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THE THEORY OF THERMAL REGULAR REGIME AND ITS APPLICATION TO THE DETERMINATION OF THERMAL CHARACTERISTICS

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Abstract—The basic regularities of the thermal regular regime theory developed by G. M. Condratjev and its practical application to the thermotechnical measurements are discussed in this paper.

Under the thermal regular regime of a body or a system of bodies one understood such a process of cooling or heating the system when: (1) the initial temperature distribution in the system does not influence the law of temperature change; (2) the law of temperature change is expressed in a simple mathematical form; (3) this law is general for all the points of the system.

These regularities of the thermal regular regime permitted: (a) to work out a number of methods to determine the thermal characteristics of different materials; (b) to determine the thermal inertia of thermometers and pyrometers; (c) to obtain the relations to calculate the kinetics of cooling or heating the complicated thermotechnical apparatus and equipment.

Résumé—Les conditions de régularité qui sont à la base de la théorie du régime thermique régulier développée par G. M. Condratjev et son application aux mesures thermiques de la technique sont précisées dans cet article.

Par régime thermique régulier d'un corps ou d'un ensemble de corps, on désigne un processus dc refroidissement ou de chauffage du système tel que: 1° la distribution des températures initiales dans le système n'influence pas la loi d'évolution des températures; 2° la loi d'évolution des températures s'exprime dans une forme mathématique simple; 3° cette loi est générale et s'applique en tout point du système.

Ces conditions de régularité du régime thermique régulier ont permis: (a) d'établir un certain nombre de méthodes pour la détermination des caractéristiques thermiques des différents matériaux, (b) de déterminer l'inertie thermique de thermomètres et pyromètres, (c) d'obtenir les relations permettant de calculer la cinétique de refroidissement ou de chauffage dans le cas d'appareillages techniques compliqués.

Zusammenfassung—In dieser Arbeit werden die Grundzüge der Theorie des regulären thermischen Zustandes, nach G. M. Condratjev, und ihre praktische Anwendung auf wärmetechnische Messungen behandelt.

Unter dem regulären thermischen Zustand eines Körpers oder eines Systems von Körpern versteht man einen Kühlungs- oder Erwärmungsvorgang, bei dem (1.) die anfängliche Temperaturverteilung in dem System das Gesetz der Temperaturänderung nicht beeinflußt, (2.) das Gesetz der Temperaturänderung in einer einfachen mathematischen Form ausgedrückt ist, (3.) dieses Gesetz für alle Punkte des Systems gültig ist.

Diese Grundzüge des regulären thermischen Zustandes erlauben (a) eine Anzahl von Methoden zur Bestimmung der thermischen Eigenschaften verschiedener Materialien anzugeben, (b) die thermische Trägheit von Thermometern und Pyrometern zu bestimmen, (c) die Kinetik der Kühlung oder Heizung von komplizierten wärmetechnischen Apparaten zu berechnen.

Abstract—В статье рассматриваются основные закономерности теории теплового регулярного режима, разработанные Г. М. Кондратьевым, и её применение в практике теплотехнических измерений.

Тепловым регулярным режимом тела или системы тел называется такой процесс её нагревания или охлаждения при котором: (1) на закон изменения температуры не влияет начальное распределение температуры в системе, (2) закон изменения температуры имеет простое математическое выражение, (3) этот закон является общим для всех точек системы.

Эти закономерности теплового регулярного режима позволили: (а) разработать ряд методов определения тепловых характеристик различных материалов, (б) определить тепловую инерцию термометров и пирометров, (в) получить расчётные соотношения для исследования кинетики охлаждения или нагревания сложных теплотехнических аппаратов и устройств.

CONDRATJEV has developed experimental methods serving to determine the thermophysical charactersitics of non-metallic materials. These methods are based on the general regularities of the unstationary temperature field of a body or system of bodies in cooling or heating processes.

It is known that the general solution of the Fourier equation for the problem of cooling of a uniform and isotropic body of any configuration is expressed by an infinite series, the terms of which have been distributed along the rapidly decreasing exponential functions of time

$$t - t_c = \sum_{i=0}^{\infty} A_i U_i \exp(-m_i \tau) \qquad (1)$$

so that the positive numbers $m_0, m_i, \ldots$ are the series of continuously increasing discrete numbers

$$0 < m_0 < m_1 < m_2 < \ldots \qquad (2)$$

$U_0, U_1, \ldots$ are the finite functions of body points co-ordinates;

$A_0, A_1, \ldots$ are also finite and constant numbers independent of time and co-ordinates. The functions of U_i satisfy the boundary conditions

$$\left(\frac{\partial U_i}{\partial n} + hU_i\right)_s = 0 \qquad (3)$$

The functions of A_i are determined from the initial conditions

$$\sum_{i=0}^{\infty} A_i U_i = f(x, y, z) \qquad (4)$$

The following symbols are assumed here: $t = t(x, y, z, \tau)$ is the temperature of a body at the point (x, y, z) at the time τ; t_c is the medium temperature; $\partial U_i/\partial n$ is the derivative of the function U_i along the external normal to the outside surface of the body S; $f(x, y, z)$ is the function which characterizes the initial distribution of temperatures; $h = \alpha/\lambda$, where α is the heat transfer coefficient and λ is the thermal conductivity coefficient. For the latter coefficients we assume that they are independent of temperature as it is generally used in the theory of heat conduction. The kinetics of cooling a body has three stages. The first one is qualified by the strong influence of the initial state of a body upon its temperature field. In general, the initial state of a body is occasional and quite independent of both the system characteristics and the conditions under which the cooling process is going on. In the course of time the influence of the initial peculiarities of the temperature field upon further change is smoothed. From the "irregular stage" the process becomes "regular" and the influence of non-uniformity of the initial temperature distribution no longer has any effect; the law of change of the temperature field has the ordinary exponential form

$$t_{reg} - t_c = A_0 U_0 \exp(-m_0 \tau) \qquad (5)$$

Condratjev gives a generalization of the above theorem for a system of bodies.†

Suppose that the thermal characteristics: thermal conductivity λ_j, thermal diffusivity a_j, specific heat c_j and also the density γ_j depend upon the co-ordinates of the points of the given part (j) of the system (if the material, for example, is non-homogeneous) but it is assumed here that λ_j, a_j, c_j, γ_j are independent of temperature in the temperature ranges observed in the system during the process.

Under these conditions the principle about the conversion from an irregular state to a regular regime, proved by Boussinesq for any uniform and isotropic body, is valid for the system of bodies as well.

So we see that the rate of change of ln

† By the system of bodies one may understand a whole complex of various solids which are in close contact. If the components of a system are liquids then we suppose that a field of temperature is uniform.

$(t - t_c)$ is the same for all the points of the system

$$\frac{\partial}{\partial \tau} \ln (t - t_c) = -m \qquad (6)$$

Therefore the temperature field of a body will be expressed by co-ordinates τ, $\ln (t - t_c)$ after the regular regime has been established, and by the system of straight parallel lines with the negative angle coefficient equal to $-m$, as shown in Fig. 1. This is a typical feature of the regular regime and is only essential for it. m plays an important role in the theory of regular regime and it is known as the rate of cooling, since it characterizes the rapidity with which the body is cooled.

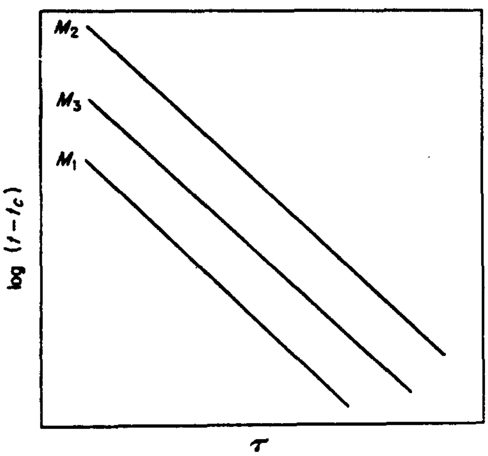

FIG. 1. The temperature field of the system at its regular cooling or heating.

The theoretical and experimental researches dealing with the cooling of bodies in various mediums indicate that the rate of cooling depends upon the heat transfer coefficient, the thermal characteristics of a body, and its size and configuration.

The rate of regular cooling of a uniform and isotropic body at the final value of heat transfer coefficient is proportional to the surface of the body and inversely proportional to its total heat capacity (C).

The coefficient of proportionality is a product of the heat transfer coefficient α and the criterion ψ which is decreasing monotonously as α is increasing.

$$m = \alpha\psi \frac{S}{C} \qquad (7)$$

$$\psi = \frac{t_s - t_c}{t_v - t_c} \qquad (8)$$

where the criterion ψ characterizes the non-uniformity of the temperature field in a body and is numerically equal to the ratio of the average surface temperature of a body to its average volumetric temperature of superheating.

If $\alpha(\mathrm{Bi}) = 0$, then $\psi = 1$

and $\alpha(\mathrm{Bi}) \rightarrow \infty \qquad \psi \rightarrow 0$

$\lim m = m_\infty$ which corresponds to $\mathrm{Bi} = \infty$ and the thermal diffusivity of the material are directly proportional:

$$a = Km_\infty \qquad (9)$$

where the coefficient of proportionality K depends only on the size and the form of a body.

The coefficient K serves as a measure of thermal inertia of a given model: the greater the value of K the smaller is m and thus the slower the cooling of a body proceeds, irrespective of what material the body is made.

K, in the theory of regular regime is called a coefficient of a body shape. This coefficient can be calculated in two ways: either at $\mathrm{Bi} \rightarrow \infty$ or considering the boundary conditions

$$U/s = 0 \qquad (10)$$

and we shall define m_∞. In many works on the regular regime theory [2–4] the value of the form coefficient has been calculated for bodies of various configurations.

The application of equation (7) was in practice restricted by the difficulty of calculating the criterion ψ. The methods of calculation used for this criterion have been developed only for bodies which have a simple configuration. Later on Condratjev and his followers Dulnev and Jaryshev proved that the equation (8) can be expressed in the more general form [5–7]:

$$M = \psi H \qquad (11)$$

where $M = m/m_\infty = mK/a$ is the criterion of the body's thermal inertia; $H = (\alpha/\lambda)(KS/V)$ is the generalized Biot criterion; V and S are the volume and the body's external surface, respectively.

For bodies of various configurations an approximate analytic expression for the criterion ψ has been found:

$$\psi = \frac{1}{\sqrt{(H^2 + 1{\cdot}437H + 1)}} \tag{12}$$

The equation (12) defines the value of criterion ψ for bodies of various configurations with an exactness sufficient for practical calculations [7, 8].

If we picture the dependence between the rate of cooling of a body and the coefficient of heat transfer (Fig. 2) then the curve will be of a non-general character which is valid for the concrete

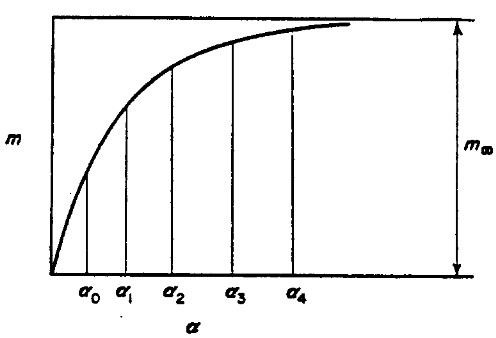

FIG. 2. The asymptotic law of m-rate increase for the regular body cooling when the heat transfer coefficient increases.

case where the configuration and the size of a body as well as the characteristics of the material are given. The dependence between the criteria M and H plotted in Fig. 3 is of a general type and it is valid with sufficient exactness for non-uniform isotropic bodies of various configurations and sizes which are made of solid or dry materials.

(a) The thermo-insulating nucleus of any arbitrary form with a metallic cover round it.†

† The "thermo-insulating nucleus" is defined as a part of a body or a system with a non-uniform temperature distribution. The "thermo-insulating cover" is a part of a body or a system with a uniform temperature distribution for the given experimental conditions.

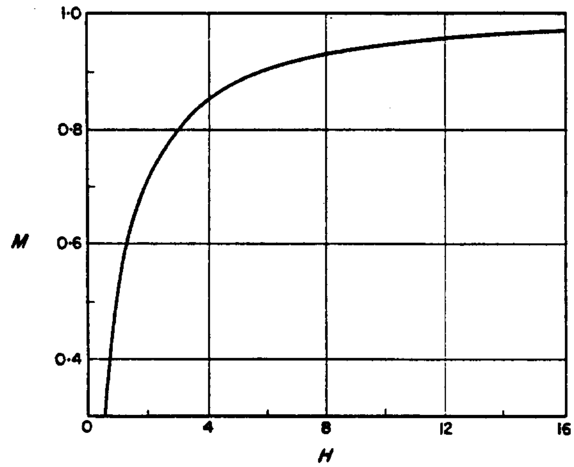

FIG. 3. The approximated universal dependence $M = M(H)$ for regular cooling or heating of a body which has any configuration.

The previous criteria are valid for these systems and to calculate them we can use formulae (11) and (12):

$$M = \frac{Km}{\lambda}\frac{\psi S_{cov}}{V}\left(\frac{\alpha}{m} - \frac{C_{cov}}{S_{cov}}\right) \tag{13}$$

where C_{cov} and S_{cov} are the total heat capacity and a cover external surface; m is the rate of cooling of the whole system and the other symbols relate to the nucleus.

(b) A metallic nucleus with a thin thermo-insulating cover round it.

Suppose we neglect the heat capacity of the cover (C_{cov}) in comparison with the heat capacity C of the nucleus then the regular thermal regime can be expressed by:

$$m\frac{C}{S}\left(\frac{1}{\alpha} + \sum_i \frac{\delta_i}{\lambda_i}\right) = 1 \tag{14}$$

where m is the cooling rate of the whole system; C and S are the heat capacity and a nucleus surface; λ_i and δ_i are the thermal conductivity coefficient and the thickness of the ith layer of the cover;‡ α is the heat transfer coefficient of the system.

(c) The simplest two-component bodies are spherical and plane bi-calorimeters.

‡ A cover may consist of several layers.

We shall define "bi-calorimeters of regular regime" as systems consisting of a metallic nucleus with a layer of close-fitting heat insulating material, which has finite heat capacity. In the spherical bi-calorimeter the nucleus (1) and the sphere cover (2) are arranged concentrically (see Fig. 4). In the plane bi-calorimeter the flat-parallel plate has a heat insulating material of thickness δ_2 round it (see Fig. 5).

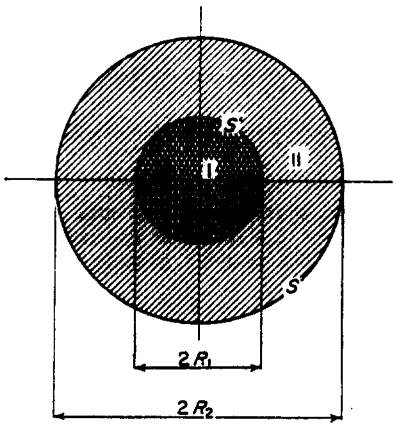

FIG. 4. A spherical bi-calorimeter.

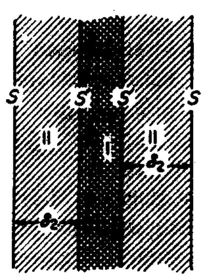

FIG. 5. A plane bi-calorimeter of a symmetric type.

Let us introduce the following values: $\phi = C_1/S^1$ is the nucleus constant; $l = R_1/R_2$ is the ratio of nucleus and cover radii; $P_1 = \delta_2/\lambda_2$ is the thermal resistance of the heat insulating layer and some new criteria such as

$$B = l\phi P_1 m$$

$$N = \frac{1 + l + l^2}{3l}\frac{C_1}{C_{cov}}$$

$$S^2 = \frac{B}{N}$$

$$\Pi = l\frac{m\phi}{\alpha}$$

Then a regular regime for all kinds of spheres with a metallic nucleus will be described by equation [2]:

$$1 - lA - NS^2 = \Pi\left\{\frac{(1-l)^2}{N}\frac{A}{S^2} + \frac{l}{N} + l - A\right\} \quad (15)$$

where $A = A(S)$ is a dimensionless parameter an expression of which is given in [2].

Note that $0 \leqslant N \leqslant \infty, 0 \leqslant l \leqslant 1, 0 \leqslant B \leqslant 1$. When we have such a case as $N \geqslant 2$, which is more frequently used, it is quite possible to reduce equation (15) to a simpler approximate form

$$B \approx \frac{1 - l\Pi - (1 + l + l^2)/3(\Pi/N)}{1 + (l - \Pi)/N} \quad (16)$$

The dependence $B = f(N,l)$ for all kinds of N and l has been plotted in Fig. 6. Analogous

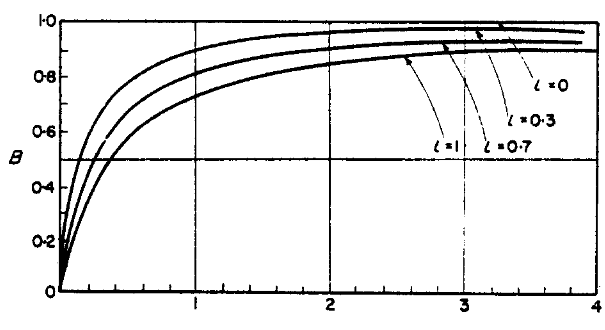

FIG. 6. The dependence $B = f(N,e)$ for the spherical bi-calorimeter at $\alpha \to \infty$.

formulae have been derived for a plane bi-calorimeter [2]. Here we shall take only the formula for the case $\alpha = \infty$. The criteria B and N for the plane bi-calorimeter are of the type

$$B = \phi P.m,\ N = \frac{C_1}{C_{cov}} \quad (17)$$

The graphical relation between criteria B and N has been presented in Fig. 6 and the curve corresponds to a plate for which $l = 1$.

In 1954 Condratjev and Dulnev gave a generalization of the thermal regular regime theory for heating both of bodies and of systems under the action of the energy sources inside the body or at its boundary [11].

The theory is based on the following assumptions: (a) the capacity of energy sources (or sinks) is constant in time; (b) the ambient temperature is also constant; (c) the heat transfer coefficient and material thermal properties are independent of the temperature.

Analysing the exact solution of the problem† of body heating under the action of the internal energy sources one may come to the following conclusion as to why in some time the process becomes regular, when the temperature at any point of the body is changing according to the simple exponential law, i.e.

$$\ln(t_\infty - t) = -m\tau + G^*(x,y,z) \qquad (18)$$

where m is the rate of heating and G^* is the co-ordinate function.

The analysis of the heating of a body of any arbitrary configuration under the influence of an energy source will bring us to the conclusion that the rate of heating has the following dependence on the heat transfer coefficient:

$$m = \alpha\psi^* \frac{S}{C} \qquad (19)$$

where

$$\psi^* = \frac{(t_\infty - t)_S}{(t_\infty - t)_V} \qquad (20)$$

the indexes S and V mean the average of the corresponding values along the body surface and its volume.

(a) The rate of heating either a body or a system is independent of the sources of power and their location in the system and is numerically equal to the rate of cooling (the sources of power are equal to zero).

(b) The rate of heating is independent of the co-ordinates.

(c) The shape coefficient K of a body which is heated by energy sources has the same physical meaning as the shape coefficient K' of a body which is heated in the medium. K and K' are equal.

† Later on we shall speak about the body heating under the influence of energy sources. All conclusions are valid for the case of a body cooling under the influence of energy sinks.

(d) The criteria ψ^* and ψ have a different physical meaning, but numerically they are equal.

(e) The temperature t_j at any point j of a body which is in a stage of regular regime, is subordinated to the following equation:

$$\frac{1}{m(t_j)_\infty}\frac{dt_j}{d\tau} + \frac{1}{(t_j)_\infty} - t_j = 1 \qquad (21)$$

where $(t_j)_\infty$ is the stationary temperature at the point j. Taking into account the first four results we can use the theory given above of a regular regime to calculate the numerical values of m and ψ^*.

Now we can show that a stationary temperature $(t_j)_\infty$ of any point j of the system depends upon the sources of power in the following way [8]:

$$(t_j) = t_c = \Sigma_{\infty\, i=1}^{n} P_i F_{ij} \qquad (22)$$

where P_i is a total output, at i-region of the bodies system; n is a number of the system regions; F_{ij}, some coefficients which are independent of either temperature or the sources' output. To determine these coefficients it is necessary to solve an ordinary system of equations for the stationary temperature field.

If we consider the heating of a body under the influence of many energy sources we can obtain an approximated solution of a problem supposing that the temperature field becomes regular from time $\tau = 0$. In this case the temperature at any j-point will be determined by the approximated formula

$$t_j \approx \{1 - \exp(-m\tau)\} \sum_{i=1}^{n} P_i F_{ij} \qquad (23)$$

The peculiarity of the above discussed regular regime lies in the fact that after the regular regime has already started the peculiarities of the initial state do not influence the temperature field. The same phenomenon of the regularization of thermal regime takes place in other cases. For example, if the temperature of the external medium t_c changes at a constant velocity $w \rightleftharpoons 0$ then after a lapse of time the temperatures of all the points of the system will change with a constant velocity equal to w. Such a regular regime was called a regular regime of the second kind and its regularities for bodies and systems of bodies have been studied in detail [12–14].

The regularization of the temperature field of a body for the oscillating change of the external temperature has not yet been thoroughly studied.† In this case we also observe the following regularity: the temperature at any point of the system is in the range of a mean value and has the same oscillating period for the ambient temperature [2, 10, 14].

An analysis of various cases of temperature field regularization made it possible to calculate the general thermal determination of a regular regime. Under the expression the "regular thermal regime" of a body or a system of bodies one may understand such a regime for the change of a system's temperature having the following properties:

(a) In the course of time a system's initial state does not influence the regularity of temperature change.

(b) The regularity of a temperature change with space–time has a simple mathematical expression.

(c) This rule is general for all points of the system.

The practical application of the regular regime theory: The regular regime theory is useful in solving various problems of practical value; in particular this theory is the basis of a technique for the determination of the thermal characteristics of materials.

(a) *The determination of the material's thermal characteristics*

The high speed methods based on this theory are fit for tests with any substance. Here we give only some of these methods.

The experimental part of the work according to any method of regular regime lies in the determination of the cooling rate m either of a body or of a system. For this purpose we generally use a differential thermocouple, one junction of which is in the body and the other in the medium. Observing the temperature change in space with time when a body is cooled in a liquid or a gas it is not difficult to define the rate of cooling, m, graphically:

$$\ln (t - t_c) = f(\tau).$$

The thermocouple junction can be at any point of a body since according to the theory the rate is independent of co-ordinates.

If the experiment is carried out in conditions of intensive heat transfer and $\alpha \geqslant 25\lambda V/KS$, it is possible to consider the heat transfer coefficient, assumed equal to infinity; using formulae (24) and (9) we find the rate of cooling and the thermal diffusivity of the material.

Cooling at very low values of the heat transfer coefficient and with a body of small size the temperature distribution in the body will be uniform. The criterion ψ is near unity and taking formula (8) we shall find the heat capacity of the material. The possible sizes of a sample will be evaluated as:

$$\frac{KS}{V} \leqslant \frac{0{\cdot}03\lambda}{\alpha}$$

Thus the error in the determination of the thermal capacity caused by non-uniformity of the temperature field will not exceed 2 per cent [10, 16]. If we know the rate of a body's cooling at two different heat transfer coefficients, using formulae (11) and (12), we shall find the thermal characteristics of the material either (λ and c) or (a and λ), and the samples may be of any configuration [15].

In the cases discussed above it is not necessary to put samples into the apparatus. The exception is made only for dry substances and fibrous materials, which are usually put into metallic jars with thin walls. In this case we calculate using the formula (13), which takes into account the cover effect upon the rate of cooling.

Bi-calorimeters based on the regular regime theory are being practised on a large scale to measure the thermal properties of solids and liquids (see item 4). Three types of bi-calorimeters have been developed: plane, spherical and cylindrical. All three have a massive metallic nucleus in the centre with a thermocouple placed into it. The material under test is put between the metallic nucleus and the metallic cover of the apparatus (Fig. 7).

† The so called regular regime of the third kind.

The preheated apparatus is intensively cooled in a liquid and the rate of cooling is determined according to formula (24).

Then the thermal conductivity of the material under test is determined by formulae (17) and (18) (see [9, 10, 16]).

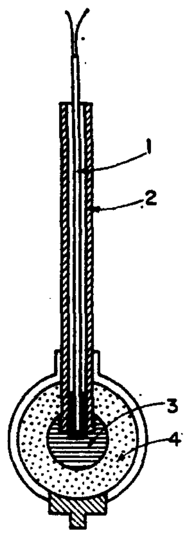

FIG. 7. A spherical bi-calorimeter. (1) A porcelain two-channel tube for a thermocouple. (2) An ebonite and textolite tube joined with the metallic nucleus (3). (4) A heat insulator under the test.

The application of bi-calorimeters for testing heat protective properties of clothing and fabrics has to be studied separately. The apparatus used for this has a simple mounting: the bi-calorimeter enveloped in a fabric has air freely flowing through it (this can be quiet or flowing, rarefied, dry or humid, etc.). The methods for the determination of heat protective properties of clothing and fabrics based on the regular regime theory, which is of a high speed by its nature, make it possible to collect information about the behaviour of different fabrics, depending on meteorological data, in a short space of time [2].

(b) *Determination of the heat transfer coefficient and total emissivity by the regular regime methods*

A new method for the determination of the heat transfer coefficient of various bodies, and total emissivity of any coverings has been developed using formulae (9) and (20). A model of high thermal conductivity material has been made to achieve this aim. Observing its process of cooling it is possible to determine the coefficient of heat transfer depending on temperature for a very short time. The total emissivity was measured analogically [10, 18, 19].

(c) *Determination of thermal inertia of thermometers and pyrometers*

This problem is of great importance for meteorology, experimental physics and engineering measurements. Therefore from the very start of exact thermometrics attention was drawn to it and became a subject of numerous investigations which are not finished even now. The theory of a regular thermal regime made it possible to analyse the notion of a constant of heat inertia and gave a new method for its experimental determination. It is rather easy to show that the value of ϵ is a convenient measure of the thermal inertia characteristic of an arrangement; $\epsilon = m^{-1}$, where m is the rate of cooling. Using equations (9), (10) and (20) we can find the dependence of the thermal inertia constant ϵ upon the heat transfer coefficient and this dependence is called the characteristic curve of heat inertia.

Recently Soviet scientists successfully completed investigations on heat inertia of various engineering arrangements based on an application of the regular regime theory [2, 10, 19].

(d) *Thermal calculations*

The theory of a regular thermal regime permits us to make approximate thermal calculations for various complex arrangements. For example, using the formulae of Section 4[2] it is possible to calculate the heat insulation of different units (aggregates) operating in unsteady state conditions [2].

Formulae (9) and (10) serve to elucidate the influence of the shape and size of a body upon the rate of its cooling or heating which is of special importance for the theory of thermal treatment.

The theory of regular regime, developed for bodies and systems with energy sources, has been used on a large scale for the last few years in the study of unstable processes in a complicated apparatus such as in a radio-electronic technique, which is a complex of cables set in piles.

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