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PHYSICS. Mechanics and molecular physics

Methodological instructions for laboratory works
designated for students of all specialties

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The present methodological instructions consist of description of 9 laboratory works on the course «Mechanics and molecular physics». Each work consists of theoretical description of laboratory work, description of experimental stand, necessary procedures and measurements, technique of processing results and questions for self-control.

Methodological instructions for laboratory works on the course «Mechanics and molecular physics» are designated for students of all specialties.

Figures -13, tables - 12, bibliography - 8 items.

Reviewer: senior teacher, Master of Science Kim E.S.

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Content

Introduction

Physics is directly related to experiment. This means that all physical laws are established and verified by accumulating and comparing experimental data.

The physical practicum is developed to help students understand more deeply the basic physical laws and acquire elementary skills of experimentation, teach to analyze the results of the experiment and to assess their accuracy.

When starting a laboratory work you should familiarize yourself with the theory of this issue using specified textbooks on physics, carefully read the methodological instructions for work and familiarize yourself with the devices that you have to use during the experiment.

The success of the experiment largely depends on the correct record of the results. For this purpose, it is necessary to have a special notebook for work in the laboratory in which you will write down the name, purpose and tasks of the work, brief summary and results of the experiment The implementation of work in the physical laboratory, as is known, includes three stages: preparation for the experiment, carrying out the experiment and making the report. At the preparatory stage it is necessary to:

a) familiarize yourself with goals and objectives;

b) understand the theoretical substantiation of those phenomena and processes, the relationships and regularities that underlie the experiment;

c) draw up the plan of actions;

d) prepare a table to record the results of the experiment.

As a result of the preparatory work the student should form a fairly clear idea of the forthcoming experiment and expected results.

The experiments begin with the installation of instruments, then you should observe and count the measured values; write down the results into tables. At the final stage the results are processed, required values are calculated and errors are estimated. When starting calculations it is necessary to follow the rules of action with approximate numbers.

Finally, based on the results of the work done it is necessary to formulate conclusions. The work output should logically complete it. The main attention should be paid to the analysis of obtained results. For this, the comparison with other similar results should be done if they are available in reference books or can be calculated theoretically; comparison with corresponding conclusions of the theory; analysis of the problem in the light of data you have received. It is necessary to find out whether the technique used is reliable; whether your results confirm the conclusions of theory; what the possible reason for the deviations is.

In experimental physics, graphs are often used for different purposes. First, for clarity and comparison with other results or with a theoretical curve; second, to determine certain values, for example, according to the slope of the graph or the interval cut off by the graph from any of the axes, etc.; third, to calibrate the instrument.

Graphical representation of information is very useful because of its visibility. From the graphs one can determine the character of functional dependence, determine the values of quantities. The graphs allow you to compare the results obtained experimentally with the theory. On the charts it is easy to find maximums and minima, it's easy to spot misses.

The construction of graphs must satisfy a number of requirements, which are given in references [1, 2, 3, 4]. The graphs are plotted on millimeter paper. On the horizontal axis, the values of argument are marked, along the vertical axis – the values of function. As a rule, straight lines do not connect experimental points with each other; they are connected with a pencil by a smooth curve so that the points should lie, as close to the curve as possible and on average be equally located on either side of this line. There is no point in trying to draw a curve through each experimental point - because the curve is only an interpretation of measurement results known from the experiment with an error. The curve constructed correctly should fill the entire field of the graph, which will be evidence of the correct choice of scales for each axis. If a significant part of the field is unfilled, then it is necessary to reselect the scales and reconstruct the graph. On the top of each graph, you should write its name, for example, "Graph of the dependence of wire resistance on the length" or "Volt-ampere characteristic of vacuum photocell."

Some mathematical methods allow drawing the theoretical curve through experimental points in the best possible way, for example, the method of least squares [3]. When drawing the graph "by eye" it is recommended to use the visual sense of zero equality for the sum of positive and negative deviations of points from the smoothed line.

1 Statistical processing of measurement results

1.1 Basic concepts and definitions

The physical experiment is connected, as a rule, with the measurement of one or another physical quantity. There are *direct measurements* when the very physical quantity is measured and *indirect measurements* when the desired value is found on the basis of a known dependence on the quantities obtained by direct measurements. Every measurement has inherent errors, so we get *an approximate value of x* in experiments instead *of the true value* of the measured quantity *a*. The difference between the measurement result and the true value is called *the absolute error of measurement*:

$$\Delta x = x - a.$$

All possible errors in measurements by the nature of manifestation can be *divided into three types*. *Systematic errors* are due to the same cause. Therefore when the experience is repeated, they usually have the *same value and sign*, i.e. systematically repeated. They are a consequence of instruments imperfection and shortcomings of measurement techniques. *Systematic errors can be eliminated* by corrections and reduced either by replacing with instruments that are more accurate or by improving the measurement technique.

A random error is a component of measurement error that varies randomly in a series of repeated measurements of the same magnitude carried out under the same conditions. Random errors are the consequence of random uncontrolled interference, the influence of which on the measurement process can not be taken into account. They are associated with limited accuracy of instruments, limited sensitivity of our senses, changes in external conditions, etc. Random errors are inevitable, they cannot be eliminated, but due to the fact that they obey probabilistic regularities, you can specify the limits within which the true value lies for a sufficiently large number of measurements.

Blunders are obviously erroneous measurements or observations resulting from the negligence of the experimenter. In the calculations, such data should be discarded and repeated measurements should be made.

Random errors with multiple repetition of the experiment are the reason for the scatter of readings of individual measurements. Let us suppose that we have *n* times measured a certain value, the true value of which is equal to a. Because of random errors, instead of a, we obtain a series of values $x_1, x_2, \dots, x_i, \dots, x_n$.. We do not know which of these measurements is closest to the true. The best way out is the arithmetic average <*x*> from the number of all measurements:

$$< x >= \frac{1}{n} \sum_{i=1}^{n} x_i. \qquad (1.1)$$

Since the average is an approximate estimate of the true value, it is also necessary to estimate the absolute value of the possible deviation of the average result from the true value. This deviation Δx is called the absolute error of the average

$$\Delta x =< x > - a. \qquad (1.2)$$

The mean value <*x*> and absolute error *Δx* determine the so-called confidence interval *(<x> ± Δx),* within which, according to experience, measured value a is enclosed. For example, the result of measuring the speed of sound is written as follows: v = (335 ± 5) m/s.

This record means that the speed of sound, according to the experience, lies in the range from *330 m/s* to *340 m/s*. However, such an assertion cannot be considered absolutely reliable. It is necessary to indicate the reliability of the result. The reliability of the result is estimated by the so-called confidence probability P.

The confidence probability is the probability that the *true value* of the measured quantity falls within the found confidence interval.

Let us suppose that in the example mentioned above the confidence interval is found with confidence probability of P equal to *0.95*. This means that the results of 95 measurements from 100 fall into the found interval and only 5 will be outside of it. The narrower the confidence interval (i.e, the smaller the absolute error *Δx*) for a given confidence probability, the more accurate the measurements.

The measurement accuracy is revealed by comparing the absolute measurement error with the average value of all measurements by calculating the so-called relative error.

Relative error is calculated by the formula:

$$\varepsilon = \frac{\Delta x}{< x >} \cdot 100\%. \tag{1.3}$$

In the example considered with the speed of sound it is equal to:

$$\varepsilon = \frac{5}{335} \cdot 100\% \approx 1{,}5\%.$$

1.2 Determination of the confidence interval based on the normal distribution law of a random variable

The confidence interval and confidence probability are substantiated by the theory of measurement errors, which is based on the normal distribution law of a random variable. This theory takes into account only random errors. In Figure 1.1, where the general form of the normal distribution is presented, it can be seen that the bulk of the results of measurement is grouped around center a. Deviations on both sides of the distribution center are observed the less frequently, the greater the absolute value *(x - a)* of such deviations is. The degree of variation of individual measurements with respect to a determines another parameter of the distribution function –parameter σ. Analysis of the function of distribution shows that at distance σ from the distribution center the curve has inflection points and for $|x - a|>\sigma$ the function tends rapidly to zero. The quantity σ^2 called the *dispersion* coincides with the mean value of the squared deviations of the results of individual measurements from the true value, i.e. $\sigma^2 = <(x\text{-}a)^2>$. Therefore, the parameter σ is called *the standard deviation* or *the mean square deviation*; σ determines also the maximum value of the distribution function, which is attained at $x = a$ and equals

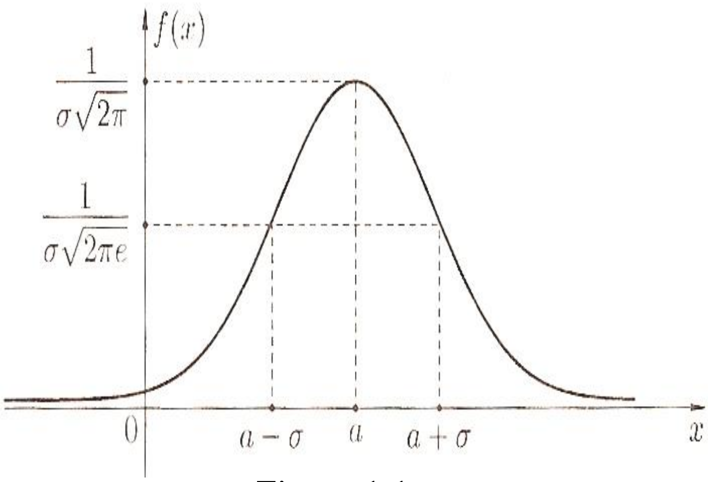


Figure 1.1

$$f_m = \frac{1}{\sigma\sqrt{2\pi}}.$$

Hence, the smaller σ the higher the maximum. On the same graph of the area under the curves the distributions corresponding to different values of σ should be the same (equal to 1), therefore on the graph the curves with the smaller value of σ look narrower and higher than the curves with large σ. Figure 1.2 shows three normal curves where $\sigma_2 > \sigma > \sigma_1$..

In measurements the value σ depends on the accuracy of chosen method, the more accurate the method is, the smaller σ is. The confidence interval is always chosen symmetric with respect to a, then the confidence probability is determined by integrating the normal distribution law from *(a - Δx)* to *(a + Δx).*

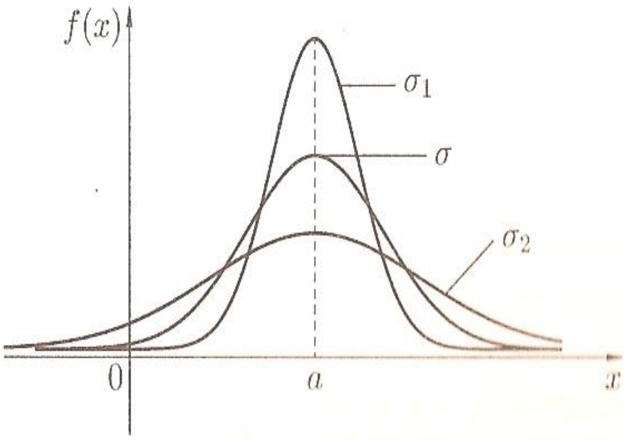


Figure 1.2

If the half-width of interval *Δx* is taken as a multiple of *σ,* then, as corresponding calculations show, for *Δx = σ*, the confidence probability is *P = 0.683*, for *Δx = 2σ P = 0.954*, and for *Δx = 3σ P = 0.997*. In measurements a and σ are unknown. Therefore, in mathematical processing measurement results, it is necessary to obtain the best estimation of *a* and *σ* from these results.

The best estimation of *a* is the arithmetic mean of <*x*> from all measurements. It can be shown that for a large number of measurements (n → ∞)

$$a = \lim_{n\to\infty} < x >.$$

The best estimate of *σ* is the sample mean square deviation of S_n, equal to:

$$S_n = \sqrt{\frac{\sum_{i=1}^{n}(x_i - < x >)^2}{n(n-1)}}. \qquad (1.4)$$

Within n → ∞ S_n coincides with *σ.*

With a large number of measurements (*n> 20*) the result is processed using the "three sigma" rule. Using formula (1.1) we find <*x*>, using the formula (1.4) we compute the sample mean-square deviation of S_n and taking it equal to *3σ*write the confidence interval in the form *x* = <*x*> ± *3σ*, the confidence probability *P* in this case is 0.997.

In laboratory practice, when a small number of measurements is made (n<10), the method developed by Student is widely used. This method is called the *method of small samplings or Student's method*.

Student's coefficients depend on the chosen value of the confidence probability *P* and the number of measurements *n*. These coefficients are calculated in the theory of probability and are given in the reference tables.

Table 1.1- Student coefficient table

n \ P	0,6	0,7	0,95	0,99
2	1,38.	2,0	12,71	63,66
3	1,06	1,3	4,30	9,92
4	0,98	1,3	3,18	5,84
5	0,94	1,2	2,78	4,60
6	0,92	1,2	2,57	4,03
7	0,90	1,1	2,45	3,71
8	0,90	1,1	2,36	3,50
9	0,90	1,1	2,31	3,36
10	0,88	1,1	2,26	3,25

1.3 Procedure of processing the results of measurements using the method of small samplings

The method of small samplings allows us to estimate the random error Δx of the arithmetic average value $<x>$. The processing of the results of measurements using the method of small samplings should be performed in the following order:

a) perform n measurements of a certain physical quantity, the results of which are$x_1, x_2, ..., x_i, ... x_n$;

b) find the average of the arithmetic value by formula (1.1);

c) determine the deviation of the result of each measurement from the mean $\Delta x_i = | x_i - <x> |$ (direct brackets indicate that we are interested only the absolute values of these differences);

d) determine the standard deviation - the sample mean square deviation of S_n by formula (1.4);

e) by the Student's coefficient table find t;

f) determine the absolute value of random error of the arithmetic mean by formula

$$\Delta x = t \cdot S_n \; ; \qquad (1.5)$$

g) determine the relative error of the arithmetic mean by formula (1.3);

h) record the final result in the form of confidence interval:

for P= 0,95 $\quad x = (< x > \pm \Delta x) \; dimention\,units, \; \varepsilon = A\%.$ (1.6)

When writing the final result one must bear in mind the following: since the very absolute error Δx is determined with an error, it must be *rounded to the first significant digit*. Only if the first significant error figure is less than 4, as a result, you can *leave* 2 *significant digits*. For example, by calculations, Δx = 5.24 m/s was obtained; it should be rounded Δx = 5 m/s. The value Δx = 0,0167 Pa·s can be rounded as follows: Δx = 0,020 Pa·s or Δx = *0,017* Pa·s.

The absolute error indicates which digit order of the result is inaccurate, so the result must be rounded to the order where the significant error number is located. For example, we obtained <v> = 2.6731 m/s and Δv = 0.08 m/s. Hence, the answer should be written like this: an absolute error indicates which digit order of the result is inaccurate, so the result must be rounded to the order where the significant error number is located. For example, we have $<v>$ = 2.6731 m/s and Δv = 0.08 m/s. Hence, the answer should be written like this:

$$v = (2{,}67 \pm 0{,}08)\ \text{m/s}; \tag{1.7}$$

or having received $<I> = 0{,}8568 \cdot 10^{-3}\ \text{kg} \cdot \text{m}^2$ and $\Delta I = 0{,}014 \cdot 10^{-3}\ \text{kg} \cdot \text{m}^2$ we write down:

$$I = (0{,}857 \pm 0{,}014) \cdot 10^{-3}\text{kg} \cdot m^2.$$

1.4 Instrument accuracy class

To characterize measuring instruments the notion of accuracy class is often used.

The accuracy class of the device γ is the largest permissible relative reduced error determined by the formula

$$\gamma = \frac{\Delta A}{A_{nom}} \cdot 100\%, \tag{1.8}$$

where ΔA is the maximum permissible absolute error of the instrument;
A_{nom} - limiting (nominal) value of the measured value on the instrument scale.

The accuracy class of instruments in accordance with the accepted standard can take the following values: 0,02; 0.05; 0.1; 0.2; 0.5; 1.0; 1.5; 2.5; 4. The accuracy class of the device is indicated on its scale. If there is no such sign on the scale, this means that the device is extra-curricular, that is, its reduced error exceeds 4%.

Knowing the accuracy class it is possible to calculate the maximum permissible absolute error of the device (which is assumed to be the same on the entire instrument scale)

$$\Delta A = \frac{\gamma \cdot A_{nom}}{100\%}. \tag{1.9}$$

2 Laboratory work MMP-1. Measuring practical work

Aim of the work: to study the technique of measurement of physical quantities and methods of processing measurement results using the example of electrical resistivity of wire.

Objectives:

- to measure resistance of a wire and to study dependence of resistance *R* of a wire on its length ℓ;

- to define electrical resistivity ρ of material of a wire;

- to carry out processing of measurement results by the Student method.

2.1 Experimental procedure

Resistance of conductors depends on their form, sizes and material they are made of, i.e. $R = \rho\frac{\ell}{S}$. If the conductor has the form of round cylinder of constant cross-section with area of $S = \frac{\pi \cdot d^2}{4}$ then its resistance is equal to:

$$R = \frac{4}{\pi}\frac{\rho\ell}{d^2}, \tag{1}$$

where ℓ - length of conductor;

d – its diameter;

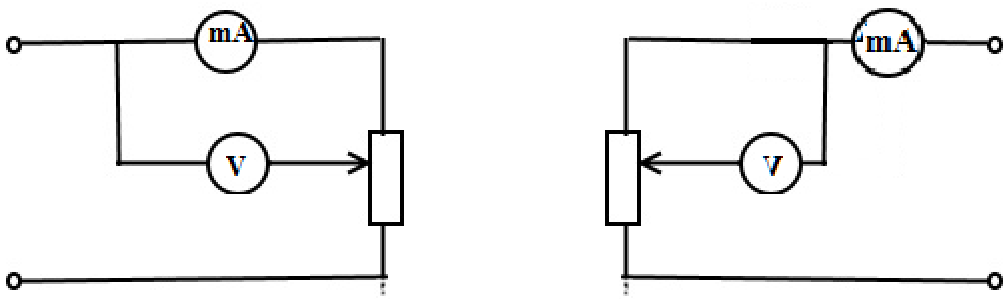
ρ - electrical resistivity.

From (1) it is easy to receive the formula:

$$\rho = \frac{\pi}{4}\frac{Rd^2}{\ell}, \tag{2}$$

which is the basic aim of this work.

The value of resistance *R* is calculated under indications of the ammeter and voltmeter (design formulas are given below).



a) b)

Figure 2.1

For more exact definition of resistance it is necessary to take into account internal resistance of electric devices - *ammeter* R_A and *voltmeter* R_V.

In figure 2.1 two possible circuits are shown: a) and b) - switching devices that are implemented with the help of switch.

When the circuit a) is turned on the resistance should be found according to the formula:

$$R = \frac{U}{I}\left(I - \frac{R_A}{U}I\right), \tag{3}$$

where R_A= 0,15 Ohm is internal resistance of the ammeter;

U and *I* are the indications of voltmeter and ammeter accordingly.

When the circuit b) is turned on the resistance is according to the formula:

$$R = \frac{U}{I}\left(I + \frac{U}{IR_V}\right), \tag{4}$$

where R_V= 2500 Ohm is the internal resistance of the voltmeter.
Both formulas can be received from Ohm's law.

2.2 Experimental installation

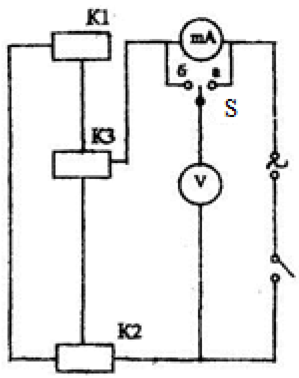


Figure 2.2

PPM-01 is an experimental stand intended to calculate the electrical resistivity of a wire (figure 2.2).

The researched wire is fixed between two motionless contacts K1 and K2. With the help of mobile contact K3 the necessary length of the wire is established, on which the voltage and current are measured. The circuit of connection (a) or (б) is selected by switch S.

2.3 Procedure and measurements

2.3.1 Fix a position of the top contact and write down in table 2.1 the length ℓ of the wire (not less than half of the total length) which is situated between bottom and average contacts.

2.3.2 Measure the diameter of wire *D* with the help of micrometer.

2.3.3 Turn on the experimental stand and choose the circuit of connection of devices with the help of switch *S*.

2.3.4 Carry out ten measurements of voltage *U* and current *I* for various (not less than 5) values of wire length ℓ_i.

Table 2.1

N	d, m	ℓ_i, m	I, mA	U, V	R, Ohm	ρ_i, $Ohm{\cdot}m$	$\langle\rho\rangle$, $Ohm{\cdot}m$	$(\langle\rho\rangle - \rho_i)^2$ $Ohm{\cdot}m$
1								

2.4 Processing the results

2.4.1 Depending on the chosen circuit to calculate an active resistance of a wire according to the formula (3) or (4).

2.4.2 Plot a graph of dependence of wire resistance R on its length ℓ.

2.4.3 Calculate the value of electrical resistivity ρ by the formula (2).

2.4.4 For all measurements according to the formula $S = \sqrt{\dfrac{\sum_{i=1}^{n}(\rho_I - \prec\rho\succ)^2}{n(n-1)}}$

find root-mean-square error *S* and size of confidential interval $\Delta\rho_{10} = t \cdot S_{10}$ where the coefficient of Student for ten measurements equals *t*=2.26 (for confidence probability P=0.95).

2.4.5 Choose any three measurements to find the value of interval $\Delta\rho_3$ using Student's method for three measurements (*t*=4.3).

2.4.6 For n=10 and n=3 find the relative error corresponding average arithmetic value according to formula $\varepsilon = (\Delta\rho / \rho) \cdot 100\%$.

2.4.7 Also calculate a relative instrument error of any individual measurement:

$$\frac{\Delta\rho}{\rho} = \frac{\Delta\ell}{\ell} + 2\frac{\Delta d}{d} + \frac{\Delta U}{U} + \frac{\Delta I}{I}.$$

2.4.8 Compare absolute and relative errors to analyze the received results and formulate conclusions.

2.5 Control questions

2.5.1 Direct and indirect measurements, regular and random errors.
2.5.2 Absolute and relative errors. A class of device accuracy.
2.5.3 Confidential intervals and confidential probability.
2.5.4 Processing the results of direct and indirect measurements.
2.5.5 Technique of carrying out of work.

3 Laboratory work MMP-5. Measuring the moment of inertia of Maxwell′s pendulum

Aim of the work: to study the laws of rigid body mechanics by investigating its flat motion.

Objectives:

- find the moment of inertia of Maxwell′s pendulum by measuring the time of its falling;
- calculate the moment of inertia of Maxwell′s pendulum with the help of theoretical formula;
- compare the received values.

3.1 Experimental procedure

Maxwell′s pendulum represents a disk fixed on alight tube and suspended on two threads (figure 3.1). If having winded up threads symmetrically on a tube to lift the disk on height *h* and then to release it without a push it will start to fall simultaneously rotating around the horizontal axis. Thus, trajectories of all points of the disk lay in parallel planes. Such motion of the disk refers to *the flat motion*.

It can be considered as *the sum of forward motion* of a body and simultaneous *rotation around horizontal axis* taking place through the center of masses.

The equations of motion of the center of masses and concerning the specified axis in this case look like:

$$ma = mg - 2T; \qquad (1)$$

$$I\varepsilon = 2Tr\,, \tag{2}$$

where m is mass of the pendulum;

I - its moment of inertia;

a - acceleration of the center of masses;

ε - angular acceleration of a pendulum;

T - tension of a thread;

r - radius of the tube (a shoulder of force of tension).

Taking into account that linear and angular accelerations in this case are connected by the ratio $a = \varepsilon \cdot r$ we shall receive from (1) and (2):

$$a = \frac{m \cdot g}{m + I/r^2}\,. \tag{3}$$

From the last expression it follows that the center of mass of a pendulum goes with constant acceleration, which depends on the moment of inertia. This circumstance underlies the considered technique.

From ratio (3), considering the formula of distance at motion with constant acceleration $h = \frac{a \cdot t^2}{2}$, we shall receive the calculated formula:

$$I = \frac{mD^2}{4}\left[\frac{g \cdot t^2}{2} - 1\right], \tag{4}$$

where $D = D_0 + d$.

Thus to define the moment of inertia of Maxwell's pendulum it is necessary to measure time t of its falling from the given height h knowing its mass m, diameter of tube D_0 and thread thickness d.

3.2 Experimental stand

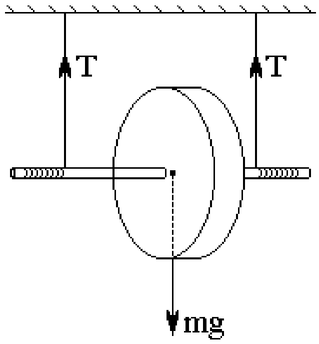


Figure 3.1

The device "Pendulum of Maxwell FPM-03" consists of a pendulum (described above), an electromagnet, two photoelectric sensors and an electronic timer connected to them measuring time in milliseconds. One of replaceable rings is put on the pendulum disk that allows changing its mass and the moment of inertia of the pendulum. The electromagnet keeps the pendulum in the top position when the electric current flows along its winding.

The length of suspension bracket of a pendulum (height h) is measured with the millimeter scale marked on a vertical column.

Key switches NETWORK, START-UP, RESET and digital sensors, which show indications are located on the panel of the timer.

3.3 Procedure and measurements

3.3.1 Level the device and to connect it to the network.

3.3.2 Adjust the length of a thread so that the edge of steel ring in the bottom position should overlap the light beam of photoelectric sensor and that the axis of a pendulum was horizontal.

3.3.3 Lift the pendulum in the top position reeling up the threads on a tube in regular intervals in one layer and fix it with the help of an electromagnet. The key START-UP should be wring out.

3.3.4 Press consistently keys RESET and START-UP that will cause the release of pendulum and start of timer.

3.3.5 Write down the indications of thetimer in table 3.1. Repeat the experiment not less than 5 times.

3.3.6Measure external diameters of the tube D_O, disk D_D and ring D_R; define the thickness of string *d*.

Table 3.1

№	*h, m*	*m, kg*	*t, s*	I, kg·m^2	<*I*>, kg·m^2	D_O, m	D_D, m	D_R, m	I_{th}, kg·m^2
1									

3.4 Processing the results

2.4.1 Write out values of mass of tube m_O, disk m_D and ring m_R engraved on corresponding details and calculate the mass *m* of the pendulum.

2.4.2 According to formula (4) calculate the values of the moment of inertia *I* for each value of time *t* received in experience.

2.4.3 Calculate the average arithmetic value <*I*> and estimate its random error ΔI for confidential probability $P = 0{,}95$.

2.4.4 Calculate the theoretical value of the moment of inertia of the pendulum by the formula:

$$I_{th} = [m_0 D_0^2 + m_D (D_D + D_0^2) + m_R (D_R + D_D)]/8$$

and compare it with value <*I*>.

3.5 Control questions

3.5.1 What does the time of the Maxwell’s pendulum fall from the given height *h* depend on?

3.5.2 How does the pendulum center of masses move? What does its acceleration depend on?

3.5.3 What is the mechanical energy of the pendulum equal to at the top position? When it passaging the bottom position? What is the relationship of these values?

3.5.4 Specify sources of errors during the experiment.

4 Laboratory work MMP– 6. Measuring the moment of inertia of rigid bodies with the help of torsional oscillations

Aim of the work: mastering the method of determining the moment of inertia of a body, which is based on the law of dynamics of rotational motion of a body.

Objectives:

- define periods of torsional oscillations of a pendulum with bodies fixed on it;
- calculate the moment of inertia of the body using the values of periods of oscillations received during the experiment.

4.1 Experimental procedure

The torsional pendulum represents the body, which is fixed on a steel wire stretch vertically. When the pendulum turns around its axis coinciding with the wire axis there are elastic forces in it, the moment of which is proportional to the turning angle φ:

$$M = -k\varphi, \tag{1}$$

where k is the factor dependent on radius and length of the wire and also from elastic properties of the material it is made of.

In this case the equation of dynamics of rotational motion looks as:

$$I\varepsilon = -k\varphi. \tag{2}$$

Taking into account the definition of angular acceleration and after small transformations, we shall write down:

$$\ddot{\varphi} + \frac{k}{I}\varphi = 0. \tag{3}$$

The last equation represents the differential equation of free torsional oscillations, whose period is equal to:

$$T = 2\pi\sqrt{\frac{I}{k}}. \tag{4}$$

It is this dependence of the period of torsional oscillations from the moment of inertia of the body suspended on a wire that underlies the offered technique. A framework is usually suspended on the wire which allows fixing the samples considerably distinguished by their sizes. This framework possesses the moment of inertia I_F. If a studied sample with the moment of inertia I_0 is fixed in it the period of such pendulum is equal to:

$$T_0 = 2\pi\sqrt{\frac{I_F + I_0}{k}}. \tag{5}$$

To exclude from the calculated formula unknown to us the quantities I_F and k it is necessary to measure the periods of oscillations T_F of an empty framework and T_S of framework with the reference sample fixed in it the moment of inertia I_S of which is known. Thus:

$$T_F = 2\pi\sqrt{\frac{I_F}{k}}\,; \tag{6}$$

$$T_S = 2\pi\sqrt{\frac{I_F + I_S}{k}}\,. \tag{7}$$

The calculated formula for the moment of inertia of the studied sample follows from the last ratio:

$$I_0 = I_S\,\frac{T_0^2 - T_F^2}{T_S^2 - T_F^2}\,. \tag{8}$$

4.2 Experimental stand

The installation (figure 4.1) consists of the steel wire stretched between two arms on which a light framework is suspended, electromagnet, universal electronic timer collected in one box and the counter of oscillations. The last two units are connected with a photoelectric sensor. There are three samples in the complete set, we conditionally accept one of them for reference. Two tags made from a magnetic material are located on either side of the framework.

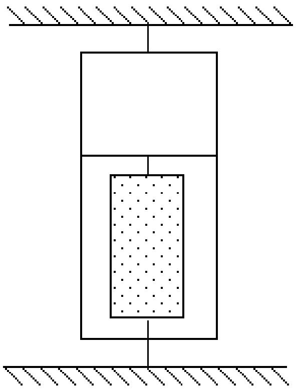


Figure 4.1

The key switches NETWORK, START-UP, RESET and STOP and digital sensors indicate time t and the number n of full oscillations of the pendulum.

4.3 Procedure and measurements

4.3.1 Level the device and connect it in a network.

4.3.2 Fasten a studied sample in the framework.

4.3.3 Turning the framework, approach its tag to the electromagnet. The former attracts the tag to itself fixing thus the pendulum in initial position.

4.3.4 Press consistently keys RESET and START-UP. The circuit of the electromagnet thus is disconnected; also, the pendulum starts to make free oscillations.

4.3.5 Define time t_0 of 20-30 full oscillations. For this purpose, it is necessary to press the STOP key when the number of oscillations is less than one unit, i.e. equal to (n - 1). Count indications of the stopwatch having stopped the counter and write down them into table 4.1.

4.3.6 Replace a studied sample by a reference one and define time t_S of n full oscillations (see items 4.3.3 – 4.3.5).

4.3.7 Remove the sample and make measurement of time t_F of n full oscillations of an empty framework. Repeat each experiment not less than three times.

Table 4.1

№	n	t_0, s	t_S, s	t_R, s	T_0, s	T_S, s	T_F, s	I_0, kg·m^2
1								

4.4 Processing the results

4.4.1 Calculate periods T_0, T_S and T_F according to formula $T = t/n$ and their average values $<T_0>$,$<T_S>$ and $<T_F>$.

4.4.2 Calculate the moment of inertia I_0 of the studied sample according to formula (8), substituting in it the average values of the corresponding periods.

Note: the value of the moment of inertia of a reference sample is given on stand in laboratory "Mechanics and molecular physics".

4.5 Control questions

4.5.1 What is the basis of the technique of experimental definition of the moment of inertia of bodies used in the given work?

4.5.2 What are the basic sources of errors in the given experiment?

4.5.3 What is the rotational moment of elastic forces when a framework turns at angle φ?

5 Laboratory work MMP-7. Determination of bullet velocity using ballistic torsional pendulum

Aim of the work: mastering the method of definition of bullet speed based on the application of conservation laws.

Objectives:

- study opportunities of application of laws of conservation of momentum and energy;
- define the speed of flight of a bullet.

5.1 Experimental procedure

The ballistic torsional pendulum represents a bar suspended by a vertical steel wire and capable to make oscillations in horizontal plane. Two targets filled by plasticine are fixed on the ends of the bar. Also, two identical cylindrical loads are located on the bar, which can be moved and fixed in a chosen position (figure 5.1). When a bullet horizontally flying with speed υ hits the target, the pendulum deviates from its balance position turning about the axis with initial angular speed ω_0. According to the law of conservation of angular momentum:

$$m_0 \cdot \upsilon \cdot r = (I + m_0 r^2) \cdot \omega_0 . \qquad (1)$$

Here m_0 is a mass of the bullet, r - shoulder of its moment equal to the distance from the axis up to that place where the bullet stopped (provided its velocity is perpendicular to the bar axes), I - the moment of inertia of the pendulum. When the pendulum turns the wire, on which it is suspended twists. There are elastic forces in it, the moment of which is proportional to pendulum turn angle φ :

$$M = -k\varphi, \tag{2}$$

where k - the factor dependent on the length, radius and wire material.

Under the action of the moment of elastic forces, the pendulum makes free torsional oscillations with the period equal to:

$$T = 2\pi\sqrt{\frac{I}{k}}\,. \tag{3}$$

The kinetic energy received by the pendulum on impact transforms into potential energy of elastic deformation of the wire. If neglected the loss of energy when the pendulum moves (owing to air resistance) it is possible to write down the law of mechanical energy conservation in the following form:

$$\frac{(I + m_0 R^2)\cdot\omega_0^2}{2} = \frac{k\varphi_M^2}{2},$$

where φ_M is the maximal angle, at which the pendulum will turn after impact.

From ratios (1) and (3) we shall receive:

$$\upsilon = \frac{\varphi_M \cdot \sqrt{k\cdot I}}{m_0 \cdot r}\,. \tag{4}$$

In (4) it is taken into account that $m_0 \cdot r^2 << \mathrm{I}$, i.e. the moment of inertia of the bullet can be neglected.

To exclude unknown quantities k and I from the calculated formula it is necessary to make measurements of periods T and T_1 of pendulum oscillations at two various positions of loads on distances accordingly R and R_1 from the axis of rotation. Then the calculated formula gets the following form:

$$v = \frac{4\pi\cdot\varphi_M \cdot mT\cdot(R_1^2 - R^2)}{m_0\cdot r\cdot(T_1^2 - T^2)}, \tag{5}$$

where m is a mass of load.

Thus, the technique of definition of the speed of flight of a bullet with the help of the ballistic torsional pendulum is based on the application of laws of conservation of angular momentum and mechanical energy. The essence of it consists in carrying out two experiences, in one of which it is necessary to define angle φ_M of pendulum deviation after impact and period T of its free oscillations. In this case, loads are located symmetrically on distance R from the axis. In the second experience loads are placed on the other distance, which we designated as R_1 and again we define the period of pendulum oscillations T_1 in our designation.

5.2 Experimental stand

The device "Ballistic torsional pendulum FRM-09" consists of the pendulum described above, shooting mechanism, photoelectric sensor, electronic timer connected to it and counter of oscillations. In addition, there is a transparent screen with the angular scale on it.

The key switches NETWORK, RESET, STOP, digital indicators of timer and a counter of oscillations are located on the front panel of the timer.

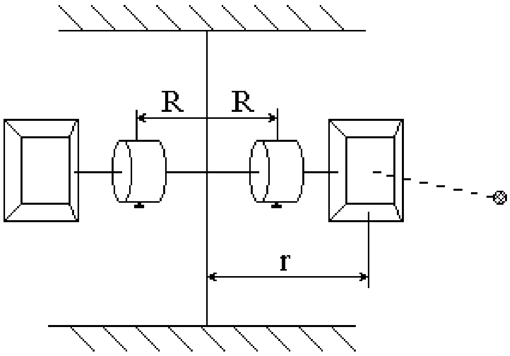


Figure 5.1

5.3 Procedure and measurements

5.3.1 Level the device.

5.3.2 Approach loads to each other as much as possible, i.e. move them to the axis and measure distance R up to the center of each load.

5.3.3 Install the pendulum in zero position, when the line at the end face of the target is located opposite to zero division of the angular scale. Connect the device to the network.

5.3.4 Put a bullet in the shooting mechanism and shot.

5.3.5 Define angle φ_M of the maximal turn of the pendulum after impact of the bullet about a target with the help of angular scale and express it in radians.

5.3.6 Define time t of n = 7÷10 full oscillations of the pendulum.

5.3.7 Measure distance r from the axis up to that place where the stopped.

5.3.8 Move apart maximum the loads and define their distance R_1 up to the axis.

5.3.9 Turn the pendulum at the angle equal to φ_M, press the RESET key, then release the pendulum and define time t_1 of n_1 full oscillations of the pendulum.

5.3.10 Repeat each experiment not less than three times. Results of measurements should be written into table 5.1.

Table 5.1

№	φ_M, rad	R, m	t, s	n	$\langle T \rangle$, s	t_1, s	n_1	$\langle T_1 \rangle$, s	R_1, m	r, m	υ, m/s	$\langle \upsilon \rangle$, m/s
1												

5.4 Processing the results

5.4.1 Calculate the periods of oscillations for each experiment according to formulas:

$$T = t/n \quad \text{and} \quad T_1 = t_1/n \ ;$$

then calculate their average values <*T*> and <T_1>.

5.4.2 Calculate the speed for each of values φ_M received during the experiment substituting in calculated formula (5) the average values of periods <*T*> and <*T1*>.

5.4.3 Calculate the average value of speed <υ>.

Note: the masse of loads m and that of the bullet m_0 are specified at the reference stand in laboratory "Mechanics and molecular physics".

5.5 Control questions

5.5.1 Under what conditions is the angular momentum of the system kept relative to a certain axis Z?

5.5.2 Under what conditions is mechanical energy of the system kept?

5.5.3 Is mechanical energy of the system kept: when a ballistic torsional pendulum and a bullet; when a bullet hits a target?

5.5.4 Under what conditions can the distance from the place where the bullet hits the target to the axis be considered equal to the shoulder of impulse of a flying bullet relative to the axis of the pendulum?

5.5.5 What circumstances and the facts define the accuracy of experiment on the given installation?

6 Laboratory work MMP–8. Studying dynamics of rotational motion using Oberbeck's pendulum

Aim of the work: verification of the law of dynamics of rotary movement of the rigid body relative to the motionless axis.

Objectives:

- define values of the moment *M* of an external force, angular -acceleration ε of a rotating body and its moment of inertia *I*;
- check up the ratio following from the law of dynamics of rotary movement in two cases: a) *I* = const, б) *M* = const.

6.1 Experimental procedure

The equation of dynamics of rotary movement of a solid body relative to the motionless axis looks like:

$$I \cdot \varepsilon_z = M_z, \tag{1}$$

where *I* is the moment of inertia of a body relative to the axis of rotation Z;

$\varepsilon_Z = \frac{d\omega}{dt}$ - projection of angular acceleration onto *Z* -axis;

M_z - total moment of external forces relative to *Z* - axis.

From equation (1) it follows that if under the action of the moment of force M_1 the body rotates relative to the motionless axis with acceleration ε_1, and under the action of the moment of force M_2 - with acceleration ε_2, then at constant value of the moment of inertia of a body (I = const) relative to the given axis, the following relation is fair:

$$\varepsilon_1 / \varepsilon_2 = M_1 / M_2 . \qquad (2)$$

Another consequence from the equation (1) consists in the fact that the relation of accelerations ε_1 and ε_2, got by the bodies with the moments of inertia I_1 and I_2 under the action of the same moment of force (M = const), opposite to the relation of their moments of inertia:

$$\varepsilon_1 / \varepsilon_2 = I_2 / I_1 . \qquad (3)$$

The verification of relations (2) and (3) is carried out with Oberbeck's pendulum. Oberbeck's pendulum represents a flywheel in the form of the cross (four mutual perpendicular bars fastened with a pulley), capable to rotate around of a horizontal axis (figure 5.1). On this axis there is a two-level disk on which the thread is fixed. A block is suspended by the other end of the thread. When the thread is wound on the disk, the block rises at a certain height *h*.

When the block descends, the thread is unwound from the disk and makes the flywheel rotate. The gravity and the force of thread tension directed to the opposite parties act to the block. Under the action of these forces, the block moves with constant acceleration according to Newton's second law:

$$ma = mg - T. \qquad (4)$$

Thus, the acceleration, distance and time of movement are connected by the formula:

$$a = 2h/t_2. \qquad (5)$$

From equation (4) taking into account (5) we shall receive the formula for thread tension:

$$T = m\left(g - \frac{2h}{t^2}\right). \qquad (6)$$

The thread tension creates rotating moment:

$$M = mr\left(g - \frac{2h}{t^2}\right) \qquad (7)$$

which transmits angular acceleration to the flywheel. The latter is connected to tangential acceleration of points of the rim of disk and its radius by ratio: $\varepsilon = a_\tau / r$.

As the thread is not stretched so, tangential acceleration of specified points of the disk is equal to acceleration of the block: $a_\tau = a$.

Hence:

$$\varepsilon = \frac{2h}{rt^2} . \qquad (8)$$

To derive a calculation formula of the moment of inertia of Oberbeck's pendulum we shall use the law of conservation of energy:

$$mgh = \frac{m\upsilon^2}{2} + \frac{I\omega^2}{2} . \qquad (9)$$

Let us s take into account that at uniformly accelerated motion without initial speed:

$$\upsilon = at = 2h/t, \omega = \varepsilon t = 2h/rt\ .$$

Then we shall receive the required formula:

$$I = mr^2\left(\frac{gt^2}{2h} - 1\right). \tag{10}$$

Thus, to verify relations (2) and (3) it is necessary to measure the time of falling of the block from the given height, radius of the disk and mass of the block, then to calculate corresponding sizes using formulas (7), (8) and (10).

6.2 Experimental stand

The installation consists of a cross (see below), two-level disk, braking electromagnet and universal electronic timer connected with two photoelectric sensors. There is also a quick-response block, through which a thread is thrown. One end of the thread is fixed on the disk, on its other end, a block (there is a set of blocks of various mass) is suspended. The complete set includes four identical cylindrical blocks, which can be put on the bars and the blocs can move along them, changing thus the moment of inertia of the pendulum.

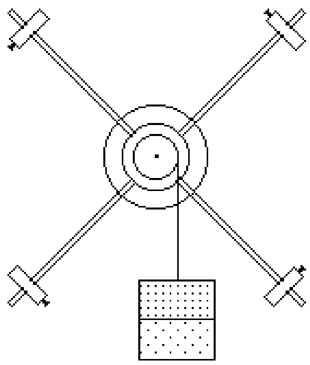


Figure 6.1

The brake electromagnet connected to the voltage source is capable to keep the flywheel together with blocks in the state of rest. When a light beam is interrupted by a falling block the top photoelectric sensing element (PSE) develops an electric pulse of zero-time and the second PSE, the sensor, develops the electric pulse of the end of time measurement and turning on the brake electromagnet. On the front panel of a stopwatch there are keyboard switches NETWORK, START-UP, RESET and digital indicators giving indications of stopwatch.

6.3 Procedure and measurements

Task 1: check the ratio (2).

6.3.1 Level the device and connect it in a network.

6.3.2 Suspend a block with mass m_1 by the thread.

6.3.3 By rotation of the cross-piece reeling up the thread on one of steps of the disk to lift the block on height h. The bottom edge of the block is installed at the level of the top photoelectric element.

6.3.4 Wring out the START-UP key blocking the electromagnet.

6.3.5 Press the RESET key, then the START-UP key that will cause the movement of the pendulum and turning on the stopwatch. Stop watch.

6.3.6 When the pendulum stops, count indications of the stopwatch and write them down into table 6.1.

6.3.7 By the millimeter metric scale put on the column define height *h* ,i.e. the length of the way gone by the block and write down into table 6.1.

Table 6.1

№	*h*, *m*	*r*, *m*	*m*, *kg*	*t*, *s*	$<t>$, *s*	*M*, *N·m*	ε, s^{-2}	$\varepsilon_1/\varepsilon_2$	M_1/M_2
1									

6.3.8 Press the RESET key and repeat the experiment (items 6.3.3÷6.3.6) not less than three times.

6.3.9 Add one or two blocks and measure time (items 6.3.3 ÷6.3.8) with a block of mass m_2.

6.3.10 Measure the diameter of used step of the disk with the help of sliding caliper and define its radius *r*.

Task 2: verification of ratio (3).

6.3.11 Suspend by the thread not less than two blocks with total mass *m*, write down the value into table 6.2.

6.3.12 Put cylindrical blocks on the bars and place them on some distance (2-5 cm) from the ends of bars. Thus, it is necessary to achieve indifferent balance of the flywheel (when the thread is not tense).

6.3.13 Measure time *t* not less than three times when the block falls from height *h* (items 6.3.3 ÷ 6.3.8).

6.3.14 Move the blocks on the bars closer to the pulley. At a new arrangement of blocks the flywheel should be in balance condition (see item 6.3.12).

6.3.15 Measure time *t* not less than three times when the block falls from height *h*.

All received data should be written into table 6.2.

Table 6.2

№	*h*, m	*r*, m	*m*, kg	Position of loads on bars	*t*, s	$<t>$, s	ε, s^{-2}	*I*, кg· m^2	$\varepsilon_1/\varepsilon_2$	I_2/I_1
1										

6.4 Processing the results

6.4.1 Using the results of measurements written in table 6.1, calculate:

a) average values of time$\langle t_1\rangle$ and $\langle t_2\rangle$ of movement of blocks m_1 *and* m_2 respectively;

b) values ε_1 and ε_2, M_1 and M_2 substituting in formulas (7) and (8) average values $\langle t_1\rangle$ and $\langle t_2\rangle$ accordingly;

c) relations $\varepsilon_1/\varepsilon_2$ and M_1 / M_2.

6.4.2 Check up the validity of ratio (2).

6.4.3 Using the results of measurements written into table 6.2 calculate:

a) average value $\langle t_1\rangle$ and $\langle t_2\rangle$times for two positions of blocks on the bars;

b) values ε_1 and ε_2, I_1 and I_2 according to formulas (8) and (10), substituting in them average values $\langle t_1\rangle$ and $\langle t_2\rangle$ accordingly;

c) relations $\varepsilon_1/\varepsilon_2$ and I_2/I_1.

6.4.4 Check up the validity of ratio (3).

6.5 Control questions

6.5.1 Does angular acceleration of a flywheel increase or decrease if , we add the second block suspended by a thread?

6.5.2 At what arrangement of blocks on bars the moment of inertia of the flywheel is the greatest? The least?

6.5.3 How does angular acceleration of the flywheel depend on the arrangement of blocks on bars?

6.5.4 Does the acceleration of the block suspended by a thread depend on the arrangement of blocks on bars?

6.5.5 What factors are not taken into account when deriving formulas in the description of the technique of experiment?

6.5.6 What are basic sources of errors in the given experiment?

7 Laboratory work MMP-10. Definition of liquid viscosity by Stokes method

Aim of the work: study the method of measuring the viscosity of liquids.

Objective: define the viscosity of liquid by Stokes method.

7.1 Experimental procedure

When a body moves in viscous liquid the force of resistance caused by forces of internal friction between liquid layers influences on it. In this case a very thin layer of the liquid adjoins to the body surface and moves with it as a single whole. This layer carries away the next layers of the liquid, which come in no turbulent movement at small speeds.

According to the theory the force of resistance to the movement of a ball in the viscous environment at small speeds and sizes is defined by the formula:

$$F = - 6\pi\eta rv, \tag{1}$$

where η - dynamic viscosity (factor of internal friction) of the liquid;

r - radius of a ball;

v - speed of uniform movement of the ball relative to the liquid.

Three forces operate on the ball falling vertically into the liquid (figure 7a):

1) gravity $\vec{P}$ directed downwards;

2) pushing out force $\vec{G}$ (force of Archimedes) directed upwards;

3) force of viscous resistance $\vec{F}$ directed upwards.

$$P = m_b g = 4/3\,\pi\, r^3 \rho_b g\,; \qquad (2)$$

$$G = m_l g = 4/3\,\pi\, r3 \rho_l g\,; \qquad (3)$$

$$F = 6\pi\eta r v\,, \qquad (4)$$

where m_b and m_l - masses of the ball and liquid respectively;

ρ_b and ρ_l - their density respectively;

g - acceleration of free fall.

Scheme of the experiment (figure 7):

a) forces acting on a metal ball in viscous liquid;

b) vessel with viscous liquid (1), covered with a lid (2) with a hole (3) in the center.

The first two forces are constant, the third one is proportional to speed υ. Therefore, when some speed υ_0 is achieved the forces of Archimedes and that of resistance in the sum can counterbalance the gravity, so the ball will start to move uniformly, i.e.

$$F + G - P = 0. \qquad (5)$$

With the account (2) - (4) we shall receive from (5)

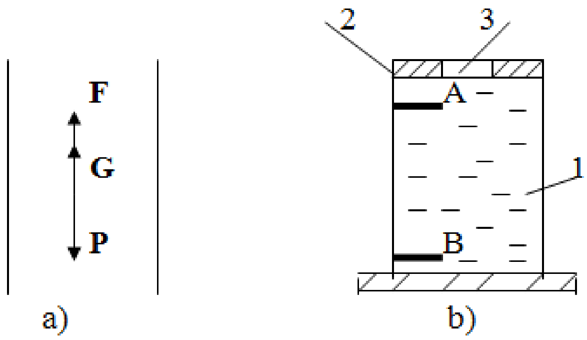


Figure 7

$$6\,\pi\eta r v_0 = 4/3\pi r^3(\rho_b - \rho_l)g\,, \qquad (6)$$

whence

$$\eta = 2gr^2(\rho_b - \rho_l)/(9v_0)\,. \qquad (7)$$

Thus, having measured speed υ_0 of uniform falling of small balls in the liquid, it is possible to define dynamic viscosity of the liquid by Stokes method.

7.2 Experimental stand

The installation (figure 7 b) to define viscosity by Stokes method consists of a glass cylindrical vessel *1* filled with the studied liquid and covered by a lid 2 with a hole 3 in the middle. The cylinder has two horizontal marks A and B, located at a distance *L* from each other, and the upper mark A should be 5-8 cm below the liquid level. The uniform motion of the ball must be established between *A* and *B*.

7.3 Procedure and measurements

7.3.1 Using a micrometer, measure carefully the diameter of the ball (at least three times). Write down values r, m and *L* into table 7.1.

7.3.2 Immerse the ball into the liquid through the hole in the lid of vessel *1*.

7.3.3 Measure time *t* of covering the distance L between the A and B by the ball using a stopwatch. Make the experiment 3 to 5 times for different balls. Write down the measurement data into table 7.1.

Table 7.1

r, m	L, m	t, s	$\upsilon_0, m/s$	$\eta, Pa \cdot s$	$\langle\eta\rangle$, $Pa \cdot s$	$\Delta\eta$, $Pa \cdot s$	$\langle\eta\rangle \pm \Delta\eta$	$\varepsilon, \%$

7.7 Processing the results of measurements

7.4.1 Determine the speed of uniform drop of the ball by formula

$$\upsilon_0 = L / t .$$

7.4.2 Calculate the dynamic viscosity of studied liquid using formula (7). The results of measurements and calculations should be written down into the table.

7.4.3 Estimate the absolute and relative errors of measurements by the method of Student.

7.4.4. Compare the obtained result with the reference value of dynamic viscosity and estimate the possible sources of errors of this method.

7.4.5 Analyze the results and formulate conclusions.

7.8 Control questions

7.8.1 What is the essence of Stokes method?

7.8.2 Under what conditions is Stokes formula valid?

7.8.3 What is the physical meaning of dynamic viscosity of a fluid?

7.8.4 What units are used to measure dynamic viscosity in SI system?

7.8.5 Why should the marks be 5-8 cm below the level of the liquid in the vessel?

7.8.6 What are possible sources of error in Stokes method?

8 Laboratory work MMP-12. Determination of air adiabatic index

Aim of the work: studying isoprocesses in an ideal gas.

Objectives:

- study Clement-Desormes method;
- determine the adiabatic index for the air by Clement-Desormes method.

8.1 Experimental procedure

To determine the adiabatic index $\gamma = C_P / C_V$ in the laboratory work isone can use the classical method known as Clement-Desormes method. Initially, the system (a gas) is in the state 1characterized by thermodynamic parameters: temperature T_1, pressure p_1, and specific volume v_1 (volume of a unit mass of gas). By performing an adiabatic expansion process the gas passes into state 2 (figure 8.1) with parameters T_2, p_2, v_2.

The system is then heated at constant volume v_2 to temperature T_3 equal to the initial temperatureT_1, so that in the final state parameters are equal to T_3,p_3,v_3. (T_3=T_1, v_3 = v_1). Since the process is adiabatic *1-2* then:

$$p_1V_1^{\gamma} = p_2V_2^{\gamma}, \tag{1}$$

where γ is the adiabatic index for this gas.

At states 1 and 3 the gas has the same temperature (the process is isothermal), then applying the law of Boyle – Marriott we have:

$$p_1 \cdot V_1 = p_2V_2 = p_3V_3. \tag{2}$$

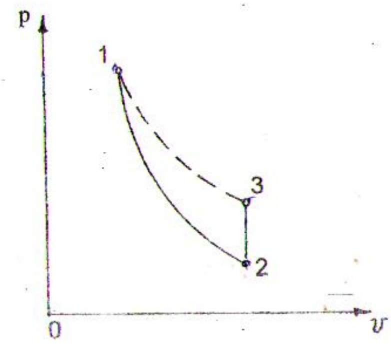


Figure 8.1

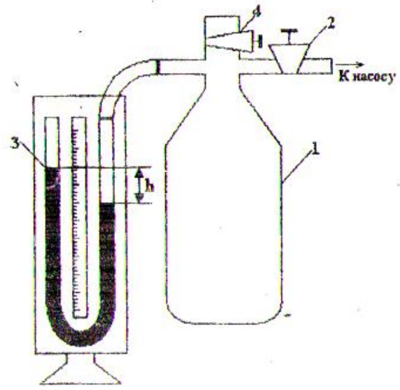


Figure 8.2

From the above equations (1) and (2) it can be defined:

$$\frac{p_1}{p_2} = \left(\frac{p_1}{p_3}\right)^{\gamma}. \tag{3}$$

Hence the adiabatic index γ is determined as:

$$\gamma = \frac{\ln(p_1 / p_2)}{\ln(p_1 / p_2)}. \tag{4}$$

Typically, the experiment is carried out in such a way that p_2 is equal to atmospheric barometric pressure. Then the pressure in states 1 and 3 can be expressed in terms of p_2:

$$p_1 = p_2 + \rho g h_1; p_3 = p_2 + \rho g h_3, \tag{5}$$

where h_1 and h_3 - manometer indications in the divisions of its scale;

ρ - density of the liquid in the manometer.

Formula (4) can be presented based on (5) as follows:

$$\gamma = \frac{\ln(1+\frac{\rho g h_1}{P_2})}{\ln(1+\frac{\rho g h_1}{P_2}) - \ln(1+\frac{\rho g h_3}{P_2})} . \quad (6)$$

Taking into account that $\rho g h_1 / p_2 \prec\prec 1, \rho g h_3 / p_2 \prec\prec 1$ and using $\ln(1+x) \approx x$ at $x \prec\prec 1$, we obtain the formula for determining the adiabatic index

$$\gamma = \frac{h_1}{h_1 - h_3} . \quad (7)$$

Thus, the air adiabatic index can be determined by formula (7) according to Clement - Desormes method - adiabatic gas state method.

8.2 Experimental stand

The experimental installation (figure 8.2) for determining the adiabatic index by Clement - Desormes method consists of one large glass cylinder connected via the valve 2 to the pump, through which the air is pumped into the vessel when the crane is opened. To measure the overpressure U - shaped manometer 3 is used. To release the air from the vessel into the atmosphere another crane 4 is used.

8.3 Procedure and measurements

8.3.1 When the glass cylinder is closed (valve 4 is closed) and valve 2 opened, the air is pumped into the cylinder, until the difference in liquid level in the manometer reaches 300-350 (mm).

8.3.2 Having closed valve 2 it is necessary to wait 3-5 minutes, until the temperature in the tank is equal to the ambient temperature and the pressure is established definitively, count h1-liquid level difference in the manometer.

8.3.3 Open quickly the valve 4 for short time and close it after stopping the hiss of the exhaust air, which corresponds to equalizing the pressure inside the cylinder with the atmospheric pressure.

8.3.4 Wait 3-5 minutes, when the air in the tank warms to the ambient temperature, then count the second difference in liquid levelsh_3 in the manometer.

8.3.5 Carry out the experiment3-5 times, changing the value of h_1.

8.3.6 The measurement results should be written into Table 8.1.

Table 8.1

№	h_1	h_3	γ	$\langle\gamma\rangle$	$\Delta\gamma$	$\gamma=\langle\gamma\rangle\pm\Delta\gamma$	ε,%	
1								

8.4 Processing the results

8.4.1 Calculate the air adiabatic index according to the formula:

$$\gamma = \frac{h_1}{h_1 - h_3}. \quad (7)$$

.

8.4.2 Estimate the absolute and relative error of measurement by the method of Student for P=0.95.

8.4.3 The results should be written into Table 8.1.

8.4.4 Compare the result e with the theoretical value of γ, calculated through the number of degrees of freedom. Estimate possible sources of error of this method.

8.4.5 Analyze the obtained results and make conclusions.

8.5 Control questions

8.5.1 What is adiabatic index γ ?

8.5.2 What is the essence of the Clement-Desormes method used in this paper to determine γ?

8.5.3 What process does it take if you open the tap 4 for a short time?

8.5.4 Which equation obeys the adiabatic process?

8.5.5 How do the internal energy and temperature of a gas change during an adiabatic process?

8.5.6 What process is called isochoric?

9 Laboratory work MMP-13. Definition of air isobaric and isochoric thermal capacities by the speed of sound

Aim of the work: mastering the method of definition of air thermal capacities by the speed sound..

Objectives:

- study the sound propagation phenomenon in gases.
- define the sound waves speed;
- define the relation C_P / C_V for air at the adiabatic process of sound waves propagation.

9.1 Experimental procedure

The ratio of isobaric and isochoric thermal capacities $\gamma = C_P / C_V$ is defined by the method based on measurement of the speed of sound in gas [1].

In mechanics the following formula for the speed of sound propagation in gases is calculated:

$$\upsilon_S = \sqrt{dp / d\rho}, \quad (1)$$

where ρ is gas density;

p - pressure dependent generally not only of r but also the temperature T.

Sound oscillations in gas represent periodic alternations of compressions and rarefactions (a limit wave). Laplace found that oscillations of density and connected with them temperature oscillations in a sound wave occur so quickly, and heat conductivity of air is so small that for such processes heat exchange does not play any role. Temperature differences between air compressions and rarefactions in a sound wave have no time to be leveled so the propagation of sound can be considered as an adiabatic process.

Let us consider how the parameters determining the conditions of an ideal gas when the gas makes an equilibrium adiabatic process are related with each other. As an adiabatic process proceeds without heat exchange with an environment the first beginning of thermodynamics at $\delta Q = 0$ in this case will become: $dU + \delta A = 0.$

For equilibrium processes $dU = C_V \cdot dT$ and $\delta A = p \cdot dV$ then we shall receive $C_V dV = 0$.

From equation of Clapeyron-Mendeleyev written for one mole of an ideal gas:

$$dT = \frac{d(PV)}{R} = \frac{Pdv + Vdp}{R} = \frac{Pdv + Vdp}{C_p - C_v}.$$

Excluding dT we shall receive $C_P pdV + C_V VdV = 0$.

Let us introduce a designation:

$$\gamma = C_P / C_V, \tag{2}$$

where C_P and C_V are mole isobaric and isochoric thermal capacities respectively; then:

$$\gamma \cdot pdV + Vdp = 0. \tag{3}$$

If into the equation (3) instead of volume to enter density, $\boldsymbol{\rho \approx 1/V}$ it will pass into:

$$\gamma \cdot pdp = \rho dp = 0, \tag{4}$$

where for the adiabatic process:

$$dp / d\rho = \gamma \cdot p / \rho. \tag{5}$$

Taking into account (5) the formula for the speed of sound in a gas, named formula of Laplace will become:

$$\upsilon_S = \sqrt{dp / d\rho}. \tag{6}$$

From equation of Clapeyron-Mendeleyev it follows:

$$p / \rho = RT / \mu.$$

Then:

$$\upsilon_S = \sqrt{\gamma \cdot RT / \mu}\,, \tag{7}$$

where μ is the molar mass of gas;

T - its temperature.

From last ratio it is possible to define the relation of thermal capacities:

$$\gamma = \upsilon^2 \cdot (\mu / RT)\,. \tag{8}$$

The speed of sound in gas is defined by the method of standing waves. If in a system the shift of phases between the falling and reflected waves makes π they under interference form a standing wave.

In a standing wave the distance between adjacent nodes or antinodes is equal to:

$$\Delta\ell = \lambda / 2\,.$$

From here $\lambda = 2\Delta\ell$. On the other hand, $\lambda = \upsilon_S / \nu$, where ν - frequency of sound oscillations.

Comparing these formulas we shall receive:

$$\upsilon_S = 2\Delta\ell \cdot \nu\,. \tag{9}$$

Thus having measured the distance between next antinodes or nodes in a standing wave and knowing the frequency of sound oscillations it is possible to define the speed of sound in gas according to formula (9) and then relation $\gamma = C_P / C_V$ according to formula (8).

9.2 Experimental stand

The experimental installation (figure 9.1) to determine the speed of sound in the air consists of a pipe at one end of which there is a source of sound-telephone 3 whose membrane is excited by an audio generator.

Piston 5 is placed inside the pipe and moved by means of a rod. A receiver-microphone 4 is located next to the phone. The electric signal that appears in the microphone under the influence of sound oscillations is fed to the input of the electronic oscilloscope 2.

When the standing wave is installed in the tube (resonance), there will be a significant increase in the amplitude of oscillations on the oscilloscope screen. In this system a standing wave occurs if the distance between the source of sound waves (phone) and the piston $l_n = (2n+1)\dfrac{\lambda}{4}$. Then the distance:

$$\Delta l = l_{n+1} - l_n = \frac{\lambda}{2}\,. \tag{10}$$

Resonance tuning can be carried out either by moving the piston in the pipe or by changing the oscillation frequency of the generator.

9.3 Procedure and measurements

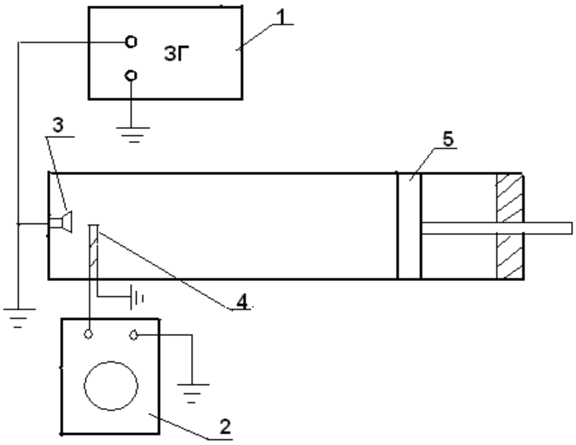


Figure 9.1

9.3.1 Turn on the audio generator and electronic oscilloscope. Install the required oscillation frequency ν on the generator;

9.3.2. Set the image size convenient for observation on the screen of figure 8.1 the oscilloscope; move the piston as close as possible to the phone.

9.3.3 Pulling slowly the piston away from the phone find the distance from the microphone to the piston, at which the first maximum amplitude of oscillations is observed on the screen. Pulling the piston further find the length of the resonator for the next two resonances.

9.3.4 Remove the piston in the opposite direction again. Repeat this process for 3-4 different frequencies.

9.3.5 Write down the measurement results into table 9.1

9.3.8 All the data should be shown in table 9.1.

Table 9.1

№ of experiment	ν, Hz	l_1, m	l_2, m	l_3, m	Δl m	$\upsilon_{зв}$, m/s	γ	$<\gamma>$	$\Delta\gamma$	$\gamma = \prec\gamma\succ \pm \Delta\gamma$	ε, %

9.4 Processing the results

9.4.1 Calculate the distance from formula (8.10) and find the mean values for each frequency.

9.4.2 Using formulas (9) and (8) calculate the speed of sound and determine the ratio γ of specific heats.

9.4.3 Estimate the absolute and relative error of measurements by the method of small samples for *P = 0.95*.

9.4.4 Write down the results of the calculations into Table 9.1.

9.4.5 Compare the obtained result with the theoretical value for air calculated in terms of the number of degrees of freedom and estimate the possible sources of errors of this method.

9.4.6 Analyze the results and formulate conclusions.

9.5 Control questions

9.5.1 What process is called adiabatic?

9.5.2 Why is the propagation of sound waves in a gas considered as an adiabatic process?

9.5.3 What are the values of the speed of sound in gases?
9.5.4 What is the essence of the method used in this work?
9.5.5 Under what condition does a standing wave appear in the pipe?
9.5.6 What is the distance between adjacent nodes or antinodes in a standing wave?

10 Laboratory work MMP – 17. Determination of entropy changes and heating and melting characteristics of tin

Aim of the work: mastering the method of determining the specific heat of the phase transition and the method of calculating the entropy change during first-order phase transitions.

Objectives:

- draw diagrams of tin heating and melting, cooling and solidification;
- determine the melting temperature and specific heat of the material sample;
- calculate the entropy change upon heating and melting the sample.

10.1 Experimental procedure

The phase transformation (or transition) is the process by which the body properties change abruptly. At the first-order phase transition, such parameters as density, internal energy, entropy of the body change abruptly. Under these circumstances energy is released or absorbed; it is called latent heat. Examples of phase changes can be changes in the aggregate state of the substance, in particular melting - a solid (crystalline) state transition into a liquid, and the reverse transition - solidification (crystallization). The first-order phase transition occurs at a strictly constant temperature and predetermined pressure.

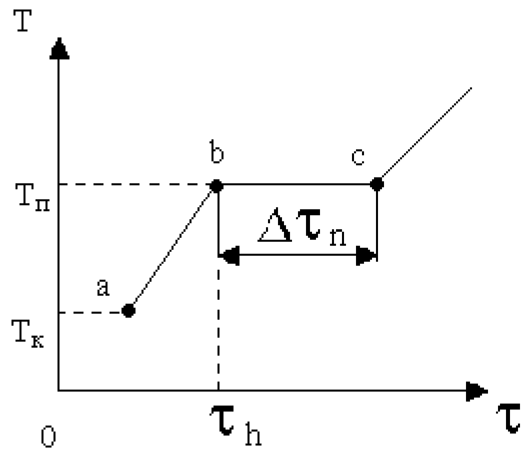


Figure 10.1

One possible way of measuring the temperature and heat of melting is to obtain an experimental melting diagram (or hardening), i.e. dependence of the temperature on melting time of the sample under constant ambient conditions. To this end, the crucible containing the test substance is placed in a furnace. While heating it, the temperature in the crucible is measured at regular intervals.

It is illustrated on an exemplary diagram of heating and melting of a crystalline substance (figure 10.1). In this figure the plot ab characterizes heating of the sample to the melting temperature; bc - section corresponds to melting. At constant heating power of the furnace the heat amount transmitted to the substance depends on the furnace heat loss to the environment. The heat loss is proportional to the difference between the temperature of the furnace and the temperature of environment.

Therefore, thermal power N supplied to the crucible with the sample can be considered constant near the melting point (point b in the diagram). Thermal power on an increasing part of the diagram is equal to the change in internal energy of the crucible with the sample per unit time:

$$N = (mc + m_1 c_1) \cdot dT / d\tau , \tag{1}$$

where m and m_1 - the masses of the sample and the crucible respectively;

c and c_1 - their specific heats;

$dT / d\tau$ - rate of temperature change when the sample is heated.

On the horizontal area *b c* all the heat power produced by the system is used to melt the sample:

$$N \cdot \Delta\tau_n = \lambda \cdot m, \tag{2}$$

here $\Delta\tau_n$ - melting time,

λ - specific heat of melting of the sample material.

By excluding *N* from formulas (1) and (2), we find:

$$\lambda = \frac{mc + m_1 c_1}{m} \cdot \Delta\tau_n \cdot \frac{dT}{d\tau}. \tag{3}$$

If we consider the heating and melting process of the substance as a reversible quasi-equilibrium process, the change in entropy of the sample at the same time can be determined by the following formula:

$$\Delta S = \int_a^b \frac{\delta Q}{T} + \int_b^c \frac{\delta Q}{T} = \int_{T_k}^{T_n} \frac{m \cdot c \cdot dT}{T} + \frac{\lambda \cdot m}{T_n} = m \cdot c \cdot \ell n \ \frac{T_n}{T_k} + \frac{\lambda \cdot m}{T_n}, \tag{4}$$

where T_k - initial (room) temperature;

T_n - melting point temperature.

10.2 Experimental stand

The scheme of laboratory installation is shown in figure 10.2. The stand consists of an electric heater (furnace), the wire is wound around the cylindrical shape crucible filled with tin, to be exact - an alloy of tin with lead (e.g., solder).

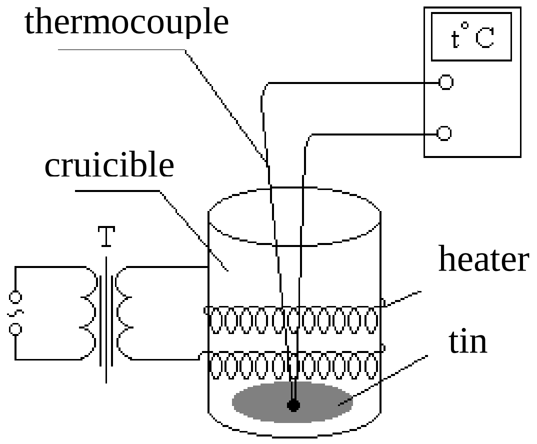


Figure 10.2

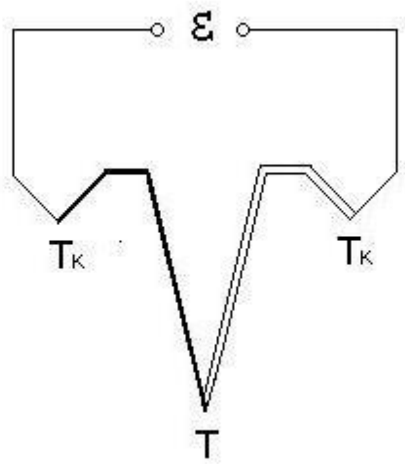


Figure 10.3

A thermocouple with a digital multi-meter is used as the thermometer, which is in direct contact with the test substance in this experiment. The thermocouple is made of two dissimilar conductors. When welding them the"bead hot" junction forms, which is brought into contact with the subject's body. The resultant thermal EMF is proportional to the temperature difference between the "hot" junction and the free ends ("cold" junctions) of the thermocouple, which should be at the same temperature (figure 10.3).

The free ends of the thermocouple are connected to a digital multi-meter, which shows temperature (in Celsius degrees) of the "hot" junction, immersed into the tin.

10.3 Procedure and measurements

Measure the initial (room) temperature of the sample with a digital multi-meter. Turn on the furnace at the same time a stopwatch. With regular time intervals, first one minute, and after achieving 180°C - every half a minute fix the thermometer indications. The tin having been melted and then the melting temperature reached about 220°C , turn off the furnace and continue to fix the measurements in the same manner as the sample temperature goes to the crystallization temperature and, further til the cooling of the sample. The data should be written into table 10.1.

Table 10.1

τ, min	0	1	2	...
$t, {}^0C$				
T, K				

10.4 Processing the results

10.4.1 Draw the obtained data on the graph with the time at horizontal axis, and temperature T at vertical axis.

10.4.2 According to the graph determine the melting temperature T_n and melting time $\Delta\tau_n$ heating rate near the melting point. To do this, select a straight ascending section of the diagram near the melting point; determine the appropriate portion of temperature and time increments ΔT and $\Delta\tau$ in the table; calculate the rate of sample heating:

$$\frac{dT}{d\tau} \approx \frac{\Delta T}{\Delta\tau}.$$

10.4.3 Calculate the thermal power transmitted to the crucible with the sample according to formula (1).

10.4.4 Calculate the specific melting heat of tin by formula (3).

10.4.5 Define the entropy change Δ by heating and melting of tin by formula (4).

10.4.6 The results should be written into table 10.2.

Table 10.2

T_k, K	$T_n,\ K$	$\Delta\tau_n$, s	$\Delta T/\Delta\tau,\ K/s$	N,W	λ, J/kg	ΔS, J/K

10.4.7 Compare the experimentally obtained T_n and λ of tin with the reference values.

10.4.8 Analyze possible sources of error of this method and make conclusions.

10.5 Control questions

10.5.1 What is called a first order phase transition?

10.5.2 What parameters change at the first order phase transition?

10.5.3 What processes are first order phase transition?

10.5.4 How to determine the temperature and specific melting heat of tin in this work?

10.5.5 What is the principle of measuring temperature by thermocouples?

10.5.6 Under what condition can we calculate the change in entropy of tin in this work?

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