NUMERICAL INVESTIGATION OF THE EFFECT OF
THE RADIATIVE PROPERTIES OF A TUBE
WATERWALL AND COMBUSTION PRODUCTS ON
HEAT TRANSFER IN TUBE FURNACES

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Heat transfer in the radiant section of a tube furnace is investigated within the framework of a mathematical
model proposed in [1]. Results of calculations showing the effect of the tube waterwall emissivity and the
partial pressure of H₂O and CO₂ in the composition of the combustion products on heat transfer are given.

Investigating the laws of combined heat transfer in tube furnaces is of great interest for ensuring their
reliability and establishing additional possibilities on optimizing the operating conditions for these units. A radiative
component whose share can be more than 90% is predominant in the heat balance of tube furnaces [1]. Therefore
the accuracy of a thermal calculation of the furnaces is largely determined by the correctness of the model of radiative
heat transfer and, in particular, by the correspondence of the radiative properties of the reaction tubes and the furnace
space, prescribed as the initial data, to their real values. However, oxidation of the reaction tubes occurs in tube
furnace operation, which results in a change in their radiative properties. Replacement of one fuel gas by another,
a change in the excess-air coefficient, and other regime and structural changes may lead to a corresponding change in
the radiative properties of the combustion products. Therefore, investigating the influence of the above factors on
heat transfer in furnaces takes on great significance.

The object of the investigation is the radiant section of a tube furnace for conversion of a hydrocarbon gas,
bounded by rows of vertically arranged tubes (Fig. 1). The reaction mixture enters the tubes from above and moves
in the same direction as the combustion products. On the furnace arch a series of gas-burner devices is symmetrically
arranged about tube waterwalls. On the furnace bottom there are smoke-removing ducts, by which the combustion
products are carried off into the convection chamber.

A uniformly distributed regime of heat transfer is realized in the radiant section of this structure. This regime
is characterized by the fact that the tube waterwall is not affected by the flame directly. The tube waterwall and the
flame are separated by a region with the relatively lower temperature of the combustion products. Here, the
recirculating turbulent character of the flow of the combustion products, the flame length, the process of fuel burn-out,
and the selectivity of the radiation of the combustion products have a substantial effect on the heat transfer.

The small width of the radiant section as compared to its length and height and the symmetric arrangement
of the gas-burner devices enable us to consider the heat transfer and the flow of gases in a cross section as a
two-dimensional problem. In [2] it is shown that, when a gaseous fuel is burned, the effect of radiation scattering in
the furnace volume can be ignored; hence, the equation of radiation transfer has the form

\[ \frac{\mu}{\Delta h} \frac{\partial I_{s,k}}{\partial x} + \frac{\xi}{\Delta h} \frac{\partial I_{s,k}}{\partial y} = \frac{\alpha_k}{\Delta h} \int_{\lambda_{h-1}}^{\lambda_h} J_{\lambda,b}(\lambda, T) d\lambda - \alpha_k I_{s,k}, \quad k = 1, N. \] (1)

The boundary condition to Eq. (1) with diffuse radiation and reflection from the walls is written as

\[ I_{s,k} = \frac{\epsilon}{\Delta h} \int_{\lambda_{h-1}}^{\lambda_h} J_{\lambda,b}(\lambda, T) d\lambda + \frac{r}{\pi} \int_{(s'n)<0} \frac{I_{s',k} \cos(s'n)}{d\omega_s} \] (2)

for directions s such that \((sn) > 0\).

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The temperature field in the radiant section volume is determined from the energy conservation equation

\[ c_p \rho \left( u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) = \frac{\partial}{\partial x} \left( \lambda + \lambda_n \right) \frac{\partial T}{\partial x} + \frac{\partial}{\partial y} \left( \lambda + \lambda_n \right) \frac{\partial T}{\partial y} + Q_v - \text{div} \ q_p. \]  

Equation (3) should be supplemented with boundary conditions. The tube waterwall is conventionally replaced by a beam-absorbing surface, impermeable to matter, on which a reaction tube temperature characterizing the tube furnaces considered is prescribed. On the burner cut we prescribe the fuel mixture temperature calculated from the initial temperatures of the fuel and the air supplied for combustion, the excess-air coefficient, the portion of burnt fuel, and other parameters. The lining temperature is determined from the condition of its adiabatic nature, which has the form

\[ \alpha_{\text{con}}(T - T_{\text{w}}) = \{q_{p}\}_w. \]  

The fields of the velocity of motion for the combustion products and of the turbulent thermal conductivity coefficient are determined by a numerical solution of the time-averaged Navier-Stokes, continuity, and (k-ε) turbulence model equations [1]. The volume density of the heat release in the flame volume is calculated using the formula

\[ Q_v = B_f Q_{p,\Delta \eta}, \]

where \( \Delta \eta \) is the change in the integral power of fuel burn-out between the two considered cross sections of the flame. The integral power of fuel burn-out is prescribed by the semiempirical dependence [3]

\[ \eta(x) = 1 - \exp \left[ -a \left( \frac{x}{L_f} \right)^2 \right]. \]

Radiative heat transfer is dealt with in the $S_2$ approximation of a discrete ordinate method. Within the framework of this method Eq. (1) is approximated by the system of differential equations relative to radiation intensities along four selected directions:

\[ \mu_m \frac{\partial I_{m,k}}{\partial x} + \varepsilon_m \frac{\partial I_{m,k}}{\partial y} = \frac{\alpha_k}{\Delta \lambda_h} \int_{\lambda_{h-1}}^{\lambda_h} J_{\lambda,k}(\lambda, T) d\lambda - \alpha_k I_{m,k}. \]