INTEGRAL IRRADIANCE FACTORS OF MULTIROW HEAT EXCHANGERS

É. M. Tyntarev UDC 536.3:535.34

A procedure for determining irradiance factors of multirow tubular heat exchangers is proposed. Numerical values of these factors are obtained for heat exchangers with a number of rows $n \leq 7$.

Solution of the problem of radiant transfer between two isothermal black bodies with the surfaces F_i and F_j leads to the determination of the geometrical radiation invariants: irradiance factors φ_{ij}, which are independent of the radiation flux intensity. These factors define the ratio of the amount of energy transferred to the irradiated surface, Q_{ij}, to the total hemispherical emission Q_i from the radiating surface

$$Q_{ij} = \varphi_{ij} Q_i.$$

The ratio of the elementary radiant flux $\delta^2 Q_{ij}$ emitted from an element of area dF_i of surface F_i onto an element dF_j of surface F_j to the total energy emitted from the element dF_i is termed the elementary irradiance factor. With the aid of Lambert's law, it can be readily shown that if the direction of the elementary radiant flux emitted from the element dF_i onto the element dF_j within the solid angle $d\omega$ forms an angle θ with the normal to dF_j, then the elementary irradiance factor is

$$\delta^2 \varphi_{ij} = \frac{1}{\pi} \cos \theta d\omega.$$

The ratio of the radiant flux δQ_{ij} emitted from an element dF_i onto the entire surface F_j to the total energy emitted by the element dF_i is termed the local irradiance factor

$$\delta \varphi_{ij} = \frac{1}{\pi} \int_{\omega} \cos \theta d\omega. \tag{1}$$

Finally, the ratio of the radiant flux Q_{ij} emitted from the surface F_i onto the surface F_j to the total radiant flux Q_i which emanates in all directions from the surface F_i is termed the integral (mean) irradiance factor

$$\varphi_{ij} = \frac{\frac{1}{\pi} \int_{F_i} \int_{\omega} \cos \theta d\omega dF_i}{F_i}, \tag{2}$$

The integral irradiance factors must be known in order to determine the principal geometrical characteristics of a system of bodies participating in heat transfer (the so-called relative surface)

$$H_{ij} = \varphi_{ij} F_i. \tag{3}$$

A number of "indirect" methods of determining relative surfaces have been proposed to avoid integration in (1) and (2). Some of these methods are described in [1]. To avoid integration, Surinov [2] proposed the so-called differential method of determining local irradiance factors, in which the latter are calculated as the partial derivative of the relative surface. This method, however, is applicable only under the condition that the relative surfaces are amenable to determination by elementary means, for example by the "strained wire" method recommended in [3] for a tube–flame system.

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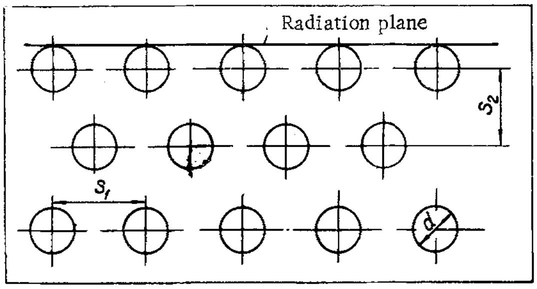

Fig. 1. Bank of tubes. Staggered arrangement.

For irradiated multirow tubular heat exchangers (treated as a two-dimensional system of bodies (Fig. 1)), it is unlikely that the relative surface or the integral irradiance factors can be determined by elementary means.

It is not by chance therefore that papers in which integral irradiance factors are calculated (for example, [4]) give numerical values of these factors only for single- and double-row heat exchangers.

The problem is greatly simplified by the use of digital computers. In fact, by compiling tables of local irradiance factors, say at intervals of 10°, for each row of tubes, a numerical method could be used to integrate a given function $\delta\varphi_{ij}$ and to obtain values of φ_{ij} for any row of a multirow heat exchanger.

Since the tube surface per unit area of the radiating plane is $\pi d/S_1$, we have for any row of tubes in a two-dimensional system

$$\varphi_{ij} = \frac{\pi d}{S_1}\,\frac{1}{\pi}\int_0^{\pi} \delta\varphi_{ij}\,d\omega, \tag{4}$$

and for a heat exchanger consisting of n rows

$$\varphi_{ij}^{(k)} = \frac{1}{\pi}\sum_{k=1}^{n}\frac{\pi d\int_0^{\pi}\delta\varphi_{ij}\,d\omega}{S_1}. \tag{5}$$

Local irradiance factors can be calculated on a digital computer either by integrating elementary irradiance factors from formula (2), or directly, as demonstrated in [5]. The simplifying assumption of a uniform distribution of radiant energy fluxes in front of each row of tubes, conventionally made in the calculation of $\delta\varphi_{ij}$, can be dropped when a digital computer is employed. This simplification resulted in the use of the so-called "parallel transfer" technique, in which the irradiance of each successive row was considered to be independent of the irradiance of the preceding rows. As a result of this, the factor of the arrangement of the tubes in the bank (staggered or straight-line order) was disregarded, as was the influence of the relative longitudinal spacing S_2. Because of this, S_i/d was considered to be the only factor to have an effect on φ_{ij}. This fact was pointed out in [6], where illegality of the assumption of a uniform radiation field behind each row of tubes was demonstrated by the example of a double-row bank.

This simplification leads to simplified formulas for calculating the irradiance factors of a multirow tubular heat exchanger

$$\varphi_{ij}^{(n)} = 1-(1-\varphi^{(1)})(1-\varphi^{(2)})\ldots(1-\varphi^{(n)}) \tag{6}$$

and even

$$\varphi_{ij}^{(n)} = 1-(1-\varphi^{(1)})^{n}. \tag{7}$$

Figure 2 shows the integral irradiance factors calculated from the approximate formulas (6) and (7) and from formula (5), for a bank of three rows of tubes arranged in straight-line order. The discrepancies are greater for a bank of four rows of tubes than for a bank with three rows; they increase with every additional row of tubes. Computations of integral irradiance factors from formulas (4) and (5) lead to the following conclusions:

1. The relative longitudinal spacing S_2/d does have an influence on φ_{ij}, but this influence is moderate. Calculations on a digital computer show that in [6] this influence was somewhat overestimated, probably owing to insignificant errors of the light model. Thus, keeping $S_1/d = 2$ constant and varying S_2/d, we find that the irradiance factor changes its value roughly by 0.02, and not by 0.05 as shown in [6].

A characteristic feature, which agrees with [6], is that the integral irradiance factor decreases with increasing S_2/d for a bank of tubes in staggered arrangement, and increases for a bank of tubes in straight-line order.

TABLE 1. Integral Irradiance Factors of Tubular Heat Exchangers (for individual rows)

S_1/d	Rows						
	1	2	3	4	5	6	7
			Tubes in straight-line order				
1,2	0,93	0,06	0,01	0	0	0	0
1,4	0,85	0,11	0,02	<0,01	<0,01	<0,01	0
1,6	0,78	0,15	0,03	<0,01	<0,01	<0,01	<0,01
1,8	0,71	0,18	0,05	0,02	0,01	<0,01	<0,01
2,0	0,65	0,20	0,07	0,02	0,01	0,01	<0,01
2,2	0,61	0,20	0,09	0,03	0,01	0,01	<0,01
2,4	0,57	0,21	0,10	0,04	0,01	0,01	<0,01
2,6	0,53	0,21	0,12	0,04	0,02	0,01	<0,01
2,8	0,50	0,21	0,12	0,05	0,02	0,02	0,01
3,0	0,47	0,21	0,12	0,06	0,03	0,02	0,01
3,5	0,40	0,20	0,14	0,08	0,04	0,03	0,02
4,0	0,36	0,19	0,14	0,08	0,05	0,03	0,02
4,5	0,32	0,18	0,14	0,09	0,06	0,04	0,03
5,0	0,29	0,17	0,14	0,09	0,07	0,04	0,03
6,0	0,24	0,15	0,13	0,10	0,08	0,05	0,04
7,0	0,21	0,14	0,12	0,10	0,08	0,06	0,05
			Tubes in staggered arrangement				
1,2	0,93	0,06	0,01	0	0	0	0
1,4	0,85	0,12	0,02	0,01	0	0	0
1,6	0,78	0,16	0,04	0,01	0,01	0	0
1,8	0,71	0,19	0,06	0,02	0,01	0,01	0
2,0	0,65	0,21	0,08	0,03	0,01	0,01	<0,01
2,2	0,61	0,22	0,10	0,03	0,01	0,01	0,01
2,4	0,57	0,22	0,12	0,04	0,01	0,01	0,01
2,4	0,57	0,22	0,12	0,04	0,01	0,01	0,01
2,6	0,53	0,22	0,13	0,05	0,02	0,01	0,01
2,8	0,50	0,23	0,13	0,06	0,02	0,01	0,01
3,0	0,47	0,23	0,14	0,06	0,03	0,01	0,01
3,5	0,40	0,22	0,15	0,08	0,04	0,02	0,02
4,0	0,36	0,21	0,15	0,09	0,06	0,03	0,02
4,5	0,33	0,20	0,15	0,09	0,07	0,04	0,03
5,0	0,29	0,19	0,15	0,10	0,07	0,04	0,03
6,0	0,24	0,17	0,14	0,10	0,08	0,05	0,05
7,0	0,21	0,16	0,13	0,10	0,08	0,06	0,05

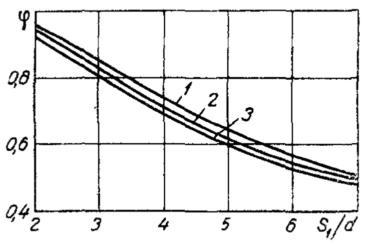

Fig. 2

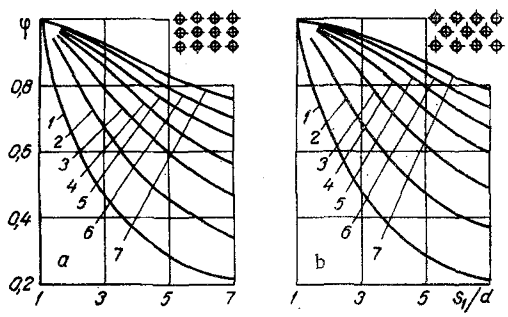

Fig. 3

Fig. 2. Values of φ calculated by different methods for a bank of three rows of tubes: 1) from formula $\varphi^{(3)} = 1 - (1 - \varphi^{(1)})^3$; 2) from formula $\varphi^{(3)} = 1 - (1 - \varphi^{(1)})(1 - \varphi^{(2)})$; 3) from formula (5).

Fig. 3. Integral irradiation factors of heat exchangers with n rows (a) bank of tubes in straight-line order; b) bank in staggered arrangement); n = 1, 2, 3, 4, 5, 6, 7 is the number of rows in a heat exchanger.

This means that the dependence of integral irradiance factors on S_2/d should not be neglected in radiant transfer calculations where accuracy is required. The error is not large, however, when certain averaged values of S_2/d are taken for each given value of S_1/d. Accordingly, we have tabulated the integral irradiance factors for each of seven rows of tubes.* The integral irradiance factors can be obtained for n rows (n = 1, 2, 3, . . . , 7) by adding together, on the basis of (5), the factors of each of the n rows.

If each of the rows of tubes has the same relative transverse spacing S_1/d, as is usually the case, the value of φ_{ij} for a heat exchanger with n rows can be obtained from the graphs in Fig. 3.

*For $S_2/d = 2$.

2. Disregarding the factor of the tube arrangement in the bank is not justified. It can be seen from Fig. 3 that there can be a large discrepancy in the values of φ_{ij} in the case of straight-line and staggered arrangements of tubes for the same values of S_1/d, the discrepancies increasing with increasing S_1/d. For the same value of S_1/d, the values of φ_{ij} are always greater for heat exchangers with a staggered arrangement than for exchangers with tubes in straight-line order.

3. The increase in the integral irradiance factors of any row (except the first) with increasing S_1/d is not continuous but has a maximum. Thus, for the second row of tubes in straight-line order, the integral irradiance factors increase when S_1/d increases from 1 to 3 and decrease when S_1/d continues to increase; for the third row, the increase in the factors continues until S_1/d reaches the value of 5, and they decrease gradually from there on. For the following rows, the behavior of the factors follows the same pattern; however, the maxima are reached at higher values of S_1/d.

At the same time, for a heat exchanger as whole, the integral irradiance factors always decrease when S_1/d decreases.

LITERATURE CITED

1. A. G. Blokh, Fundamentals of Heat Transfer by Radiation [in Russian], Gosénergoizdat (1962).
2. Yu. A. Surinov, in: Heat Transfer and Thermal Modeling [in Russian], ÉNIN, Izd. AN SSSR, Moscow (1959).
3. V. V. Mitor, Heat Transfer in Steam Boiler Furnaces [in Russian], Gosénergoizdat (1963).
4. Thermal Design of Boiler Units: Standard Method [in Russian], Gosénergoizdat, Moscow–Leningrad (1957).
5. É. M. Tyntarev, "Determination of local irradiance factors of heat-exchanger tubes," TsKTI, Issue 18, Leningrad (1967).
6. S. N. Shorin, G. L. Polyak, Kolchenogova, et al., in: Heat Transfer and Thermal Modeling [in Russian], ÉNIN, Izd. AN SSSR, Moscow (1959).