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A.Ye. Khussanov<sup>1</sup>, V.M. Atamanyuk<sup>3</sup>, B.M. Kaldybayeva<sup>1</sup>,  
A. Zh. Abilmagzhanov<sup>2</sup>, D.Zh. Janabayev<sup>1</sup>, Z.C. Kobeyeva<sup>1</sup>

<sup>1</sup>M.Auezov South Kazakhstan University, Shymkent, Kazakhstan;<sup>2</sup>D.V.Sokolsky Institute of Fuel, Catalysis and Electrochemistry, Almaty, Kazakhstan;<sup>3</sup>Lviv Polytechnic National University, Lviv, Ukraine.

E-mail: khussanov\_1975@inbox.ru, atamanyuk@ukr.net, kaldybaeva.b@mail.ru,  
arlandez\_81@mail.ru, janabaev19@mail.ru, kobeebazagi82@mail.ru

## MECHANISM OF FILTRATION DRYING OF ORGANIC MATERIALS OF FIBROUS STRUCTURE AND RESULTS OF RESEARCH OF EXTERNAL HEAT EXCHANGE

**Abstract.** One of the high-intensity methods for removing both free and bound moisture is filtration drying. This is due to the fact that during filtration drying, the heat agent is filtered through the porous structure of the wet material, which is placed on the perforated partition in the direction "wet material–perforated partition". The velocity of the heat agent in the pores and channels of a stationary layer of wet material determines the thickness of the boundary layer (hydrodynamic, thermal, and diffusion) and, accordingly, the values of the heat and mass transfer coefficients. In addition, the surface of heat and mass transfer is the total surface of the pores and channels through which the heat agent is filtered. The filtration rate of the heat agent is determined based on technical and economic considerations, given that its increase affects the growth of pressure loss. Moreover, the actual speed of the heat agent relative to the layer elements is much higher than in the case of drying by any other methods (in a fluidized bed, during drying in pneumatic transport dryers, etc.). Large heat and mass transfer surfaces and the speed of the heat agent in the pores and channels of the stationary layer of wet material provide high heat and mass transfer coefficients and, accordingly, the intensity of filtration drying. This article presents the results of the study of external heat exchange between the heat agent and dry particles of organic materials of fibrous structure, in particular raw cotton and its stems, and the mechanism of filtration drying.

**Ключевые слова:** cotton fiber, heat transfer, mass transfer, hydrodynamics, filtration drying, porosity, organic materials of fibrous structure.

**Introduction.** Organic materials of a fibrous structure are characterized by an irregular shape of the fibers, roughness of the external surface, the presence of protrusions, depressions, and a network of pores of different sizes. During processing or other technological processes, moisture gets into the pores of these materials, and also wetting the outer surface [1-2]. As a result, the properties of fibrous materials deteriorate and the layer structure is formed unevenly. The surfaces of some particles can be screened by the surfaces of others, while forming non-flowing or partially flowing zones for the thermal agent, which will certainly affect the kinetics of filtration drying [3-7]. Moisture from non-flowing zones will evaporate only due to molecular diffusion, which will lead to an increase in the total drying time [8]. For the study of filtration drying, organic materials of a fibrous structure were selected: raw cotton and its stems, which differ in shape and internal structure. According to the method given in [8], the influence of the temperature and filtration rate of the heat agent on the kinetics of filtration drying was studied.

The intensity of filtration drying of organic materials of a fibrous structure largely depends on the amount of heat that is transferred from the heat agent to the wet particle and is determined by the filtration rate of the heat agent, the temperature difference between the surface of the solid particle and the heat agent, as well as the surface of the interfacial contact [9,10].

Moisture in organic materials of a fibrous structure is located mainly inside and partially on the surface. During drying, moisture evaporates due to heat input, and the driving force of the process is the temperature difference between the heat agent and the material particles.

Based on the analysis of the kinetic curves of drying of crushed and granular materials, it can be concluded that filtration drying is characterized by three main stages of moisture removal: mechanical displacement, mass transfer at a constant rate of moisture removal, and intra-diffusion moisture removal at a rate that decreases [8-11].

The presence or absence of mechanical displacement is determined by the presence of free moisture, which is contained by the surface tension forces between the particles that form the layer and the processing technology of organic materials of a fibrous structure. The intensity of mechanical displacement is determined by the pressure drop and the amount of free moisture. The greater the pressure drop, the smaller the channels formed by the layer particles, free moisture will be removed. Of course, the maximum amount of moisture that can be removed is determined by the free volume and structural structure of organic materials of a fibrous structure, which determine the amount of moisture that can be contained [8-11].

**Experimental part.** To implement the process of drying raw cotton, as noted in [12,13], the industry uses drum-type dryers and fluidized bed dryers, which are energy-consuming and expensive. Therefore, we were faced with the task of developing a new type of dryer that would reduce the energy costs of the drying process.

Generalization of results of experimental and theoretical research of hydrodynamics and heat and mass transfer during filtration drying of organic materials of a fibrous structure in particular, we explored the drying of seed cotton and stalks, are allowed to offer the design of the dryer, which takes into account the physico-mechanical properties of raw cotton and its stems, to improve the methodology of calculation of the main dimensions of this installation and calculate the optimal process parameters of the heat agent.

We suggest using a schematic diagram of a drum-type filtration drying unit for drying raw cotton, the design of which is described in [14-17].

The essence of filtration drying is to filter the heat agent through the porous structure of the dispersed material in the direction "material layer-perforated partition" due to the pressure drop [9-16].

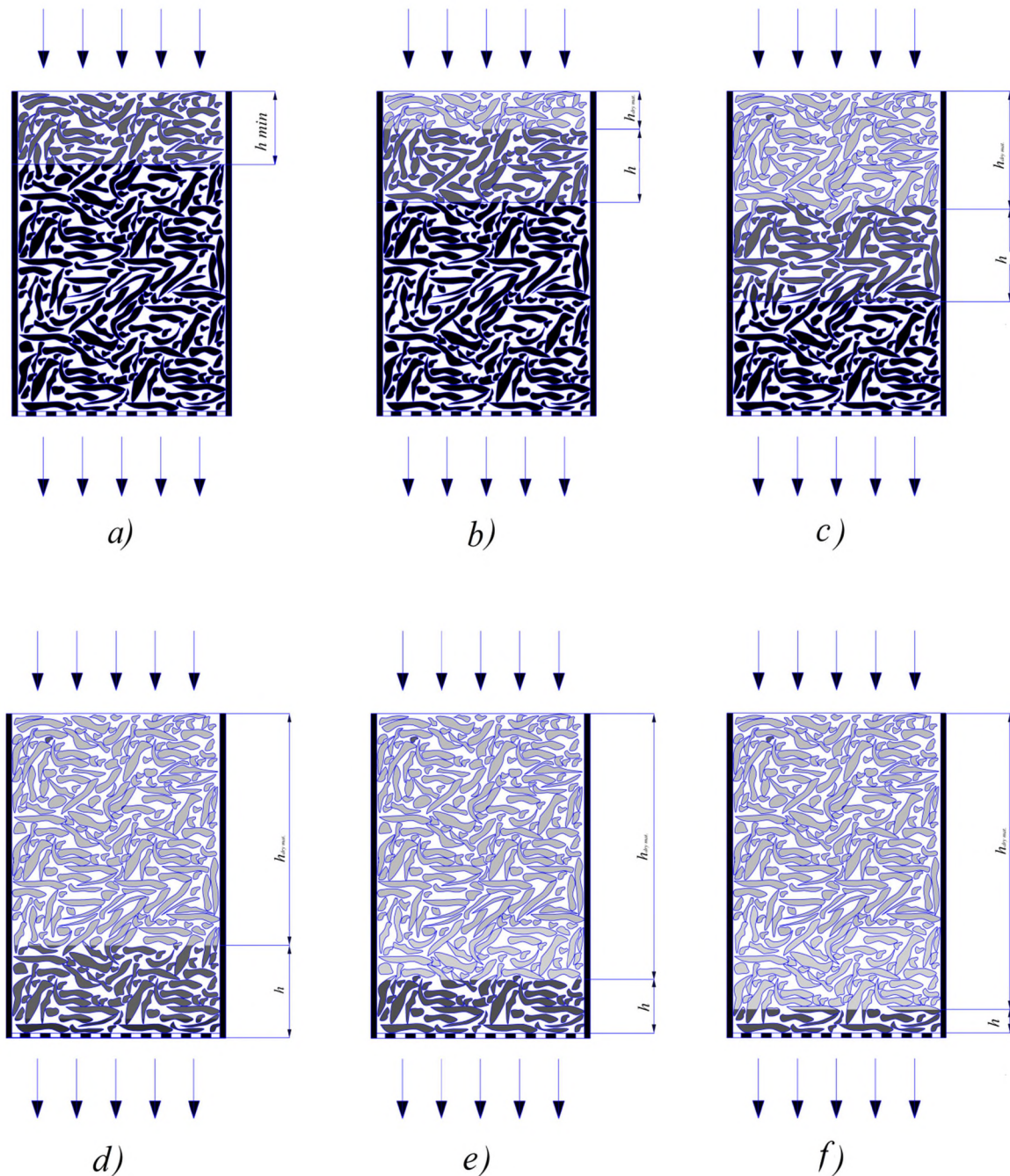
It is known that during filtration drying, in the same way as in the processes of ion exchange, extraction from the solid phase, mass transfer, etc. does not occur over the entire height of the layer [9], but only at a certain height, which is called the mass transfer front. During filtration drying in the beginning is formed by the front height (figure 1 a), at this altitude, thermal agent, filtrating through the porous structure of the wet layer of raw cotton and its stems, gives up its heat to the material and is saturated with moisture, if the layer height is significant, but moisture is sufficient, then after some time the moisture content of the heat agent reaches saturation, as a consequence, its temperature decreases to the temperature of the wet thermometer. In the future, the heat agent under the influence of a pressure drop continues to filter through the porous structure of the layer, but it no longer takes part in mass transfer.

The filtration drying mechanism is schematically shown in figure 1.

After removing external moisture from the upper layers of raw cotton and its stems, the mass transfer front expands in the direction of the heat agent movement. This is because exterior moisture material, which is first in contact with fresh thermal agent is removed faster than the material of the lower layers, where the thermal agent is saturated with moisture and its drying capacity is less, so after some time in the upper layers does not remain external moisture begin to evaporate moisture from the upper layers of the material, while the evaporation rate depends on the coefficient of internal diffusion of moisture from the raw cotton and its stems [18,19]. This causes the formation of a moisture transfer front with height  $h$  (figure 1b). After some time, the evaporation of internal moisture in the upper layers is completed and there is an equilibrium between the dispersed material and the heat agent, a layer of dry material  $h_{dry\ material}$  appears, which does not take part in mass transfer (figure 1 c), and the mass transfer zone moves to the perforated partition. After the frontal part of the mass transfer front reaches the perforated partition (figure 1 d), its height  $h$  begins to decrease, the heat agent is only partially saturated with moisture vapor, and its temperature at the exit from the layer begins to increase (figure 1 e,f).

It is known that in many works devoted to filtration drying [10-12], the concept of drying in the first and second conditional periods was used to describe kinetics by analogy with convective drying.

Analyzing the filtration drying mechanism shown in figure 1, we conclude that the entire process can be divided into the period of full saturation of the heat agent (figure 1 a-d) and the period of partial saturation of the heat agent (figure 1 e,f), which actually corresponds to the physical essence of the process.



a) formation of a mass transfer front with a height of  $h_{min}$ ; b) simultaneous existence of a layer of dry and wet material  $h_{dry\ material}$ ; c) moving the mass transfer zone in the direction of the perforated partition; d) reaching the frontal part of the mass transfer front of the perforated partition; e, f) reducing the mass transfer zone and completing the drying process.

Figure 1 - the Mechanism of the filtration drying of raw cotton and its stems

**Theoretical part and discussion of the results.** Taking into account that during filtration drying, the layer contains both dry and wet materials that take part in heat exchange (the dry material is heated to a temperature close to the temperature of the heat agent), it is necessary to study the process of heat exchange between dry and wet particles of raw cotton and its stems.

Figure 2 – temperature Change of the heat agent at the exit from the layer of dry raw cotton and its stems, at different speeds of the heat agent movement (the height of the material layer is 26 mm)

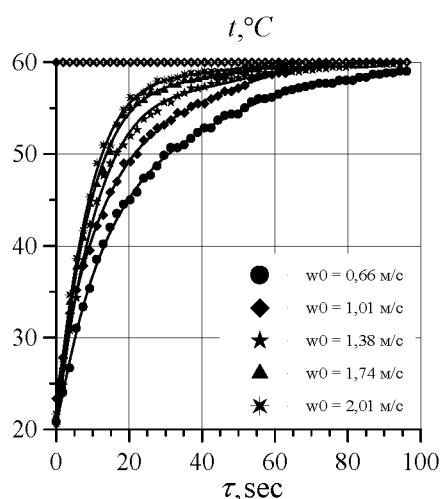


Figure 3 - Change in the temperature of the heat agent at the exit of the layer of dry raw cotton and its stems at different speeds of the heat agent and (the height of the material layer is 26 mm)

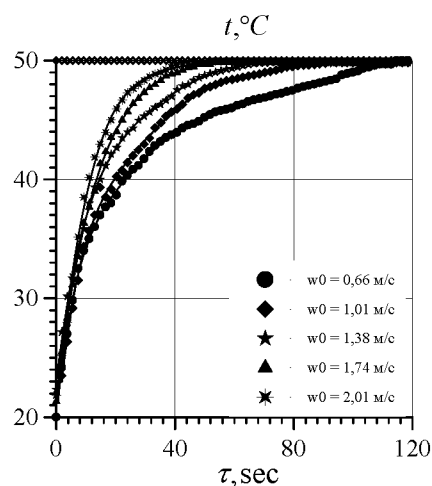
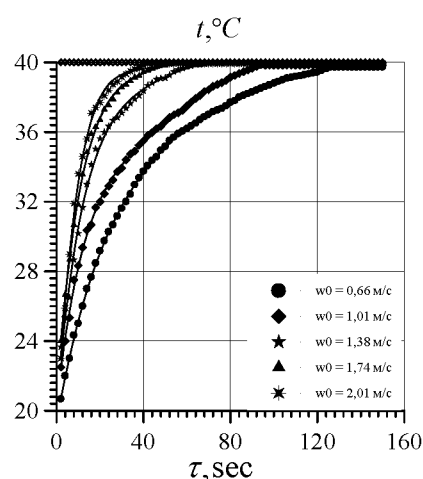


Figure 4 – temperature Change of the heat agent at the exit from the layer of dry raw cotton and its stems at different speeds of the heat agent movement (the height of the material layer is 26 mm)



The average values of the temperature of the heat agent at the exit from the layer of dry raw cotton and its stems are experimentally determined in figures 2-4, at different temperatures of the heat agent, which varied in the range: 40-60 °C, and at different speeds of the heat agent from 0.66 to 2.01 m/s. The temperature value of the heat agent was chosen due to the transience of the heating process of raw cotton particles and their stems, the average size of which does not exceed 2 mm.

The presented graphic dependences of the temperature change of the heat agent at the exit from the material layer allow us to determine the coefficient of heat transfer from the heat agent to dry particles of raw cotton and its stems.

Given that the heat agent is filtered through a layer of dry raw cotton and its stems and the porosity of the layer is high ( $\varepsilon_{\text{layer of material}} = 0.900 \div 0.960 \text{ m}^3/\text{m}^3$ ), it is assumed that the temperature of the heat agent is the same on all sides of the particle. It is impossible to experimentally measure the surface temperature ( $\bar{T}_n$ ) of raw cotton and its stems, so it was estimated based on the analytical dependences for the average layer temperature and the temperature on the surface of a solid particle, given in [8] for cylindrical particles. Due to the fact that the material particles were washed by the heat agent from all sides, it was assumed that the distribution of the temperature field over the particle diameter is parabolic. The average temperature of the surface of solid particles ( $\bar{T}_n$ ) it was determined as follows: the average temperature of the particles ( $\bar{T}$ ) was determined from the heat balance equation:

$$V_c \cdot \rho \cdot c \cdot (t_n - t_n) = \Delta Q = m \cdot c_s \cdot (\bar{T} - T_0), \quad (1)$$

where:  $m$  – weight of raw cotton and its stems, kg;  $c_s$  – heat capacity of raw cotton particles and their stems, kJ/(kg·K);  $\bar{T}$  – the average temperature of the layer, °C;  $T_0$  – the initial temperature of the particle, °C.

$$\bar{T} = \bar{t} - \left( \bar{t} - T_0 \cdot e^{-\mu_n^2 F_0} \right) \cdot \left( 1 - \frac{r}{R} \right) \cdot e^{-\mu_n^2 F_0}, \quad (2)$$

where:  $\bar{t}$  – average temperature of the heat agent, °C;  $R$  и  $r$  – particle radius and current radius, respectively ( $0 < r < R$ ), м;  $\mu_n$  – root of the characteristic equation;  $F_0$  – the criterion Fourier.

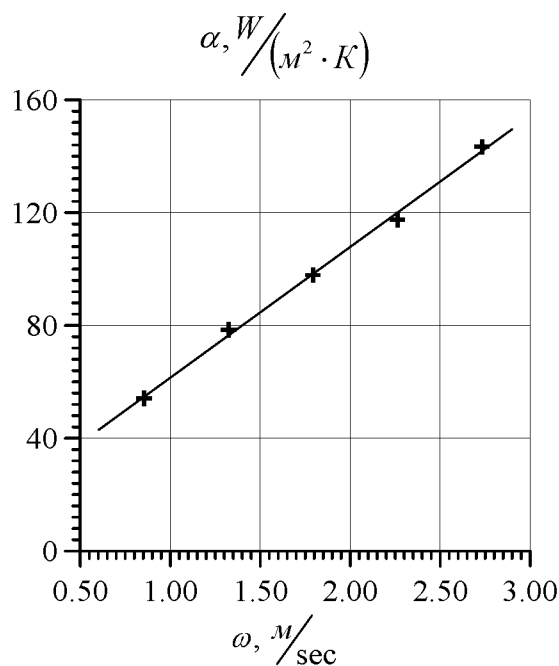


Figure 5-Dependence of the heat transfer coefficient  $\alpha$  on the actual filtration rate  $\omega$  of the heat agent at a temperature of 60 °C

Based on the experimental values shown in figures 2-4, the value of the heat transfer coefficients  $\alpha$  was calculated according to the heat transfer equation [20]:

$$\alpha = \frac{\Delta Q}{F \cdot (\bar{t} - \bar{T}_n) \cdot \Delta \tau}, \quad (3)$$

where:  $\Delta Q$  – calculated according to the heat balance equation for the heat agent, J;  $\bar{t}$  – the average temperature of the heat agent at the exit from the layer according to the experimental data shown in figures 2-5, °C;  $F$  – effective heat and mass transfer surface,  $\text{m}^2$ ;  $\Delta \tau$  – change in the time, in seconds.

The values of the heat transfer coefficient obtained by us are averaged over the layer, due to the fact that the heat agent moves along a complex trajectory of channels between the particles that form the material layer, its speed changes many times with respect to the particle surface, so the local heat transfer coefficient changes. Figure 5 shows the calculated values of the heat transfer coefficient  $\alpha$  from the actual speed of the heat agent.

**Conclusions.** The mechanism of filtration drying of a layer of raw cotton and its stems and the existence of a period of full and partial saturation of the heat agent is revealed. Criteria dependences are proposed for determining the heat transfer coefficients from the heat agent to the layer of dry particles of raw cotton and its stems. As we can see from the obtained graphic dependences, the experimental values of the heat transfer coefficient from the heat agent to dry particles of raw cotton and its stems, depending on the actual filtration rate, are approximated by a straight line. An increase in the speed leads to an intensification of the heat exchange process. This is due to the fact that at a higher filtration rate, a greater amount of heat agent is filtered through the channels between the particles and a greater amount of heat enters the material layer. The error between the theoretically calculated values and the experimental data does not exceed 14.2%, which is quite acceptable for design calculations of new drying equipment.

**А.Е. Хусанов<sup>1</sup>, В.М. Атаманюк<sup>3</sup>, Б.М. Калдыбаева<sup>1</sup>,  
А.З. Абильмагжанов<sup>2</sup>, Д.Ж. Джанабаев<sup>1</sup>, З.С. Кобеева<sup>1</sup>**

<sup>1</sup>М.Өуезов атындағы Оңтүстік Қазақстан университеті, Шымкент, Қазақстан;

<sup>2</sup>Д.Сокольский атындағы «Жанармай, катализ және электрохимия институты» АҚ, Алматы, Қазақстан;

<sup>3</sup>«Львов политехника» ұлттық университеті, Львов, Украина

#### **ҚҰРЫЛЫМЫ ТАЛШЫҚТЫ ОРГАНИКАЛЫҚ МАТЕРИАЛДАРДЫ СҮЗГІЛЕП КЕПТІРУ МЕХАНИЗМІ ЖӘНЕ СЫРТҚЫ ЖЫЛУ АЛМАСУДЫ ЗЕРТТЕУ НӘТИЖЕЛЕРІ**

**Аннотация.** Еркін және байланысты ылғалды жоюдың жоғары қарқынды әдісінің бірі – сүзгілеп кептіру. Сүзгілеп кептіру барысында жылу агенті ылғалды материалдың кеуекті құрылымы арқылы сүзіледі, ол перфорацияланған бөлікке орналастырылған «ылғал материал – перфорацияланған оқшау» бағытында қозғалады. Ылғал материалдың стационарлық қабатының кеуектері мен арналарындағы жылу агентінің қозғалыс жылдамдығы шекара қабатының қалыңдығын (гидродинамикалық, жылу және диффузиялық) және тиісінше жылу және масса беру коэффициенттерінің мәнін анықтайды. Сонымен қатар, жылу және масса алмасу беті жылу агенті сүзілетін кеуек пен арналардың жалпы беті болып саналады. Жылу агентінің сүзу жылдамдығының ұлғаюы қысымның жоғалуына әсер ететіні негізге алынып, техникалық-экономикалық тұрғыдан анықталады. Сонымен қатар, қабат элементтеріне қатысты жылу агентінің нақты жылдамдығы кез-келген басқа әдістермен (қайнаған қабатта, пневматикалық кептіргіште кептіру барысында және т.б.) кептіргенге қарағанда әлдеқайда жоғары. Ылғал материалдың стационарлық қабатының кеуегі мен арналарындағы жылу және масса алмасудың үлкен беті және жылу агентінің жылдамдығы жылу мен массаның жоғары коэффициенттерін және сәйкесінше сүзгілеу кептіру қарқындылығын қамтамасыз етеді. Мақалада жылу агенті мен талшықты құрылымның органикалық материалдарының құрғақ бөлшектері, атап айтқанда, мақта шикізаты мен сабағын сүзгілеп кептіру механизмі арасындағы сыртқы жылу алмасуды зерттеу нәтижелері келтірілген. Зерттеу нәтижелері бойынша шитті мақта қабатын және сабағын сүзгілеп кептіру механизмі және жылу агентінің толық әрі ішінара қанығу кезеңі анықталды. Құрғақ мақта шикізатының қабатынан және оның сабақтарынан шыққан жылу агенті температурасының орташа мәні эксперименталды түрде анықталды, 40 – 60<sup>0</sup>С және жылу агентінің жылдамдығы бойынша 0,66-дан 2,01 м / с дейін түрлі температурада жылу агенті өзгереді. Жылу агентінің температуралық мәні шитті мақта бөлшектері мен сабағын қыздыру үдерісінің жылдамдығына байланысты таңдалады, олардың орташа мөлшері 2 мм аспайды. Ұсынылған материал қабатынан шыққан жылу агентінің температура өзгерісінің графикалық тәуелділігі жылу агентінен шикі мақта мен сабағының құрғақ бөлшегіне жылу беру коэффициентін анықтауға мүмкіндік береді.

Жылу агентінен шитті мақтаның құрғақ бөлшек қабатына және сабағына жылу беру коэффициенттерін анықтау үшін критериалды тәуелділік ұсынылады. Графикалық тәуелділіктен жылу агентінен алынған мақта шикізатының құрғақ бөлшектеріне және сабағына жылу беру коэффициентінің тәжірибелік мәні нақты сүзу жылдамдығына байланысты түзу сызықпен жақындағанын анықтауға болады. Жылу алмасу үдерісінің қарқындылығы жылу агенті жылдамдығының артуына байланысты екендігі анықталды, бұл бөлшектердің арасындағы арналар арқылы сүзу жылдамдығы жоғары болғанда жылу агентінің мөлшері көбірек сүзіліп,



материал қабатына көбірек жылу өтеді. Теориялық есептелген мән мен эксперименттік мәліметтердің арасындағы сәйкессіздік 14,2% аспайды әрі бұл жаңа кептіру жабдықтарының жобалық есебіне өте қолайлы.

**Түйін сөздер:** макта талшығы, жылу алмасу, масса алмасу, гидродинамика, фильтрациялық кептіру, кеуек, талшықты құрылымның органикалық материалдары.

А.Е.Хусанов<sup>1</sup>, В.М. Атаманюк<sup>3</sup>, Б.М. Калдыбаева<sup>1</sup>,  
А.З. Абильмагжанов<sup>2</sup>, Д.Ж. Джанабаев<sup>1</sup>, З.С. Кобеева<sup>1</sup>

<sup>1</sup>Южно-Казахстанский университет им. М.Ауезова, Шымкент, Казахстан;

<sup>2</sup>Институт топлива, катализа и электрохимии им. Д.Сокольского, Алматы, Казахстан;

<sup>3</sup>Национальный университет «Львовская политехника», Львов, Украина

### МЕХАНИЗМ ФИЛЬТРАЦИОННОЙ СУШКИ ОРГАНИЧЕСКИХ МАТЕРИАЛОВ ВОЛОКНИСТОЙ СТРУКТУРЫ И РЕЗУЛЬТАТЫ ИССЛЕДОВАНИЯ ВНЕШНЕГО ТЕПЛООБМЕНА

**Аннотация.** Одним из высокоинтенсивных методов удаления как свободной, так и связанной влаги является фильтрационная сушка. Это обусловлено тем, что во время фильтрационной сушки тепловой агент фильтруется сквозь пористую структуру влажного материала, который размещен на перфорированной перегородке в направлении «влажный материал–перфорированная перегородка». Скорость движения теплового агента в порах и каналах стационарного слоя влажного материала определяет толщину пограничного слоя (гидродинамического, теплового и диффузионного) и соответственно значения коэффициентов тепло- и массоотдачи. Кроме этого поверхностью тепло- и массообмена является суммарная поверхность пор и каналов, сквозь которые фильтруется тепловой агент. Скорость фильтрации теплового агента определяют исходя из технико-экономических соображений, учитывая то, что ее увеличение влияет на рост потери давления. Причем, действительная скорость движения теплового агента относительно элементов слоя значительно выше, чем в случае сушки любыми другими методами (в кипящем слое, во время сушки в пневмотранспортных сушилках и др.). Большие поверхности тепло- и массообмена и скорость теплового агента в порах и каналах стационарного слоя влажного материала обеспечивают высокие коэффициенты тепло- и массоотдачи и соответственно интенсивность фильтрационной сушки. В этой статье приведены результаты исследования внешнего теплообмена между тепловым агентом и сухими частицами органических материалов волокнистой структуры, в частности хлопка сырца и его стеблей и механизм фильтрационной сушки. По результатам исследований установлен механизм фильтрационной сушки слоя хлопка-сырца и его стеблей и существование периода полного и частичного насыщения теплового агента. Экспериментально определены усредненные значения температуры теплового агента на выходе из слоя сухого хлопка-сырца и его стеблей, при разных температурах теплового агента, которая изменялась в пределах: 40 – 60 °С, и при различных скоростях движения теплового агента от 0,66 до 2,01 м/с. Значение температур теплового агента выбрано ввиду быстротечности процесса нагрева частиц хлопка сырца и его стеблей, усредненный размер которых не превышает 2 мм. Представленные графические зависимости изменения температуры теплового агента на выходе из слоя материала позволяют определить коэффициент теплоотдачи от теплового агента в сухие частицы хлопка сырца и его стеблей.

Для определения коэффициентов теплоотдачи от теплового агента к слою сухих частиц хлопка-сырца и его стеблей предложены критериальные зависимости. Из графических зависимостей можно установить, что полученные экспериментальные значения коэффициента теплоотдачи от теплового агента в сухие частицы хлопка-сырца и его стеблей в зависимости от действительной скорости фильтрования аппроксимируются прямой линией. Установлено, что интенсификация процесса теплообмена зависит от роста скорости теплового агента, это объясняется тем, что при большей скорости фильтрования через каналы между частицами профильтровывается большее количество теплового агента и в слой материала поступает большее количество тепла. Расхождение теоретически рассчитанных значений от и экспериментальных данных не превышает 14,2%, что вполне приемлемо для проектных расчетов нового сушильного оборудования.

**Ключевые слова:** волокно хлопка, теплообмен, массообмен, гидродинамика, фильтрационная сушка, пористость, органические материалы волокнистой структуры.

#### Information about the authors

Alisher Ye. Khussanov, Candidate of technical sciences, Associate Professor of M. Auezov South Kazakhstan University, Shymkent, Kazakhstan. khussanov\_1975@inbox.ru, <https://orcid.org/0000-0002-1563-6437>;

Volodimir M. Atamanyuk, Doctor of Technical Sciences, Professor of Lviv Polytechnic National University, Lviv, Ukraine. atamanyuk@ukr.net, <https://orcid.org/0000-0002-8707-2319>;

Botagoz M. Kaldybayeva, PhD, Associate Professor of M. Auezov South Kazakhstan University, Shymkent, Kazakhstan, kaldybaeva.b@mail.ru, <https://orcid.org/0000-0002-1570-2107>;

Arlan Zh. Abilmagzhanov, Candidate of Chemical Sciences, Head of Applied Research laboratory of JSC “D.V. Sokolskiy Institute of Fuel, Catalysis and Electrochemistry”, Almaty, Kazakhstan, arlandez\_81@mail.ru, <https://orcid.org/0000-0001-8355-8031>;

Dauren Zh. Dzhanaabayev, PhD Doctoral Student M. Auezov South Kazakhstan University, Shymkent, Kazakhstan. janabaev19@mail.ru, <https://orcid.org/0000-0001-6522-0536>;

Zagira S. Kobeyeva, PhD Doctoral Student M. Auezov South Kazakhstan University, Shymkent, Kazakhstan. kobeabazagi82@mail.ru, <https://orcid.org/0000-0002-7471-5098>

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