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*Сендвічеві панелі зі стільниковим заповнювачем на основі полімерного паперу «Nomex» широко використовуються у відповідальних конструкціях різноманітного призначення. В процесі виробництва таких панелей деякі чинники технологічного процесу, такі як нанос зв'язуючого на стільниковий заповнювач, температурні режими сушки і полімеризації нанесеного шару, найбільш істотно впливають на фізико-механічні характеристики готових виробів. Специфічним фактором виробництва стільникового заповнювача з полімерного паперу є його багатостадійне просочення складом апретуючого, а потім зв'язуючого на заключних операціях з наступним сушінням і термообробкою стільникових блоків. В результаті цих операцій має місце нерівномірний тепло- і масоперенос (міграція) зв'язуючого від центральної площини панелі до периферійних торцевих її зон. Досліджено закономірності цього нерівномірного тепло- і масопереносу зв'язуючого уздовж довжини стільникового каналу. Показано, що ці явища обумовлені гідродинамічним рухом зв'язуючого, що викликані градієнтами температури, його густини та коефіцієнта поверхневого натягнення. На основі цього розроблено метод визначення товщини шару зв'язуючого уздовж каналів стільників при відомих (заданих) законах зміни густини та поверхневого натягнення уздовж довжини чарунки стільникового заповнювача. Метод дозволяє технологічними засобами знизити нерівномірність масопереносу, забезпечивши потрібний допуск на фізико-механічні характеристики стільникових заповнювачів з полімерного паперу. Розглянута задача масопереносу дозволила глибше розкрити механізми формування нерівномірного шару просочення на етапах процесу сушіння при виробництві стільникового заповнювача з полімерного паперу. Використовуючи отримані механізми і технологічні можливості регулювання характеристик зв'язуючих, можливо поліпшити рівномірність товщини шару уздовж каналів стільників до значень, які забезпечать потрібний допуск на фізико-механічні характеристики стільникового заповнювача*

*Ключові слова: стільниковий заповнювач, фізико-механічні характеристики, полімерний папір, нерівномірний тепло- і масоперенос, зв'язуюче, гідродинамічний рух, рівномірність просочення*

UDC 629.7.002.3; 678.7-416

DOI: 10.15587/1729-4061.2018.150387

## METHOD FOR DETERMINING THE THICKNESS OF A BINDER LAYER AT ITS NON-UNIFORM MASS TRANSFER INSIDE THE CHANNEL OF A HONEYCOMB FILLER MADE FROM POLYMERIC PAPER

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### 1. Introduction

Extension of the scope of application of sandwich structures with a honeycomb filler in various areas of technology in some cases became possible solely using the honeycombs based on polymer paper “Nomex”. Such structures have several unique features: lightness at a high level of mechanical characteristics, good heat and sound

insulating characteristics, high fatigue resistance and shock suppression [1, 2].

These properties led to their widespread use in important structures for aircraft interiors, for heat and noise insulation of the underbody space of carrier rockets, as well as in building structures [3, 4].

In the process of production of such structures, some factors of the technological process significantly affect phys-

ical-mechanical characteristics of finished products. These factors include application of a binder on the honeycomb filler, temperature modes of drying and polymerization of the applied layer [5].

These technological defects are capable to integrate and transform, leading to variations in the characteristics of sandwich structures and an increase in kinetics of destructivity even in the process of initial load [6].

While the defects of honeycomb fillers from the metal foil have been studied rather deeply and the methods for their reducing have been recently developed, the defects of the honeycomb from polymer paper have not been sufficiently investigated [7, 8].

In this regard, development of the technological methods for enhancing the sustainability of quality parameters and physical and mechanical characteristics of honeycomb fillers based on polymer paper “Nomex” for critical structures is a relevant task.

## 2. Literature review and problem statement

A rather large number of publications, such as [7], deal with the problems of analysis of a high range of dispersion of physical and mechanical characteristics of honeycomb fillers and identification of the causes. In paper [9], the analysis of emergence and interaction of errors that appear during the production of honeycomb filler and a sandwich panel in general was carried out. However, the approach, implemented in [9], is focused not on the technological possibilities of the implementation of the appropriate operations of the process of making honeycomb filler, but rather on ensuring the regulated deviation of bearing capacity of a particular structure – a panel.

Paper [10] deals with the development of scientifically grounded methods for normalization the fields of tolerances for the technological parameters of the basic operations of the process of honeycombs production and defects that arise in this process. However, a number of questions, the solution of which can significantly affect the final results and will require separate examination, were not taken into consideration. Thus, the article only mentions a substantial lagging behind of the temperature in a dense pack of honeycomb units and weakening of heat transfer intensity in it, which will lead to the emergence of defects in the form of incomplete polymerization of the units.

Article [11] presents the results of mathematical modeling of technological ways of correction of physical-mechanical characteristics of honeycomb fillers based on the outcomes of the implementation of the method of imposing the matrices, constructed with regard to restrictions for the geometric parameters of honeycombs. The obtained results eventually make it possible to improve the typical technological processes of honeycomb production. However, these results do not make it possible to establish a definite technological method that ensures realization of the permissible area of the regulated physical and mechanical characteristics of honeycomb filler from polymeric paper.

Most of the results obtained in papers [10, 12–14], were systematized in [7]. The paper contains the results, which include the analysis of the state of the problem of enhancing the quality of honeycombs from polymer paper, the features of production, quality evaluation, which are caused by the technological defects that occur during the execution

of operations. However, in article [7], only the multi-level structural classification of defects of honeycombs from polymer paper was synthesized. This only allows the identification of a causal relations between the nature of the occurrence and types of manifestation in the product, associated with the electrostatic phenomena and non-uniform mass transfer of the binder.

The identity of the process of production of honeycomb filler from foil and polymer paper testifies to the relevance of propagation of the respective approaches, mathematical models and the methods for analysis of technological defects on polymer honeycombs with regard to some specifics. At the same time, at least two factors among all the factors related to the technology of production of polymer honeycombs, are characteristic of only this type of filler and is the source of manifestation of defects, which influence its quality [6, 7].

The first of these factors is the original existence of electrostatic fields in polymer paper in the state of its delivery. The dynamics of the transformation of this factor during the subsequent operations of the technological process and its influence on the defects that arise directly during these operations currently are not studied deeply enough [7, 12].

The other specific factor in the production of honeycomb fillers from polymer paper is its multi-stage impregnation with the dressing composition and then the binder in the final operations with subsequent drying and thermal treatment of honeycomb units. These operations result into occurrence of non-uniform heat and mass transfer (migration) of the binder from the central plane of the panel to its peripheral end areas [13]. The measurement of the thickness of the applied layer of the binder within the honeycomb channels proves non-uniformity of its distribution along the thickness, which is also visually observed on the cut of the honeycomb unit (Fig. 1) [13, 14]. As a rule, the impregnation layer is the largest in the ends of honeycomb and its thickness is reduced inside the honeycomb channel [7].

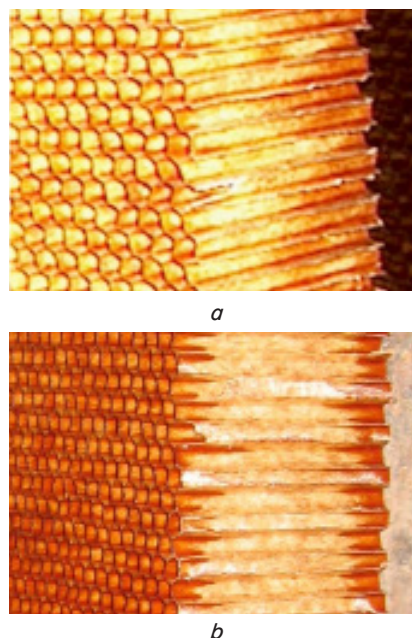


Fig. 1. Photographs of the phenomenon of mass transfer inside honeycomb channels after high-temperature drying: *a* – mass transfer of the binder composition towards the right face with higher temperature; *b* – mass transfer of the binder composition to both ends of honeycombs at symmetric heating

In papers [13, 14], based on the experimental research, it was concluded that the formation of a thinner layer in the middle of the honeycomb channels is associated not with a higher rate of evaporation from inside of honeycombs, but is rather caused by a hydrodynamic flow in the layer of a binder. In articles [13, 14], the assumption is made that the cause of such phenomena is related to the existence of temperature gradient along the length of the honeycomb channel that is formed at high-temperature drying of honeycomb units in a heating stove.

Thus, these features and the associated defects of the production of honeycomb fillers from polymeric paper cause the need for the development of the method for their studying. Practical implementation of this method will ensure the improvement of their quality for the effective application of this type of honeycombs in crucial structures for various purposes.

### 3. The aim and objectives of the study

The aim of this study is to develop a method for determining the thickness of the binder's layer along the honeycomb channel, which would enable a decrease in non-uniformity of mass transfer with the help of technological means, ensuring the required tolerance for physical and mechanical characteristics of honeycomb fillers from polymer paper "Nomex".

To achieve this aim, it is necessary to solve the following problem – to identify the regularities of non-uniform heat and mass transfer of the binder along the length of the honeycomb channel, which are caused by its hydrodynamic motion due to temperature gradients, the density of the binder and its coefficient of surface tension.

### 4. Materials and methods to study the heat and mass transfer process of the binder inside a channel of the honeycomb filler made from polymeric paper

The methods of non-equilibrium thermodynamics – evaporation, condensation, mutual diffusion of the components of the binder, as well as of hydrodynamics in thin layers of a liquid binder were used. To substantiate the use of the calculation models, we used the experimental data that were obtained in the measurements of the thickness of the binder's layer along the honeycomb channel and data on determining the density of the binder.

### 5. Results of research into regularities of non-uniformed heat and mass transfer of the binder along the length of the honeycomb channel

The final high temperature drying of honeycomb units in an aerodynamic heating stove causes the appearance of temperature gradient along the length of the honeycomb channels. Hydrodynamic flow in a thin layer of the binder on the polymer paper surface leads to the formation of coating of irregular thickness. This is due to the non-uniformity of density  $\rho(x)$  and coefficient of surface tension  $\sigma(x)$  of the impregnation composition before its final hardening along the length of the honeycomb channel  $x$ .

It can be assumed that the formation of non-uniformity of impregnation composition  $\rho(x)$  and  $\sigma(x)$  is influenced by

evaporation rate along the length of the honeycomb channels at the stages of preliminary drying. This non-uniformity is especially influenced by high-temperature drying with the subsequent polymerization of the binder.

Non-uniformity of the solvent evaporation from the depth of honeycomb channels leads to the emergence of temperature gradient along the honeycomb channel and, as a consequence, to non-uniformity of density and surface tension along it.

This causes the appearance of the so-called stationary hydrodynamic flow in a thin layer of the impregnation composition [15, 16].

We will consider a thin non-uniformly heated layer of liquid composition of impregnation on a horizontal plane of polymer paper in the gravity field, when the temperature is assigned by function of coordinate  $x$  along the entire length of the impregnation layer. This flow can be described by using the equation of motion of hydrodynamics in the Navier-Stokes equation system

$$\rho \left[ \frac{\partial \bar{V}}{\partial t} + (\bar{V} \Delta) \bar{V} \right] = \bar{R} - \text{grad}(\rho) + \mu \Delta \bar{V} + \left[ \xi + \frac{\mu}{3} \right] \text{grad}(\text{div} \bar{V}), \quad (1)$$

where  $\rho$  is the fluid density;  $\bar{V} = \bar{V}(x, z, t)$  is the fluid velocity vector;  $p = p(x, z, t)$  is the pressure in a liquid layer at level  $z$ ;  $\mu, \xi$  are the first and second viscosity coefficient;  $\bar{R}$  is the vector of stress of bulk gravity force

We will supplement this equation with the continuity equation

$$\frac{\partial \rho}{\partial t} + \text{div}(\rho \bar{V}) = 0. \quad (2)$$

In our case, one-dimensional layered laminar flow along axis  $x$  with the layer height  $z$ , when only one component of velocity  $V_x$  is preserved and the others are equal to zero, and the mass forces act only along axis  $z$ , the Navier-Stokes motion equation for coordinates  $x$  and  $z$  take the following form:

$$\rho \left( \frac{\partial V_x}{\partial t} + V_x \frac{\partial V_x}{\partial x} \right) = - \frac{\partial p}{\partial x} + \mu \frac{\partial^2 V_x}{\partial x^2} + \left( \xi + \frac{\mu}{3} \right) \frac{\partial}{\partial x} \left( \frac{\partial V_x}{\partial x} \right), \quad (3)$$

$$R_z - \frac{\partial p}{\partial z} + \left( \xi + \frac{\mu}{3} \right) \frac{\partial}{\partial x} \left( \frac{\partial V_x}{\partial x} \right) = 0, \quad (4)$$

where  $R_z = -g\rho$  is the component of the bulk force stress, which is determined by gravity field and directed to the opposite side of axis  $z$ .

The equation of continuity (2) for our case will be recorded in the following form:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho V_x)}{\partial x} = 0. \quad (5)$$

When the fluid is non-compressed and the flow is non-stationary ( $\frac{\partial V_x}{\partial t} = 0$  and  $\rho = \text{const}$ ), the constant of velocity in the direction of flow  $\frac{\partial V_x}{\partial x} = 0$  follows from continuity equation (5).

Then we will derive from equation of motion (3)

$$\frac{\partial p}{\partial x} = \mu \frac{\partial^2 V_x}{\partial x^2}, \quad (6)$$

and, respectively, from equation of motion (4), we will derive:

$$\frac{\partial p}{\partial z} = -\rho g. \quad (7)$$

Integrating equation (7) with the boundary condition that at the border of the binder's layer and gas, pressure is equal to  $p_h$ , we will obtain dependence that makes it possible to determine the change in pressure along axis  $z$ , which is caused by the influence of gravity field in the binder layer

$$p = p_0 + \rho g(h - z), \quad (8)$$

where  $p_0$  is the atmospheric pressure on the free surface of the impregnation layer,  $h$  is the maximum height of the impregnation layer in cross-section  $x$ .

Equations (6) and (8) enable description of the flow in a thin layer of liquid binder on the surface of polymer paper without taking into consideration the forces of surface tension of the binder layer. As the separation surface of gas – fluid (the air – the binder) is curved, the pressure from both sides is different near the separation boundary. To determine this pressure difference (surface pressure), we will write down the condition of thermodynamic equilibrium taking into consideration the separation surface, in this one-dimension case in the form of [15]:

$$\left[ p_0 - p_h - \sigma \left( \frac{1}{R} \right) \right] n_z = (-\sigma_{xz}) n_x + \frac{\partial \sigma}{\partial x}, \quad (9)$$

where  $p_0$  is the atmospheric pressure;  $\sigma$  is the coefficient of surface tension gas – fluid;  $\sigma_{xz}$  is the viscous tension at the boundary of the binder layer surface and the air;  $n_z, n_x$  are the orts of the normal along the corresponding axes  $z$  and  $x$ ;  $R$  is the radius of curvature of the binder layer surface.

Viscous tensor of tensions for the given case will be determined from

$$\sigma_{xz} = \mu \frac{\partial V_x}{\partial z}. \quad (10)$$

The radius of curvature of the surface layer of the binder is determined by the approximated formula, provided that the surface slightly deviates from the flat one [15]:

$$\frac{1}{R} = -\frac{d^2 h}{dx^2}. \quad (11)$$

Then the boundary condition (9) considering (10) and (11) will be recorded in the following form:

$$\left[ p_0 - p_h + \sigma \left( \frac{\partial^2 h}{\partial x^2} \right) \right] n_z = -\mu \frac{\partial V_x}{\partial z} n_x + \frac{\partial \sigma}{\partial x}. \quad (12)$$

Given that in this case the left part of the equation (12) depends on variable  $z$ , and the right one depends on variable  $x$ , the equation is satisfied when these parts are equal to zero, each separately:

$$p_h = p_0 + \sigma \left( \frac{d^2 h}{dx^2} \right); \quad (13)$$

$$\mu \frac{\partial V_x}{\partial z} = \frac{d\sigma}{dx}. \quad (14)$$

Substituting the resulting value of  $p_h$  in equation (8), we will obtain the value of pressure  $p$  considering the gravity field and forces of surface tension

$$p = p_0 + \rho g(h - z) + \sigma \left( \frac{d^2 h}{dx^2} \right). \quad (15)$$

The resulting dependence (15), which determines the pressure in the layer of the binder, will be substituted in equation (6):

$$\mu \frac{\partial^2 V_x}{\partial z^2} = \frac{\partial}{\partial x} \left[ p_0 + \rho g(h - z) + \sigma \left( \frac{d^2 h}{dx^2} \right) \right]. \quad (16)$$

The boundary conditions for the integration of this equation will be as follows:

- on the polymeric paper surface, velocity  $V_x|_{z=0} = 0$ ;
- at the boundary the air – the binder ( $z=h$ ), the boundary condition is determined by the resulting equation (14).

It is easy to show that in equation (16), term  $\sigma \left( \frac{d^2 h}{dx^2} \right)$ , is at least by two orders of magnitudes lower than the other, which makes it possible to simplify this equation:

$$\mu \frac{\partial^2 V_x}{\partial z^2} = \frac{\partial}{\partial x} [p_0 + \rho g(h - z)]. \quad (17)$$

Provided that  $\rho = \text{const}$ , we will write down:

$$\mu \frac{\partial^2 V_x}{\partial z^2} = g\rho \frac{dh}{dx}. \quad (18)$$

Integrating equation (18) by  $z$ , we will obtain

$$\mu \frac{\partial V_x}{\partial z} = g\rho z \frac{dh}{dx} + C. \quad (19)$$

We will determine integration constant  $C$  in equation (19) from boundary condition (14):

$$C = \frac{d\sigma}{dx} - g\rho h \frac{dh}{dx}.$$

Substituting the value of  $C$  in (19), we will obtain

$$\mu \frac{\partial V_x}{\partial z} = g\rho \frac{dh}{dx} (z - h) + \frac{d\sigma}{dx}. \quad (20)$$

Integrating again equation (20) in the range from 0 to  $z$ , we will obtain the solution in the form

$$\mu V_x = g\rho \left( \frac{z^2}{2} - hz \right) \frac{dh}{dx} + z \frac{d\sigma}{dx}. \quad (21)$$

From the condition of the flow stationarity, when the layer's boundary has been established,  $\int_0^h V_x dz = 0$ . After integration of (21), we obtain the equation in the form

$$\frac{\rho}{3} \frac{dh^2}{dx} = \frac{1}{g} \frac{d\sigma}{dx}. \quad (22)$$



To determine function  $h(x)$ , we will assign in the first approximation the dependence of the distribution of surface tension coefficient  $\sigma(x)$  along surface  $x$  in the linear form

$$\sigma(x) = \sigma_e - a_\sigma x. \tag{23}$$

Then equation (22) is a non-uniform linear first-order differential equation with constant coefficients relative to the distribution of the square of the impregnation layer thickness of the binder  $h^2$  along the horizontal surface of honeycomb  $x$  [17].

Substituting (23) into equation (22), we obtain:

$$\frac{1}{3}\rho \frac{dh^2}{dx} = -\frac{1}{g} a_\sigma. \tag{24}$$

After integrating this equation, we will obtain the dependence of the square of the impregnation layer thickness  $h^2$  along the length of the honeycomb channel:

$$h^2 = -\frac{3}{g\rho} a_\sigma x + C. \tag{25}$$

Integration constant  $C$  in equation (25) will be determined from the condition that on the end of the honeycomb, that is, at  $x=0$ , the impregnation layer thickness is maximum  $h=h_e$ :

$$C = h_e^2. \tag{26}$$

Substituting the value of constant (26) in (25), we obtain the solution in the form:

$$h^2 = h_e^2 - \frac{3}{g\rho} a_\sigma x. \tag{27}$$

or ultimately

$$h = \sqrt{h_e^2 - \frac{3}{g\rho} a_\sigma x}, \tag{28}$$

where  $h_e$  is the maximum impregnation layer thickness in the honeycomb end;  $\rho$  is the thickness of the binder;  $a_\sigma$  is the coefficient of formula (23), according to the accepted law of distribution.

Calculation of distribution  $h(x)$  from formula (28) can be carried out only on condition that magnitudes  $h_e$ ,  $\rho_e$  and  $a_\sigma$  are taken from the experimental data.

To do this, we will use the experimental data, obtained in the measurements of the binder's layer thickness along the honeycomb channel (Fig. 2) [7, 13] and the data on determining the density of the binder (Table 1) [7, 14].

The obtained experimental data on determining the density of the binder at the stage of high-temperature drying (Table 1) showed that after impregnation and air drying it was  $\rho_{\min}=900 \text{ kg/m}^3$ , and after high-temperature drying  $\rho_{\max}=920 \text{ kg/m}^3$ . Inside the honeycomb channel, polymerization is complicated given the fact that the dimensions of the channel are small compared to its length and, as a consequence, there is a gradient of temperature (Fig. 2) [14]. That is why we believe with a certain assumption that in the depth of the channel, in the place where the thickness of the binder becomes minimal, its density remains equal to the measured minimum density  $\rho_{\min}$ . This is possible because the basic process of flowing occurs at the parameters of a binder that correspond to maximum fluidity of the impregnation composition  $\rho=\rho_{\min}$ . We will do in the similar way when calculating  $h(x)$  and at the stages of intermediate impregnations with technological drying.

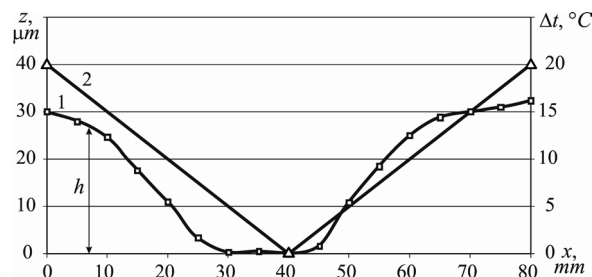


Fig. 2. Distribution of the binder's layer thickness and the temperature along the length of honeycomb channel at symmetric heating of the honeycomb unit: 1 – binder's layer thickness; 2 – temperature

At the known value of  $\rho$ , we will obtain the dependence for determining the dependence coefficient  $a_\sigma$  from equation (27):

$$a_\sigma = \frac{g\rho(h_e^2 - h^2)}{3x}. \tag{29}$$

Table 1

Parameters of the layer of the binder at the stages of impregnation of the honeycomb unit from polymer paper "Nomex" (PSP-1-2.5-4.5, square of honeycomb surface  $S=7.839 \text{ m}^2$ , panel thickness  $H=2 \cdot 10^{-2} \text{ m}$ )

No. of entry	Parameters	Unit weight $m$ , kg	Drying time $t$ , hours	Total weight of layer after operation, kg	Weight of solvent, evaporated from the layer, kg	Density of binder's layer $\rho$ , $\text{kg/m}^3$
1	Before dressing	$m_1=0.2375$	0	0	0	0
2	Shortly after dressing	$m_2=0.280$	0	$m_2-m_1=0.0425$	0	810
3	After dressing and air drying	$m_3=0.243$	$t=24$ at $20 \text{ }^\circ\text{C}$	$m_3-m_1=0.0055$	$m_2-m_3=0.037$	900
4	After the first impregnation by the binder	$m_4=0.384$	0	$m_4-m_3=0.1400$	0	800
5	After the first impregnation and air drying	$m_5=0.319$	$t=24$ at $20 \text{ }^\circ\text{C}$	$m_5-m_3=0.0570$	$m_4-m_5=0.084$	900
6	After the second impregnation by the binder	$m_6=0.4525$	0	$m_6-m_5=0.1230$	0	880
7	After the second impregnation and air drying	$m_7=0.343$	$t=24$ at $20 \text{ }^\circ\text{C}$	$m_7-m_5=0.1055$	$m_6-m_7=0.080$	900
8	After the third impregnation by the binder	$m_8=0.510$	0	$m_8-m_6=0.1670$	0	880
9	After the third impregnation and air drying	$m_9=0.390$	$t=24$ at $20 \text{ }^\circ\text{C}$	$m_9-m_7=0.0470$	$m_8-m_9=0.120$	900
10	After high temperature drying in the oven	$m_{10}=0.350$	$t=7$ at $(20\dots190) \text{ }^\circ\text{C}$	0	$m_{10}-m_9=0.040$	920

Substituting the values of the experimental points ( $h_i, x_i$ ) from the diagram (Fig. 2) to (32), we obtain  $N-1$  of values  $a_{\sigma i}$ :

$$a_{\sigma i} = \frac{g\rho(h_e^2 - h_i^2)}{3x_i} \text{ for } 2 < i < N, \quad (30)$$

where  $N$  is the number of points on the experimental curve  $h(x)$ .

Taking root mean square of these values, we obtain the mean value of the coefficient:

$$\bar{a}_\sigma = \sqrt{\frac{1}{N-2} \sum_{i=2}^N a_{\sigma i}^2}. \quad (31)$$

Substituting the values of  $h_e$  and  $\bar{a}_\sigma$  in equation (28), we obtain the dependence of the layer height  $h$  considering the experimental data:

$$h = \sqrt{h_e^2 - \frac{3}{g\rho} \bar{a}_\sigma x}. \quad (32)$$

Fig. 3 shows the diagrams of the change in the height of the binder's layer along the honeycomb channel, obtained by calculation dependence (32), and the experimental data [7, 14].

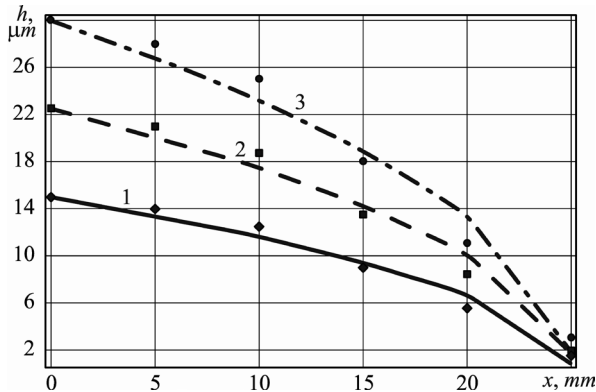


Fig. 3. Comparison of the experimental data of a change in the height of the binder layer along the honeycomb channel with the calculation dependence: ●, ■, ◆ – experimental data; – calculation dependence; 1 – second impregnation; 2 – third impregnation; 3 – high temperature drying

A comparative analysis of the received theoretical and experimental results [7, 14] showed the adequacy of the developed mathematical model and the validity of the theoretical positions that were put forward. The discrepancy between the theoretical and practical results does not exceed 5% (Fig. 3).

## 6. Discussion of results of studying the regularities of non-uniform heat and mass transfer of the binder along the length of the honeycomb channel

The proposed method of solution of the problem of mass transfer of the binder makes it possible to determine the thickness of the layer along the channels  $h(x)$  at the known (assigned) laws of the change of density  $\rho(x)$  and surface tension  $\sigma(x)$  along the length of the cell of the honeycomb

filler. The merit of this study is the possibility of solving the problem of determining the law of change  $\sigma(x)$  by the distribution of the layer's thickness  $h(x)$ , known from the experiment. As it can be seen from the diagrams (Fig. 3), as an increase in the number of impregnations, the thickness of the layer near the boundaries of the honeycombs increases, gradually decreasing into the depth of honeycombs (curves 1, 2). Thus, for the case when the measurements were carried out after the stage of high-temperature drying, the maximum thickness of the binder's layer is observed at the outer edge of the honeycomb and makes  $h_e=30 \mu\text{m}$  at  $x=0$ . A decrease in the thickness of the binder's layer begins to be observed at distancing from the honeycomb edge and its minimum value is  $h_{\text{min}}=3 \mu\text{m}$  at the distance from the honeycomb edge  $x=25 \text{ mm}$ . Similar data on the thickness of the binder's layer were obtained at the stages of the second and the third technological dryings. We will note that an increase in the thickness of the layer also occurs at the last stage of high-temperature drying (curve 3).

Due to the linearization of the law of changes in surface tension coefficient, proposed in the first approximation, quite a satisfactory convergence of the experimental and theoretical results was obtained. Due to coefficient  $\bar{a}_\sigma$ , obtained as a result of calculations, we received the difference between the maximum and current surface tension coefficients  $\sigma_e - \sigma(x)$ .

The obtained results prove the findings that were previously experimentally obtained [7, 13, 14] that the formation of a thinner layer in the middle of the honeycomb channel is associated not with a higher rate of evaporation from the middle of the honeycombs, but are caused by the hydrodynamic flow in the binder's layer.

The reason for these phenomena is also associated with the existence of a temperature gradient along the length of the honeycomb channel that is formed at high temperature drying of the honeycomb unit in a heating stove.

This study is limited to the possibility of solving the problem of mass transfer of the binder only at known (assigned) laws of change of density  $\rho(x)$  and surface tension  $\sigma(x)$  along the length of the cell of honeycomb filler. It is possible to solve the reverse problem of determining the change of density  $\rho(x)$  and surface tension  $\sigma(x)$  in the binder's layer by the distribution of its thickness  $h(x)$  at the selected technological stage of drying, known from the experimental data.

The considered problem of mass transfer made it possible to reveal deeper the mechanisms of the formation of a non-uniform impregnation layer at the stages of the drying process in the production of honeycomb filler from polymeric paper. Using the obtained mechanisms and technological capabilities of the regulation of binder's characteristics, it is possible to improve the uniformity of the layer's thickness along the honeycomb channels to the values that will provide the required tolerance for the physical-mechanical characteristics of the honeycomb filler. However, it is necessary to carry out additional theoretic and experimental studies in order to identify a more complete mechanism of the examined processes and intensities.

## 7. Conclusions

The regularities of non-uniform heat and mass transfer of the binder along the length of the honeycomb channel were identified. It was theoretically shown that the non-uniform

thickness of the binder's layer along the honeycomb channels is caused by its hydrodynamic motion, rather than a higher rate of its evaporation from the middle of the honeycombs. This motion is caused only by temperature gradients, density of the binder and its surface tension coefficient.

We proposed a method for determining the thickness of the layer of the binder along the honeycomb channel that made it possible to reveal the mechanisms of its formation. Thus, for the stage of high-temperature drying, the maximum thickness of the layer of the binder is observed at the outer honeycomb edge and is  $h_e=30\ \mu\text{m}$  at  $x=0$ . A decrease

in the thickness of the binder's layer begins to occur at distancing from the honeycomb edge and its minimum value is  $h_{\min}=3\ \mu\text{m}$  at the distance from the honeycomb edge  $x=25\ \text{mm}$ . Similar data on the thickness of the binder's layer were received at the stages of the second and the third technological drying.

Using this method in conjunction with the technological regulation of the binder's characteristics, it is possible to ensure the required tolerance for the physical-mechanical characteristics of honeycomb filler based on polymer paper "Nomex".

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