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UNSTEADY HEAT TRANSFER DURING ENCAPSULATION OF DISPERSED MATERIALS IN QUASI-LIQUEFIED STATE

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Abstract. Experimental and analytical investigations of the heat transfer process during encapsulation of dispersed materials in quasi-liquefied state are presented. The heat-transfer coefficients for different types of materials have been determined during their heating depending on air rate.

Keywords: unsteady heat transfer, kinetics, quasi-liquefaction, dispersed material.

1. Introduction

During encapsulation of dispersed materials in quasi-liquefied state using film-forming solutions it is necessary to heat the particles till operating temperature. In the batch apparatus such heating is a separate technological stage [1]. In the continuous apparatus the heating may proceed in the separate area or directly in the area of coating growing in parallel with film-forming agent plating depending on design [2].

Irrespective of apparatus type in the certain periods of time the dispersed material is in the state of unsteady heat transfer. The intensity of this stage depends on heat carrier rate and temperature, as well as on material physical properties [3, 4]. Therefore, to produce and use the encapsulated materials the investigations of heat transfer kinetics during encapsulation of dispersed materials in pseudo-liquefied state are in demand. It will grant the possibility to employ a scientific approach to the choice of encapsulation technological parameters, provide the high productivity of the equipment and obtain the materials with predicted properties.

2. Experimental

Heat transfer between the air and material layer during heating occurs at the moment of dispersed material loading into an apparatus and ends as particles are heated till the operating temperature. The experiments were carried out in the batch cylindrical apparatus of quasi-liquefied state. During the experiments the working part of the apparatus was insulated to avoid heat losses throughout the walls. Before the material loading the apparatus was heated to the operating temperature, hence there was no heat exchange between the air and apparatus walls. At the beginning the dispersed material temperature was 293 K. The temperature of heat carrier was 348 K and it was measured using chromel-copel thermocouple and 7-channels smart convertor PVI-0298 with computer recording. The change of heat carrier temperature was fixed from the moment of loading and till approaching of the air temperature at the apparatus outlet to the initial values.

The used solid materials were: polydispersed layer – granulated mineral fertilizers (ammonium nitrate, calcium nitrate, carbamide and nitroamophose) and layer of particles with irregular geometry – seeds which may undergo the presowing encapsulation by chemical protectants for plants and chemical elements of additional fertilizing (fodder beet, spinach).

3. Results and Discussion

The dependencies of heat carrier temperature on time at different values of liquefying air rates within the range between the first and the ssecond critical values are represented in Fig. 1.

The analysis of the experimental results shows that the increase in air rate decreases the time necessary for the layer to be in temperature equilibrium with the heat carrier. The reason is that the higher air rate decreases the layer thickness at the boundary air–particle surface and increases the amount of heat transferred from the particle at the same space of time. These observations are in an agreement with the results of heat-and-mass transfer in the quasi-liquefied state obtained by other authors [3, 7, 8].
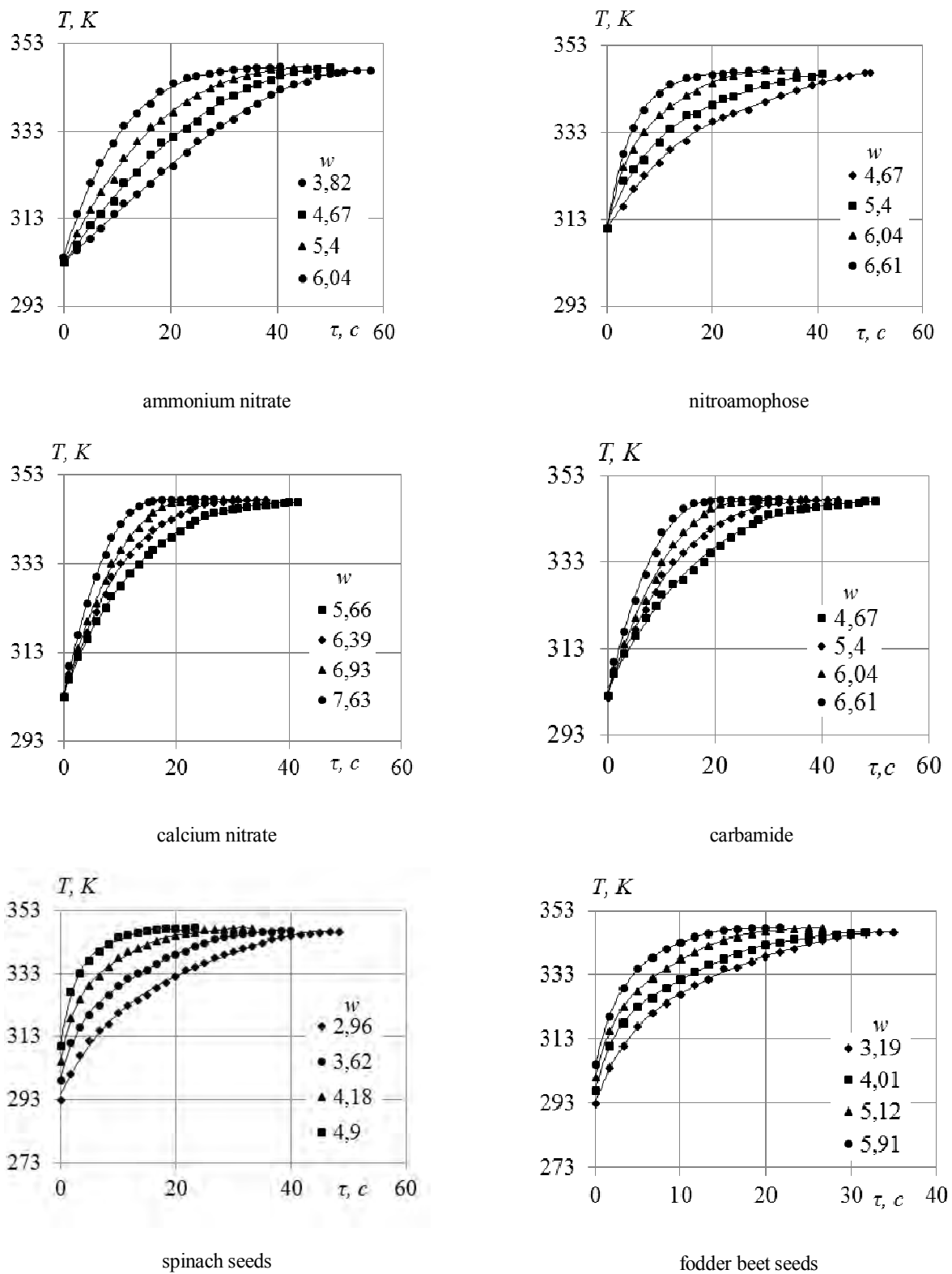
Fig. 1. Liquefying air temperatures at its different rates (*w*, m/s)
in the layer during the heating of dispersed material in quasi-liquefied state

The heat-transfer coefficient α which determines the amount of heat donated or accepted by the surface unit for time unit is an important thermal characteristic of the heat transfer processes. The coefficient is determined experimentally and the theory of generalized variables is used for its generalization. According to the theory the criterial dependencies between dimensionless numbers are obtained.

The coefficient α is determined on the basis of heat transfer equation [3] which includes the surface temperature of the solid matter. It is problematic to measure the surface temperature of the particle in quasi-liquefied state and therefore to determine the coefficient α we used the method based on the theory of unsteady heat conductivity.

On the basis of heat balance equations (Eq. (1)) we determined the average temperature of the solid particles as a time function $\overline{T} = f(t)$.

$$\Delta Q = M_p C_p \left(\overline{T} - T_0\right) \Delta t = V r c \left(t_{in} - t_{out}\right) \Delta t \qquad (1)$$

where ΔQ – the heat transferred from the liquefying air to the particles, J/kg·K; M_p – particles mass, kg; C_p – material heat capacity, J/kg·K; V, r and c – consumption (m³/s), density (kg/m³) and heat capacity (J/kg·K) of the liquefying air, respectively; t_{in} and t_{out} – liquefying air temperature at the inlet and outlet of the dispersed material layer, respectively, K; Δt – time, s.

The solution of the equation of unsteady heat conductivity with boundary conditions of the third order for the average temperature of the spherical solid particle in dimensionless units gives Eq. (2) [5]:

$$\Theta = \frac{\overline{T} - T_0}{t_a - T_0} = 1 - \sum B_n \exp\left(-m_n^2 Fo\right) \qquad (2)$$

where Θ – the function of Fo and Bi numbers; m_n – roots of the characteristic equation; $Fo = at/R^2$ – Fourier number; $Bi = aR/l$ – Bio number; t_a – temperature of the liquefying air in the material layer, K; $\overline{T}$ and T_0 – average and initial temperatures of the material particles, respectively, K.

The amount of heat ΔQ transferred from the liquefying air to the material particles is calculated according to the heat balance equation for the heat carrier, t_a is accepted as averaging temperature of the heat agent in the material layer for investigated space of time according to the measurements represented in Fig. 1.

At the considerable space of time we may limit ourselves in Eq. (2) by the first term of series. After some transformations we obtain Eq. (3):

$$\Theta = \frac{t_a - \overline{T}}{t_a - T_0} = B_1 \exp\left(-m_n^2 Fo\right) \qquad (3)$$

where

$$B_1 = \frac{6 Bi^2}{m_1^2 \left(m_1^2 + Bi^2 - Bi\right)} \qquad (4)$$

To determine the root of the characteristic equation m_1 we find the logarithm of Eq. (3):

$$\ln \Theta = \ln B_1 - m_1^2 Fo = \ln B_1 - m_1^2 \frac{at}{R^2} \qquad (5)$$

Then we build the plot $\ln(\Theta) = f(\tau)$, where a sloping angle of the corresponding kinetic curves is equal to:

$$tg\, b = m_1^2 \frac{a}{R^2} = m_1^2 \frac{l}{crR^2} \qquad (6)$$

where λ – the heat conductivity factor of the liquefying air, W/m·K; c – heat capacity of the liquefying air, J/kg·K; ρ – density of the liquefying air, kg/m³.

Using the value of Bi number, calculated according to Eq. (4) we calculate the values of the coefficient α. The obtained results are averaged relative to the layer height and represented in Fig. 2.

One can see from Fig. 2 that the coefficient α increases with the increase in air rate according to the linear law. It is explained by greater heat application with the increase of liquefying air amount and decrease of boundary heat layer around the particle due to the gas flow turbulization. The obtained results (Fig. 2) are in the agreement with the data of other authors [6].

The experimental results are generalized in accordance with Eq. (7) [5]:

$$Nu_e = A\, Re_e^n\, Pr^m \qquad (7)$$

Taking into account that physical parameters of the air are changed within the narrow range, we assume $Nu_e \sim Pr^{0.33}$ [3, 7]. To determine the coefficients A and n in Eq. (7) the experimental data were described as the dependence $Nu_e/Pr^{0.33} = f(Re_e)$ in the logarithmic coordinates (Fig. 3).

One can see from Fig. 3 that the experimental points for all materials are approximated by practically parallel lines. Thus, the exponents near Reynolds number are equal for different materials. The difference in vertical placement of the lines is explained by the influence of particles size on the heat-transfer coefficient. The same as for the heat-transfer coefficient, the dependence of Nusselt number on the rate of heat agent flowed around the particles is correlated with the data from Ref. [8, 9] for different by size balls made from glass and plastics.

The determined coefficients A and n are given in the Table. The value of the coefficient A is a function of particle size and exponent n is the same for all materials and equals approximately to 0.9.

To take the effect of geometrical sizes of particles d and apparatus D_a into consideration it is necessary to introduce the geometric simplex d/D_a into Eq. (7).
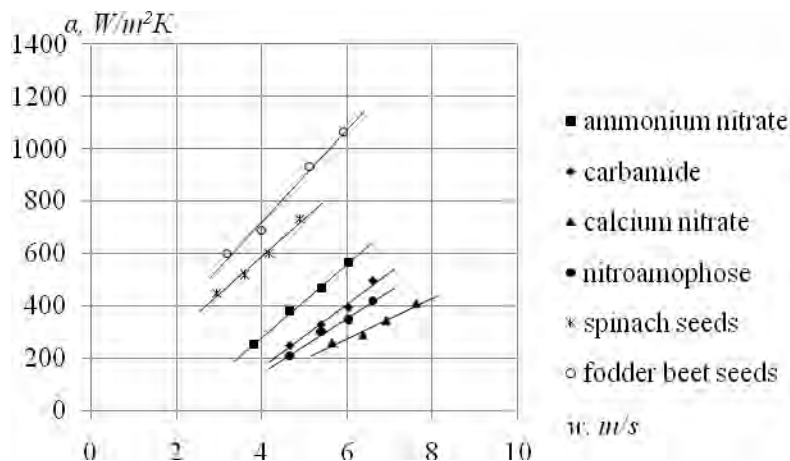
Fig. 2. Dependence of the heat-transfer coefficients on dummy rate
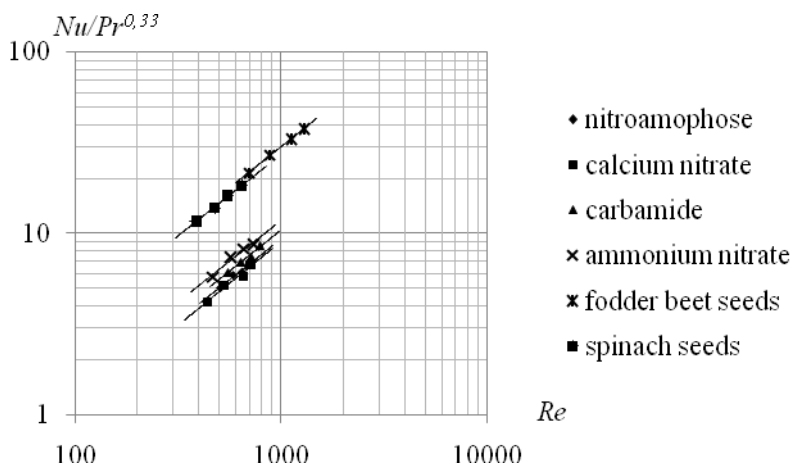of the liquefying air for the dispersed materials heating

Fig. 3. Generalization of the experimental results concerning
the heat-transfer coefficients during the dispersed material heating by liquefying air

Table

The values of A and n in Eq. (7) for a determination

Material	A	n
Calcium nitrate	0.016	0.9
Nitroamophose	0.017	0.9
Ammonium nitrate	0.020	0.9
Carbamide	0.019	0.9
Spinach seeds	0.053	0.9
Fodder beet seeds	0.059	0.9

The value A may be approximated by exponential Eq. (8) depending on the geometric simplex.

$$A = A'\left(\frac{d}{D_a}\right)^k \qquad (8)$$

The experimental data are approximated in the best way by two curves (Fig. 4). The first curve is drawn through the points that correspond to the coefficient A obtained for the seeds and model particles, the second – for granulated fertilizers. The points on the graph are situated from the left to the right in ascending order of particles size. The exponent in Eq. (8) is the same for both curves and equals to 0.67. A' for the first curve is 0.418; for the second – 0.253.
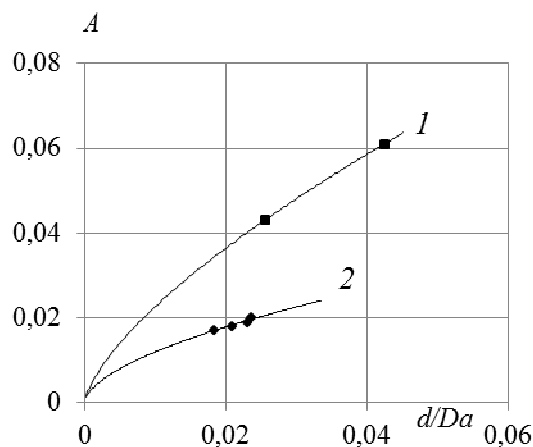
Fig. 4. Coefficient *A vs.* geometric simplex *d/D$_a$* for dry materials: seeds (1) and granulated fertilizers (2)

Thus, Eq. (7) takes a view of Eqs. (9) and (10)

– for calcium nitrate, nitroamophose, carbamide, ammonium nitrate and model particles:

$$Nu_e = 0.005 \, \mathrm{Re}_e^{0.9} \, \mathrm{Pr}^{0.33} \left(\frac{d}{D_a} \right)^{0.67} \qquad (9)$$

– for spinach and fodder beet seeds:

$$Nu_e = 0.017 \, \mathrm{Re}_e^{0.9} \, \mathrm{Pr}^{0.33} \left(\frac{d}{D_a} \right)^{0.67} \qquad (10)$$

4. Conclusions

The obtained generalized dependencies allow to determine the heat-transfer coefficients of the dispersed materials heating till the operating temperature. The difference between different dispersed materials may be explained by the different form of particles. Thus, the seeds are characterized by complex geometry having the essential influence on the streamline conditions of heat agent. Therefore, for the seeds the difference between theoretically calculated Nusselt number and experimental data is approximately 26 %.

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НЕСТАЦІОНАРНИЙ ТЕПЛООБМІН ПІД ЧАС КАПСУЛЮВАННЯ ДИСПЕРСНИХ МАТЕРІАЛІВ У СТАНІ ПСЕВДОЗРІДЖЕННЯ

Анотація*. Наведено експериментально-аналітичні дослідження процесу теплообміну під час капсулювання дисперсних матеріалів у стані псевдозрідження. Визначено коефіцієнти тепловіддачі під час нагрівання дисперсного матеріалу у стані псевдозрідження у залежності від швид-кості повітря для різних типів матеріалів.*

Ключові слова: *нестаціонарний теплообмін, кінетика, псевдозрідження, дисперсний матеріал.*