SELECTION OF RADIATOR SPECTRUM IN INFRARED HEATING AND DRYING DEVICES

L. N. Ryzhkov and Z. A. Luchsheva

UDC 66.047.355

The criteria which determine the relative efficiency of radiators in infrared heating and drying are examined. It is shown that the relative efficiency of a properly chosen radiator can be quite high.

The most important problem of infrared heating is the attainment of correspondence between the spectral composition of the incident radiation and the optical properties of the object heated. With a proper choice of radiator spectral characteristics, determining the rate or quality of processing, maximum energy transfer of the incident flux will be obtained.

The special effects of certain finite spectral intervals of radiation on processing occurs because of the following optical properties of materials:

a) some materials have spectral regions of radiation penetration, which makes possible the intensification of the heating process because of internal heat sources [1];

b) some materials have spectral regions with high degrees of blackness, which permit accelerating the heating process by proper choice of radiator spectrum [3];

c) in the interaction of radiation and matter in certain wavelength bands there occurs nonthermal effects produced by direct quantum mechanical effect of the radiation on chemical bonds responsible for the velocity of the particular process occurring; acceleration of polymerization [7], acceleration of expulsion of bonded water, etc.

In all three cases the criterion of radiator efficiency will be a maximum in the percentage of energy falling in predetermined spectral intervals:

$$\eta_{\mathrm{rad}} = \frac{\Delta q_e}{q} = \frac{\sum\limits_{\Delta\lambda} \int\limits_{\lambda_1}^{\lambda_2} F(\lambda T)\, J_0 d\lambda}{\int\limits_0^{\infty} F(\lambda T)\, J_0 d\lambda}. \quad (1)$$

This criterion characterizes the ability of a radiator to generate radiation in isolated spectral intervals, the significance of which is determined by the technological process in question. Thus, the radiator efficiency criterion is close in meaning to the coefficient of heat utilization η_{hu} [2]. The spectral characteristic of a radiator $F(\lambda T)$ for simple radiators is expressed as a function of the radiator's blackness, and for a gray radiator is equal to unity. The choice of range for summation ($\Delta\lambda$) is determined by the technological criteria of infrared heating efficiency, which may be simple (relative time, relative quantity of heat), or complex (economic criteria, complexes of simple criteria, etc.).

Consequently, despite the seeming simplicity of Eq. (1), to calculate the function it is necessary to know the spectral function of the technological criterion of process efficiency, $\eta_T = f(\lambda)$ which is not always simple to determine experimentally. This is due to the absence of sufficiently powerful infrared radiation sources capable of producing a flux density in narrow spectral intervals equal to that of a polychromatic integral source. If the values of the technological criterion for efficiency vary in different spectral ranges, Eq. (1) becomes more complicated

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 22, No. 2, pp. 136-141, January, 1972. Original article submitted January 28, 1971.

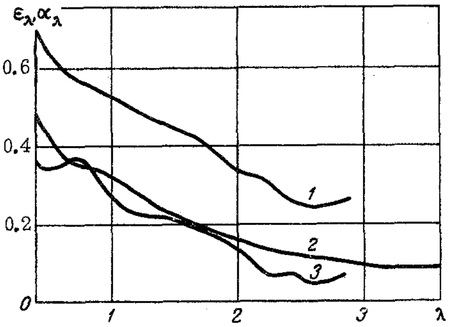

Fig. 1. Radiation capability versus wavelength [4] for: 1) stainless steel; 2) polished aluminum; 3) aluminum leaf.

$$\eta_{rad} = \frac{\sum\limits_{\Delta\lambda} q_e (\eta_T)_\lambda}{q} = \frac{\sum\limits_{\Delta\lambda} (\eta_T)_\lambda \int\limits_{\lambda_1}^{\lambda_2} F(\lambda T)\, J_0 d\lambda}{\int\limits_0^\infty F(\lambda T)\, J_0 d\lambda}, \tag{1a}$$

where $(\eta_T)_\lambda = \tau_0/\tau_{IR}$ for $(q_e)_{\Delta\lambda} = q$.

Thus the radiator efficiency criterion is not simply a characteristic of the radiator, but a value determining its suitability relative to a specific technological process.

We will examine the choice of a radiation source for the specific example of heating a thermotechnically thin opaque material, whose heating is described by Stark's formula. In this case the heating time will be inversely proportional to the corrected radiation coefficient, if the latter does not change during the heating process. Therefore, as a first approximation, as a technological criterion of IR heating efficiency one may take the relative corrected blackness. If this value changes during the heating process both the degree of blackness and the IR heating efficiency coefficient must be calculated as mean integral values.

$$\eta_T = \frac{\tau_0}{\tau_{IR}} = \frac{\varepsilon_{IR}}{\varepsilon_0}. \tag{2}$$

As a standard of blackness one may choose either the value usually taken for calculation in the gray approximation, or the value for a "gray" radiator at fixed temperature. A typical example of selectively absorbent surfaces is the unoxidized surface of a pure metal. The most characteristic spectral functions of blackness for several representatives of this class are shown in Fig. 1. It is evident from Fig. 1 that the greatest degree of blackness occurs in the visible and near-IR range, and therefore it is necessary to attempt to increase the portion of the energy in this spectral range [3], which implies the use of high-temperature radiators.

A qualitative evaluation of the relative advantages of radiators with differing spectral characteristics can be conducted in our case with Eq. (2), having set the specific configuration and spectral data.

The effective degree of blackness of a selectively adsorbent body is defined as the ratio of resultant heated object flux to the total flux at a given radiation temperature and heated object temperature:

$$\varepsilon_{IR} = \frac{c'_{co}\Theta_p - c''_{co}\Theta'}{c^0_{co}(\Theta_p - \Theta')}. \tag{3}$$

By total flux we understand the thermal flux of radiation between "black" surfaces of identical configuration. If we assume that the surface of the surrounding walls is incommensurably greater than the radiator surface, and that the natural radiation of these walls may be neglected, a solution may be derived for the problem of heat transfer between two infinite lamina.

Such an assumption will be valid for a large difference between the temperature of the radiator and the radiation temperature. In that case the resulting flux will be completely determined by the initial spectral composition of the radiator and the spectral properties of the object and walls. A schematic diagram is given in Fig. 2. The corrected radiation coefficients in this case will be mean integral values:

$$c'_{co} = \sum_{\Delta\lambda} \frac{\sigma_0}{\frac{1}{\varepsilon'} + \frac{1}{\alpha''} - 1} \eta_\lambda; \tag{4}$$

$$\eta_\lambda = \frac{\int\limits_{\lambda_1}^{\lambda_2} F(\lambda T)\, J_0 d\lambda}{\int\limits_0^\infty F(\lambda T)\, J_0 d\lambda}. \tag{5}$$

An analogous expression can be obtained for c''_{co}. If Eqs. (1), (5) are compared, we can write

$$\eta_{rad} = \sum_{\Delta\lambda} \eta_\lambda,$$

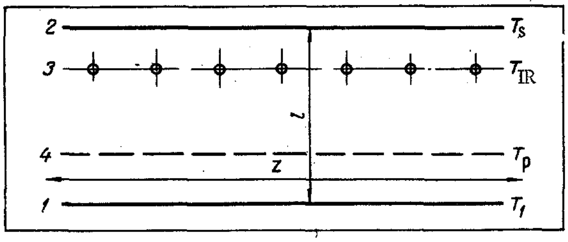

Fig. 2. Method of calculating emissivity; $z \gg l$: 1, T_1) surface and temperature of object heated; 2, T_s)surface and temperature of cooled screen; 3, T_{IR})surface and temperature of infrared radiators; 4, T_p) equivalent surface (2 + 3) and temperature thereof.

i.e., the radiator efficiency criterion enters the technological criterion as an analytic function and requires no further calculation. Therefore, comparison of radiators of different types and temperatures, considering the smooth character of the spectral curves of Fig. 1, may be performed by the technological efficiency criteria, i.e., by Eq. (2).

As an illustration we will examine the practical case of choosing a radiation source for heating of an aluminum leaf under deformation (400-450°K) in a chamber with walls of polished aluminum. The spectral curves for these materials are given in Fig. 1. For comparison the efficiency criteria for different radiator temperatures are calculated at constant radiation temperature. The results of calculating technological efficiency criteria as functions of the temperature of a "gray" radiator are presented in Fig. 3. The spectral composition of the radiation is determined by the function $F(\lambda T)$ and the characteristic temperature by means of the Planck function in accordance with Eq. (5).

For a "gray" radiator $F(\lambda T) = 1$, and the spectral composition of the radiation is determined solely by the Planck function for the temperature of the radiating surface. However, as Fig. 3 shows, even in this case the efficiency of using a high temperature radiator can be quite high (up to 10 for $T_p = 450$°K and $T_1 = 400$°K).

The effect of nongrayness in the original spectral composition of the radiation, i.e., $F(\lambda T)$, may be evaluated by use of a simplified model of the spectral composition of xenon lamp radiation. A cooled cylindrical xenon lamp has a spectral composition in the visible portion of the spectrum which corresponds to a brightness temperature of about 6000°K. The cooling water absorbs the entire longwave portion of the spectrum ($\lambda > 1.5\ \mu$). Consequently, one may expect greater efficiency than with a gray radiator, since a large portion of the original energy occurs in a spectral range with high values of absorption coefficient.

In fact, calculation by Eq. (2) for the same conditions gives a value $\eta_T > 20$. However, it must be noted that in this case Eq. (2) ceases to be the technological efficiency criterion for IR heating due to the large (up to 60%) losses in the cooling water. Therefore one must turn to an economic comparison, which is possible only in a concrete examination of apparatus of a given type.

In conclusion, we will examine the choice of an IR source in the case where the technological criterion defines only the summation range in accordance with Eq. (1).

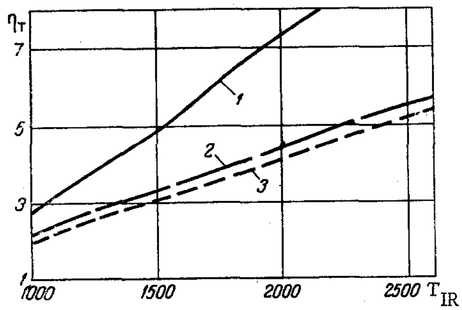

Fig. 3

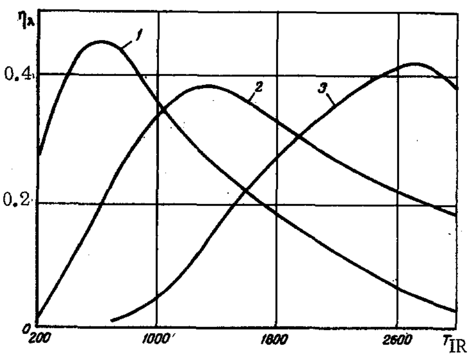

Fig. 4

Fig. 3. IR heating efficiency criteria for aluminum versus "gray" radiator temperature: 1) $T_p = 450$°K; 2) 650; 3) 750.

Fig. 4. Efficiency criteria of "gray" radiatior for various spectral ranges: 1) 3.1-6 μ; 2) 1.8-3.1 μ; 3) 0.8-1.5 μ.

We will assume that the radiation must perform three distinct processing functions on the material, and that it is necessary to ensure a maximum portion of the radiation in the spectral ranges 3.1-6, 1.8-3.1, and 0.8-1.5 μ, respectively, for each of the three processes. We assume, as in the preceding case, that the spectral composition of the radiation is determined solely by the radiator temperature [6], i.e., the Planck function in accordance with Eq. (5). The value of the numerator for $F(\lambda T) = 1$ is most conveniently determined from the tables of [5]. The results of calculation are presented in Fig. 4, from which it follows that, even for coarse division of spectral ranges the efficiency criterion $\eta_{rad} = \eta_\lambda$ sharply differentiates radiators as to application. All other conditions being equal, the efficiency of a radiator of the TÉN type for the first process is 4-5 times as high as a high-temperature radiator. An opposite conclusion could be drawn for the second and third processes of infrared drying.

It follows from the above that, in consideration of the complexity of the IR absorption spectrum of the majority of organic materials, the importance of correctly determining radiator efficiency coefficients increases.

It also follows that attention must be directed to the lack of knowledge of the function $F(\lambda T)$ for the majority of industrial radiation sources [6].

NOTATION

T	is the temperature;
η_T, η_{rad}, η_{hu}, η_λ, $(\eta_T)_\lambda$	are the efficiency coefficients: technological, radiator, heat utilization, spectral range, technological spectral;
σ_0	is the Boltzmann constant;
c_{co}	is the corrected radiation coefficient of system;
J_0	is the Planck function;
ε_{IR}, ε_0	are the effective degree of blackness or emissivity in IR heating and in the "gray" approximation;
τ_{IR}, τ_0	is the heating time for infrared heating and in the "gray" approximation;
ε_λ	is the spectral emissivity of material;
α_λ	is the spectral absorption capability;
q	is the incident (absorbed) radiant flux;
Δq_e	is the useful portion of incident (absorbed) flux;
$\Theta = (T/100)^4$	is the corrected temperature.

Subscripts and Superscripts

', " and 1,2	denote the bodies as indicated in Fig. 2.

LITERATURE CITED

1. L. V. Lykov, Theory of Thermal Conductivity [in Russian], Vysshaya Shkola, Moscow (1967).
2. M. A. Glinkov, Fundamentals of General Heating Theory [in Russian], Metallurgizdat, Moscow (1961).
3. L. N. Ryzhkov and V. A. Krivandin, Izv. VUZ. Chernaya Metallurgiya, No. 9 (1965).
4. Handbook of Thermophysical Properties of Solid Materials, Vol. 1, Pergamon Press, New York (1961).
5. A. A. Apanasevich et al., Tables of Energy and Photon Distribution in Equilibrium Radiation Spectra [in Russian], Izd. AN BSSR, Minsk (1961).
6. L. N. Ryzhkov, in: Heat and Mass Transfer [in Russian], Vol. 11, Minsk (1969).
7. L. L. Pavlovskii and V. I. Rychkov, New Developments in Technique and Technology of Paint and Varnish Films [in Russian], 4th Edition, NIITÉI, Moscow (1970).