# METHOD FOR MEASURING THE THERMORADIATIVE CHARACTERISTICS
# OF FOOD PRODUCTS IN THE PROCESS OF IR IRRADIATION
# BY A HEMISPHERICAL INTEGRAL FLUX

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The method of "hemispherical source of radiation" and the optical scheme of a
dual-beam measuring apparatus for measuring the thermoradiative characteristics
of light-scattering materials are described.

In real thermodynamic setups (furnaces, closed chambers, etc.), food products are irra-
diated by diffuse and mixed (diffuse and directed) fluxes of radiation [1-3]. At the same
time, experimental data on the spectral and integral characteristics, found from one set of
irradiation conditions, are used without justification in calculations under entirely different
conditions [1-3]. Most data on the spectral and integral thermoradiative characteristics of
food products are obtained with irradiation by a flux of radiation oriented at a small angle
($\Theta$ = 5-10°) and in addition the temperature of the sample in the course of the measurements
remained practically constant [3-5]. The magnitudes of the reflectivity, transmissivity, and
absorbitivity depend to a large extent on the irradiation conditions and the temperature of
the sample and can differ by more than 20% [3].

The calculation of heat treatment processes with IR irradiation of capillary-porous col-
loidal bodies is at the present time quite difficult due to the absence of a number of neces-
sary data on spectral and integral thermoradiative characteristics of materials and their
changes in the course of IR treatment (baking, searing, drying, etc.).

To measure the spectral and integral thermoradiative characteristics of capillary-porous
colloidal bodies in the course of IR irradiation, we developed a method of "hemispherical
source of radiation" and an optical scheme of a dual-beam measuring setup. The method devel-
oped makes it possible to create, in measuring the thermoradiative characteristics, a diffuse
flux of radiation, and the composition of the spectral density of which $E_d$ is equivalent to
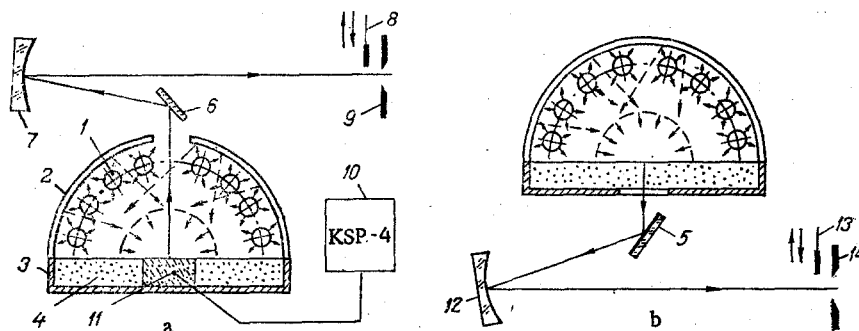the radiation in closed chambers of commerical IR setups.



Fig. 1. Schematic diagram of the hemispherical source of radiation and of the
main measuring block: 1) radiator; 2) semicylindrical reflector; 3) mobile
bottom; 4) material under investigation; 5, 6) flat mirrors; 7, 12) spherical
mirror; 8, 13) blind; 7, 14) output slit of the monochrometer of IKS-14A spec-
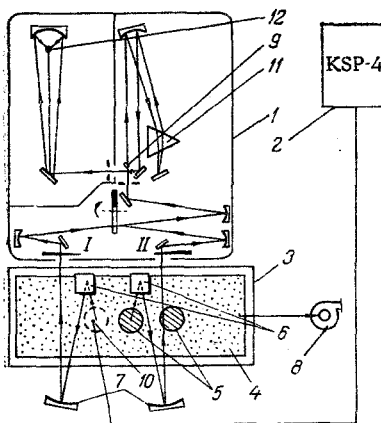trophotometer; 10) KSP-4 potentiometer; 11) thermocouple.

Fig. 2. Dual-beam optical scheme of the setup for measuring the thermo-
radiative characteristics of materials in the process of IR irradiation
with a diffuse flux: 1) monochrometer of IKS-14A spectrophotometer;
2) KSP-4 potentiometer; 3) movable bottom; 4) material under study;
5) reflection or transmission etalons; 6) flat mirrors; 7) spherical
mirrors; 8) fans; 9) flat output mirror; 10) thermocouple; 11) prism;
12) radiation detector.

The main measuring block (Fig. 1) consists of "linear" radiators 1, a semicylindrical
reflector 2, and a mobile bottom 3, on which the layer of material 4 under study and two re-
flection or transmission etalons are situated. The semicylindrical reflector and the mobile
bottom are made of aluminum. The mutual arrangement of the radiators and their distance up
to the material under study are chosen so as to correspond to the real arrangement in the
thermoradiation setups. It is known that each element of the filament of the linear IR radi-
ator can be viewed as an independent source of diffuse radiation. In addition, when the ma-
terial is irradiated, the incident flux is repeatedly reflected from all bodies participating
in the heat transfer, the reflector, the sample, and the radiators, which leads to the for-
mation of a diffuse flux of radiation with a complicated spectral composition [3].

Thermocouples and a multipoint automatic KSP-4 potentiometer are used to monitor and re-
cord the temperature in the sample. The thermocouples are placed at different distances from
the surface of the sample and permit measuring the temperature at different depths in the
course of IR irradiation of the material under investigation.

The optical scheme of the dual-beam measuring setup for determining the thermoradiative
characteristics of food products and other light-scattering materials (Fig. 2) consists of two
flat 6 and two spherical 7 mirrors, two reflection or transmission etalons 5, and a monochrom-
eter 1 of a dual-beam spectrophotometer (IKS-14A).

The setup makes it possible to investigate the change in the spectral and integral hemi-
spherical coefficients of brightness $\rho(2\pi; \Theta_R, \varphi_R)$ and $t(2\pi; \Theta_T, \varphi_T)$ in the course of IR irradia-
tion by different radiators of food products and other materials. The dual-beam method per-
mits determining the integral or spectral directed-hemispherical reflectivity or transmissiv-
ity relative to the incident flux, which differs in magnitude and spectral composition from
the flux radiated by the IR generators.

This setup makes it possible to measure the thermoradiative characteristics of materials
irradiated by different "light" and "dark" IR generators: lamps of the type KG, TENy; panel-
type electrically heated radiators in the form of metallic or ceramic plates of semicylindri-
cal form.

When performing measurements with the dual-beam method, two fluxes of radiation are com-
pared in the spectral instrument; one of the fluxes is reflected (transmitted) by the etalon,
and the second is reflected (transmitted) by the sample under study. During the measurement
process, the surface of the etalon is positioned in the same plane with the surface of the
sample. Special materials that reflect diffusively in the IR region of the spectrum can be
used as reflection etalons: MS-14 milk glass, neutral ONS glass, coatings consisting of MgO,
$Al_2O_3$, $BaSO_4$, etc. [4].

A special wavy surface, reflecting diffusively in the IR region of the spectrum, with a dual structure of microirregularities, on which aluminum, which reflects IR radiation non-selectively, was deposited in a deep vacuum, was used as the reflection etalon [6].

Both fluxes, the one from the sample and from the etalon, are output through the window in the semicylindrical reflector 2 (see Fig. 1) and with the help of mirrors 6 and 7 are directed, respectively, into the etalon and sample channels of the dual-beam IKS-14A spectrophotometer. A small rarefaction is created by the fan 8 (Fig. 2), which is connected to the chamber with a flexible hose, in the thermoradiation chamber in order to protect the mirrors 6 and 7 from the vapor liberated with the irradiation of the sample.

When it is necessary to measure the integral quantities $\rho(2\pi; \Theta_R; \varphi_R)$ and $t(2\pi; \Theta_T; \varphi_T)$ a flat mirror 9 (Fig. 2), directing the radiation flux, bypassing the prism, directly onto the output slit and onto the radiation detector 12, is positioned behind the output slit of the monochrometer of the IKS-14A spectrophotometer.

The theoretical basis for the method is the reciprocity relation between the measured value of the hemispherical coefficient of brightness $\rho_\lambda(2\pi; \Theta_R; \varphi_R)$ and the directed-hemispherical reflectivity $R_\lambda(\Theta; \varphi; 2\pi)$ [7]. By measuring the coefficient of brightness for different angles of observation it is possible to determine the hemispherical value $R_\lambda(2\pi)$ for different conditions of irradiation. Based on Helmholtz's theorem on the reversibility of the radiant flux for isotropic media [7], for equal angles of incident $\Theta, \varphi$ and reflection $\Theta_R, \varphi_R$:

$$\rho_\lambda(2\pi; \Theta_R; \varphi_R) = R_\lambda(\Theta; \varphi; 2\pi). \tag{1}$$

The following relation also holds for the transmissivity:

$$t_\lambda(2\pi; \Theta_T; \varphi_T) = T_\lambda(\Theta; \varphi; 2\pi). \tag{1'}$$

The expressions (1), (1') form the foundation of the method of measuring the coefficients of not completely diffuse reflection $R_\lambda(\Theta; \varphi; 2\pi)$ and transmission $T_\lambda(\Theta; \varphi; 2\pi)$ with directed irradiation, determined by the angles $\Theta, \varphi$ of a narrow beam of radiation within a solid angle $d\omega$.

The intensity of the monochromatic radiation incident per unit area of the sample $dS$ from the area $dS_i$ of the hemispherical source of radiation near some point visible from the center of the sample in the direction $\Theta', \varphi'$, by definition, equal [6, 8]

$$dI_{\lambda,i} = B_{\lambda,i}(\Theta'; \varphi') \cos \Theta' d\omega_i, \tag{2}$$

where $B_{\lambda,i}(\Theta'; \varphi')$ is the brightness of the surface of the hemispherical source of radiation at the point $(r; \Theta'; \varphi')$ in the direction of the normal to the element $dS_i$; $d\omega_i = \dfrac{dS_i}{r^2}$ is the solid angle. The intensity of the monochromatic radiation, reflected from the samples and from the etalon in the direction of the output opening of the hemispherical source of radiation, is determined from the expressions

$$dI_{\lambda,R} = B_\lambda(\Theta, \varphi) d\omega, \tag{3}$$

$$dI_{\lambda,s} = B'_{\lambda,s}(\Theta'_s; \varphi'_s; \alpha) d\omega', \tag{4}$$

where $B_\lambda(\Theta; \varphi)$ is the brightness of the surface of the sample in the direction $\Theta, \varphi$; $B_{\lambda,s}(\Theta'_s; \varphi'_s; \alpha)$ brightness of the surface of the hemispherical source of radiation at the point $(r; \Theta'_s; \varphi'_s)$ in the direction $\alpha$ of the comparison beam on the output opening; $\alpha$ angle between the comparison beam and the normal to the surface of the hemispherical source of radiation at the point $(r; \Theta'_s; \varphi'_s)$.

If the solid angles $d\omega = d\omega'$ are equal, then the reflectivity of the specimen, according to [3, 4], equals the ratio of the brightnesses:

$$\frac{dI_{\lambda,R}}{dI_{\lambda,s}} = \frac{B_\lambda(\Theta, \varphi)}{B'_{\lambda,s}(\Theta'_s; \varphi'_s \alpha)} = \rho_\lambda(2\pi; \Theta_R; \varphi_R) = R_\lambda(\Theta; \varphi; 2\pi). \tag{5}$$

Thus, with the help of the proposed method, it is possible to measure the brightness of the radiation reflected by the sample in the direction of the angle $\Theta_R$ for hemispherical irradiation, and to compare to the brightness of the radiation incident on the surface of the sample. The ratio of the signals in the radiation detector is proportional to the magnitude of the hemispherical coefficient of brightness $\rho_\lambda(2\pi; \Theta_R; \varphi_R)$ and, therefore, the hemispherical reflectivity $R_\lambda(\Theta; \varphi; 2\pi)$.
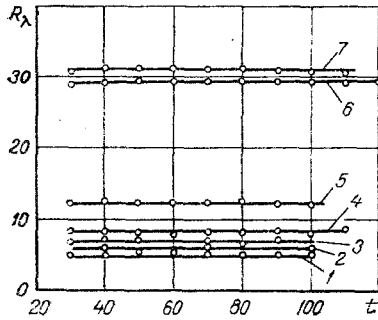
Fig. 3



Fig. 4

Fig. 3. Dependence of the hemispherical coefficients of reflection ($\lambda$ = 2 $\mu$m) on the temperature with conductive heating of food products with a thickness of 10 mm; 1) potato (W = 78.8%); 2) beet (W = 80.2%); 3) carrot (W = 76.3%); 4) soft part of bread (W = 43%); 5) bread crust (W = 31.3%); 6) barley (W = 11.8%); 7) wheat flour (W = 8.4%). $R_\lambda$, %; t°, C
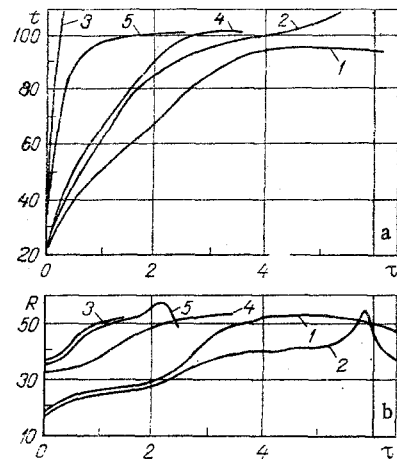
Fig. 4. Change in the temperature and integral reflectivity of food products with a thickness of 15 mm in the course of irradiation by KG-1000 lamps: 1) carrot (W = 74.8%); 2) potato (W = 78.2%); 3) semolina (W = 7.2%); 4) apple pulp (W=76.4%); 5) wheat dough (W = 42.2%); $\tau$, min; R, %.

Equation (5) permits determining the true magnitude of the reflectivity of the sample for any angles $\Theta$, $\varphi$ not only in the case when the brightness of the surface of the hemispherical source of radition B'$_{\lambda,s}$ is identical at all points turned toward the sample, but also if the radiation incident on the sample is completely diffuse. When these conditions are not met, the measurements of $R_\lambda$ will contain an error. The magnitude of the error depends on the scattering properties of the sample, the polarization of the radiation by the sample and by the monochrometer, and by the presence of output windows in the hemispherical source of radiation [6].

Analogous arguments lead to the conclusion that

$$t_\lambda(2\pi;\ \Theta_T;\ \varphi_T) = T_\lambda(\Theta;\ \varphi;\ \pi). \tag{6}$$

The technique for measuring the spectral function $R_\lambda(\Theta;\ \varphi;\ 2\pi)$ of the material studied involves the following. First, two identical reflection etalons 5 (Fig. 2) are placed on the mobile bottom. The integral radiation from the IR generators, reflecting from the etalons with the help of the mirrors 6 and 7, is directed into the channels I and II of the monochrometer of the IKS-14A spectrophotometer. The indications of the instrument $N_e$ are recorded for some definite wavelength $\lambda$. Then, the mobile bottom is displaced so that one etalon is moved from channel I into channel II and the material being studied appears in channel I (Fig. 2). In so doing, the radiation reflected by the materials studied and by the reflection etalon enters into the channels I and II. The indications of the instrument $N_s$, corresponding to the reflectivity of the specimen relative to the etalon, is recorded. The absolute magnitude of the spectral coefficient of reflection of the sample for a given wavelength $\lambda$ is calculated from the formula

$$R_\lambda = \frac{N_0}{N_e}\ R_e. \tag{7}$$

In measuring the spectral transmissivity of the sample, the hemispherical source of radiation and the mobile bottom are positioned so that with the help of mirrors 5 and 12 (Fig. 1b) the radiation fluxes passing through the sample and the transmission etalon are directed into channels I and II of the monochrometer of the IKS-14A spectrophotometer. For this, three opening are cut out of the bottom; two of the openings serve as transmission etalons, while the radiation flux passing through the sample is output through the third one. The absolute magnitude of the spectral coefficient of transmission is calculated from the relation

$$T_\lambda = \frac{N_o'}{N_e'} \, T_e,\tag{8}$$

where $N'_s$ and $N'_e$ are the indications of the recording instrument, corresponding to the transmission of the sample and of the etalon; $T_e$ is the coefficient of transmission of the etalon.

When the mirror 9 (Fig. 2) is placed in the IKS-14A monochrometer, the integral fluxes of radiation from channels I and II, reflected by the sample and by the etalon and passing through the sample and etalon, are directed directly into the radiation detector 12, bypassing the prism 11.

With the help of the setup described above data on the temperature and integral reflectivity of different materials and products (carrots, potatoes, semolina, apple pulp, wheat dough, etc.) can be obtained from a single experiment in the course of irradiation by KG-1000 halogen lamps. In addition, the dependence of the spectral reflectivity of a number of materials on the temperature with conductive heating was investigated (Fig. 3). The technique for measuring the temperature dependence $R_\lambda(t)$ using the attachment with the IR integrating sphere to the IKS-21 spectrophotometer is described in [6].

The investigations showed that in the case of conductive heating from 30 to 100°C the spectral reflectivity with $\lambda = 2$ μm of potatoes, beets, carrots, and other materials remains practically constant with an increase in temperature (Fig. 3).

Under IR irradiation the temperature of the materials investigated changes nonuniformly. (Fig. 4a). The temperature of semolina changes very rapidly (curve 3). The nearly linear increase in the temperature of semolina with IR irradiation occurs due to its low moisture content (W = 7.2%), since the absorbed IR irradiation energy is expended primarily on heating the sample and very little is expended on drying. For other moist materials, the temperature increases gradually up to a definite value (about 100°C) and then remains practically constant (curves 1, 2, 4, 5), which corresponds to the period of constant rate of drying (pulp of apples and carrots, wheat dough). The temperature increase for potatoes, after the four minutes of heating, corresponds to the stage of roasting of the potato, with which a sharp increase in temperature is observed, as a result of which the sample increases in size and its surface is deformed.

The integral reflectivity of food products in the course of IR irradiation, in contrast to the spectral reflectivity with conductive energy input, does not remain constant (Fig. 4b). Thus it increases by 33% for carrots (curve 1) and by 22% for apple pulp and wheat dough (curve 4, 5). The change in the reflectivity occurs nonlinearly, which is related to the complicated physiocochemical processes occurring with IR irradiation in food products. Thus the low reflectivity of water (1.6-4.8%) in the spectral range 1.0-15.0 μm decreases the reflectivity of the material in the presence of moisture and especially on its surface. The decrease of the moisture content explains the rapid increase in the reflectivity of samples of carrot, potato, and wheat dough (curves 1, 2, 5) during initial IR irradiation, when the surface moisture is removed.

The peaks in curves 2 and 5 at the end of the IR irradiation process correspond to the moment when the surface becomes charred.

The agreement between the results of the measurements of the integral quantity R, obtained using the proposed method, and the value calculated using the procedure in [3] is good: the deviations are ±2%. Thus, for example, the measured magnitude of the integral reflectivity of dough at the beginning of the baking process constitutes 36% (Fig. 4, curve 5), which agrees well with the value of R calculated using the procedure in [3], equal to 37%.

Thus, the apparatus described above can be used to investigate the change in the spectral and integral thermoradiative characteristics of materials in the process of IR irradiation in setups and to obtain data required for engineering calculations of IR setups.

## NOTATION

R and T, reflectivity and transmissivity of the layer of material; $\varphi$, $\Theta$, angles of incidence or observation; $\omega$, solid angle; $\rho$, $t$, brightness coefficients; S, surface area, $m^2$; I, intensity of the monochromatic radiation; B, brightness of the surface; $\lambda$, wavelength, μm. The indices are: $\lambda$, spectral index; R, reflection; T, transmission; s, sample; e, etalon; sp, sphere; and s, source.

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# EQUATION OF STATE AND THERMODYNAMIC PROPERTIES

## OF THE CONDENSED PHASE OF A PURE SUBSTANCE

P. M. Kessel'man and S. A. Inshakov                    UDC 536.22

It is shown that the equation of state of a liquid obtained with the cell model contains three individual constants, determinable from experiment. The equation possesses good extrapolation properties.

In [1] the cell model of a liquid with (6-12) effective potential and variable parameters was used to obtain an equation of state

$$\frac{p}{NkT\rho} = 1 - 1.744 \frac{\varepsilon_l}{kT} [(b_{0l}\rho)^2 - 0.4654 (b_{0l}\rho)^4], \tag{1}$$

which describes the thermal properties of the liquid pahse with a high degree of accuracy and conveys the fundamental principles governing change in liquid micro- and macroproperties.

In contrast to the well-known Lennard-Jones–Devonshire [2] and Frenkel [3] theories in which a fixed liquid structure is postulated, [1] considered change in liquid structural characteristics with change in temperature, which agrees with experimental data on the temperature dependence of the coordination number of simple liquids [4]. This major assumption allows the model in question to approach a real liquid.

Moreover, for the pair potential a (6-12) effective potential dependent on the temperature through the parameters $\varepsilon(T)$ and $\sigma(T)$ was used, which allows extension of this model to a wide class of complex liquids including polar ones.

In Eq. (1) each term has a definite physical meaning. The first term corresponds to the "ideal gas" state of a liquid, in which the mean distance between closest neighbors is equal to $R_e$. In this case the liquid density is equal to the orthometric value, i.e., the value obtained from the ideal gas curve (Fig. 1, point a). The second and third terms in Eq. (1) consider respectively the contributions of molecular attraction and repulsion, when the dis-