UDC 536.2, 536.7
DOI: 10.15587/1729-4061.2019.156649

REVEALING SPECIAL FEATURES OF HYDRODYNAMICS IN A ROTOR-DISK FILM VAPORIZING PLANT

S. Kostyk
PhD, Senior Lecturer*
E-mail: kostyksergey@ukr.net
V. Shybetskyy
PhD, Associate Professor*
E-mail: v.shybetsky@gmail.com
S. Fesenko
PhD, Assistant*
V. Povodzinskiy
PhD, Associate Professor*
*Department of Biotechnology and Engineering
National Technical University of Ukraine
«Igor Sikorsky Kyiv Polytechnic Institute»
Peremohy ave., 37, Kyiv, Ukraine, 03056

Наведено узагальнення отриманих результатів комп'ютерного моделювання фізичних процесів в роторно-дисковому плівковому випарному апараті. Оптимізація режиму роботи не може бути здійснена без встановлення особливості протікання фізичних процесів. Запропоновано комп'ютерну модель гідродинаміки, з урахуванням всіх конструкційних особливостей, початкових та граничних умов. Результати комп'ютерного моделювання дають можливість адекватно оцінювати ефективність використання роторно-дискового плівкового випарного апарату (РДПВА) для концентрування термолабільних матеріалів. Встановлені особливості протікання фізичних процесів в конструкції РДПВА, за допомогою комп'ютерного моделювання гідродинаміки у середовищі ANSYS використовуючи k-ε модель турбулентності. В результаті моделювання отримано поля швидкостей рідин, що концентрується (w_{max}=0,413 м/с), та газової фази (wmax=8,176 м/с), а також величину значень напружень зсуву τ=0,94·10^{-6} Па. Встановили, що для газового теплоносія характерні високотурбулентні потоки з максимальними значеннями кінетичної енергії TKE_{max}=8,985·10^{-1} м^2/с^2. Достовірність результатів забезпечується коректністю, повнотою та адекватністю фізичних припущень в постановці задачі та на етапі її розв'язку із застосуванням системи автоматизованого проектування ANSYS. Встановлено, що запропонована конструкція є ефективною альтернативою обладнання для концентрування розчинів. Отримані дані можуть бути використані при проектуванні тепломасообмінного обладнання для високоефективного зневоднення термолабільних матеріалів

Ключові слова: роторно-дисковий плівковий випарний апарат, тепловіддача, k-ε модель турбулентності, вимушена конвекція, ANSYS, CFX, напруження зсуву

1. Introduction

Current economic realities prompt manufacturers to reduce costs per unit of output and to improve performance of production lines. That relates to the pharmaceutical industry as well, where there is a large range of products, some types of which are very specific and require special conditions. Specifically, these include probiotic medicinal preparations, vaccines and hormones, which are represented in the form of lyophilizate and are the thermolabile substances. Dehydration of such thermolabile substances necessitates the search for new technologies and requires that those already in use should be improved.

The main techniques that are currently used worldwide for dewatering the materials, which are not resistant to the prolonged action of high temperatures, include: sublimation drying, vacuum drying, spray drying, drying in a bubbling layer, film evaporating plants [1]. All types of plants that implement the proposed processes have a series of negative factors, which lead to the disintegration of acting substances, namely due to a high temperature, a change in aggregate state (freezing during sublimation), as well as due to mechanical damage caused by shear stresses. In each particular case, it is necessary to consider the cumulative effect of all the above negative factors. Plants of the film type represent an interesting alternative because the temperature of dehydration does not exceed the temperature of the wet thermometer; they have a developed specific surface of heat-and-mass exchange; in addition, they have a capability to minimize damage to living cells through shear stresses.

Based on the identified necessity to use this type of plants and given their high effectiveness, we propose a structure of the rotor-disk film vaporizing plant (RDFVP). It is a relevant engineering task to study the features of RDFVP hydrodynamics and to devise a calculation procedure based on mathematical modeling and computer simulation, which would make it possible in the future to industrially implement a given technology.

2. Literature review and problem statement

One implementation of alternative ways for the dehydration of thermolabile substances could be a band dryer that uses a heat pump [2]. The paper considers the principles of mathematical modelling of the drying process and gives a scheme of the installation to perform the process. However, due to the properties of the target product, this type of drying cannot be used in pharmacy and biotechnology. The issue on confirming the adequacy of a mathematical model via computer simulation or a physical experiment remains unresolved.

Technology of vacuum drying makes it possible to obtain lyophilized products but is associated with large amounts of energy. To improve energy efficiency of the process, a scheme was built that includes heat pumps and several drying chambers [3]. A given scheme is based on utilizing wood for energy generation: this circumstance, under conditions for meeting the requirements to proper manufacturing practices by pharmaceutical plants, prevents its industrial application.

Another technique to obtain a finished dosage form, which includes simultaneous drying and forming, is the use of a 3D printer [4]. The reported study confirmed a possibility to use the technology based on a layered surfacing method to obtain personalized medicines and to ensure their stability. The work leaves unresolved the issues on applying the technique for substances that have a lower temperature of degradation, as well as technology efficiency.

To improve the performance of a technological line and to improve the quality of a finished thermolabile product, a combined effect of several factors could be exploited. The implementation of such an interaction is reported in a paper by authors from Brazil: ultrasound and vacuum were applied [5]. The aim of the work was to evaluate the influence of ultrasonic waves and vacuum, combined or not, on the kinetics of drying and the impact of such methods on the product quality. The research results indicate a decrease in the time of drying, as well as improvement in the product characteristics. However, using the method for the cells of microorganisms, which are more sensitive to ultrasound, requires further studying.

Various production sectors employ methods for estimating the efficiency of heat-and-mass exchange and hydrodynamic processes that simultaneously solve optimization tasks thereby constructing new research methods [6].

Effective intensification of heat exchange processes in heat-and-mass exchange equipment is a rather complex and relevant task, which directly depends on the characteristics of hydrodynamics [7]. The cited work considers modeling of different modes of fluid flow in the transition from laminar to turbulent movement. However, the research was conducted for a very narrow range of applied tasks and could be used as a solely methodological basis for other equipment.

When designing and improving heat-and-mass exchange equipment, one should pay attention to the large number of different factors that could affect the overall technical execution and certain structural solutions. The efficiency of dehydration in plants of the film type directly depends on the gradient of concentrations, the gradient of temperature, geometry of the design, velocity of heat-carrier motion, materials that the equipment elements are made of, as well as a heat-and-mass exchange surface area. It should be noted that for case of dehydration of thermolabile materials, especially biotechnological and enzyme preparations, an important factor is the time of contact with a heat-carrier and the shear stresses that occur in a flow of liquid at its concentration [8].

Based on the conducted analysis, the structure of RDFVP was designed, which makes it possible to concentrate the thermolabile solutions at high efficiency [1]. At the built bench, a series of experimental studies were performed, resulting in the acquisition of drying curves and in the derived empirical criterial Nusselt equation, enabling the calculation of parameters for heat dissipation [9]. A mathematical model was proposed for a given structure that accounts for the fluid dynamics behind the growing liquid film at the surface of a disc attachment, which is partially immersed in the liquid and is carried to a contact region with a heat carrier [10].

Mathematical model considering the accepted assumptions:

$$\begin{cases}
\dfrac{\partial W_r}{\partial r}+\dfrac{\partial W_\phi}{\partial \phi}=0;\\
\rho\left(W_r\dfrac{\partial W_r}{\partial r}+\dfrac{W_\phi}{r}\dfrac{\partial W_r}{\partial \phi}-\dfrac{W_\phi^{\,2}}{r}\right)=\\
=\rho g_r+\mu\left(\begin{gathered}\dfrac{\partial^2 W_r}{\partial r^2}+\dfrac{1}{r}\dfrac{\partial W_r}{\partial r}+\dfrac{1}{r^2}\dfrac{\partial^2 W_r}{\partial \phi^2}-\\-\dfrac{W_r}{r^2}-\dfrac{2}{r^2}\dfrac{\partial W_\phi}{\partial \phi}+\dfrac{\partial^2 W_r}{\partial z^2}\end{gathered}\right);\\
\rho\left(W_r\dfrac{\partial W_\phi}{\partial r}+\dfrac{W_\phi}{r}\dfrac{\partial W_\phi}{\partial \phi}+\dfrac{W_r\cdot W_\phi}{r}\right)=\\
=\rho g_\phi+\mu\left(\begin{gathered}\dfrac{\partial^2 W_\phi}{\partial r^2}+\dfrac{1}{r}\dfrac{\partial W_\phi}{\partial r}+\dfrac{1}{r^2}\dfrac{\partial^2 W_\phi}{\partial \phi^2}-\\-\dfrac{W_\phi}{r^2}+\dfrac{2}{r^2}\dfrac{\partial W_r}{\partial \phi}+\dfrac{\partial^2 W_\phi}{\partial z^2}\end{gathered}\right).
\end{cases} \qquad (1)$$

Boundary conditions:

$$z=0;\;\; W_r=0;\;\; W_\phi=\omega\cdot r; \qquad (2)$$

$$z=\delta;\;\; W_r=0;\;\; W_\phi=0. \qquad (3)$$

A given mathematical model was solved in the analytical form; it has made it possible to derive a velocity field and the distribution of a film thickness over the surface of the RDFVP disk attachment (Fig. 1), which ranged from $2.628\cdot10^{-4}$ m to $7.1\cdot10^{-4}$ m [10].

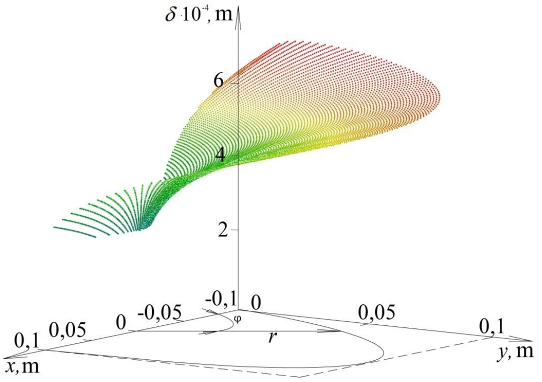

Fig. 1. Diagram of the film surface formed when a disk immerses in liquid

However, the studies conducted earlier do not fully describe the physical processes in RDFVP. The following features remain unexplored: the hydrodynamics of film at the surface of a disk attachment, the distribution of temperature fields, the distribution of velocity fields, of both the concentrated fluid and a gas heat-carrier. Unresolved is the issue on diffusion at film evaporation; the magnitude of shear stresses when the attachment moves in the liquid was not established.

A mathematical notation of the above-mentioned features is a rather complex task that depends on many parameters. Resolving such models typically involves a series of simplifications, which affect the accuracy of results and the validity of models.

When examining a system, while solving non-standard problems, one may need to describe and study additional factors that affect the course of the process. In this case, first, there is a need to employ high-performance computer systems [11]. The ANSYS platform has established itself as a leading software product to solve the tasks related to studying physical processes that occur in heat-and-mass exchange equipment [12]. Description of the processes occurring in liquid systems is based in the ANSYS environment on using the k-ε turbulence model [13]. However, to prove the adequacy of the model, there is in most cases a need to confirm the correctness of decision making via experimental research [14].

Mathematical notation and computer simulation of physical processes that occur in film plants have been lacking, up to now, in open sources, which is why our research deals with the generalization of knowledge obtained when constructing a computer model of fluid dynamics in RDFVP.

3. The aim and objectives of the study

The aim of this study was to establish patterns in the fluid dynamics and the efficiency of heat-and-mass exchange at the surface of a RDFVP disk attachment under conditions of forced convection.

To accomplish the aim, the following tasks have been set:

– to devise a computer model of the RDFVP hydrodynamics that would account for all structural features, and to establish optimal operating parameters;

– to estimate a possibility of using RDFVP to concentrate the thermolabile materials for biotechnological synthesis.

4. Materials and methods to study the hydrodynamics of a rotor-disk film vaporizing plant

4. 1. Procedure of computer simulation

Computer simulation of fluid dynamics and heat-and-mass exchange necessitate constructing a 3D model of the examined object; for the case of RDFVP, it is the geometry of two volumes: a liquid and a gas phase. Applying the method of finite elements, both volumes are split into a set of basic components in the form of a grid, using the built-in module Mesh. For the liquid phase, boundary conditions are assigned as if it were an immobile liquid at the contact surface with the RDFVP walls (designated as “Wall”), the parameters for temperature and gravitational force are also assigned. A gas heat-carrier is assigned as a moving system with physical and dynamic parameters. The interface of interaction between surfaces of the gas and liquid objects in a contact is designated as “General connection”, that is, speed at the surface of one element, at each particular point, is equal, in terms of magnitude and direction, to the speed at the surface of another one. Such implementation is given in [15]. The difference is the absence of rotary motion, which, when a model is simplified, eliminates the need to further configure a given interaction. To reduce the number of iterations, we consider the volume of a single RDFVP disk attachment, in this case, the side surfaces of the cut-out element are assigned at the boundaries as “Symmetry” [16]. Such an approach provides an opportunity to reduce requirements to computational costs, however, it has a series of limitations and can only be used for cases when there are no disturbances in the refused region.

A similar procedure is described in paper [17]; based on the construction of a physical computer model it makes it possible to establish optimal process parameters at the design stage.

4. 2. Geometry of the structure and the operation principle of a rotor-disk film vaporizing plant

RDFVP includes a body with a container for solution 1, heat exchange shirt 2 channel for the movement of a gas heat-carrier 3, a shaft with a series of disk attachments 4 mounted unto it. Disks are partially immersed in the solution to be dehydrated; they are set into rotational motion by drive 5, thereby carrying a film to the region of contact with a gas heat-carrier (Fig. 2) [1].

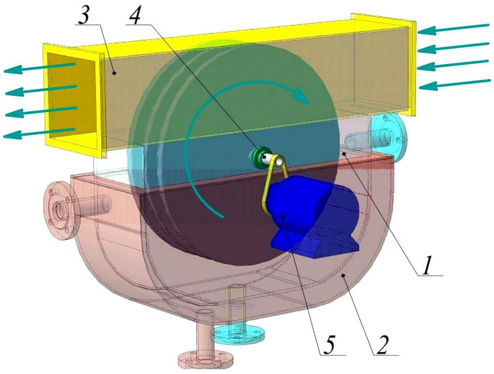

Fig. 2. Schematic of rotor-disk film vaporizing plant: 1 – body; 2 – heat-exchange shirt, 3 – channel for a gas heat-carrier, 4 – shaft with disk attachments, 5 – electric drive

Electric drive 5 in RDFVP makes it possible to change the rotation speed of disk attachments in a range from 0.25 to 5 rev/s [9]. While rotating, the disks carry the liquid at their surface to a contact region with a heat-carrier blown along channel 3 of RDFVP. Part of the moisture evaporates from the surface and, together with the heat-carrier, is discharged from the working area of the plant. Heat-exchange shirt 2 performs the function of thermostating, by supplying a heat-carrier to maintain the optimum temperature of concentration. It should be noted that an important factor during the concentration of thermolabile substances is the rate of dehydration, that is the duration of contact with the heating gas heat-carrier. Due to the rotation of disk attachments, the contact time is reduced to a minimum, while the liquid manages to evaporate from a thin layer of the film and thus there is no damage to the concentrate.

5. Results of computer simulation of the hydrodynamics of a rotor-disk film vaporizing plant

In order to determine the features of the hydrodynamics and effectiveness of the proposed structure in detail, we have derived, by using the platform ANSYS Workbench, a physical pattern of the process that employed the actual geometrical and physical parameters for the experimental installation. The procedure for constructing a computer-based mathematical model implies using the k-ε turbulence model, building geometric arrays that correspond to the volume of working heat-carriers, followed by the formation of a grid by splitting into the finite elements, and setting the parameters at the interface liquid–gas. In a general case, simulation involved the following boundary parameters that were defined as rational in the course of a field research. Motion speed of the gas carrier is 6 m/s, rotation frequency of the disk attachment is 1 rev/s, diameter of the disk attachment is 0.2 m. The thermal-physical properties of a gas heat-carrier were assigned for air at a temperature of 80 °C, the thermal-physical properties of the concentrated liquid were assigned for a 20 % aqueous solution of molasses at a temperature of 40 °C [1, 9, 10].

The resulting hydrodynamics model is in good agreement with a field research at an actual experimental bench, which confirms its adequacy (Fig. 3).

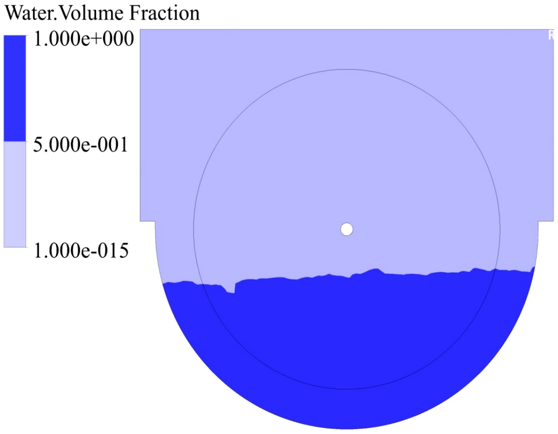

Fig. 3. Result of the physical modeling of hydrodynamics in RDFVP

An analysis of the derived hydrodynamics model allows us to argue on that the intensity of a gas heat-carrier flow directly depends on the geometry of the RDFVP channel. Flow rate significantly increases when the channel is between disc attachments, in this case, its maximum value is $w_{\max}$=8176 m/s (Fig. 4). Increasing the speed leads to the displacement of a gas heat-carrier flow mode towards an increase in the Reynolds number (Re>85,000).

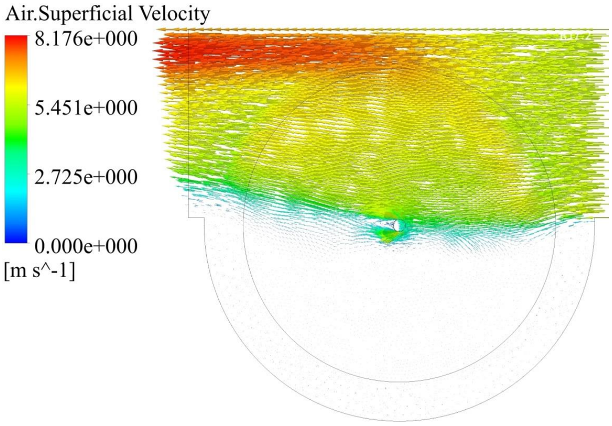

Fig. 4. Gradient of velocity and trajectory of a gas heat-carrier flows in RDFVP

This fact testifies to a significant turbulization of the flow in the region of heat-and-mass exchange elements, which positively affects the value for a coefficient of heat dissipation from the specific heat exchange surface. A maximum value for the kinetic energy of turbulence is $TKE_{\max}=8.985\cdot10^{-1}$ m^2/s^2 (Fig. 5), such an indicator shows the intensive heat-and-mass exchange in the region of contact between the gas phase and the liquid film and accelerates its evaporation.

Not less important is the value for a flow velocity of the liquid phase that is must be concentrated. On the one hand, it is necessary to create conditions for the homogenization of solution when the dewatered liquid film is dissolved in it, on the other hand, it is required to form the flows of liquid with low shear stress values, for the case of concentration of biotechnological materials.

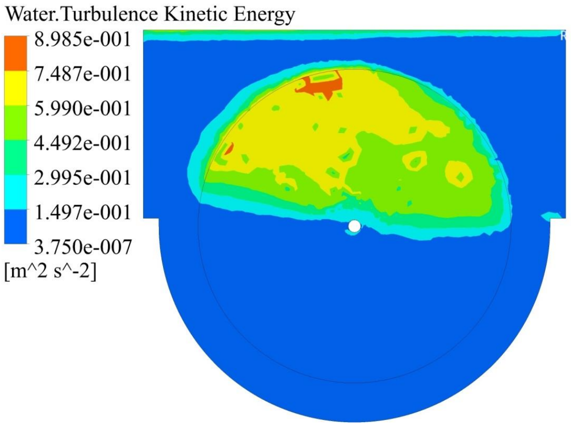

Fig. 5. Turbulization of a gas heat-carrier flow in RDFVP

An analysis of simulation results revealed that the maximum flow rate of a liquid phase is $w_{\max}$=0.413 m/s (Fig. 6). In this case, the trajectory of the flows generated by disk attachments testifies to a significant displacement of volumes of liquid that has a positive effect on diffusion processes. Owing to the hydrodynamics model, we managed to differentiate the flows that helped establish that the volume of liquid is dominated by tangential and radial flows, with the less pronounced axial flows. As is known, the product of the rate of flow displacement by the dynamic viscosity of the fluid is the magnitude of the shear stress. When concentrating biotechnological materials, one should take into consideration the permissible shear stress value according to the classification of the living microorganism. For the case of concentrating the cells of eukaryotes, this indicator is the lowest; based on the scientific literature, it ranges within $\tau=10^1$–10^2 Pa [18].

An analysis of the shear stress distributions near the surfaces of disk attachments (vertical asymptotes) enables us to conclude that at given optimum conditions for conducting the process, the maximum values for shear stresses along the surface of a disk attachment do not excess $\tau=10^{-6}$ Pa (Fig. 7), therefore the use of RDFVP is rational at dehydration of cell cultures.

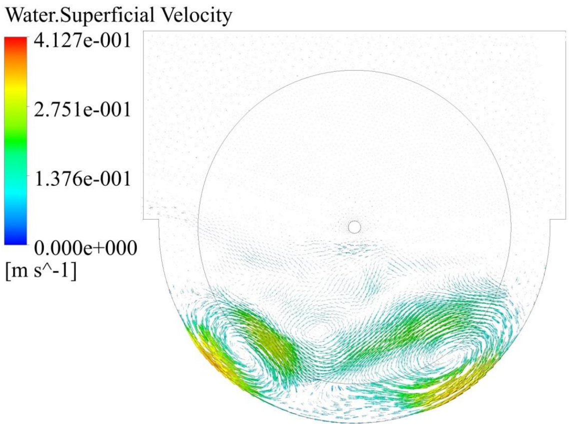

Fig. 6. Gradient of velocity and trajectory of the flows of liquid concentrated in RDFVP

The results obtained make it possible to assert that the proposed structure enables the concentration under labile conditions, taking into consideration the shear stresses and temperature parameters.

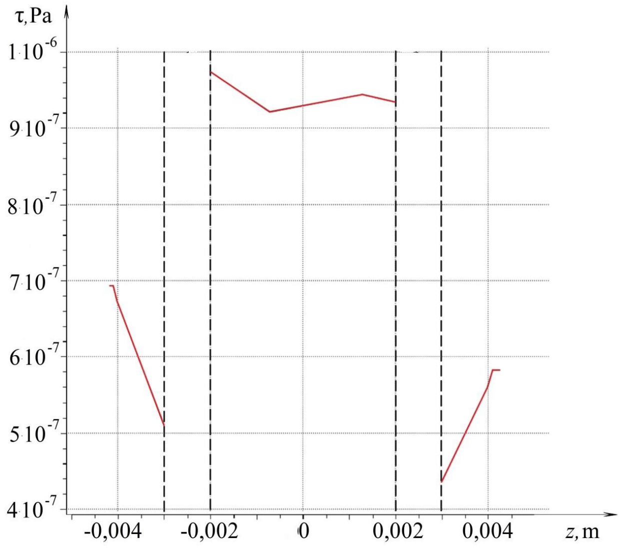

Fig. 7. Distribution of shear stress magnitude τ along the *z* coordinate

6. Discussion of results of studying a heat exchange element

In determining the effectiveness of a given scheme of air feed for the concentration of thermolabile substances in RDFVP, it is advisable to apply the distribution diagram of air velocities (Fig. 1). There is a uniform front of the motion of a gas heat-carrier, without clearly expressed zones of stagnation and local maxima. A given diagram makes it possible to establish rational parameters for a gas phase flow velocity at which the most intense evaporation would occur, on the one hand, and there would not be detachment of a film of fluid into a gas heat-carrier (loss of product) from the surface of a disk attachment, on the other hand. The average speed between the attachments is W_{av}=6.814 m/s. Establishing the adequacy of the built computer model implied comparison of results for the magnitude of a gas phase velocity at the inlet and outlet from the plant, which we managed to measure in the course of experiment [9]. Thus, the magnitude of velocity at the inlet to the plant during an experimental study is $w_{\max}$=6 m/s, and in the working zone beyond the disk attachments is $w_{\max}$=7.3 m/s; in turn, the model in this region shows the following result: at the inlet to the plant is $w_{\max}$=6 m/s, the working region beyond disk attachments is $w_{\max}$=7.42 m/s.

When analyzing a fluid flow at the surface of a disk attachment, one should take into consideration the following factors: the forces of inertia that arise as a result of the rotation of the disk, gravitational force, and the force of friction that occurs at the interface separating the phases gas–liquid. Due to the low speed of rotation of the disk, the inertial component of forces is much smaller than the two other components, so it may be disregarded in the analysis of film detachment from the surface of the disk. At the same time, under the influence of gravitational force, the thin layer of the fluid film moves in a laminar mode while disturbances to its motion regime can be introduced only by the incident flow of a gas heat-carrier. A factor for evaluating the gas heat-carrier flow turbulization is the kinetic energy of turbulence.

In a bench experiment, it was found visually that at a speed of 12 m/s the film is almost completely detached from the surface of the disk. Simulation for a speed of 12 m/s has made it possible to establish maximum values for $TKE_{\max}$=3.094 m^2/s^2, which can be used for establishing the rational speed parameters at which there are no local detachments of the flow. For the case of air speed of 6 m/s, a maximum value is reduced to $TKE_{\max}$=8.985·10^{-1} m^2/s^2 (Fig. 5).

When concentrating the products of biotechnological synthesis, it is necessary to prevent sedimentation of cells at the surfaces of equipment, to ensure the uniformity of the process and to reduce loss of the product. In RDFVP, such a "bottleneck" could be the lower part of the body, which contains the fluid that is sent to the concentration. It is incredibly difficult to experientially obtain data on the movement of fluid between the disks at the bottom, because of costly equipment for measuring parameters and the complexity of its installation within the limited space between disks. On the other hand, such a task can be solved by using computer simulation or mathematical modeling. Fig. 6 shows that during rotation of discs two circulation profiles form in a liquid, to the right and left from the plant's transverse axis. The direction of liquid motion in a bottom part is from the center, where the flow rate is barely greater than 0.05 m/s, accelerating to a speed of 0.39 m/s in both directions, and, approaching the free surface, it swirls, thereby changing the direction to opposite, and returns the liquid to the center again. At such a motion the likelihood of stagnant zones near the bottom decreases. This ensures the uniformity of displacing the layers of fluid and makes it difficult for cells to settle on the plant's walls, at concentration of the cultured liquid.

Another factor that affects quality of the finished product is damage to the living cells due to shear stresses, which arise as a result of different speeds of the environment at different sides of the cell wall. Data from literature indicate that for the cells of eukaryotes the magnitude of these stresses must not exceed 10^2 Pa [18]. In the course of our research, it was found that the greatest values for a shear stress are reached between the disks (Fig. 7). The average value in this region is 0.94·10^{-6} Pa and the maximum is 0.98·10^{-6} Pa. At the outer sides of extreme disks, the magnitude of shear stresses is reduced on average by 30 %, and ranges from 0.44·10^{-6} to 0.7·10^{-6} Pa. The most dangerous areas, in terms of damage to cells, are a transition from the fluid that sticks to the surface of the disc to the fluid in the free volume. Comparison of shear stresses arising in RDFVP to maximally permissible ones points to the possibility of applying this type of plant in order to concentrate products of biotechnological origin.

General analysis of results allows us to argue that the computer model adequately describes the RDFVP hydrodynamics. We performed comparison for the thickness of the film of the liquid obtained from mathematical modeling simulating in the environment ANSYS (difference between the results does not exceed 5 %).

As regards the design of RDFVP, the issue that is left unresolved relates to modeling a mass exchange in the system gas–liquid (evaporation from film), which could be addressed in the further research.

7. Conclusions

1. We have built a computer model of hydrodynamics, taking into consideration all structural features, which

makes it possible to adequately evaluate the efficiency of using a rotor-disk film vaporizing plant for the concentration of thermolabile materials. We have established optimal parameters for a gas phase velocity ($w_{\max}$=8.176 m/s), at which there is no detachment and transportation of the film of liquid from the surface of the disk, while maintaining maximum speed for the renewal of parameters for a gas phase at the mass exchange surface. It was determined that at disk rotation speed 1 s^{-1} two circulation profiles form in the liquid that reduce the possibility for particles to settling on the walls of the plant, at a maximum value for the fluid flow rate $w_{\max}$=0.413 m/s. We were able to differentiate the flows in a liquid into radial and tangential, with a slight axial component.

2. It was established that when disks are displaced there are shear stresses in the liquid phase with a maximum value of $0.98\cdot10^{-6}$ Pa. A comparison of the acquired data to those maximally permissible, 10^2 Pa, at which cellular structures are not destroyed, proves the possibility of using RDFVP in order to concentrate the thermolabile materials of biotechnological synthesis. A possibility to derive optimal parameters for the course of the process by using computer simulation ensures the introduction of RDFVP to an actual production line at minimal cost.

References

1. Kostik S., Obodovich A. N. Issledovanie tekhnicheskih i teplofizicheskih harakteristik universal'nogo sushil'nogo stenda po obezvozhivaniyu termolabil'nyh materialov // Molodoy ucheniy. 2014. Issue 4. P. 195–198.
2. Sposob sushki termolabil'nyh materialov v lentochnoy sushil'noy ustanovke s primeneniem teplovogo nasosa / Sorokovaya N. N., Snezhkin Yu. F., Shapar' R. A., Sorokovoy R. Ya. // Naukovi pratsi ONAKhT. 2015. Vol. 2, Issue 47. P. 91–97.
3. Safin R. R., Khakimzyanov I. F., Mukhametzyanov S. R. Non-volatile Facility for Vacuum Drying of Thermolabile Materials // Procedia Engineering. 2017. Vol. 206. P. 1063–1068. doi: https://doi.org/10.1016/j.proeng.2017.10.595
4. Low temperature fused deposition modeling (FDM) 3D printing of thermolabile drugs / Kollamaram G., Croker D. M., Walker G. M., Goyanes A., Basit A. W., Gaisford S. // International Journal of Pharmaceutics. 2018. Vol. 545, Issue 1-2. P. 144–152. doi: https://doi.org/10.1016/j.ijpharm.2018.04.055
5. Ultrasound-assisted vacuum drying of nectarine / Souza da Silva E., Rupert Brandão S. C., Lopes da Silva A., Fernandes da Silva J. H., Duarte Coêlho A. C., Azoubel P. M. // Journal of Food Engineering. 2019. Vol. 246. P. 119–124. doi: https://doi.org/10.1016/j.jfoodeng.2018.11.013
6. Luo X., Yang Z. A new approach for estimation of total heat exchange factor in reheating furnace by solving an inverse heat conduction problem // International Journal of Heat and Mass Transfer. 2017. Vol. 112. P. 1062–1071. doi: https://doi.org/10.1016/j.ijheatmasstransfer.2017.05.009
7. Assessment of RANS turbulence models for numerical study of laminar-turbulent transition in convection heat transfer / Abdollahzadeh M., Esmaeilpour M., Vizinho R., Younesi A., Pàscoa J. C. // International Journal of Heat and Mass Transfer. 2017. Vol. 115. P. 1288–1308. doi: https://doi.org/10.1016/j.ijheatmasstransfer.2017.08.114
8. Zhang C., Li Y. Thermodynamic analysis on theoretical models of cycle combined heat exchange process: The reversible heat exchange process // Energy. 2017. Vol. 124. P. 565–578. doi: https://doi.org/10.1016/j.energy.2017.02.103
9. Features of heat forced convection in a rotor-disc film evaporator / Obodovich A. N., Ruzhinskaya L. I., Kostyk S. I., Bulakh N. M. // Promyshlennaya teplotekhnika. 2016. Vol. 37, Issue 6. P. 22–28.
10. Obodovich A. N., Ruzhinskaya L. I., Kostik S. I. Matematicheskoe modelirovanie processa obrazovaniya pogranichnogo sloya na poverhnosti vrashchayushchegosya diska, chastichno pogruzhennogo v kul'tural'nuyu zhidkost' i obduvaemogo gazovym teplonositelem // Promyshlennaya teplotekhnika. 2014. Vol. 36, Issue 2. P. 86–92.
11. Experimental investigation of convective heat transfer from sewage in heat exchange pipes and the construction of a fouling resistance-based mathematical model / Song J., Liu Z., Ma Z., Zhang J. // Energy and Buildings. 2017. Vol. 150. P. 412–420. doi: https://doi.org/10.1016/j.enbuild.2017.06.025
12. Heat Exchange Numerical Modeling of a Submarine Pipeline for Crude Oil Transport / Lanzafame R., Mauro S., Messina M., Brusca S. // Energy Procedia. 2017. Vol. 126. P. 18–25. doi: https://doi.org/10.1016/j.egypro.2017.08.048
13. Influence of various aspects of low Reynolds number k-ε turbulence models on predicting in-tube buoyancy affected heat transfer to supercritical pressure fluids / Zhao C.-R., Zhang Z., Jiang P.-X., Bo H.-L. // Nuclear Engineering and Design. 2017. Vol. 313. P. 401–413. doi: https://doi.org/10.1016/j.nucengdes.2016.12.033
14. Jafari M., Farhadi M., Sedighi K. Thermal performance enhancement in a heat exchanging tube via a four-lobe swirl generator: An experimental and numerical approach // Applied Thermal Engineering. 2017. Vol. 124. P. 883–896. doi: https://doi.org/10.1016/j.applthermaleng.2017.06.095
15. Shybetskiy V., Semeniuk S., Kostyk S. Design of consrtuction and hydrodynamic modeling in a roller bioreactor with surface cultivation of cell cultures // ScienceRise. 2017. Issue 7 (36). P. 53–59. doi: https://doi.org/10.15587/2313-8416.2017.107176
16. Hydrodynamics of fermenter with multi-shaft stirrer / Zakomornyi D. M., Kutovyi M. H., Kostyk S. I., Povodzynskyi V. M., Shybetskyi V. Yu. // ScienceRise. 2016. Vol. 5, Issue 2 (22). P. 65–70. doi: https://doi.org/10.15587/2313-8416.2016.69451
17. Mathematical simulation of hydrodynamics of the mixing device with magnetic drive / Kostyk S. I., Ruzhynska L. I., Shybetskyi V. Yu., Revtov O. O. // ScienceRise. 2016. Vol. 4, Issue 2 (21). P. 27–31. doi: https://doi.org/10.15587/2313-8416.2016.67275
18. Cell Membranes Resist Flow / Shi Z., Graber Z. T., Baumgart T., Stone H. A., Cohen A. E. // Cell. 2018. Vol. 175, Issue 7. P. 1769–1779.e13. doi: https://doi.org/10.1016/j.cell.2018.09.054