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IDENTIFICATION OF FLOW MODELS IN CAPILLARY-POROUS AND GRANULAR MEDIUMS

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Abstract. *The article describes simple and reliable techniques for parametric identification of filtration models and media flow in a layer of granular material. Experimental installations of the simplest design are used. Experiments are processed in the Excel environment.*

As the examples are determination of the transport properties of a capillary-porous material and the determination of the dependence of the aerodynamic drag of a grain layer during air purging.

Keywords*: parametric identification, flow, capillary-porous, granular material.*

ІДЕНТИФІКАЦІЯ МОДЕЛЕЙ ТЕЧІЙ У КАПІЛЯРНО-ПОРИСТИХ І ГРАНУЛЬОВАНИХ МАТЕРІАЛАХ

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Анотація. *У статті описані прості і надійні методики параметричної ідентифікації моделей фільтрації і течії середовищ в шарі зернистого матеріалу. Використовуються експериментальні установки найпростішої конструкції. Обробка експериментів проводиться в середовищі Excel.*

Як приклади розглядається визначення транспортних властивостей капілярно-пористого матеріалу і встановлення залежності аеродинамічного опору шару зерна при продувці повітрям.

Ключові слова*: параметрична ідентифікація, потік, капілярно-пористий, зернистий матеріал.*

ИДЕНТИФИКАЦИЯ МОДЕЛЕЙ ТЕЧЕНИЙ В КАПИЛЛЯРНО-ПОРИСТЫХ И ГРАНУЛИРОВАННЫХ СРЕДАХ

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Аннотация. *В статье описаны простые и надежные методики параметрической идентификации моделей фильтрации и течения сред в слое зернистого материала. Используются экспериментальные установки простейшей конструкции. Обработка экспериментов проводится в среде Excel.*

В качестве примеров рассматривается определение транспортных свойств капиллярно-пористого материала и установление зависимости аэродинамического сопротивления слоя зерна при продувке воздухом.

Ключевые слова*: параметрическая идентификация, течение, капиллярно-пористый, зернистый материал.*

Introduction. Methods of modeling are used to study processes in various technical objects. As a rule, full-scale experiment requires significant material and financial costs. Often a full-scale experiment is almost impossible. Physical modeling does not always provide reliable information in sufficient volume.

Computational experiment (based on mathematical modeling) allows us to conduct the research faster and cheaper [1]. It is especially important to ensure sufficient reliability of the results obtained in the computational experiment.

The reliability of information obtained in the computational experiment depends on the quality of mathematical models. The models, most often, are formed on the basis of a phenomenological approach. However, when already existing systems are the subject to research, the methods of parametric identification based on the processing of experimental data are in use. As a rule, experimental data are noisy. To obtain a clear picture of the process under investigation, it is required to suppress noise.

Another problem may arise when assigning the coefficients of mathematical models, especially in the absence of reliable information about the physical properties of materials and working media. To determine these properties, the researcher has to use special settings and parametric identification methods from experimental data.

The purpose of the article is to show simple and accessible approaches in solving the specified problem with minimal expenditure of material and computing resources.

Statement of the problem and the literature review. The parametric identification of two models is considered in the article:

− transfer of water in a plate made of capillary-porous plastic;

− the flow of water (air) in a layer of granular material.

Identification of models is carried out on the basis of data obtained at experimental facilities. Data processing is carried out in the EXCEL environment.

Basic requirements for experimental installations:

− simplicity of design;

− absence of complex regulating devices;

− use of the simplest measuring instruments (ruler and stopwatch).

Capillary-porous materials are used to supply water in a series of indirect-evaporative air coolers [2]-[4]. The most commonly used plates are made of porous plastic (myplast) [5].

Models of flow of working media in porous or granular material are used in the investigation of grain drying processes [6], when moisture is transferred in the details of structures [7]-[9] and when determining the bearing capacity of soils.

Identification of the model of water transfer in capillary-porous material. The transport properties of capillary-porous materials are important for the calculation of mass transfer processes in a porous plate (for example, in air coolers of the evaporative type).

Such indicators include:

Pz − the porosity of the material;

Kd − the Darcy coefficient;

Hs − the maximum height of the fluid in the material.

The rise of water in a porous plate (without evaporation from the outer surface) is described by equation (1).

$$h \cdot \frac{dh}{d\tau} \cdot A + h = Hs, \qquad A = \frac{Pz}{Kd \cdot g}. \tag{1}$$

To carry out the experiments, the device was used (Fig. 1).

The studies were carried out for plates cut from a sheet of dry porous plastic with a thickness of 1,25 mm. As a waterproofing, a transparent Scotch tape was used.

In Fig. 2 markers indicate the results of three experiments. The result of the approximation of the dependence h = f (τ) (for all three experiments) is shown by a solid line.

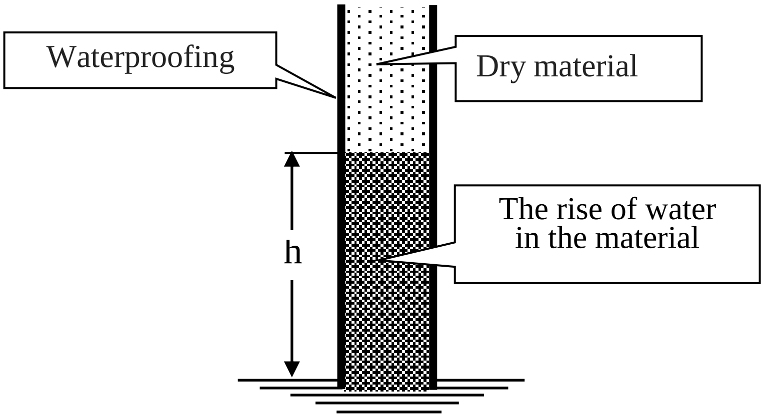

Fig. 1. Scheme of the experimental device

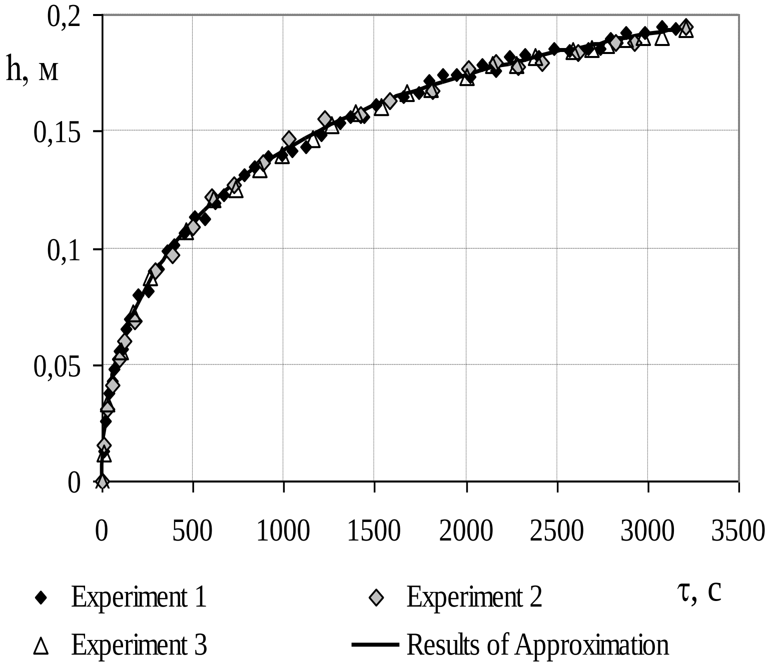

Fig. 2. Experimental dependencies and their approximation

To approximate the experimental dependences, we used formula (2).

$$h = Hs \cdot \left(1 - \exp\left(b_0 + b_1 \cdot \tau^{n_1} + b_2 \cdot \tau^{n_2} + b_3 \cdot \tau^{n_3}\right)\right). \qquad (2)$$

To approximate the dependencies, we used the method of least squares. Approximation was carried out in the Excel environment (add-on «Finding solutions»).

The derivative h' was calculated from (3).

$$h' = \frac{dh}{d\tau} = -H_s \cdot \exp\left(b_0 + b_1 \cdot \tau^{n_1} + b_2 \cdot \tau^{n_2} + b_3 \cdot \tau^{n_3}\right) \cdot \\ \cdot \left(b_1 \cdot n_1 \cdot \tau^{n_1 - 1} + b_2 \cdot n_2 \cdot \tau^{n_2 - 1} + b_3 \cdot n_3 \cdot \tau^{n_3 - 1}\right). \quad (3)$$

The values of A and Hs are determined by minimizing the functional δ (4).

$$\delta = \sum_{i=1}^{i_n} \left(A \cdot h_i \cdot h_i' + h_i - H_s\right)^2. \quad (4)$$

The values of h_i and h'_i were calculated using formulas (2) and (3) for a series of times (i_n) with a time step of 10 s to 50 s.

Minimization δ leads to a system of linear algebraic equations (5).

$$\begin{aligned} & A \cdot \sum_{i=1}^{i_n} \left(h_i \cdot h_i'\right)^2 + H_s \cdot \sum_{i=1}^{i_n} \left(-h_i \cdot h_i'\right) = \sum_{i=1}^{i_n} \left(-h_i^2 \cdot h_i'\right) \\ & A \cdot \sum_{i=1}^{i_n} \left(-h_i \cdot h_i'\right) + H_s \cdot \sum_{i=1}^{i_n} (1) = \sum_{i=1}^{i_n} (h_i). \end{aligned} \quad (5)$$

Solution (5) allows us to find the values A = 9500 s/m and Hs = 0.212 m.

To evaluate the reliability of the values of A and Hs, a numerical solution (1) was performed by the trapezium method (6) with step Δτ = 5 c.

$$h_i = \left(-1 \pm \sqrt{1 - 4 \cdot \frac{A}{\Delta\tau} \cdot \left(-\frac{A}{\Delta\tau} \cdot h_{i-1}^2 + h_{i-1} - 2 \cdot H_s\right)}\right) \Big/ \left(\frac{2 \cdot A}{\Delta\tau}\right). \quad (6)$$

Figure 3 shows the results of experiments (markers) and control calculations (line).

Identification of the air filtration model in the grain layer. When drying and fumigating grain, it is important to know the peculiarities of the process of blowing the fixed layer of grain by air (or other gases). The process of air filtration in a fixed grain layer is considered, when the effects of liquefaction and the wobbling of individual grains are absent.

A mathematical model is used as a system of equations (7).

$$\sum_{i}^{n} \frac{dV_{a_i}}{dx_i} = 0, \text{ and } \frac{dP}{dx_i} = -A_a\left(V_{a_i}\right) \cdot V_{a_i}, \quad (7)$$

where V_a − is the flow rate of air relative to the free space;

P − is the air pressure in the gaps between the grains;

$A_a(V_a)$ − is the coefficient reflecting the aerodynamic drag in the grain layer;

n − is the dimension of the problem.

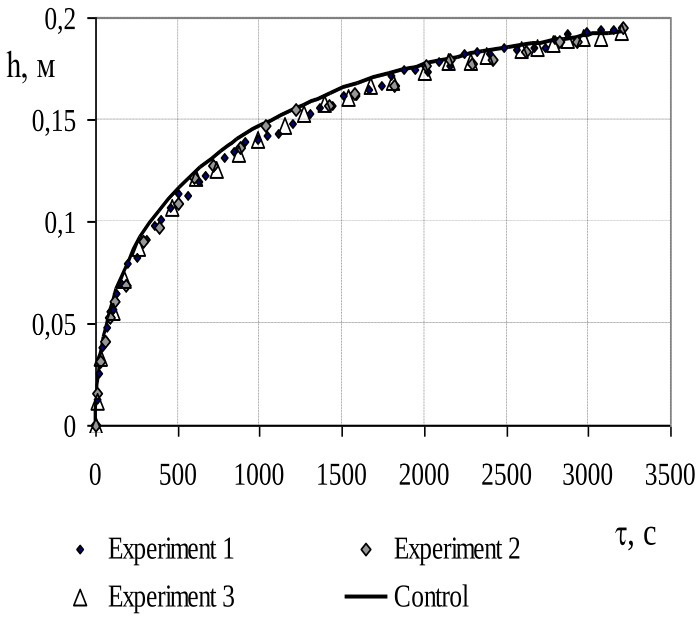

Fig. 3. Evaluation of identification results

The experimental determination of the dependence of the coefficient A_a on the filtration rate requires a high accuracy in determining the air velocity. It is extremely difficult to provide sufficient accuracy for measuring air velocities at low speeds. Therefore, in the experiment, water is used as a filter medium, and then, using the theory of similarity, the recalculation for air flow is done.

To study the filtration of water in the grain layer, a simple installation was used (Fig. 4).

In each experiment, a new dry grain was placed in the working cylinder from the same source. Each experiment was carried out with natural water filtration at a temperature of 20 ° C.

The approximating formula for generalizing a number of experimental dependences H = f (τ) had the form (8).

$$H = H_0 \cdot \left(1 - \exp\left(b_0 + b_1 \cdot \tau^{n_1} + b_2 \cdot \tau^{n_2} + b_3 \cdot \tau^{n_3}\right)\right), \quad (8)$$

where H_0 − is the initial level of water in the pressure cylinder.

To approximate the dependencies, we used the method of least squares. Approximation was carried out in the Excel environment (add-on «Finding solutions»).

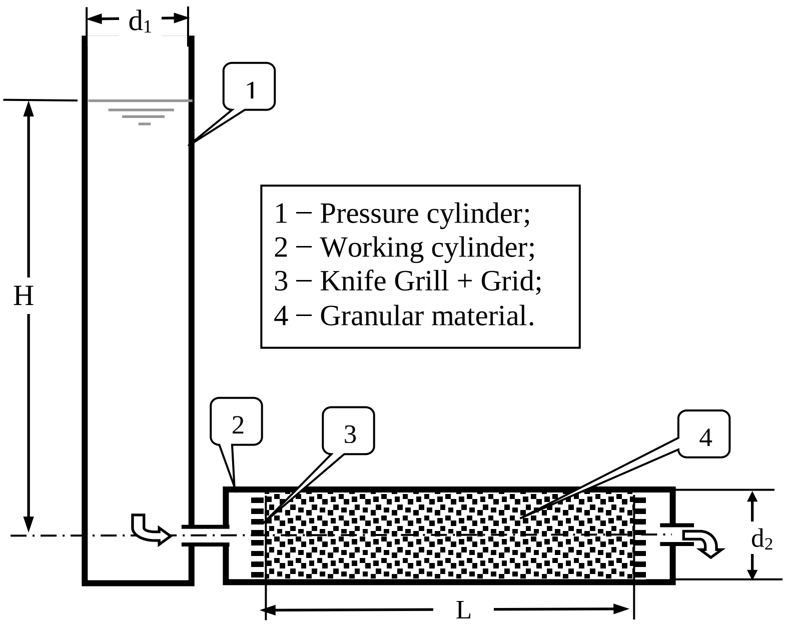

Fig. 4. Scheme of the experimental installation № 1 for the study of filtration

The derivative H 'was calculated from (9).

$$H' = \frac{dH}{d\tau} = -H_0 \cdot \exp\left(b_0 + b_1 \cdot \tau^{n_1} + b_2 \cdot \tau^{n_2} + b_3 \cdot \tau^{n_3}\right) \cdot \\ \cdot \left(b_1 \cdot n_1 \cdot \tau^{n_1 - 1} + b_2 \cdot n_2 \cdot \tau^{n_2 - 1} + b_3 \cdot n_3 \cdot \tau^{n_3 - 1}\right). \quad (9)$$

The results of the experiments (markers) and the approximating dependence (solid line) are shown in Fig. 5.

The flow of water in the granular material is described by the dependence (10).

$$\frac{dP_w}{dx} = -A_w \cdot V_w, \quad (10)$$

where P_w − is the change in pressure along the direction of water movement;

A_w − is the coefficient reflecting the backfill resistance when water is filtered;

V_w − is the water velocity in the grain layer, referred to the free space.

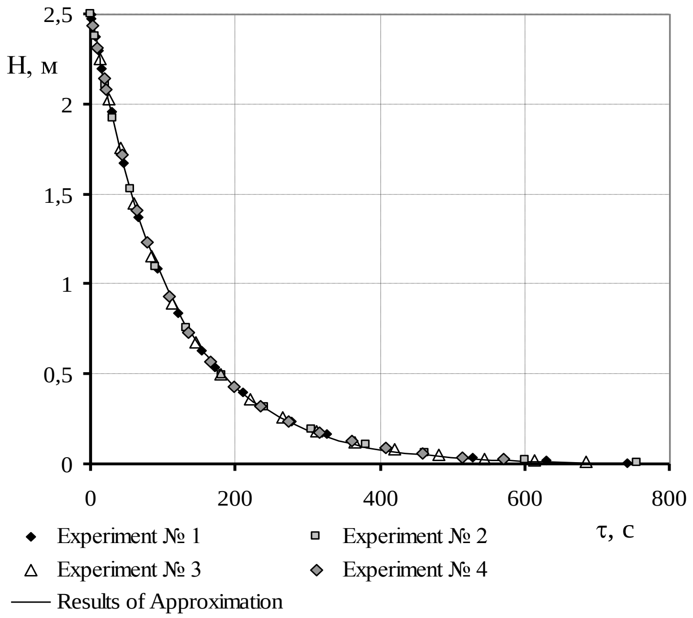

Fig. 5. Results of filtration experiments

In accordance with Fig. 4, (11) and (12) follow.

$$\Delta P_w = -H \cdot \rho_w \cdot g \,, \tag{11}$$

$$V_w = -\frac{dH}{d\tau} \cdot \left(\frac{d_1}{d_2}\right)^2 , \tag{12}$$

where H – is the water level in the pressure cylinder;

ρ – is the density of water;

g – acceleration of gravity.

The decrease in water pressure along the filtration direction is described (according to Fig. 4) by formula (13)

$$\frac{\Delta P_w}{L} = -A_w \cdot V_w \,, \tag{13}$$

where L – is the length of the experimental section.

To determine the value of A_w (according to (11)-(13)), formula (14) is used

$$A_w = -\frac{H}{\left(\frac{dH}{d\tau}\right)} \cdot \frac{\rho_w \cdot g}{\left(L \cdot \left(d_1 / d_2\right)^2\right)} \,. \tag{14}$$

An analysis of the results of published sources showed that the nonlinear dependence $A_w\ (V_w)$ is well described by formula (15).

$$A_w = a + b \cdot \left| V_w \right| + c \cdot {V_w}^2 . \qquad (15)$$

Taking into account (10) - (15), we can write the equation of water filtration in a granular layer (16).

$$\frac{dH}{d\tau} \cdot \left(\left(a + b \cdot \left| V_w \right| + c \cdot {V_w}^2 \right) \cdot \frac{L}{\rho_w \cdot g} \cdot \left(\frac{d_1}{d_2} \right)^2 \right) + H = 0 \cdot \qquad (16)$$

Equation (16) can be represented in a more convenient form (17).

$$a \cdot \frac{dH}{d\tau} + b \cdot \left| V_w \right| \cdot \frac{dH}{d\tau} + c \cdot {V_w}^2 \cdot \frac{dH}{d\tau} + H \cdot D = 0 , \qquad (17)$$

where $D = \frac{\rho_w \cdot g}{L \cdot C_0}$; $\quad V_w = -\frac{dH}{d\tau} \cdot C_0$; $\quad C_0 = \left(\frac{d_1}{d_2} \right)^2 \cdot$

To find the values of a, b, c, we minimize the functional δ (18).

$$\delta = \sum_{i=1}^{i_m} \left(a \cdot \left. \frac{dH}{d\tau} \right|_i + b \cdot \left| V_w \right|_i \cdot \left. \frac{dH}{d\tau} \right|_i + c \cdot {V_{wi}}^2 \cdot \left. \frac{dH}{d\tau} \right|_i + H_i \cdot D \right)^2 \cdot \qquad (18)$$

The values of H_i, H'_i and V_{wi} were calculated using formulas (8), (9) and (12) for series of values of the time instants (i_m) with a time step of 10 s.

It is necessary to ensure a minimum value of δ.

$$\frac{d\delta}{da} = 0; \quad \frac{d\delta}{db} = 0 \ ; \quad \frac{d\delta}{dc} = 0 . \qquad (19)$$

Under the conditions (19), one can obtain a system of three linear algebraic equations (20).

$$a \cdot \sum_{i=1}^{i_m} \left(\left. \frac{dH}{d\tau} \right|_i \right)^2 + b \cdot \sum_{i=1}^{ii_m} \left| V_w \right|_i \cdot \left(\left. \frac{dH}{d\tau} \right|_i \right)^2 + c \cdot \sum_{i=1}^{i_m} {V_{wi}}^2 \cdot \left(\left. \frac{dH}{d\tau} \right|_i \right)^2 = ,$$
$$= \sum_{i=1}^{i_m} \left(-H_i \cdot D \cdot \left. \frac{dH}{d\tau} \right|_i \right)$$
$$a \cdot \sum_{i=1}^{i_m} \left| V_w \right|_i \cdot \left(\left. \frac{dH}{d\tau} \right|_i \right)^2 + b \cdot \sum_{i=1}^{i_m} \left| V_w \right|_i^2 \cdot \left(\left. \frac{dH}{d\tau} \right|_i \right)^2 + c \cdot \sum_{i=1}^{i_m} \left| V_w \right|_i^3 \cdot \left(\left. \frac{dH}{d\tau} \right|_i \right)^2 = , \qquad (20)$$
$$= \sum_{i=1}^{i_m} \left(-H_i \cdot D \cdot \left| V_w \right|_i \cdot \left. \frac{dH}{d\tau} \right|_i \right)$$

$$a \cdot \sum_{i=1}^{i_m} |V_w|^2{}_i \cdot \left(\frac{dH}{d\tau}\bigg|_i \right)^2 + b \cdot \sum_{i=1}^{i_m} |V_w|_i^3 \cdot \left(\frac{dH}{d\tau}\bigg|_i \right)^2 + c \cdot \sum_{i=1}^{i_m} |V_w|_i^4 \cdot \left(\frac{dH}{d\tau}\bigg|_i \right)^2 = .$$
$$= \sum_{i=1}^{i_m} \left(-H_i \cdot D \cdot |V_w|^2{}_i \cdot \frac{dH}{d\tau}\bigg|_i \right)$$

The solution of the system (20) is carried out by the Excel method by inversion of the matrix. The values a = 1.10E + 06, b = -6.60E + 06, c = 3.99E + 07 are obtained.

To control the reliability of the obtained values, a more complex installation № 2 was used (Figure 6).

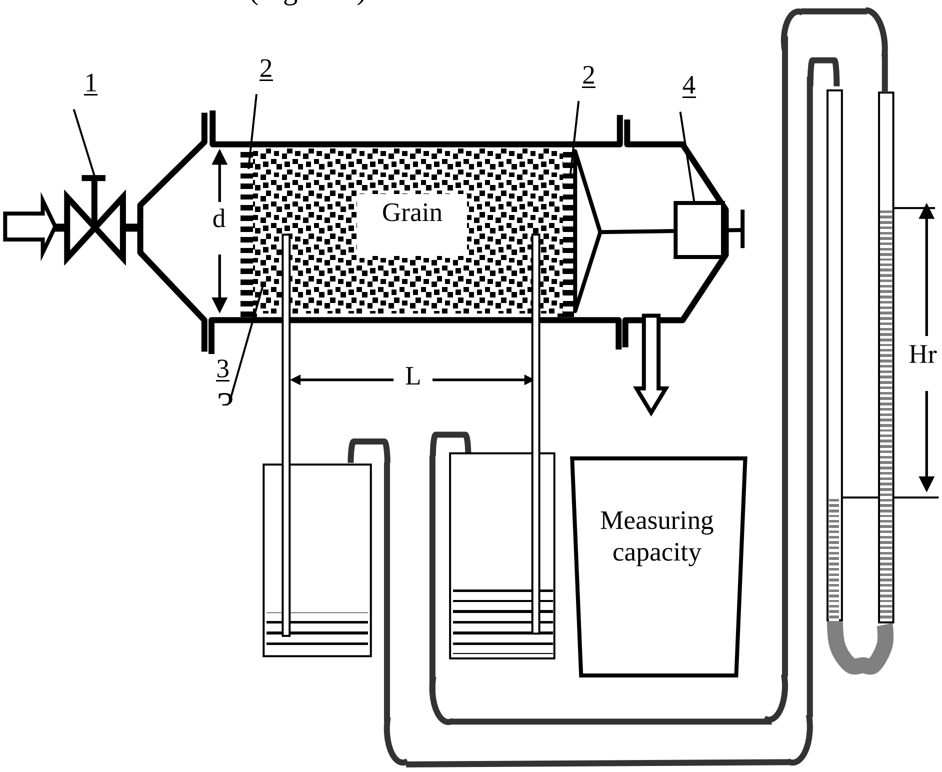

Fig. 6. Scheme of the experimental installation № 2:
1 − Control valve; 2 − Knife grating + grid; 3 − Working cylinder;
4 − The device of compression of grain; 5 − Mercury difmanometer;
6 − Buffer capacity

The results of processing the experimental dependences at installation № 2 allowed obtaining the values a = 1,120E + 06; b = -6,990E + 06; c = 4,250E + 07.

Fig. 7 shows a comparison of the dependences A_w = f (V_w) obtained at different settings.

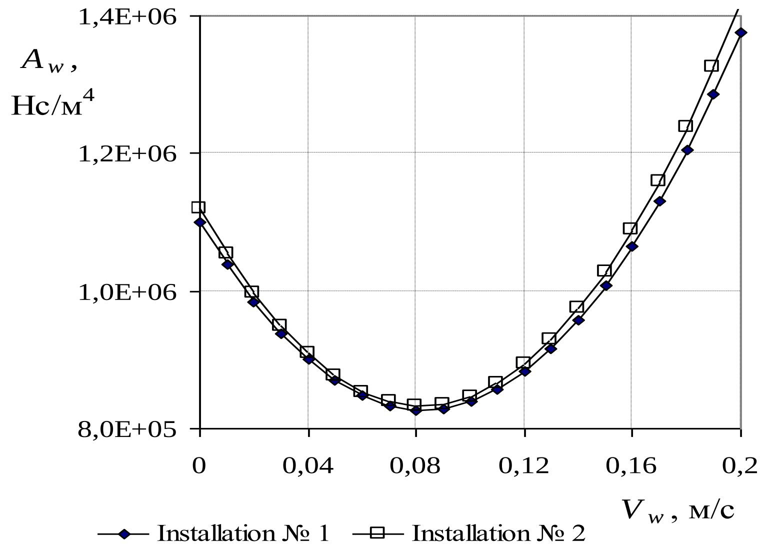

Fig. 7. Comparison of results

For the transition from the dependence A_w (V_w) (for water) to the dependence A_a (V_a) (for air), the similarity theory was used when the Reynolds (21) and Euler (22) numbers were equal.

$$\frac{V_w \cdot L_o}{\nu_w} = \frac{V_a \cdot L_o}{\nu_a}, \tag{21}$$

$$\frac{\Delta P_w}{\rho_w \cdot V_w} = \frac{\Delta P_a}{\rho_a \cdot V_a}, \tag{22}$$

where V − is the fluid velocity related to the free space;
L_0 − is characteristic size;
ΔP − is lowering the pressure of the fluid in the direction of motion;
ρ − is the density of the fluid;
ν − is the kinematic viscosity coefficient.
The subscripts *w* and *a* correspond to water and air.

The characteristic dimensions for the flow of water and air in the grain layer are the same, therefore (23)

$$V_a = V_w \cdot \frac{\nu_a}{\nu_w}, \qquad A_a = A_w \cdot \frac{\rho_a \cdot \nu_a}{\rho_w \cdot \nu_w}. \tag{23}$$

The dependence of the aerodynamic resistance of the grain layer during the blowing is shown in Fig. 8.

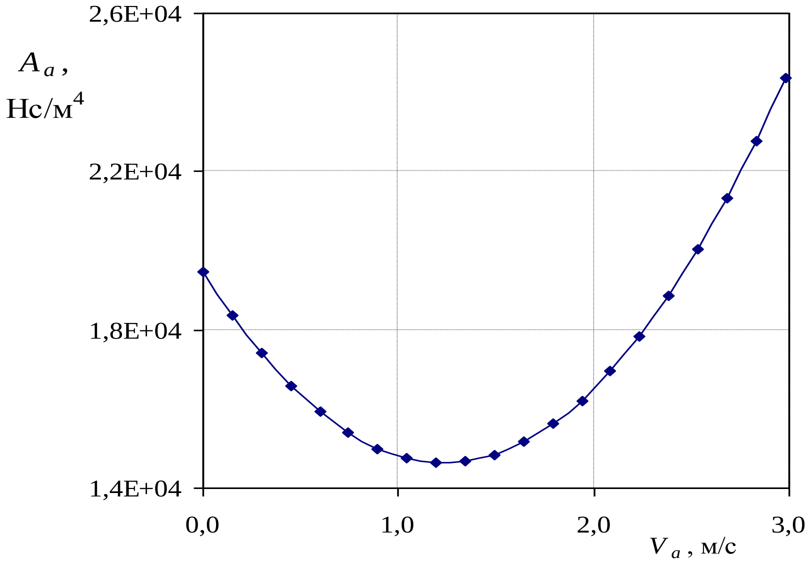

Fig. 8. Aerodynamic resistance of the grain layer

Conclusion. Methods for the identification of flow patterns in a capillary-porous and granular material are proposed. The simplest experimental setups are used. The results of the experiments are processed in an environment of available software. The use of techniques does not require deep knowledge of mathematics and programming.

The described techniques can be successfully used in practical activities, when it is necessary to obtain reliable results at minimal expenses.

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