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## INTRADIFFUSION MASS TRANSFER DURING DRYING OF SLAG GRAVEL RAW GRANULE

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**Abstract.** Intradiffusion mass transfer during drying of a single raw granule of slag gravel has been investigated. The physical model of moisture distribution in the single particle during its drying in the second period has been suggested. The process of intradiffusion mass transfer during drying slag gravel raw granule has been described mathematically. The effect of intradiffusion coefficient on the temperature has been studied.

**Keywords:** intradiffusion coefficient, drying kinetics, moisture content, raw granule, moisture content gradient.

### 1. Introduction

It is known that nearly 50 % of all electrical power produced in Ukraine accounts for electric power stations (EPS). At the same time constant accumulation of ash-slag wastes takes place at EPS spoils. Nowadays their amount is 400 million tons. The utilization level of EPS ash-slag wastes is approximately 1 % of the existing resources [1]. While energy carriers and natural sources are limited slag may be used as a secondary raw material for the production of building materials [2, 3]. One of the prospective ways of ash-slag wastes utilization is the production of slag gravel, the technology of which provides preliminary drying of the raw material (slag, clay) and raw granules. The prime cost of slag gravel is mainly determined by energy consumption for drying process because costs for this process amount to 30 % of the whole production costs. Due to the imperfection of technological equipment and low efficiency of heat power usage the drying process consumes more heat energy than it is necessary for moisture conversion into vapor. Therefore, investigation of the drying process with the aim of energy consumption decrease and development of high-productivity drying plants is of particular interest.

It is known that during drying the internal moisture is removed worst of all, because about 15 different types of mass-and-heat transfer take place in the internal mass transfer [4]. The first stage of the theoretical analysis of drying of disperse materials in the second period is investigation of the processes proceeded in the single particle; therefore we studied intradiffusion mass transfer during drying of a single slag gravel granule.

### 1.1. Theoretical Background

S. Rudobashta and co-workers [5, 6] grounded the necessity of investigations at microkinetic level (description of the drying process of a single granule or differentially thin layer in apparatus), which allows to construct the general mathematical model describing the process kinetics. To describe microkinetics of granulated polymers drying, in particular internal mass transfer in polymer granule, the author [6] represents unidimensional nonlinear microkinetic task of polymer granule drying as follows:

$$\frac{du}{dt} = \text{div}(D_e(u,t) \cdot \text{grad } u), 0 < x < R, t > 0 \quad (1)$$

The dependence of diffusion effective coefficient on moisture content

$$D_e = D_0 \cdot \exp \left[ -bu - \frac{E_{D_0}^* \cdot (1-du)}{R^* \cdot T} \right] \quad (2)$$

where  $D_0$  – formal value of the diffusion effective coefficient at  $T \rightarrow \infty$ ,  $\text{m}^2/\text{s}$ ;  $b$  and  $d$  – constants:  $b > 0$  and  $0 < du < 1$ ;  $E_{D_0}^*$  – diffusion activation energy,  $\text{kJ/mol}$ ;  $u$  – moisture content,  $\text{kg H}_2\text{O}/\text{kg dry mat}$ .

The mathematical model given in [6] contains unknown values present in Eq. (1), which need to be determined by the experiments and which are valid only for the investigated material.

Mosyuk M. [7] investigated the intradiffusion mass transfer during filtration drying of “energetic

willow". The coefficients of intradiffusion were determined and their dependence on the temperature of grinded "energetic willow" was obtained:

$$D_w^t = D_w^{293} + 0.427 \cdot 10^{-10} \cdot (T - 293) \quad (3)$$

It was established that coefficients of moisture diffusion into environment during drying depends on the particles structure, moisture content and heat agent temperature. To solve the mathematical model the author assumed that particles of "energetic willow" are in the form of cylinder, therefore this model is valid only for the particles with the mentioned form.

In [8-10] the coefficient of moisture intradiffusion was determined inside a solid particle whose pores are filled with water. The drying process proceeds in the second period. The authors developed the mathematical model of moisture distribution in the ball-shaped particle during its drying and solved the differential equation allowing to determine the character of moisture content distribution in the pores of the solid particle during the second period of drying. In [8] the dependence  $D_w$  on external hydrodynamics was determined. It is approximated by the power Eq. (3) within the limits of Reynolds number  $650 \leq Re \leq 2200$ .

$$\frac{D_w}{D_0} = 2.77 \cdot 10^{-2} \cdot Re^{0.32} \quad (4)$$

However, the Eq. (3) is valid only for the investigated granulated materials which are characterized by the definite porosity and internal structure. Therefore it is impossible to use it for other materials.

To develop the mathematical models of intradiffusion mass transfer during filtration drying the authors [5-10] assumed simplifications affecting the accuracy of obtained results. Therefore the further theoretical and experimental investigations are topical tasks.

The aim of this work was to study the intradiffusion mass transfer during drying of a single raw granule and to determine the intradiffusion coefficient depending on heat agent temperature.

## 2. Experimental

### 2.1. Investigation Object

Raw granules of slag gravel were chosen to be an investigation object since their drying is the urgent problem for ash-slag wastes utilization plants. The raw granules are prepared *via* granulation of homogeneous charge. Previously dried clay and slag are grinded to the size of 140  $\mu\text{m}$ . The obtained charge with a percentage ratio of clay:slag = 86:14 is fed on dish nodulizer irrigated by water. The diameter of the formed raw granules is 10–20 mm, the internal porosity is 24–25 %

relative to the volume. The granules moisture content is 13–15 %. Thus in accordance with the process flowsheet it is necessary to dry them to the moisture content of 2 % before it goes to furnace.

## 2.2. Investigation Procedure

The experiments were carried out at the plant represented in [9]. The granule was placed in the container through which the heated air was passed. Thus the conditions of temperature balance on the particle surface were created. The temperature above granule was sustained by means of RT-100 thermoregulator and two thermocouples. The change of moisture content (counting on dry mass) was determined after definite time intervals using weight method (AXSIS-3000 balance, accuracy 0.01 g). The experiment was stopped when granule weight was constant for 120–180 s.

## 3. Results and Discussion

### 3.1. Physical Model of the Process

Fig. 1 represents the ball-shaped particle with  $R$  radius and pores. The process of moisture conversion into vapor in every pore leads to the origin of moisture flow in vaporized state from the interface "water-vapor" to the external surface of the particle. Vaporized moisture from the surface transfers to the heat agent *via* convective diffusion. Fig. 1 shows the material state during the second period at time  $t$ . Condensed moisture is situated on the radius  $r_0$ , which is the interface of two phases at the same time. Above liquid there is vapor in the saturated state with moisture content  $x_{sat}$ ;  $r$  – running radius with moisture content of  $x$ . Moisture content on the particle surface corresponds to moisture content of

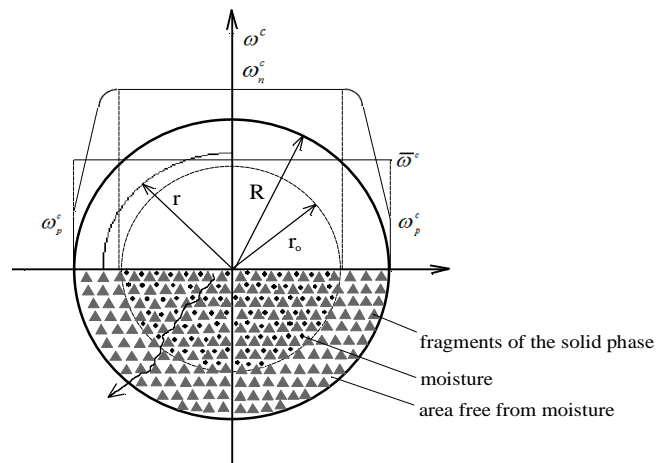


Fig. 1. Moisture distribution inside the raw granule at time  $t$

the heat agent  $x(R) = x_1$ . During drying the interface moves inside the particle and its average moisture content decreases. The heat agent temperature was varied from 323 to 373 K and the particle initial temperature was  $293 \pm 0.5$  K. The interface moves during drying, the temperature remains constant and equal to the temperature of wet thermometer.

### 3.2. Kinetics of a Single Raw Granule Drying

The experimental results of a single raw granule drying are represented in Fig. 2.

The increase of heat agent rate (Fig. 2a) from 0.29 to 0.89 m/s, *i.e.* by three times, does not affect the process time. It means that only intradiffusion transfer of moisture takes place; the external hydrodynamics does not influence the kinetics of granule drying. The kinetic curve is characterized by the second period of drying, *i.e.* osmotic- and adsorption-bound moisture is removed. Fig. 2b represents the kinetic curves of the raw granule drying at different temperatures of the heat agent. The increase of temperature from 323 to 373 K leads to three times decrease of the drying time. The reason is the increase of the heat agent drying potential.

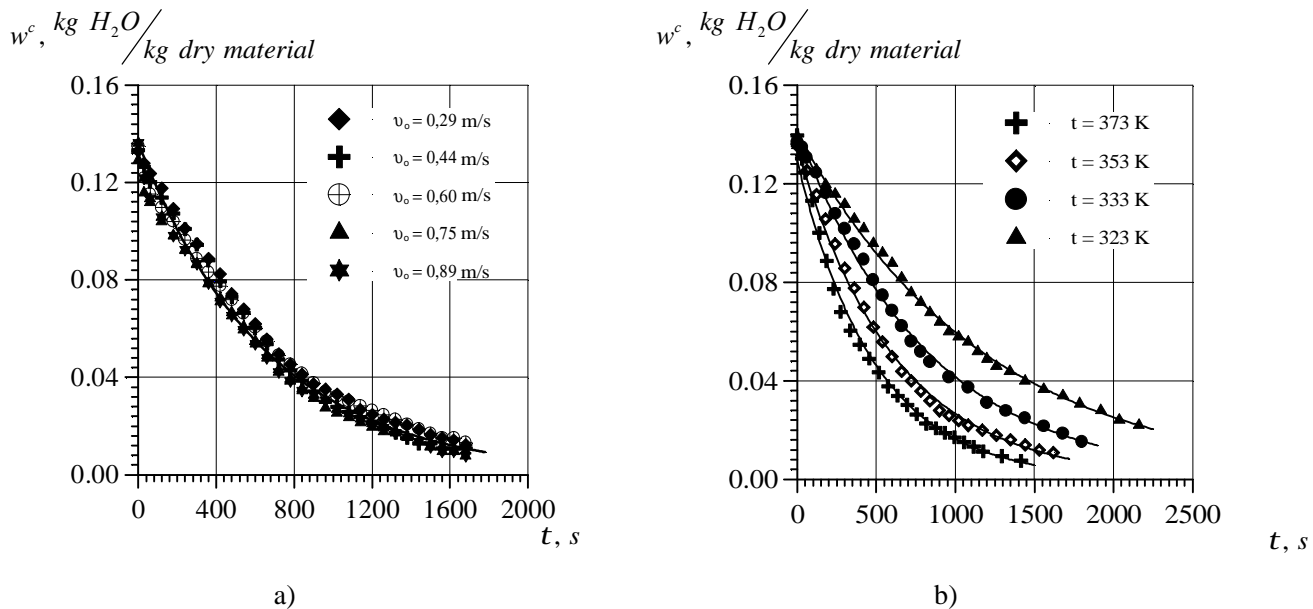


Fig. 2. Kinetics of a raw granule drying at (a) different heat agent rates ( $T = 333$  K) and different temperatures (b)

### 3.3. Determination of Intradiffusion Mass Transfer Coefficient

To analyze the intradiffusion mass transfer inside the raw granule of slag gravel we determined the intradiffusion coefficient on the basis of mathematical solution of intradiffusion differential equation with corresponding initial and boundary conditions.

For the ball-shaped particles the mentioned equation looks as follows [7]:

$$\frac{\partial c}{\partial t} = D_w \cdot \left( \frac{\partial^2 c}{\partial r^2} + \frac{2}{r} \cdot \frac{\partial c}{\partial r} \right) \quad (5)$$

Taking into account that  $c = w^c \cdot r_{d.m.}$  Eq. (5) converts into (6):

$$\frac{\partial w^c}{\partial t} = D_w \cdot \left( \frac{\partial^2 w^c}{\partial r^2} + \frac{2}{r} \cdot \frac{\partial w^c}{\partial r} \right) \quad (6)$$

To determine the intradiffusion coefficient it is necessary to solve the differential Eq. (6). Let us note that this equation is the same as the differential equation of heat conductivity, where coefficient  $D_w^*$  is the same as coefficient of thermal diffusivity  $a$ . The creation of the mathematical model provides for the following assumptions:

- the single raw granule has the form of ball;
- the granule is uniformly blown by air flow;
- all granule pores are kinetically equal, *i.e.* moisture is uniformly distributed in granule volume ensured by conditions of granule formation;
- the moisture content of the heat agent  $x_1$  is not changed during drying; obviously its value corresponds to the moisture content of air at the granule surface ensured by the great volume of the heat agent, small surface of the granule and small amount of moisture.

The raw granule contains surface moisture in small amount; here bound moisture predominates, which is evaporated during the second period. The results represented in Fig. 2a confirm this fact. Taking into account the considerable internal porosity of the granules ( $e = 0.24-0.25$ ) and free access of the heat agent to the granule, we may assume that diffusion Bio number  $Bi_d$  is considerable as well. Further it is necessary to check its value and to reduce the task as itself to the boundary conditions of the first type.

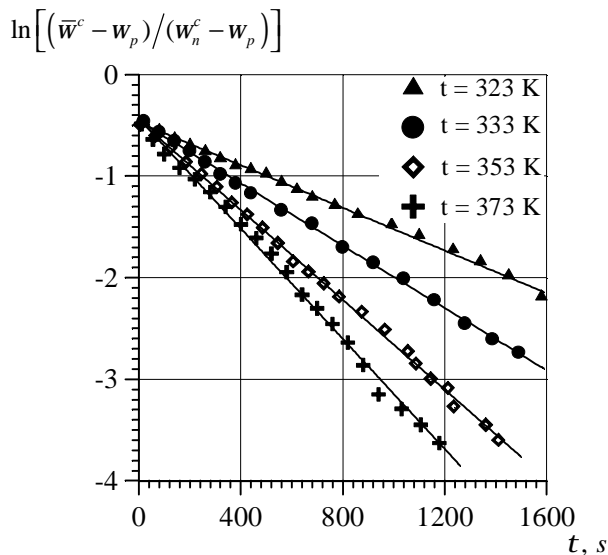
Then the boundary conditions may be represented as follows:

$$\begin{cases} w^c(r, t = 0) = w_n^c, & w^c(r = R, t) = w_p^c, \\ \left(\frac{\partial w^c}{\partial r}\right)_{r=0} = 0 \end{cases} \quad (7)$$

where  $D_w^*$  – intradiffusion coefficient,  $m^2/s$ ;  $r$  and  $R$  – running and particle’s radii, respectively,  $m$ ;  $w^c, w_p^c, w_n^c$  – running, equilibrium and initial moisture content of the raw granule, respectively,  $kg\ H_2O/kg$  dry mat.

Taking into consideration the above mentioned assumptions the solution of Eqs. (6) and (7) may be represented as follows:

$$\frac{\bar{w}^c - w_p^c}{w_n^c - w_p^c} = \sum_{n=1}^{\infty} B_n \cdot e^{-m_n^2 \cdot Fo} = \sum_{n=1}^{\infty} \frac{6}{p^2 \cdot n^2} e^{-\frac{p^2 \cdot n^2 \cdot D_w^* \cdot t}{R^2}} \quad (8)$$



**Fig. 3.** Dependence of  $\ln\left[\frac{\bar{w}^c - w_p^c}{w_n^c - w_p^c}\right]$  on drying time of the raw granule

where  $m_n$  – roots of the characteristic equation;  $t$  – time,  $s$ ;  $F_0 = D_w^* \cdot t/R^2$  – Fourier number;  $B_n = 6/m_n^2$ .

At great values of  $F_0$  (great values of  $t$ ) we may ignore terms of sum  $n > 1$ . The solution of Eq. (8) with the first term after finding the logarithm looks like:

$$\ln\left(\frac{\bar{w}^c - w_p^c}{w_n^c - w_p^c}\right) = \ln\frac{6}{p^2} - p^2 \cdot \frac{D_w^* \cdot t}{R^2} \quad (9)$$

The graphical dependence of a linear character  $\ln\left[\frac{\bar{w}^c - w_p^c}{w_n^c - w_p^c}\right]$  vs  $t$  is represented in Fig. 3.

The intradiffusion coefficient  $D_w^*$  may be calculated using slope of the line to the abscissa and has the following view (Fig. 4):

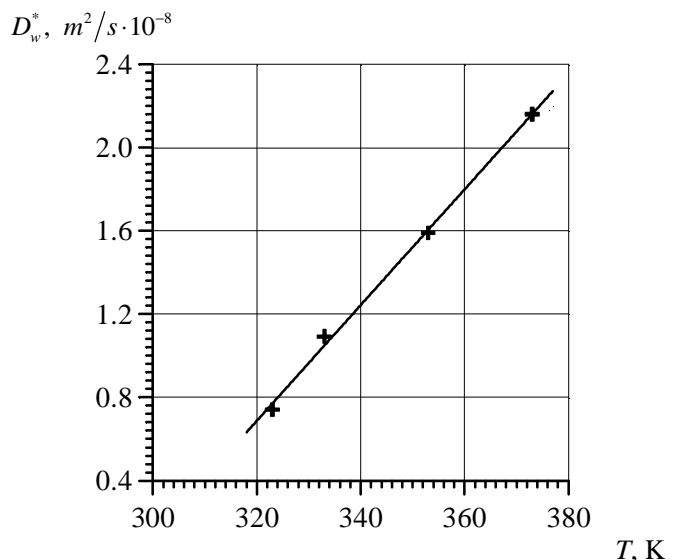
$$D_w^* = \frac{tga \cdot R^2}{m^2} \quad (10)$$

The intradiffusion coefficient of moisture from the single raw granule is represented below at different temperatures.

$T, K$	323	333	353	373
$D_w^* \cdot 10^{-8}$	0.74	1.09	1.59	2.16

Fig. 4 shows that the increase of the heat agent temperature linearly increases the intradiffusion coefficient; therefore it may be approximated as follows:

$$D_w^i = D_w^{293} + 2.5 \cdot 10^{-10} \cdot (T - 293) \quad (11)$$



**Fig. 4.** Dependence of the intradiffusion coefficient on temperature for the raw granule calculated in accordance with (10)

It is known that coefficient of moisture diffusion into environment during drying is within the range from  $10^{-6}$  (capillary-porous materials) to  $10^{-12}$  m/s (low-porous materials) [5-10] and depends on particles structure, temperature and moisture content. These values correlate with those obtained by us.

The obtained dependence (11) is in a good agreement with experimental values determined at 323–373 K. The maximal error does not exceed 8 %.

To check  $Bi_d$  ( $Bi_d = b \cdot R / D_w^*$ ) relative to the conditions of the first type we took into account that during calculations the average moisture content in the particle  $\bar{w}_n^c$  was used. It may be determined by experiment. Therefore we used the method based on inserting of experimental data into theoretical equations to determine the intradiffusion coefficient. The adequacy of the accepted assumption may be ascertained by  $Bi_d$  control. We chose the maximum values of the intradiffusion coefficient  $D_w^* = 1.6 \cdot 10^{-8}$  m<sup>2</sup>/s; granule radius  $R = 8.8 \cdot 10^{-3}$  m; coefficient of mass transfer under the mentioned conditions  $b = 0.11$  m/s [11]. The obtained value of Bio diffusion number is  $6.05 \cdot 10^4 \gg 50$ . This fact confirms the intradiffusion regime of drying and validity of our hypothesis concerning the boundary conditions of the first type.

#### 4. Conclusions

Intradiffusion mass transfer during drying of a single raw granule of slag gravel was mathematically described on the basis of intradiffusion differential equation. The dependence of intradiffusion coefficient on temperature was investigated. The calculated values of the intradiffusion coefficient correlate with the dependencies obtained by other authors.

#### References

- [1] Burbán N. and Atamanyuk V.: I Mignarod. Congress “Zahyst Navkolyshnogo Seredovysha. Energooshadnist. Zbalansovane Pryrodokorystuvannya. Ukraine, Lviv 2009, 16.
- [2] Van der Sloot H., Hoede D. and Comans N.: Environ. Aspects of Constr. Waste Mat., 1994, **60**, 483.
- [3] Safiuddin Md. Jumaat M., Salam M. *et al.*: Int. J. Phys. Sci., 2010, **5**, 1952.
- [4] Frolov V.: I Conf. “Sovremennye Energoberegayushie Teplovye Technologii”, Russia, Moskva 2002, **2**, 7.
- [5] Rudobashta S. and Dmitriev V.: II Conf. “Sovremennye Energoberegayushie Teplovye Technologii”, Russia, Moskva 2005, **1**, 51
- [6] Rudobashta S.: Inzh.-Phys. Zh., 2010, **83**, 705.
- [7] Mosyuk M.: PhD thesis, Lviv Polytechnic National Univ., Lviv 2012.
- [8] Atamanyuk V.: Doctoral thesis, Lviv Polytechnic National Univ., Lviv 2007.
- [9] Atamanyuk V. and Gumnytskyi Ya.: Prom. Teplotechnika, 2009, **31**, 36.
- [10] Atamanyuk V. and Gumnytskyi Ya. Chem. & Chem. Techn., 2009, **3**, 129.
- [11] Atamanyuk V., Barna I. and Matkivska I.: Visnyk Khark. Polyt. Inst., 2012, **17**, 146.

#### ВНУТРІШНЬОДИФУЗІЙНЕ МАСОПЕРЕНЕСЕННЯ ПІД ЧАС СУШІННЯ СИРЦЕВОЇ ГРАНУЛИ ШЛАКОВОГО ГРАВІЮ

**Анотація.** Досліджено внутрішньодифузійне масоперенесення під час сушіння одинарної сирцевої гранули шлакового гравію. Запропоновано фізичну модель розподілу вологи в одинарні частинці під час її сушіння у другому періоді. Математично описано процес внутрішньодифузійного масоперенесення під час сушіння сирцевої гранули шлакового гравію. Досліджено залежність коефіцієнта внутрішньої дифузії від температури.

**Ключові слова:** коефіцієнт внутрішньої дифузії, кінетика сушіння, вологовміст, сирцева гранула, градієнт вологовмісту.