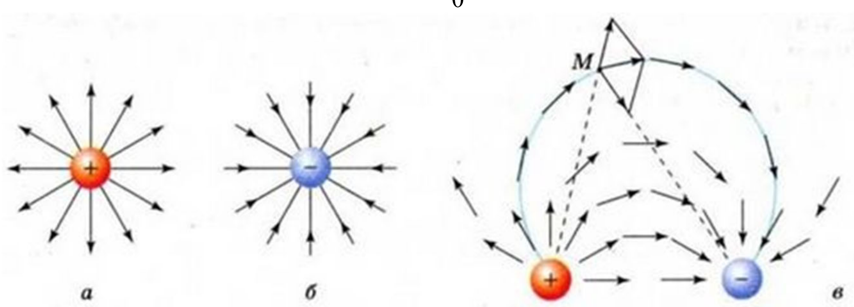


Fig. 6.1b. Lines of electric flux for point charges (a, b) and dipole (c).

Exercise 6.3b. Write down the *superposition principle for electric fields*:

____

____

____

____ (6.4b)

Problem 6.4b. Two point charges $q_1 = +5$ nC and $q_2 = -8$ nC are situated on the distance $r = 20$ cm from each other. The point N is situated in the middle between these charges. Find the strength of the electric field E at the point N. The relative permittivity of the medium is $\varepsilon = 5$.

Data:	***Solution:***

Answer ____

Electric dipole is ____

____

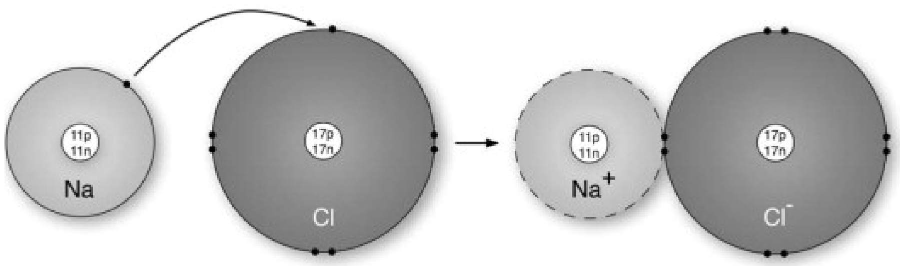


Fig. 6.2b. The formation of NaCl electric dipole molecule.

The electric dipole moment is____

____

The electric dipole moment is determined by the following formula:

$$\vec{P} = q\vec{l} \qquad (6.5b)$$

The moment of the force couple acting on the electric dipole, located in an electric field is:

$$\vec{M} = \left[\vec{P} \times \vec{E}\right] \qquad (6.6b)$$

Exercise 6.5b. Write down the parameters definitions and their units in formulas (6.5b) – (6.6b):

$\vec{P}$ is ____

$\vec{l}$ is ____

$\vec{E}$ is ____

The electric potential of the field at the point can be defined as the work required to bring the positive charge from this point to infinity per unit of charge:

$$\phi = \frac{W_\infty}{q} \tag{6.7b}$$

The work on bringing the charge from point 1 to point 2 is:

$$W_{12} = q\left(\phi_1 - \phi_2\right) = qU \tag{6.8b}$$

The potential of the point charge field in a homogeneous dielectric is:

$$\varphi = \frac{q}{4\pi\varepsilon_0\varepsilon r} \tag{6.9b}$$

Exercise 6.6b. Write down the parameters definitions and their measurement units in formulas (6.7b) – (6.9b):

φ is ______________________________

W is ______________________________

q is ______________________________

U is ______________________________

r is ______________________________

Example of problem solution

Two point charges q_1 = 3 nC and q_2 = –5 nC are placed on the distance r_1 = 10 cm from each other. Calculate the work W, that has to be done against the electric field forces, to remove charges at the distance r_2 = 40 cm.

Data:	***Solution:***
q_1 = 3 nC q_2 = -5 nC r_1 = 10 cm r_2 = 40 cm	$W = \frac{q_1 q_1}{4\pi\varepsilon_0\varepsilon}\left(\frac{1}{r_1} - \frac{1}{r_2}\right),$
W – ?	$W = \frac{5\times10^{-9}\times3\times10^{-9}}{4\times3.14\times8.85\times10^{-12}}\left(\frac{1}{0.1} - \frac{1}{0.4}\right) \approx 3\times10^{-19}\ (J).$

Check of measurement units.

Including that: $[C] = [\text{A}\times s], [F] = \left[\frac{C}{V}\right], [V] = \left[\frac{W}{\text{A}}\right], [W] = \left[\frac{J}{s}\right]$, obtain:

$$[W] = \left[\frac{\text{C}\times\text{C}}{\frac{\text{F}}{\text{m}}\times\text{m}}\times\text{m}\right] = \left[\frac{\text{C}\times\text{C}}{\frac{\text{C}}{\text{V}}}\right] = [\text{C}\times\text{V}] = \left[\frac{\text{A}\times\text{s}\times\text{W}}{\text{A}}\right] = \left[\frac{\text{s}\times\text{J}}{\text{s}}\right] = [\text{J}].$$

Answer: to remove the charges at the distance 40 cm against the forces of the electric field, the work, that has to be done, is equal to $W = 3\times10^{-19}\ (J)$.

Conductors and Dielectrics in the Electric Field

Exercise 6.7b. Give definitions to the following terms, write down the physical measurement units:

Conductors are ______________________________

____

Capacitance is ______________________________

____

Electrical capacitor is ______________________________

____

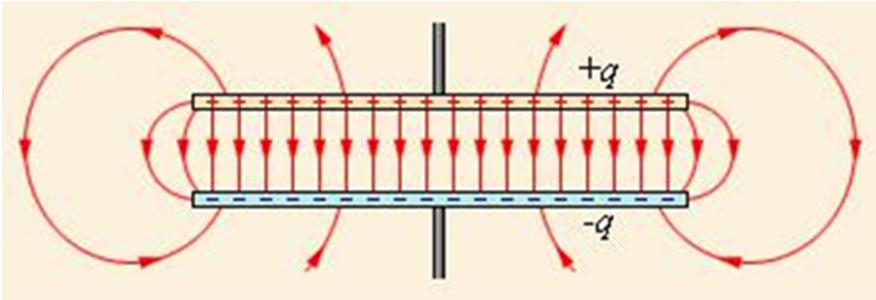


Fig. 6.3b. Parallel plate capacitor.

Exercise 6.8b. Write down the necessary formulas in Table 6.1b. Determine the parameters and their units of measurement.

Table 6.1b

Conductors in The Electric Field (basic formulas)

Title	Formula
Electric capacitor charge	(6.10b)
The capacitance of a plane capacitor	(6.11b)
The total capacitance of capacitors are connected in parallel	(6.12b)
The total capacitance of capacitors are connected in series	(6.13b)

where *C* is ____

U is ____

A is ____

d is ____

Problem 6.9b. The capacitance of a capacitor bank, which consists of two series-connected capacitors, is $C = 100$ pF and charge $q = 20$ nC. Determine the capacitance of the second capacitor and the potential difference (*voltage*) on the plates of each capacitor, if $C_1 = 200$ pF.

Data:	***Solution:***

Answer: ____

Exercise 6.10b. Define the following terms and complete the Table 6.2b:

Dielectrics are ____

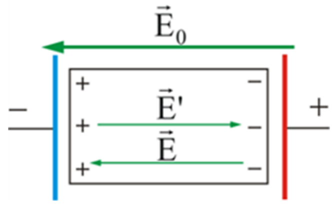
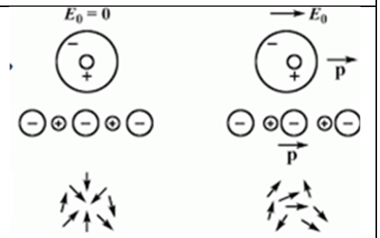
____

Polarization is ____

____

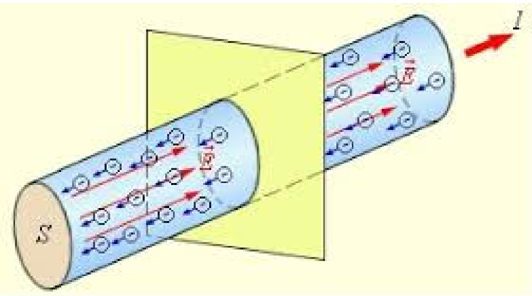
Table 6.2b

Main Characteristics of Dielectrics

Title	Definition	Formula and units	Picture
Polarization		(6.14b)	
Polarizability		(6.15b)	

Direct Electric Current

Exercise 6.11b. Define the following terms, their parameters and units of measurement:



Electric current is____

The electric current is determined by the following formula:

$$I = \frac{dq}{dt}, \tag{6.16b}$$

Direct electric current is ____

For direct current (DC):

$$I = \frac{q}{t}. \tag{6.17b}$$

The ratio of the current through a small surface element to the area of this element is called the *current density*:

$$j = \frac{dI}{dA}, \tag{6.18b}$$

where I is __________________________________

t is ____

j is ____

A is ____

Exercise 6.12b. Fill in the Table 6.3b, define the parameters and their units of measurement:

Table 6.3b

Ohm's Laws

Law	Formula
Ohm's law in the general case for a chain section	(6.19b)

Ohm's law for the complete chain	(6.20b)
Ohm's law in the differential form	(6.21b)

where U is ____________________

ε is ____________________

R is ____________________

r is ____________________

σ is ____________________

Exercise 6.13b. complete the Table 6.4b, define the parameters and their units of measurement:

Table 6.4b

The Laws of Direct Electric Current

Title	**Formula**
The power of electric current	
Joule-Lenz law	(6.22b)
The first Faraday law	(6.23b)
The second Faraday law	(6.24b)

where P is ____________________

Q is ____________________

m is ____________________

k is ____________________

F is ____________________

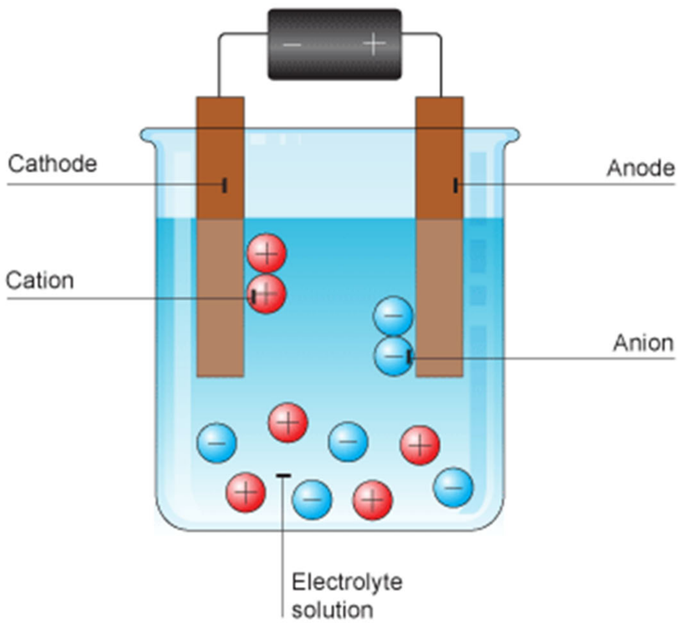


Fig. 6.4b. Illustration of an electrolysis

Electrolysis is ____
____

Control questions

1. What is the test body?
2. What is the electric field strength?
3. What is the electric potential?
4. Formulate the superposition principle.
5. What is called an electric dipole?
6. Series and parallel connection of resistors and capacitors.
7. What is the essence of Einhoven's theory?
8. How do electric fields affect living organisms?

Individual assignments

1. Electric moment of the water molecule dipole is $p = 6.2\times10^{-30}$ C·m. Including that this dipole is created by positive and negative charges, equal to the charge of the electron, find the length of the dipole.
2. An electric eel has the organ for accumulating electrical energy. It is a kind of capacitors battery. Their charges are near to 800 V. The discharge power is 1 kW. Assuming that the discharge time is 10^{-4} s, determine the capacitance of this capacitor bank.
3. Between the two electrodes, to which a constant voltage $U = 36$ V is applied, there is a part of the tissue. Conditionally, we can assume that the tissue consists of two layers of dry skin and muscles with blood vessels. Thickness of each skin layer is $l_1 = 0.3$ mm, thickness of inner tissue is $l_2 = 9.4$ mm. Find the current density and voltage drop in the skin and muscle (vascular) tissue, treating them as conductors. How does the potential change in a direction perpendicular to these layers?
4. Between the inner part of the cell and the outer solution there is a potential difference (rest potential) $U = 80$ mV. Assuming that the electric field inside the membrane is homogeneous, and the thickness of the membrane is $l = 8$ nm, find the strength of the field.
5. The device for defibrillation creates a shock in the part of the heart, discharging the capacitor charged to a voltage $U = 4.8$ kV. Resistance of the body between the electrodes is $R = 400$ Ω. Calculate the current strength at the beginning of the capacitor discharge.
6. Calculate the speed of an electron passed the accelerating potential difference of 100 V. The initial speed of the electron is equal to zero.
7. Find the mass of copper that will be plated on a cathode during the electrolysis for one hour if the electric current is equal to 5 A.