PHYSICAL MECHANICS

LABORATORY MANUAL IN GAS DYNAMICS, HYDRODYNAMICS, AND PHYSICAL MECHANICS

EDITED BY
PROFESSOR E. E. SON
Moscow 2006

CONTRIBUTORS

A.S. Koroteev
M.A. Meshkov
A.T. Onufriev
A.A. Paveliev
Yu.G. Rakogon
R.A. Safarov
V.A. Sechenov
Yu.A. Shcherbina
N.N. Shirokov
V.A. Volkov
E.E. Son
S.M. Starikovskaya
A.Yu. Starikovskii
B.K. Tkachenko
V.P. Vakatov
M.V. Vasiliev
V. Yu. Velikodnyi
E.N. Voznesenskii
A.P. Zuev

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Reviewers: Department of Plasma Physics of the Moscow Engineering-Physics Institute (State University) A. I. Leont'ev, Full Member of the Russian Academy of Sciences.

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A series of experimental laboratory works on gas dynamics, hydrodynamics of a viscous fluid, thermo- and aerodynamics, turbulent flows, plasma physics at normal and high temperatures that constitute the subject matter of physical mechanics for students of the second, third, and fourth years of study at the Faculty of Aerophysics and Space Investigations (FASI) of the Moscow Engineering-Physics Institute (State University) in "Applied Mathematics and Physics." The educational cycle, "Physical Mechanics," at the Faculty incorporates a course of lectures, seminars, and laboratory work. Experimental works are intervened with numerical simulation on personal computers with visual observations.

The book is intended for engineering physics and applied physics specialties of higher educational establishments.

INTRODUCTION

The trends in the activities of the base departments of the Faculty of Aerophysics and Space Investigations (FASI) of the Moscow Engineering-Physics Institute are connected with theoretical and experimental investigations of the phenomena of external and internal gas dynamics and hydrodynamics. Among them are the problems of entry of space apparatuses into dense atmospheric layers, design and creation of rocket engines, gas-dynamic lasers, electrophysical systems, and other technical facilities that use a gas, liquid, or plasma as the working medium. Fundamental investigations carried out at the base departments of FASI are related to the study of the phenomena occurring in the atmosphere, ocean, and other geospheres with respect to the physics of combustion and explosion.

The above trends constitute the subject matter of the faculty cycle, "Physical Mechanics." The faculty cycle for training students includes courses of lectures, seminars, and laboratory work on aerophysics, applied gas dynamics, hydrodynamics, and physical mechanics for the training of bachelor of science candidates on "applied mathematics and physics" in the second, third, and fourth years of education.

The fundamental education in the field of continuum mechanics, hydrodynamics of media with different rheologies, and nonequilibrium systems is unthinkable if the skills of an experimental work have not been acquired, if students have not become familiar with the methods of creating dynamic media and their diagnostics. Despite the long history of the development of experimental methods, recent years have witnessed qualitative changes in this area due to the appearance of new types of probes based on a new elementary base and wide introduction of computation engineering in the methods of the processing of measurements.

The laboratory work at FASI on continuum mechanics and physical mechanics is intended for both getting acquainted with the methods of measurements and carrying out laboratory works closely approximating up-to-date scientific experiments.

The general orientation of the cycle is associated with the investigation of the thermophysical properties of gases and plasma that include the thermodynamic properties of ideal and nonideal gases and plasma, chemical reactions, including dissociation and ionization, elementary processes in gases and plasma, and the optical properties of gases. Studied in the cycle are the hydrodynamics of motion of high-temperature gases and plasma, as well as radiative transfer. Considered in the cycle are the most general principles of hydrodynamic description with allowance for chemical reactions, self-consistent electromagnetic fields, and of translational, rotational, and vibrational nonequilibrium states; hydrodynamic, thermal, and plasma instabilities at linear and nonlinear stages; and transition from laminar modes of flow to turbulent ones. Most hydrodynamic flows are turbulent; therefore, attention is specially paid to practical methods of visualization and calculation of turbulent flows. It should be noted that the up-to-date methods of describing turbulent flows with combustion are based on the method of probability density functions that have been studied first in the world experimentally at the department of physical mechanics.

The laboratory work at the second year of education acquaints students with gas-dynamic flows; that at the third year deals with more complex types of laminar and turbulent flows of air and gases with internal degrees of freedom; that at the fourth year deals with investigation of present-day complex flows, as well as electrophysical and thermophysical phenomena, often at the level of modern scientific investigations. Experimental works are accompanied by numerical simulation on personal computers with visualization of the processes.

The work on compilation of the laboratory manual was begun at FASI at the end of 1960 by V. M. Ievlev, T. V. Kondranin, A. S. Koroteev, A. T. Onufriev, A. A. Paveliev, Yu. G. Rakogon, I. N. Rei, R. A. Safarov, V. A. Sechenov, A. A. Serebrov, Yu. A. Shcherbina, E. S. Shchetinkov, E. A. Son, B. K. Tkachenko, V. P. Vakatov, M. N. Vasiliev, V. A. Volkov, E. N. Voznesenskii, and by many other teachers. At the present time, this laboratory manual is being modified in an effort to update it, make it adequate for the needs of the FASI Department, and to reflect promising trends in high technologies in the field of continuum mechanics and physics.**ii**

The book prepared for publication rests on the materials submitted by the teaching staff of the Department of Mechanical Physics and those who served on the staff earlier. The setting of the text, preparation of figures, and preparation of laboratory aids were accomplished on the basis of modern technologies by D. E. Belov and O. S. Galkevich, to whom the contributors express their gratitude.

The publication of the Laboratory Manual was made possible due to the support from the REC-011 project of the joint program "Fundamental Investigations and Higher Education" at the American Civil Research and Development Foundation (CRDF) and from the Ministry of Education and Science of the Russian Federation.

E. E. Son

Head of Department, Professor, Doctor of Sciences
(in Physics and Mathematics)
Merited Scientist of the Russian Federation

Contents

WORK 1

MEASUREMENT OF FLAME TEMPERATURE BY THE SPECTRAL-LINE REVERSAL METHOD

V. P. Vakatov and A. P. Zuev

1.1. Introduction

The urgent problems of science and technology require measurements of the temperature of emitting bodies and radiative heat fluxes from them. Conventional contact methods are of limited utility because of the simultaneously arising complex problem of convective heat transfer. Optical methods of measurement have been placed in the forefront. The major advantages of these methods are that they do not need direct contact with a measured object and do not distort its parameters.

In the present laboratory work, the temperature of heated bodies is measured by two techniques: (i) a pyrometric one, with the aid of which the temperature of glowing metals is determined (the description of a pyrometer is given in Section 1.6) and (i) the spectral-line reversal method, with the aid of which the temperature of the flame of a propane burner is determined. Section 1.2 presents the theory of radiation on which the proposed methods of measurements are based. Section 1.3 introduces the readers to the characteristic features of the radiative properties of real media.

The main content of this laboratory work can be extended by studying the processes of heat exchange between the flame of a propane burner and a metal plate inserted into the flame. The reference sources needed for processing experimental data on heat transfer are given in Sec. 1.7.

At the end of Work 1 the literature is cited that may be needed for further study of optical methods and radiation theory. The majority of illustrative experimental results given have been borrowed from Refs. [1–3].

The presentation employs the International System of Units (SI). The sole exception is the use of the following units: 1 μm = 10^{-6} m to measure the radiation wavelength and 1 kPa = 10^3 Pa to measure pressure.

1.2. Some Information on Radiation

Emission and absorption of thermal radiation. Kirchhoff's law. Blackbody and Planck distribution function. The Stefan–Boltzmann law.

A material medium at any temperature is capable of emitting electromagnetic radiation due to the fluctuation of charges caused by thermal motion. Such a medium is also capable of absorbing outer radiation incident on it, and in this case the energy of electromagnetic waves may again be converted into thermal energy. Electromagnetic waves, being the carriers of thermal energy, differ from waves that correspond to other modes of radiation only by wavelength; it is precisely the wavelength on which the action of radiation depends when the latter is incident on a substance.

The spectrum of emitted radiation embraces a wide range of frequencies; this is attributed to a large number of the degrees of freedom of particles that form such media, to their thermal motion, and to the forces of interaction between them. Consequently, for the theoretical study of thermal radiation, it is necessary to apply statistical methods. The theory of radiation can be presented most sequentially from the standpoints of quantum mechanics or electromagnetic wave theory. However, for many practically important cases, one may adhere to a phenomenological approach, which has been favored by us.

We introduce the concept of *spectral radiation intensity*, $I_\lambda dSdtd\lambda d\Omega$, as the quantity of energy transferred by radiation through an element of unit area, the normal to which coincides with the direction of radiation propagation in unit time, in the unit spectral wavelength interval, and in the unit solid angle. In what follows, the differentials $dSdtd\lambda d\Omega$ are not written but they should be kept in mind. If the normal of the selected area

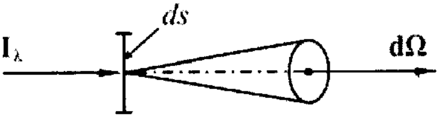

Figure 1.1. Toward the notion of radiation intensity.

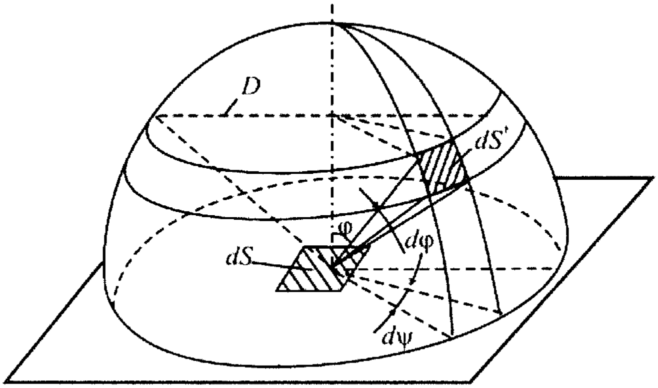

Figure 1.2. Determination of the solid angle from the elemental area dS'.

dS makes an angle φ with the direction of radiation and $d\Omega$, the energy transmitted through this inclined element of area in time dt will be

$$dU = I_\lambda \cos(\varphi)\, d\lambda\, dS\, d\Omega\, dt\,. \tag{1.1}$$

If we consider that the selected area dS is located on the surface of an emitting medium (the temperature of which is T), the intensity of emission from this surface is called *the emissive capacity of the body surface* or *the spectral surface density of radiation in the direction of the normal*, and it is designated by $E_\lambda(T)$.

In the case of isotropic or, as it is said, diffuse radiation from the surface dS, the energy emitted in the time dt inside the solid angle $d\Omega$ within the interval of wavelengths $d\lambda$ is equal to

$$dU = E_\lambda\,(T)\cos(\varphi)\, d\lambda\, dS\, d\Omega\, dt\,, \tag{1.2}$$

which is Lambert's law.

In order to calculate the total amount of energy emitted by the element of diffuse surface dS in the wavelength interval $d\lambda$, it is necessary to integrate expression (1.2) over the solid angle $d\Omega$ over the hemisphere. If in integration we make use of spherical coordinates, as shown in Fig. 1.2, we obtain

$$d\Omega = \frac{dS}{r^2} = \sin(\varphi)\, d\varphi\, d\psi\,, \tag{1.3}$$

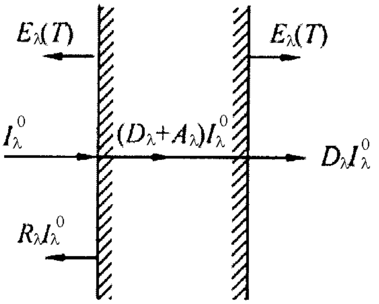

Figure 1.3. Various processes connected with radiation.

$$\frac{U}{dt} = K_\lambda\,(T)\;dS\;d\lambda\; = \;E_\lambda\,(T)\;dS\;d\lambda$$

$$\times\int_0^{2\pi} d\psi \int_0^{\pi/2} \sin\,(\varphi)\cos\,(\varphi)\;d\varphi\; = \;\pi E_\lambda\,(T)\;dS\;d\lambda\,. \qquad (1.4)$$

The quantity $K_\lambda(T)$ is sometimes called *the hemispherical spectral radiant flux surface density*. Relation (1.4) is very important in measurements of radiation; it shows that the total energy emitted by the surface element dS into a semispace is π times greater than the energy emitted by it in the direction of the normal to the surface within the limits of a unit solid angle.

When some radiation I_λ^0 is incident on the body, one can consider several processes shown in Fig. 1.3. Part of the incident radiation I_λ^0 may penetrate to the interior of the body and part of it, I_λ^R, be reflected from it.

Moreover, part of the radiation that penetrates inside a body can *be absorbed*, I_λ^A (and converted into a new form of energy, e.g., thermal), and part of it will pass through the body intact, I_λ^D. From the energy conservation law it is clear that

$$I_\lambda^0 = I_\lambda^R + I_\lambda^A + I_\lambda^D\,. \qquad (1.5)$$

We introduce the following notions:

- $R_\lambda = I_\lambda^R / I_\lambda^0$ — spectral *reflectivity*,
- $A_\lambda = I_\lambda^A / I_\lambda^0$ — spectral *absorptivity*,
- $D_\lambda = I_\lambda^D / I_\lambda^0$ — spectral *transmissivity*.

From these definitions and from equality (1.5), it follows that

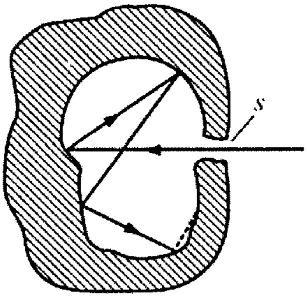

Figure 1.4. Toward the concept of blackbody.

$$R_\lambda + A_\lambda + D_\lambda = 1\,. \tag{1.6}$$

The properties of media can be different, and two of these quantities separately or both quantities simultaneously can be equal to zero. We will consider in more detail the case $A_\lambda = 1$. The body that at any temperature completely absorbs the radiation of arbitrary frequency incident on it is called the blackbody. There are no such bodies in nature; soot and platinum black seem to be black only in the visible region of the spectrum. The properties of the blackbody are best reproduced by a small hole in a closed cavity whose walls are made of an absorbing material. The radiation that penetrates through the hole S into the cavity will be absorbed almost entirely there (see Fig. 1.4). Consequently, the cross-sectional area of the hole is the absorbing surface of the blackbody. If the hole is taken to be rather small, it practically will not influence the radiation inside the cavity. Moreover, if the cavity walls are made of a homogeneous substance and are kept at temperature T, then in the course of time an equilibrium must set in between the radiation emitted and absorbed by the walls

$$E_\lambda(T) + R_\lambda I_\lambda(T) = I_\lambda(T)\,. \tag{1.7}$$

The equilibrium radiation set inside the cavity is homogeneous and isotropic and may be characterized by a single quantity — the spectral blackbody radiation intensity $B_\lambda(T)$. Thus, it follows from the previous equality that

$$E_\lambda(T) = (1 - R_\lambda)\,B_\lambda(T) = A_\lambda B_\lambda(T)\,, \tag{1.8}$$

whence

$$\frac{E_\lambda(T)}{A_\lambda} = B_\lambda(T)\,, \tag{1.9}$$

which is Kirchhoff's law. This law shows that the ratio between the emissivity and absorptivity is the same for all substances and is equal to the spectral blackbody intensity; a body that strongly absorbs any radiation emits the same radiation strongly in the case of thermal radiation.

Since in the case depicted in Fig. 1.3 $A_\lambda = 1$, then from Kirchhoff's law we obtain

$$E_\lambda(T) = B_\lambda(T)\,; \tag{1.10}$$

that is, the blackbody radiation intensity (the radiation that will be emitted from the cavity through the hole *S*) is equal to the intensity of thermal equilibrium radiation at the same temperature.

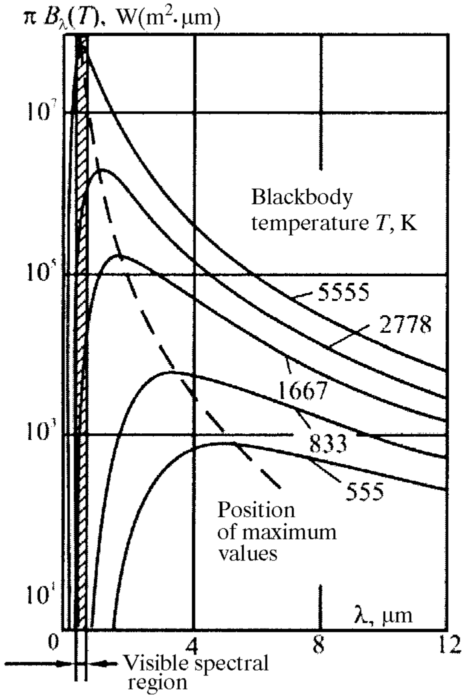

Figure 1.5. Spectral hemispheric blackbody radiation density $\pi B_\lambda(T, \lambda)$ versus the wavelength for several values of temperatures.

The function $B_\lambda(T)$ is the same for all the substances and it can be found theoretically. This was done by Planck in 1905 as follows:

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5 \left(e^{hc/\lambda kT} - 1\right)}, \tag{1.11}$$

where c is the speed of light in vacuum, $c = 3.0 \cdot 10^8$ m/s, h is the Planck constant, $h = 6.63 \cdot 10^{-34}$ J·s, and k is the Boltzmann constant, $k = 1.38 \cdot 10^{-23}$ J/K.

In the literature, use is more often made of the hemispherical spectral surface blackbody radiation density, which, according to Eq. (1.4), is equal to $\pi \cdot B_\lambda(T)$. Figure 1.5 depicts the graphs of the function $\pi \cdot B_\lambda(T)$ for several values of temperatures. For the convenience of computations we give the expression for the hemispherical spectral surface blackbody radiation density in terms of the constants C_1 and C_2 as follows:

$$K_\lambda^p(T) = \pi B_\lambda(T) = \frac{C_1}{\lambda^5 \left(e^{C_2/\lambda T} - 1\right)}, \tag{1.12}$$

where $C_1 = 2\pi hc^2 = 3.74 \cdot 10^{-16}$ W·m^2, $C_2 = hc/R = 1.44 \cdot 10^{-2}$ K.

Knowing the Planck distribution law, it is not difficult to determine the total energy emitted by one side of the unit surface into the hemisphere in the entire spectral interval (from 0 to ∞),

$$N_S(T) = \int K_\lambda^p(T)\, d\lambda = \int_0^\infty \pi B_\lambda(T)\, d\lambda = \sigma_s T^4, \tag{1.13}$$

which is the Stefan–Boltzmann law, where σ_s is the Stefan–Boltzmann constant.

$$\sigma_S = \frac{12\pi^5 k^4}{15c^2 h^3} = 5.67 \times 10^{-8} \;\; \mathrm{W/m^2 \cdot K^4}.$$

Expression (1.13) for $N_S(T)$, in contrast to (1.12), can be called the hemispherical integral blackbody radiation intensity. (In what follows, the term integral will mean that radiation corresponds to all wavelengths.)

Table 1.2. Specific resistance and thermal conductivity of some metals at $T = 273$ K

	$\rho \cdot 10^8$ $\Omega \cdot$m	λ, W/m·K
copper	1.6	380
aluminum	2.5	210
tungsten	5.1	170
nickel	7.6	83
steel	10.0	50

$$\lambda_{\max} T = 2.66 \times 10^{-3} \ \text{m K}. \tag{1.41}$$

From this equation it follows that at radiator temperatures not exceeding 700 K, the maximum of the energy distribution curve is at a wavelength longer than 4 μm. And, consequently, for temperatures above 700 K the influence of the electromagnetic theory should be considered with caution. A comparison between experimental and calculated values of the integral emissivity shows satisfactory agreement. In some cases, for example, for platinum, relation (1.39) is unexpectedly satisfied at very high temperatures when a considerable portion of radiation is in the region of short wavelengths. For a more accurate determination of a radiant flux from heated metals, one should use experimental values of emissivity instead of relation (1.39).

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