DETERMINATION OF THE ANGULAR IRRADIATION COEFFICIENTS IN DRYING OVENS BY THE METHOD OF OPTICAL SIMULATION

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A procedure is described by which the method of optical simulation for determining the angular irradiation coefficients in the active zone of various heat-radiation dryers can be evaluated.

For a rigorous design of thermal drying apparatus operating on the principle of radiative heat transfer, it is necessary to know the angular irradiation coefficients of a given system comprising the infrared source and the dried (heat cured) object. Various known analytic formulas are used nowadays for calculating the angular coefficients φ when the interrelations between transmitter surfaces and receiver bodies are relatively simple [1-3]. In the case of actual complex systems, however, simulation methods are effective and most preferred among them is the method of optical simulation.

The theoretical principles underlying the optical simulation of radiative heat transfer have been explained in [4].

V. N. Adrianov has developed a method of optical simulation by which the angular irradiation coefficients can be determined in rather complex systems, where the bodies involved have arbitrary shapes while the space separating them is filled with a radiation attenuating medium [5]. This method has been further extended in [6].

Here the authors show results of simulating radiative heat transfer in certain heat-drying spatial configurations which represent the heat-radiation ovens developed at the Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, where the medium may, within acceptable accuracy limits, be considered diathermal. The correct theoretical approach to the design of these and similar devices leads to problems which do not admit a practical analytical solution. The fact is that the conveyor belt in such an apparatus carries articles for drying (heat curing) along with other apparatus components, i.e., it has a cellular structure with a widely varying fill factor χ of a certain nominal irradiated surface F_i (this term will be explained later).

The simulation method was applied to horizontal (Fig. 1a) and vertical (Fig. 1b, c) conveyors for drying and curing coatings on small production articles. In the horizontal apparatus, tubular infrared sources were arranged above the conveyor symmetrically with respect to the longitudinal conveyor axis ($l_1 \geq \delta$).

Some part of the radiant flux passes through the conveyor, is reflected from a screen underneath, and strikes the plane of the conveyor from below. In this way, the plane in which the articles for drying are located on the conveyor is irradiated not only from the array of sources directly (direction 13) but also from the lower reflector (direction 43). The articles are held in place on the conveyor by means of special frames (Fig. 3b). In the vertical oven the articles are suspended on solid hangers 3 and are irradiated only from the hemispherical luminaire above. The walls 2 of these drying ovens are made of polished duraluminum. At some distance from the walls are placed tubular light or dark infrared radiators 1.

The apparatus for optical simulation has the shape of a rectangular parallelepiped. On its housing is mounted a coordinator which carries the photo set, capable of displacing ($\Delta = \pm 0.25$ mm) and locating the

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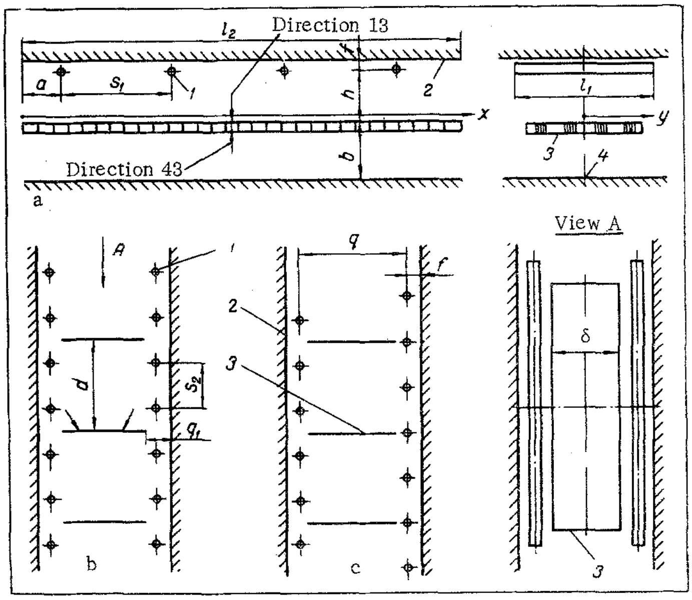

Fig. 1. Schematic diagram of drying-oven models: a) horizontal oven [1) radiators; 2) upper reflector; 3) conveyor; 4) lower reflector]; b) vertical oven with a symmetrical array of tubular radiators; c) vertical oven with a staggered array of tubular radiators [1) radiators; 2) reflecting walls; 3) suspension rig].

latter along the three spatial axes. Inside the housing are installed models of the test oven and of the cellular surface with production articles and other structural components, based on the criteria of geometrical and optical similarity. Dimensions h and q are taken as the characteristic ones for designing the models of a horizontal and a vertical heat-radiation drying oven. An analysis of test data has made it possible to establish the optimal dimensions: h = 150 mm and q = 420 mm.

Tubular infrared radiators are simulated by special gas-filled glow-discharge microlamps ($l_1/d > 60$) with a positive column and an active region, 5 mm inside diameter. This, in combination with a thin layer of dull white paint coating on the outside active surface, yields a close approximation of a Lambertian surface. In order to achieve a constant radiation density over the entire lamp length for our test, the negative glow and the Faraday were covered with dull black paint. The lamps were filled with neon, considering that the reflectivity (absorptivity) in the orange-red range (neon spectrum) and in the near-infrared range is not much different for all metallic surfaces [9]. Furthermore, the neon spectrum peaks at a wavelength between 600 and 900 nm which is close to the maximum-sensitivity wavelength for the silicon photocell used in our test (Fig. 2a) [8].

A special photo unit in the form of a cube with a flat 8 × 14 mm silicon photocell on each wall was installed for the measurement of light fluxes. Each photocell had its own set of leads brought out through a switch to a photovoltmeter. In series with the photocell circuits were connected shunts for easy determination of the photocell currents on the basis of known photocell voltages. The photocells mounted into the cubicle walls had somewhat different sensitivities. For this reason, correction factors were established for each against a standard photocell.

We note that a valuable property of silicon photocells is their peculiar spectral sensitivity characteristic, which varies very little with the angle of light incidence until the latter becomes $\alpha \geq 70°$ (Fig. 2a).

As is well known, the radiation field of a finite cylinder consists, in the longitudinal section, of a family of confocal hyperbolas [6, 10]. From the end toward the center of the cylinder the asymptotes of these hyperbolas tend to become ultimately perpendicular to the cylinder axis. When irradiated bodies lie at small distances from such a finite cylinder, one may assume, to the first approximation, that the rays within the center portion of the cylindrical radiator are perpendicular to its axis. With a radiation field like this, it is simple to analytically determine the surface interrelation for a horizontal conveyor with an opaque surface. The problem becomes more complicated when the conveyor structure is cellular, inasmuch as the character of the intereffect between structural components and radiation sources is indeterminate then. In this case the necessary data can be obtained by optical simulation.

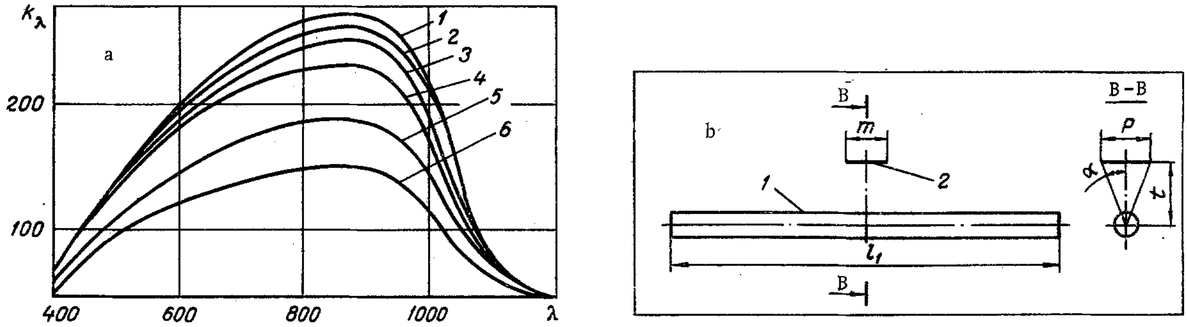

Fig. 2. a) Sensitivity characteristic of a silicon photocell: k_λ as a function of the wavelength λ and of the incidence angle α; 1) $\alpha = 0°$; 2) 50°; 3) 70°; 4) 80°; 5) 85°; 6) 87°. b) Schematic diagram of a total-light-flux measurement: 1) radiator; 2) photocell.

Thus, assuming a simple radiation field pattern in the middle part of a cylindrical radiator, one can derive an expression for the angular irradiation coefficients in a system which consists of radiators and a surface element with an infinitesimally small width $\Delta\delta$ along the axis of a horizontal conveyor. It is assumed here also that the magnitude of the attenuation factor k_4 (which will be discussed later) can be determined experimentally. Calculations have shown that four components of the radiant flux striking this surface must be taken into account: the directly incident flux as well as the once, twice, and thrice reflected fluxes. The radiant fluxes after more than three reflections need not be considered, because their effect on the absolute value of the angular coefficients, as has been explained already, amounts to less than 0.5%. In all, with the laws of geometrical optics taken well into consideration, we have the following expression:

$$\varphi_{13}^{\Delta\delta} = \frac{\Delta\delta}{2\pi l_1 n} \sum_{i=1}^{n} \left[h \int_0^{l_2} \frac{dx}{N_i^2 + h^2} + R(2f + h) \int_0^{l_2} \frac{dx}{N_i^2 + (2f + h)^2} + R^2 k_4^2 (3h + 2b + 2f) \int_0^{l_2} \frac{dx}{N_i^2 + (3h + 2b + 2f)^2} \right.$$
$$\left. + R^3 k_4^2 (4f + 3h + 2b) \int_0^{l_2} \frac{dx}{N_i^2 + (4f + 3h + 2b)^2} \right], \tag{1}$$

where $N_i = (i-1)s_1 + a - x$; l_1, h, f, b, a, and s_1 are geometrical dimensions (Fig. 1).

We note that, according to the subsequent analysis, $\Delta\delta$ can be made equal to 1 cm (Fig. 3a) without causing a large error.

Knowing the angular coefficient $\varphi_{13}^{\Delta\delta}$ and having experimentally determined the distribution f(y) of local angular coefficients across the conveyor width, one can write the expression for the mean-over-the-surface angular irradiation coefficient at the receiver as

$$\varphi_{13}^{\bar{\delta}} = \xi \sum_{\Delta\delta_i} \varphi_{13}^{\Delta\delta_i}, \tag{2}$$

where

$$\xi = \rho^{-1} \int_{-\rho/2}^{+\rho/2} f(\rho)\, d\rho, \tag{3}$$

and $\rho = \delta/2l_1$ is the dimensionless coordinate (Fig. 4a).

With a cellular structure of the conveyor surface (small parts on the rig) taken into consideration, the final expression for the angular irradiation coefficient becomes

$$\varphi_{13}^{\varkappa} = \chi\xi \sum_{\Delta\delta_i} \varphi_{13}^{\Delta\delta_i}, \tag{4}$$

where $\chi = F_{pp}/F_0$ is the fill factor of the conveyor rig with articles, F_{pp} is the horizontal surface area of all articles on a rig, and F_0 is the surface area of the conveyor.

For determining the angular irradiation coefficient one must know the total light flux of one lamp Φ_t. For this, a photocell is located as shown in Fig. 2b. Here we have

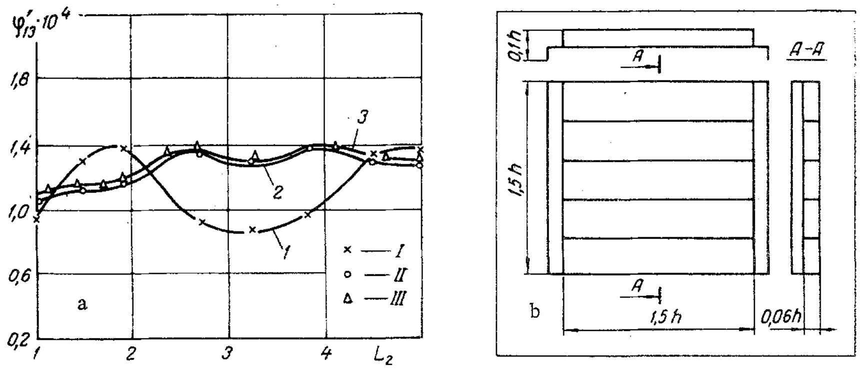

Fig. 3. a) Variation of the local angular irradiation coefficient along the conveyor with a rig: 1) $s_1 = 3$; 2, 3) 1.6; I, II) test points; III) points calculated according to formula (2). b) Rig, a metallic frame which holds articles on the conveyor.

$$\Phi_t = \frac{I}{\frac{mc}{180l}\operatorname{arctg}\frac{P}{2t}}, \tag{5}$$

with the photocell constant c.

We note that, by a preliminary selection of illumination sources, tests can be performed with lamps whose total light fluxes do not differ by more than ±5% from the standard.

For the determination of local angular irradiation coefficients, one of the photocells is placed in the plane of the test surface. With the photocell current I and the total light flux from all lamps known, one can calculate the local angular irradiation coefficient as follows:

$$\varphi_{13}^{\text{loc}} = \frac{I}{\sum_{i=1}^{n} \Phi_{t_i}}.$$

The mean angular irradiation coefficient is determined as the sum of the local angular irradiation coefficients for the surface. During the tests we varied the dimensionless design parameters within the following ranges: $B = b/h = 0.2$-1.0; $F = f/h = 0.15$-0.25; $A = d/h = 0.35$-1.0; $S_1 = s_1/h = 1.5$-3.0; $D = d/q = 0.3$-1.0; $S_2 = s_2/q = 0.5$-1.5; $L_2 = l_2/h = 1.0$-10; $\Delta = \delta/h = 1.0$-1.5.

The fill factor χ was varied within the 0-0.5 range. A theoretical analysis and test results have shown that the following procedure for determining the angular irradiation coefficients for the given types of oven design is appropriate. One determines the local angular coefficient at any point on the conveyor surface turned toward the radiators. For this, according to Fig. 3a and depending on the radiator pitch s_1, one determines first the value φ'_{13} referred to $\Delta\delta$ at the necessary distance l_2 (φ'_{13} is calculated per 1 cm^2 surface area). If the surface point under consideration does not lie on the conveyor axis but is offset along the y-axis, then the correction factor $k_1 = \varphi_{13}/\varphi'_{13}$ is found from Fig. 4a, with φ_{13} denoting the local angular coefficient at the point offset from the axis. One then determines the local angular coefficient at any point in the conveyor plane facing the reflector screens below. For this, one finds k_2 from Fig. 4b. Here $k_2 = \varphi''_{43}/\varphi_{13}$, with φ''_{43} denoting the local angular coefficient in the direction 43 at any point in the conveyor plane. We note that for plotting the graph, the ratio of local angular coefficients for direct and reflected light respectively was at any point on the conveyor surface assumed independent of the radiator pitch.

Since under actual conditions the end surfaces of the holding frames (conveyor rig in Fig. 3b) exhibit some screening effect on the irradiation of the held articles by reflected flux, this must be accounted for by another correction factor $k_3 = \varphi'_{43}/\varphi''_{43}$ found from Fig. 4c, with φ'_{43} denoting the local angular coefficient at the respective point on the conveyor surface and including the screen effect of the end surfaces of the holding frames. Finally, from Fig. 4d one also determines the correction factor $k_4 = \varphi_{43}/\varphi'_{43}$ accounting for the conveyor fill, with φ_{43} denoting the respective value of the angular coefficient for reflected radiation.

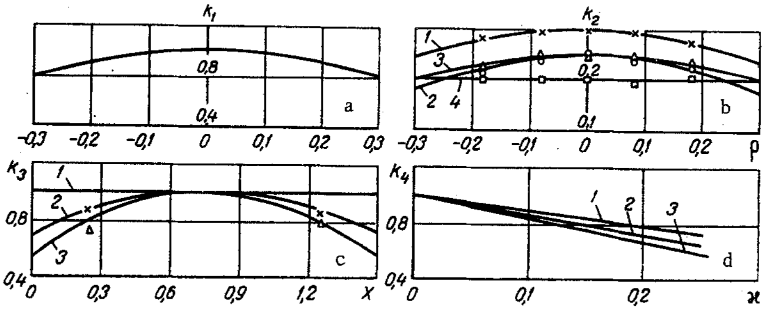

Fig. 4. Correction factors k_i as functions of the geometrical dimensions of the drying oven (ρ, x) and of the conveyor fill factor $\varkappa$: a) $k_1 = f(\rho)$; b) $k_2 = f(\rho)$ [1) B = 0.2; 2) 0.333; 3) 0.667; 4) 1.0]; c) $k_3 = f(x)$ [1) B = 1.0; 2) 0.3-0.7; 3) 0.2]; d) $k_4 = f(\varkappa)$ [1) B = 0.3; 2) 0.7; 3) 1.0].

In this way, one can determine the values of φ_{13} and φ_{43} for any point of a horizontal conveyor with a rig. We note that, for oven dimensions other than those used in our experiment, it is easy to plot a graph analogous to Fig. 3a on the basis of several points calculated by computer according to formula (1). This formula, as a comparison between theoretical and experimental data has shown, yields a close agreement of results (Fig. 3a).

Conveyors with vertically installed operating ovens have also a good potential for use in heat-radiation drying apparatus. The oven configuration and a typical rig were simulated in experiments performed on this test stand. The model of the drying zone in such an apparatus is shown schematically in Fig. 1b, c. The radiators were distributed symmetrically (Fig. 1b) or in a staggered pattern (Fig. 1c). Flat opaque hangers were moved along the vertical channel; only three such hangers with articles in an actual production setup are shown in Fig. 1b, c.

The purpose of this simulation was to determine the values of dimensions s_2, q, and d at which the irradiation of the hanger surface would be most uniform and maintained during the transport of hangers along the vertical channel. In the calculation of local angular irradiation coefficients we considered only the light flux from lamps between hangers, since tests had shown the effect of other lamps to be negligible. Local and mean angular irradiation coefficients were determined on the basis of test data. It thus became possible to design the dimensionless ratios for a drying oven $D = d/q = 0.75$ and $S_2 = s_2/q = 1.0$ optimally with respect to uniform irradiation of articles. We note that $\varphi = 0.15$ applies to the total hanger surface.

An analysis of the results obtained by optical simulation has yielded the following practical conclusions:

1. The optimum value of B is 0.3-0.6.

2. In order to ensure an acceptable uniformity of resultant fluxes striking an article, and to increase the angular irradiation coefficient, it is worthwhile to make $S_1 = 1.0$-1.6.

3. The conveyor rig used in industry absorbs a large part of direct and reflected radiation, as a result of which the irradiation of articles in the direction 13 becomes quite nonuniform. It stands to reason to reduce the height of the hanger structure to less than 0.06h and to make it of a higher-reflectivity material.

NOTATION

R is the reflection factor;
l_2 is the conveyor length;
I is the photocell current;
Φ_t is the light flux from a lamp, in relative units;
n is the number of radiators;
i is the consecutive number.

Subscripts

1 refers to radiators;
2 refers to upper reflector;

3 refers to irradiated body;
4 refers to lower reflector.

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