HEAT AND MASS TRANSFER DURING FILTRATION DRYING

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Abstract

The article analyzes the process of heat and mass transfer during filtration drying through a layer of dried material. Equations are presented to describe the transfer of heat from a gas flow to particles of wet material, experimental data according to the values of the Nusselt and Sherwood criteria. A leveling is given to determine the mass transfer coefficient with a known heat transfer coefficient.

Key words: filtration drying, heat transfer coefficient, mass transfer, Nusselt criterion, Sherwood criterion, molecular diffusion.

Introduction

The intensity of filtration drying largely depends on the amount of heat that is transferred from the thermal agent to the wet particle and is determined by the filtration rate of the thermal agent, the temperature difference between the surface of the solid particle and the gas flow, as well as the surface of the interphase contact [1].

During filtration drying, a thermal agent washes the surface of a wet particle, and a number of processes occur: heat exchange between the thermal agent and the surface of the particle, evaporation of moisture from the surface of the material (mass transfer), heat movement inside the particle (heat transfer), moisture movement inside the particle (mass transfer). Moisture in the layer of dispersed material is between the particles, on their outer surface, as well as inside the particles in cracks, pores and capillaries. Therefore, a distinction is made between external and internal heat and mass transfer. During drying, the following processes occur simultaneously: heat transfer, complicated by mass transfer. The main principles of heat and mass transfer during drying of wet materials are described in subsequent works [3,4].

To determine the average heat transfer coefficients from the thermal agent to the layer of dry particles through the layer of dispersed material based on experimental values, the values of the heat transfer coefficients are calculated α according to the heat transfer equation [5]:

$$\alpha = \frac{\Delta Q}{F \cdot \left(\bar{t} - \bar{T}_{n.} \right) \cdot \Delta \tau}.$$

(1)

Where ΔQ - the amount of heat transferred to the layer and calculated according to the heat balance equation for the thermal agent; $\bar{t}$ - arithmetic mean temperature of the thermal agent at the inlet and outlet of the layer; F - particle surface.

average temperature $\overline{T}_n$ surface of solid particles is estimated from the heat balance equation and is defined as the average temperature $\overline{T}$ particles:

$$\Delta Q = m \cdot c_s \cdot \left(\overline{T} - T_0\right), \qquad (2)$$

Where m – mass of particles in the layer; c_s – heat capacity of the material; $\overline{T}$ – average temperature of layer particles; T_0 - initial temperature of the particle.

As is known, heat is transferred from a thermal agent to a wet material in three ways: convection, thermal conductivity and radiation. During the process of filtration drying, heat from the thermal agent to the wet particle is transferred convectively, then the heat transfer equation under stationary conditions can be written in the form of the Newton-Richmann law.

In practice, a system of differential equations is used to describe the transfer of heat from a gas flow of particles of wet material, and similarity theory is used to generalize the results. In general, the criterion equation for the case of forced flow of a thermal agent around a wet surface has the form:

$$Nu = 2 + A \cdot \mathrm{Re}^n \cdot \mathrm{Pr}^{0,33} \cdot Gu^m, \qquad (3)$$

Where $Nu = \dfrac{\alpha \cdot d}{\lambda}$ – Nusselt criterion;

$Gu = \dfrac{t - t_{M.m.}}{t}$ – Gukhman criterion;

$Pr = \dfrac{v}{a}$ – Prandtl number; v – coefficient of kinematic viscosity; a - coefficient of thermal conductivity; t, $t_{M.m.}$ – temperature of the thermal agent and wet thermometer, [^0C]; A, n, m – unknown coefficients that depend on the mode of movement of the thermal agent and are determined experimentally.

When generalizing hydrodynamics, the main linear dimension is usually taken to be the equivalent diameter d_e channels through which the thermal agent is filtered. When analyzing heat transfer and mass transfer processes, the same linear dimension is used, which is most characteristic of processes in a stationary layer of materials.

Considering that the physical parameters of air change in a narrow range, according to the recommendations it is accepted $Nu \sim \mathrm{Pr}^{0,33}$. To determine the unknown coefficients "A" and "n", the experimental values are represented by the dependence $\dfrac{Nu}{\mathrm{Pr}^{0,33}} = f\left(\mathrm{Re}\right)$ in a logarithmic coordinate system.

Experimental data for all materials are approximated by parallel lines, which means that the exponent of the Reynolds number will be the same for all materials studied. The vertical arrangement of straight lines indicates the influence of the granulometric composition of the material on the heat transfer coefficient. The Nusselt number depends on the filtration mode of the thermal agent and the particle size of the material.

The value of the coefficient "A" depends on the geometric dimensions of the particles, and the exponent "n" is constant and equal to 0.9. Therefore, to generalize experimental values, similarly to generalizing the hydrodynamics of filtration drying, it is advisable to introduce a geometric simplex into the criterion equation (3) $\dfrac{d_{ч.}}{D_a}$ to take into account the influence of the geometric dimensions of particles and container on the heat transfer process [10].

If experimental data are approximated by several results, then the exponent is the same and equals n= 0.67, and the coefficient "A" for different materials will be different depending on the geometric simplex and it can be approximated by power relations of the form:

$$A = A' \cdot \left(\frac{d_ч}{D_a} \right)^n \tag{4}$$

then dependence (1.24) can be written for various dispersed materials in the form:

$$Nu = 1{,}0 \cdot Re^{0,9} \cdot Pr^{0,33} \cdot \left(\frac{d_{ч.}}{D_a} \right)^{0,67} \tag{5}$$

- for a layer of wet coal:

$$Nu = 1{,}2 \cdot Re^{0,9} \cdot Pr^{0,33} \cdot \left(\frac{d_{ч.}}{D_a} \right)^{0,67} \tag{6}$$

- for polyacrylamide, carbon black, superphosphate, ammophos and coarse sand:

$$Nu = 2{,}0 \cdot Re^{0,9} \cdot Pr^{0,33} \cdot \left(\frac{d_{ч.}}{D_a} \right)^{0,67} \tag{7}$$

The reasons for such a discrepancy between various finely dispersed materials are explained by the different shapes of particles and the roughness of their outer surface, therefore the conditions of flow around the surface of particles for different materials will be different, it is also necessary to take into account the mutual shielding of particles from each other, which will be different for different materials, and as a result, part the surface is not washed by a thermal agent and does not take part in heat exchange. It is impossible to determine the coefficient of mutual screening of peat or coffee sludge particles experimentally (for example, as for coal) due to the fragility of the particles [10].

Similarly, as for dry dispersed materials, generalizations for wet dispersed materials are carried out according to equation (3), presenting experimental data on the dependence $\dfrac{Nu}{Pr^{0,33}} = f(Re)$ in a logarithmic coordinate system, which made it possible to determine the unknown coefficients "A" and "n".

The literature contains a large number of criterion equations in which the coefficients are determined A, n, m, however, their use for a layer of fibrous materials is impossible, so such coefficients are determined experimentally.

Mass transfer coefficient β is one of the main kinetic coefficients that allows you to calculate the rate of mass transfer. Equations for determining the mass transfer coefficient β given in [49] in the case of forced movement of a thermal agent along a wet surface:

$$Sh = 2 + A^{'} \cdot Re^{n^{'}} \cdot Sc^{0,33} \cdot Gu^{m^{'}}, \tag{8}$$

Where $Sh = \dfrac{\beta \cdot d}{D}$ – Sherwood criterion; $A^{'}$, $n^{'}$, $m^{'}$ – unknown coefficients determined experimentally.

Similarly, as for heat transfer, taking into account that the physical parameters of the thermal agent changed slightly during the experiment, according to the recommendations [79], it can be accepted that Sh ~$Sc0.33$.

Unknown values of coefficients A, n, m are determined from the graphical dependence $Sh/Sc^{0,33} = f(\mathrm{Re})$,obtained on the basis of experimental data.

Similarly, as for heat transfer, the approximating lines are parallel to each other. The granulometric composition of dispersed materials also affects the mass transfer process, as evidenced by different values $Sh/Sc^{0,33}$ at the same Reynolds number. In addition to the size of the granules, the mass transfer process is also affected by the surface roughness of the particles and their internal structure. Peat and coffee sludge have deviations in their location on the graphical dependence; this can be explained by the difference in the structural structure of these particles, as well as the difficulty of determining their equivalent diameter, which would adequately describe the heat transfer and mass transfer properties of the layer.

Generalization of experimental values made it possible to present dependence (8) for determining the mass transfer coefficient in a thin layer of dispersed materials, taking into account the geometric parameters of the layer and apparatus in the form:

- for a layer of wet coal (except for the fraction $5 . 0$; $1 0 . 0$; 103 m), medium-grained and coarse-grained sand:

$$Sh = 1,62 \cdot Re^{0,9} \cdot Sc^{0,33} \cdot \left(\frac{d_{ч.}}{D_a} \right)^{0,67} \tag{9}$$

- for a layer of wet coal fraction $5.0; 10.0; 103$ m:

$$Sh = 1,3 \cdot Re^{0,9} \cdot Sc^{0,33} \cdot \left(\frac{d_{ч.}}{D_a} \right)^{0,67} \tag{10}$$

- for a layer of wet carbon black, ammophos and superphosphate:

$$Sh = 0,7 \cdot Re^{0,9} \cdot Sc^{0,33} \cdot \left(\frac{d_{ч.}}{D_a} \right)^{0,67} \tag{11}$$

It is known that the coefficient of molecular diffusion depends on the regime of flow of a thermal agent around solid particles. The method for determining the internal diffusion coefficient is based on the mathematical solution of the differential equation of internal diffusion. The paper presents internal diffusion coefficients for a three-dimensional model. For spherical particles this equation in spherical coordinates is:

$$\frac{\partial w^c}{\partial \tau} = D_w \cdot \left(\frac{\partial^2 w^c}{\partial r^2} + \frac{2}{r} \cdot \frac{\partial w^c}{\partial r} \right) \tag{12}$$

But it is impossible to use this dependence to calculate the internal diffusion coefficient for particles of fibrous materials.

During filtration drying in the first period, heat is simultaneously transferred from the thermal agent to the surface of the material being dried and moisture is transferred from the surface of the particles to the thermal agent. Both processes are convective: convective heat transfer and convective mass transfer. Characteristic of both processes is the dependence of the heat flux density or mass on the surface of the material being dried, the difference in temperature or concentration (moisture content). Both processes are characterized through heat transfer coefficientsα and mass transferβ . The greatest influence on their value is hydrodynamics, which, as was said, is estimated by the Re number. From the given dependencies (5) - (7) it is clear that for both cases the equations in generalized variables are similar to each other and are characterized by the same exponents of the Reynolds number, which indicates the same influence of hydrodynamics on the heat transfer and mass transfer coefficients. Despite the different nature of heat transfer and mass transfer processes, which is estimated by Prandtl and Schmidt numbers, experimentally determined complexes $\dfrac{Nu}{\Pr^{0,33}}$ And $\dfrac{Sh}{Sc^{0,33}}$ coincide with each other for the same Reynolds numbers.

In order to determine analogies between these processes, equating these complexes with each other:

$$\frac{Nu}{\Pr^{0,33}} = \frac{Sh}{Sc^{0,33}} \tag{13}$$

or

$$\frac{\alpha \cdot d_e}{\lambda \cdot \left(\dfrac{v}{a} \right)^{0,33}} = \frac{\beta \cdot d_e}{D \cdot \left(\dfrac{v}{D} \right)^{0,33}} \tag{14}$$

where can you get it:

$$\frac{\alpha}{c \cdot \rho} = \beta \cdot \left(\frac{a}{D} \right)^{0,67} \tag{15}$$

Considering,What $\dfrac{D}{a} = Le -$ Lewis number, the above dependence can be represented as:

$$\beta = \frac{\alpha}{c \cdot \rho} \cdot Le^{2/3} \tag{16}$$

It follows that for the first period of filtration drying the mass transfer coefficient can be determinedβ , if the heat transfer coefficient is knownα.

Thus, an analysis was carried out of the operation of drying devices using the principle of air filtration through a layer of dried material, as well as design equations to determine their main characteristics, such as hydrodynamic parameters, mass transfer, heat transfer.

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