PHYSICS

EDUCATION IN ENGLISH

Module 2

Molecular Physics and Thermodynamics

$$A=\int_{V_1}^{V_2} p\,dV$$

A. G. Bovtruk, S. L. Maximov,

S. M. Menaylov, A. P. Vyala, A. P. Polischuk

PHYSICS

Module 2

Molecular Physics and Thermodynamics

Manual

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Authors:

Alla G. Bovtruk, Sergey L. Maximov,
Sergey M. Menaylov, Alevtina P. Vyala, Arkady P. Polischuk

Reviewers:

PhD, prof. **Eugene V. Korshak**
(Kyiv, NPU, Methods of physics teaching department);

PhD, ass. prof. **Yuriy T. Gerasimenko**
(Kyiv, NAU, General physics department)
The English language consultant

ass. prof. **Margarita V. Karpenko**
(Kyiv, NAU, The Foreign languages department)
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У той час, коли Україна приєднується до Болонського процесу та вступає до «Європи знань», видання англомовних навчальних посібників є вкрай необхідним. Даний посібник розроблено для використання в умовах кредитно-модульної системи.

Модуль 2 «Молекулярна фізика й термодинаміка» складається з навчальних елементів, які містять теоретичне ядро, задачі для аудиторної та індивідуальної роботи, а також лабораторний практикум. Розглянуто програмні питання з основ молекулярно-кінетичної теорії газів і класичної термодинаміки.

Для студентів усіх спеціальностей та всіх форм навчання вищих технічних навчальних закладів.

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Ukraine’s joining Bologna process requires creating new books in physics (in English in particular). The book is developed for all forms of studying physics on the Credit-based Modular System basis in higher school.

"Physics. Module 2. Molecular physics and thermodynamics" presents the essential principles of molecular-kinetic theory of gases and classical thermodynamics. It contains Study Units which include theoretical information, test questions, sample problems, laboratory works and individual home tasks.

It is designed for students of engineering specialities.

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PREFACE

Aim of Studying Physics

The discipline “Physics” is aimed at studying basic physical phenomena and laws, mastering fundamental concepts and theories of classical and modern physics, up-to-date research methods, and finally formation of scientific outlook. Therefore, the ***tasks*** are the following:

- learning objective laws of the world and connections between physical phenomena;
- mastering ways and methods of problem solving;
- acquaintance with experimental equipment, formation of practical skills of experiment performance;
- formation of skill to see the concrete physical essence to be applied in practice.

As a result of studying the discipline «Physics», students are supposed to ***know***:

- physical meaning and definition of every term and concept used;
- basic physical phenomena, laws, theories, and spheres of their practical application in engineering;
- major methods of physical research;
- the system of units of physical magnitudes.

Students ought to get the following ***skills***:

- to apply physical laws to solve practical problems;
- to use physical laws and research methods while studying engineering and special disciplines;
- to carry out physical measurements;
- to estimate errors.

Physics is the basis for studying all other special technical disciplines in higher educational institutions. Physics explains and gives comprehension of physical phenomena, familiarizes with concepts, models and laws. The aim of studying physics as well as higher mathematics is to give students a thorough grounding for further mastering engineering subjects.

Foreword to Module M2 "Molecular Physics and Thermodynamics"

This manual represents the second module of the discipline “Physics”. It helps master essential principles of molecular-kinetic theory of gases and classical thermodynamics.

As a result of studying this module, students must ***know*** the definitions of such concepts as *pressure, temperature, work, heat, internal energy, efficiency of heat engine, entropy, basic laws of kinetic theory of gases and the first, second and third laws of thermodynamics.*

The part of physics that is devoted to studying physical properties of substances conditioned by their molecular structure, character of motion of molecules and forces of interaction between them is called ***molecular physics***. It is based on molecular-kinetic theory (MKT). According to this theory, **all bodies are composed of a huge amount of small particles — molecules and atoms. These particles interact between themselves and are in continuous chaotic motion that is called thermal motion.**

Two methods exist to study and analyze this interaction: thermodynamic and molecular-kinetic (statistical) ones.

Thermodynamic method is a phenomenological (descriptive) method. The structure of substance is not considered and exclusively macroparameters and characteristics are applied.

Molecular-kinetic or statistical method may be called the “microscopic” one. Molecular structure and laws conditioned by it are taken into account here. However, as all bodies are composed of a huge number of chaotically moved particles it is impossible to write down and solve the equations of motion for each separate particle. Therefore, mathematical statistics and theory of probability are used here. They evaluate special average characteristics that determine properties of the system of particles as a whole.

Thermodynamic and molecular-kinetic methods are intercommunicated and supplement each other.

Students must get ***skills*** to apply research methods of molecular physics and thermodynamics, plot different graphs, estimate errors of physical measurements, and use theoretical knowledge for practical problem solving.

It is necessary to ***understand***, that molecular physics and thermodynamics supplement each other, but differ in approaches to the phenomena that are studied in this module. Besides that, students will familiarize with many aspects that are necessary during electric and magnetic phenomena study.

The differential and integral calculus is widely used in the module but at the level for first year students.

Module “Molecular physics and thermodynamics” consists of the following study units (**SU**):

Preliminary SU — Brief physical data, Glossary;
SU 1 — Molecular-kinetic theory;
SU 2 — Transport phenomena;
SU 3 — Real gases;
SU 4 — First law of thermodynamics;
SU 5 — Second and third laws of thermodynamics;
SU 6 — Laboratory works;
SU 7 — Individual home tasks;
Supplementary SU — Key words, Help tables.

The Preliminary unit contains the basic concepts and laws of mechanics that are necessary to study efficiently this module and the glossary with explanations of terminology in mathematics and physics.

Study units 1 — 5 include theoretical material, test questions, sample problems, as well as problems to solve in class. Study unit 6 has instructions to perform laboratory works. Study unit 7 contains problems to be solved by students on their own. Supplementary units lighten the work with the module.

The block diagram of the module is represented in Fig. 1.

For proper studying the module, we advise using self-check questions. Each question is supplied with information where to find an answer in the case of difficulty.

Concepts, which are studied in the module, are basic for all engineering specialties; they are used in engineering thermodynamics, aerodynamics and so on.

Study Unit 1

MOLECULAR-KINETIC THEORY

Having worked through the Study Unite, students will know the main statements and notions of molecular-kinetic theory, be able to formulate, write, and analyze laws of molecular physics, Maxwell and Boltzmann distributions and apply theoretical knowledge to solve practical problems.

1.1. Some Basic Notions of Molecular Physics and Thermodynamics

A set of bodies that can exchange energy or substance between themselves or with external bodies is called the **thermodynamic system**. Note that a thermodynamic system may consist of one body also. If energy or substance exchange between a system and external bodies is absent, the thermodynamic system is called the **isolated** one.

Different quantities that characterize the state of a system are called the **parameters of state**. Such parameters like pressure (P), temperature (T), volume (V), density (ρ) are called the **macroparameters** as they are connected with the system in total. Such quantities as mass of a molecule (m_0), its different velocities, energy and so on are called the **microparameters**, as they describe the structure elements of the system.

A system may be in an equilibrium pr in a nonequilibrium state. If all the parameters of a system have definite values and do not change as long as is desired (under unchanging external conditions), the state of a system is called an **equilibrium** one. If at least one of the parameters does not have a definite value, a state is called a **nonequilibrium** one.

If a system that is in a nonequilibrium state to isolate from surroundings, it will transit to an equilibrium state. The process of such transition is called a **process of relaxation** (or simply **relaxation**). The time that is needed to diminish the initial deviation of a parameter from its equilibrium value by e times ($e = 2.71828...$) is called the **time of relaxation**. Each parameter of a system has a time of relaxation. The greatest of these times defines the relaxation time of the whole system.

A transition of a system from one state to another is called a thermodynamic process. There are reversible and irreversible processes.

An equilibrium process is called a **reversible** one if being conducted in the forward and opposite directions, a system passes through the same states and no changes occur in the surroundings. If not, a process is called an **irreversible** one. It is clear, that a nonequilibrium process is always irreversible, but an equilibrium process is always reversible. Real processes may infinitely approach an equilibrium process if they occur sufficiently slowly.

Let us take coordinate axes and lay off the values of two parameters along them, for example, P and V (Fig. 1). Then an equilibrium state of a system can be depicted by a point (see point *1* or *2*), and a reversible process — by a curve. A nonequilibrium state cannot be depicted at all because its parameters have no definite values.

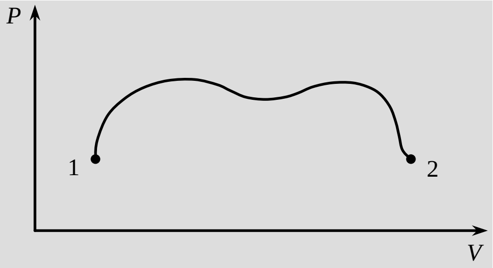

Fig. 1

A process in which a system returns to its initial state after a number of changes is called a **cyclic process** or a **cycle**. Cycles may be both reversible and irreversible.

As we know, absolute masses of molecules and atoms are measured in SI in kilograms. However, in molecular physics the so-called **relative atomic mass A_r** and the **relative molecular mass M_r** are also used.

The **atomic mass unit** (**amu**) is the unit of mass equal to 1/12 of the mass of the carbon isotope ^{12}C ($m\left(^{12}\text{C}\right)$):

$$m_{\text{amu}} = \frac{m\left(^{12}\text{C}\right)}{12} = 1{,}66 \cdot 10^{-27}\ \text{kg}.$$

The relative molecular mass is determined by the equation

$$M_r = \frac{m_0}{m_{\text{amu}}} = \frac{m_0}{\frac{1}{12} m\left(^{12}\text{C}\right)}, \tag{1}$$

where m_0 is the absolute value of the mass of a molecule expressed in kilograms.

Then the mass of a molecule is equal to the product $m_0 = m_{\text{amu}} \cdot M_r$. The same way the mass of an atom is determined: $m_{at} = m_{\text{amu}} \cdot A_r$ (the relative atomic masses A_r are given in the periodic table of the elements).

To characterize a thermodynamic system, the amount of a substance in this system must be known. In SI, this amount of a substance is expressed in moles.

A **mole** (mol) is the amount of a substance containing a number of particles (atoms, molecules, ions, etc.) equal to the number of atoms in 0.012 kg of the carbon isotope ^{12}C. Multiple and submultiple units are also used: the kilomole (1 kmol = 10^3 mol); the millimole (1 mmol = 10^{-3} mol), the micromole (1 μmol = 10^{-6} mol).

According to this definition, one mole of any substance contains the same number of particles. This number was found experimentally and called the **Avogadro constant N_A**:

$$N_A = \frac{0,012}{m\left(^{12}\text{C}\right)} = \frac{0,012}{12 \cdot m_{\text{amu}}} = \frac{10^{-3}}{m_{\text{amu}}} = 6,02 \cdot 10^{23}\,\text{mol}^{-1}.$$

(From this formula we have $m_{\text{amu}} \cdot N_A = 10^{-3}\,\text{kg/mol}$).

At the standard conditions ($T = 273$ K and $P = 1.01 \cdot 10^5$ Pa) one mole of any substance has the same volume — $22.4 \cdot 10^{-3}$ m^3/mol and the same number N_A of molecules.

The **molar mass μ** is the mass of one mole of a substance. The molar mass is equal to the product of the mass of a molecule m_0 of a given substance and the Avogadro constant N_A:

$$\mu = m_0 \cdot N_A = m_0 \cdot 10^{-3} / m_{\text{amu}} = 10^{-3} \cdot M_r \text{ kg/mol} = M_r \text{ g/mol}. \qquad (2)$$

Pay attention that the relative molecular mass M_r is a dimensionless quantity, but the molar mass μ has a dimension and it is measured in kg/mol (or g/mol). The molar mass expressed in grams numerically equals the relative molecular mass.

The relative molecular mass is determined by the sum of the relative masses of the atoms contained in a molecule. For example, the molar mass of CO_2 is $44 \cdot 10^{-3}$ kg/mol, because its relative molecular mass is $M_r(CO_2) = M_r(C) + M_r(O_2) = 12 + 2 \cdot 16 = 44$. Thus, the molar mass μ of CO_2 in grams is 44 g/mol, and in kilograms is $44 \cdot 10^{-3}$ kg/mol.

To find the number of moles ν in a given substance, we have to divide the mass of a substance by its molar mass:

$$\nu = \frac{m}{\mu}. \tag{3}$$

Then the total number of molecules N contained in a given substance is:

$$\boxed{N = \nu N_A = \frac{m}{\mu} N_A.} \tag{4}$$

The number of molecules per unit volume is called the **concentration of** molecules:

$$n = \frac{N}{V} = \frac{mN_A}{\mu V} = \frac{\rho}{m_0}, \tag{5}$$

where ρ is the density of a substance.

To find the pressure of a mixture of gases, the ***DALTON LAW*** is applied: **the pressure of a mixture of gases is equal to the sum of the partial pressures of these gases**

$$\boxed{P = \sum_{i=1}^{n} P_i.} \tag{6}$$

The **partial pressure** is a pressure that each gas would have in case it alone occupies the total volume where a mixture is contained.

In SI a pressure unit is the pascal (Pa), 1 Pa = 1 N/m^2. Other units are also used (but not in SI):

- the bar (bar) — 1 bar = 10^5 Pa;
- the standard (physical) atmosphere (atm) — 1 atm $\approx 1{,}013 \cdot 10^5$ Pa = = 1,013 bar;
- the technical atmosphere (at) — 1 at $\approx 0{,}98 \cdot 10^5$ Pa = 0,98 bar;
- the millimeter of mercury (mm Hg) — 1 mm Hg = 133,3 Pa; 1 atm = 760 mm Hg.

1.2. Equation of State of an Ideal Gas

In molecular physics as well as in mechanics, definite models to study the behavior of real systems are used. One of such models is an ideal (perfect) gas.

An **ideal gas** model states:

- molecules of a gas are material points;
- the interaction between them is negligibly small;
- collisions between molecules themselves and vessel walls are perfectly elastic.

It is important to note that as there is no interaction between gas molecules, a potential energy of interaction equals zero.

A real gas is close to an ideal one at low densities. It was found that such gases as air, oxygen, nitrogen differ slightly from an ideal gas even in usual conditions (at room temperature and atmospheric pressure). Especially close in their properties to an ideal gas are helium and hydrogen.

Experiments showed that, at low enough densities, one mole of an ideal gas obey the relation that is called Mendeleev—Clapeyron equation or the **equation of state of an ideal gas**:

$$\boxed{PV_\mu = RT,} \tag{7}$$

where V_μ is a volume of 1 mol of an ideal gas, R is the **universal gas constant**. To find the universal gas constant, the standard conditions may be used: $T = 273$ K, $P = 1.01 \cdot 10^5$ Pa and $V_\mu = 22.4 \cdot 10^{-3}$ m^3/mol. Then

$$R = PV_\mu / T = 8.31 \text{ J/(mol·K)}.$$

For any mass of a gas m, that occupies a volume $V = V_\mu \cdot m/\mu$ Equation (7) looks like the following:

$$\boxed{PV = \frac{m}{\mu} RT,} \tag{8}$$

where μ is the molar mass of a gas.

From Eq. (8), the density of an ideal gas may be determined:

$$P = \frac{m}{\mu V} RT = \frac{\rho}{\mu} RT,$$

that is

$$\rho = \frac{P\mu}{RT}. \tag{9}$$

We may rewrite Eq. (8) introducing the concentration of molecules $n = N/V$ (the number of molecules per unit volume). For this, we multiply and divide the right-hand side of this equation by the Avogadro constant N_A:

$$PV = \frac{m}{\mu} N_A \frac{RT}{N_A} \Rightarrow P = \frac{m}{\mu} N_A \cdot \frac{1}{V} \cdot \frac{RT}{N_A}.$$

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