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CHOICE OF PARAMETERS OF HIGH-TEMPERATURE JET RECOVERY UNITS

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The results of mathematical modeling of the process of jet heat transfer are presented. Nomograms are constructed for the technical-economic analysis of the design.

The sharp intensification of heat transfer accompanying the flow of a jet of liquid (or gas) onto an interface is being increasingly used in the design of diverse heat-engineering systems and units. A number of designs of jet recovery units [1] have been proposed in recent years. Among these units the modular jet recovery units designed at the Gas Institute of the Ukrainian SSR Academy of Sciences are most widely used [2].

The most important feature of systems with jet blowing is that their basic parameters vary over a wide range. This makes it impossible to compare existing experimental data on convective heat transfer at jet impact [3-5] and limits their applications in the design of jet systems.

In this work results were obtained based on the numerical solution of the system of differential equations of conservation of momentum, mass, and energy, closed with the help of the two-parameter $k - \varepsilon$ model of turbulence.

The working scheme of the model is shown in Fig. 1. We are studying a separate opening (nozzle) with a diameter of d_{op} in a perforated plate and a cylindrical region of radius R surrounding it into which an air jet with an effective cross section d_0 and velocity U_0 (the rate of flow of air through the nozzle is given by $\rho_0 U_0 \pi d_0^2/4$) flows. Since in this case for a correctly designed jet system the effect of the drifting flow on the hydrodynamics and heat transfer should be small, it is ignored in the formulation of the problem. The heat-transfer surface, which the jet strikes, is defined in terms of the equivalent radius R from the condition $\pi R^2 = F/N$ (F is the total area of the heat-transfer surface and N is the total number of openings in the perforated plate). The boundary conditions for the temperature were set so as to take into account the effect of the recirculating air on the character of the heat transfer. The temperature of the recirculating flux at the inlet into the working region (top part of the boundary 2 in Fig. 1) was assumed to equal the mean temperature T_{tb} of the heated air leaving the volume (bottom part of boundary 2). This value of the temperature was also used for the surface of the perforated plate, and a constant temperature T_p was given on the heat-transfer surface 4. On the remaining boundaries (axis of symmetry and the bottom part of the boundary 2 through which the air leaves the working region) the condition $\partial T/\partial r = 0$ was imposed.

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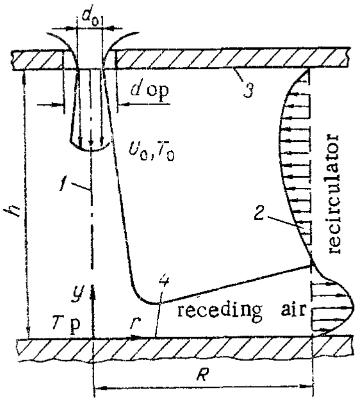

Fig. 1

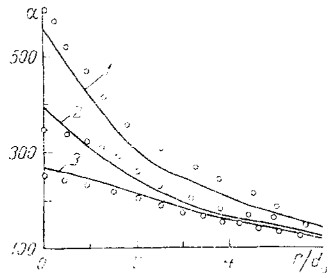

Fig. 2

Fig. 1. Diagram of the jet flow against the heat-transfer surface: 1) symmetry axis; 2) boundary of the working region; 3) surface of the perforated plate; 4) heat-transfer surface.

Fig. 2. Local heat-transfer coefficient versus the distance to the critical point under conditions of air blown against a surface with U_0 = 61 m/sec and $d_0 = 6.35 \cdot 10^{-2}$ m; 1, 2, 3) h/d_0 = 6, 16, and 24. The solid lines show the calculation using the $k-\varepsilon$ model; the dots show the experimental values from [4]. α is shown in $W/(m^2 \cdot K)$

The radial component of the velocity at the nozzle cutoff was assumed to equal zero, while the axial component was assumed to be constant. On the solid surfaces 3 and 4 both velocity components vanish, while on the "liquid" boundary 2 and on the symmetry axis 1 the conditions $\partial U/\partial r = 0$, $\partial V/\partial r = 0$ are imposed.

The entire working region was covered with a grid, arranged as a chess board [6], with 20 nodes along the y axis and 26 nodes along the r axis. The following equations were solved on this grid: a) two-dimensional system of Navier–Stokes equations in the variables U – V (using the method of contour integration [7]); b) the system of equations describing the transport of the kinetic energy of the turbulence, its generation and dissipation (standard two-parameter $k-\varepsilon$ model [6]); and c) energy equation.

Comparison of the numerous calculations performed with the most reliable experimental data [3-5] enabled more accurate determination of the parameters of the $k-\varepsilon$ model of turbulence and finding the optimal arrangement of the nodes in the difference grid. Figure 2 shows the comparison of the calculation with experiment, performed using a 20 × 26 node grid. The agreement obtained may be regarded as fully satisfactory, keeping in mind the limitations of the $k-\varepsilon$ model of turbulence in the case of the calculation of jet systems and some inconsistency between the experimental data obtained by different authors.

In accordance with the practical goal of this work – to determine the parameters of reasonable and efficient designs of high-temperature jet recovery units – in carrying out the calculations two extreme values of the temperature of the heat exchange surface were chosen as the representative temperatures: T_p = 873°K (the limit of stability of lightly doped steels) and T_p = 1273°K (the lower boundary of stability of heat-resistant steels). The air temperature at the cutoff of the nozzle T_0 was set equal to 323°K.

Analysis of the experimental and theoretical results shows that decreasing the equivalent diameter of the jet d_0 (with other conditions remaining unchanged) increases the heat-transfer coefficient. On the other hand, one should keep in mind the difficulty of fabricating perforated plates with a large number of openings with a small diameter and the real danger of contaminating them with the dust contained in the air used for combustion. Based on these practical considerations, the effective diameter of the jet d_0 was set equal to $2.25 \cdot 10^{-2}$ m, which corresponds to $d_{op} = 2.5\text{-}3 \cdot 10^{-2}$ m, depending on the form of the input edge of the opening.

The calculations performed under these conditions showed that when the similarity relations of the jet system are satisfied (h/d_0 = const, R/d_0 = const, U_0 = const) the temperature to which the air is heated $T_{tb} - T_0$ and the average heat flux onto the heat-transfer surface $\bar{q}$ increase approximately in proportion to the temperature difference $T_p - T_0$. This makes it possible to introduce the dimensionless air heating temperature

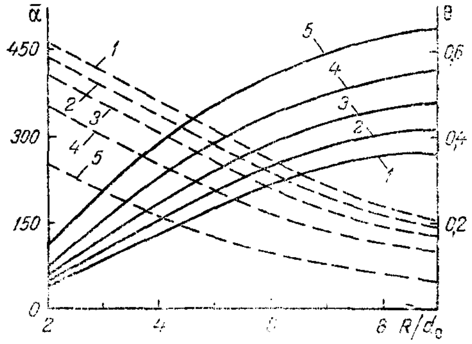

Fig. 3. Average heat-transfer coefficient (broken lines) and the relative heating of the air (solid lines) versus the parameter of the jet system under isothermal conditions: 1, 2, 3, 4, 5) U_0 = 100, 80, 60, 40, and 20 m/sec; T_0 = 323°K, T_p = 873-1273°K; h/d_0 = 6, d_0 = 2.25·10⁻² m.

$$\Theta = \frac{T_{tb} - T_0}{T_p - T_0} \quad (1)$$

and the average heat-transfer coefficient

$$\bar{\alpha} = \frac{\bar{q}}{T_p - T_0}. \quad (2)$$

Figure 3 shows the computed dependence of these quantities on R/d_0 and U_0 for h/d_0 = 6. One can see that increasing the velocity U_0 with R/d_0 = const gives rise to monotonic growth of $\bar{\alpha}$ and decrease of Θ. This dependence is quite complicated, however, and it cannot be represented in a simple criterional form.

The nomograms in Fig. 3 permit determining (with an error of about 15%) the values of Θ and $\bar{\alpha}$, if the main parameters of the jet system U_0, R/d_0 are known. Because the values of these parameters are unknown at the design stage there arises the problem of choosing their optimal values taking into account the specific conditions of operation of the recovery unit.

To formulate the simplest problem of optimization of the parameters of the jet system we introduce the irrigation intensity

$$g = \rho_0 U_0 / 4 (R/d_0)^2, \quad (3)$$

which represents the mass flow rate of air per unit heat-transfer surface area. The relative heating of the air Θ can be easily expressed in terms of $\bar{\alpha}$ and g:

$$\Theta = \bar{\alpha}/gC_p. \quad (4)$$

Let g = const be given. Then the optimal value of the parameter R/d_0 is one for which $\bar{\alpha}$ and Θ reach their maximum values.

Figure 4a shows (the broken curve $\bar{\alpha}_{max}$ (R/d_0)) the solution of the optimization problem posed above. The dependence of the main parameters of the jet system on g, corresponding to the lines $\bar{\alpha}(g, R/d_0) = \bar{\alpha}_{max}$, is shown in Fig. 4b.

In designing recovery units operating at a high (1500-1800°K) temperature of the waste gases, the most important problem is their reliability. The main measure for raising the reliability consists of lowering the temperature of the wall of the metallic recovery unit by increasing the average coefficient of heat-transfer $\bar{\alpha}$ from the walls to the heated air. In jet recovery units $\bar{\alpha}$ is increased by increasing the velocity U_0 at the cutoff of the nozzle and by increasing the density of the perforations. For example, $\bar{\alpha}$ = 200 W/(m^2·K) is achieved with g = 0.4 kg/m^2·sec and R/d_0 = 6.2 (Fig. 4). These parameters of the jet system correspond to U_0 = 53 m/sec and 1640 perforations per square meter of the heat-transfer surface, if it is assumed that d_0 = 2.25·10⁻² m, d_{op} = 2.5-3·10⁻² m. High values $\bar{\alpha}$ = 400 W/(m^2·K) require g = 2.6 kg/(m^2·sec), R/d_0 = 3.4. This corresponds to a velocity of U_0 = 93 m/sec at the nozzle cutoff and 17,100 perforations per square meter.

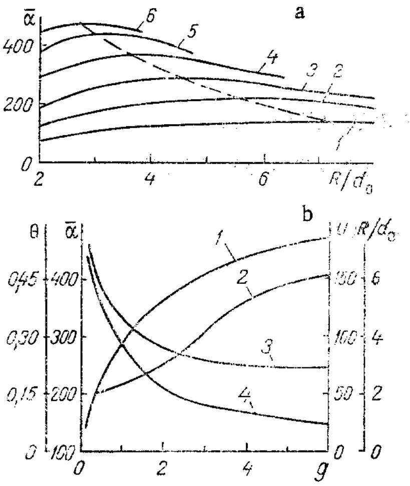

Fig. 4. Optimal parameters of the jet system: a) dependence of the mean heat-transfer coefficient (solid lines) on R/d_0 for different values of g, kg/(m²•sec): 1) 0.25; 2) 0.5; 3) 1; 4) 2; 5) 4; 6) 6; b) dependence of the optimal parameters on the irrigation intensity; 1) $\bar{\alpha}$; 2) U; 3) R/d_0; 4) Θ. U, m/sec.

The nomograms constructed in this work can be used as the basis for a general technical-economic analysis of the design of high-temperature jet recovery units. In especially important cases, for example, when the temperature of the outgoing flue gases is high, such an analysis must be supplemented by check calculations performed on a computer using the program developed.

NOTATION

y and r, coordinates; d_{op} and d_0, diameters of the opening and the effective cross section of the jet, m; U and V, velocity components, m/sec; ρ, density, kg/m³; T, temperature, °K; h and R, distance from the nozzle cutoff to the heat-transfer surface and the radius of the cylindrical region into which the jet flows, m; α, heat-transfer coefficient, W/(m²•K); C_p, heat capacity, J/(kg•K); g, irrigation intensity, kg/(m²•sec); and Θ, dimensionless heating temperature of the air.

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