Bulgarian Chemical Communications, Volume 50, Special Issue K (pp. 49 – 57) 2018

Hydrodynamics and heat transfer in a centrifugal film evaporator

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Received March 20, 2018, Accepted July 24, 2018

Evaporators with a rotating surface (a disk or a cone) are used for the concentration of liquids in the food, pharmaceutical industries and bioindustry. They are also relevant for water recovering from liquid waste in life support systems for spacecraft and space stations. The paper reviews the works on the study of characteristics of a liquid film (thickness, wave parameters) flowing under the action of a centrifugal force and heat transfer during film condensation and film evaporation. In most theoretical and experimental studies, the flow of a film on a rotating surface was investigated when R/R_i (the ratio of the radius of the entire surface to the radius of the jet irrigation) is less than 5, which is typical for installations with a small radius of the rotating surface. The authors of the paper give new data on the film characteristics at $R/R_i > 5$, which is relevant for the food and pharmaceutical industries.

Keywords: Centrifugal, Film, Condensation, Evaporation

INTRODUCTION

Most multicomponent liquids, sea water, juices, etc. contain heat-sensitive substances that can lead to deterioration of the quality of the useful product during evaporation. These processes are intensified with the temperature increase. Conducting the process of concentration in a solution film significantly improves the situation. In film devices, high speeds of a thin layer of liquid processed product are achieved, which drastically shortens the time of its contact with the heat exchange surface. The most effective method for concentrating heat-sensitive liquids is evaporation in a film on a rotating surface. Thus, in comparison with other evaporators, centrifugal ones allow the process to be realized with a minimum thermal load in the shortest possible time (see Fig.1).

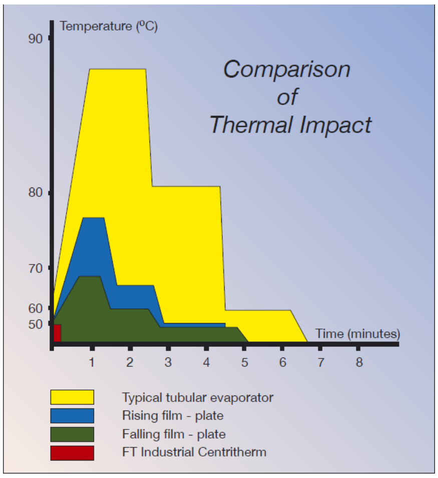

Fig. 1. Comparison of thermal impact for different types of evaporators [1]

In this paper we analyze the existing studies on the hydrodynamics of a film, the condensation of vapor, and the evaporation of a liquid in a film flowing on a rotating surface, including the data published by the authors.

Types of centrifugal evaporators and their applications

One of the first to describe and study the characteristics of a centrifugal evaporator for desalination of sea water was Hickman [2]. The rotating surface was in the form of a disk with a diameter of 1.27 and 2.8 m.

Bromley and co-workers [3, 4] describe and study a multistage evaporator for sea water with a rotating surface in the form of disks. The evaporator consists of a number of evaporator plates, up to 30, located directly above one another. When sea water was desalinated, the productivity of the 29-stage device was G_d = 1440 kg/h, the heat transfer coefficient was about h = 8500 W/m^{2}K.

Despite the very high heat transfer coefficients in centrifugal evaporators, they have not found wide application in the processes of sea water desalination. This is due to the fact that in the 1970-1980 the reverse osmosis method was used for desalination of sea water. In such desalination plants with relatively small dimensions, the energy consumption was 5-10 kWh/m^3, which was much more effective.

In 1962, a vacuum centrifugal steam compressor distiller was developed in the USA with a rotating surface of practically cylindrical shape, called VCD to be used in life support systems for space objects. Its characteristics are: G = 1.3...1.6 l/h, n = 150…250 rpm. From 1962 to 2008, about 10 prototypes were developed and tested. The last

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VCD flight model was installed on the ISS in 2008 and is still operational [5].

In 1976-1990, multi-stage centrifugal distillers (CD) for water recovery systems for space missions were developed in the Kyiv Polytechnic Institute (Ukraine) [6-13]. The CD employs a variation of the thin-film vacuum rotary distillation concept. The system uses a multistage rotating distiller (n = 600 ... 1200 rpm) coupled with a thermoelectric heat pump (THP).

To concentrate various heat-sensitive liquids, Alfa Laval (Sweden) and Centrotherm (Australia) produce a centrifugal evaporator with a conical surface [14].

Characteristics of a liquid film on a rotating surface

To design and operate a centrifugal film evaporator, first of all, knowledge of the thickness of the film is required to calculate the heat transfer coefficient.

The motion of a fluid film on a rotating surface is described by the Navier-Stokes equation and the continuity equation [15]. For the case of laminar steady flow and assuming that the angular velocity of the fluid is equal to the speed of rotation of the disk, these equations are reduced to a simple balance of forces in the direction R:

$$-\omega^2 R = \frac{1}{\rho}\frac{d\tau_r}{dz} \qquad (1)$$

Integration of (1) gives the distribution of radial shear direction:

$$\tau_r = \rho R\omega^2\left(\delta - z\right) \qquad (2)$$

Re-integration gives a velocity profile:

$$u = \frac{R\omega^2\delta^2}{\nu}\left(\frac{z}{\delta} - \frac{1}{2}\frac{z^2}{\delta^2}\right) \qquad (3)$$

which is parabolic for a laminar flow.

The thickness of the film on the rotating disk can be obtained after calculating the volume flow.

$$Q = \int_0^{\delta} 2\pi Rudz = \frac{2\pi}{3}\frac{R^2\omega^2\delta^3}{\nu} \qquad (4)$$

From equation (4), the average thickness of the liquid film for the case of laminar flow was first obtained by Hinze and Milborn [16]:

$$\delta = \left(\frac{3}{2\pi}\frac{Q\nu}{R^2\omega^2}\right)^{1/3}. \qquad (5)$$

A similar solution was obtained in the study [17], taking into account the tangential component of the relative velocity of motion:

$$\delta^+ = \left(\frac{3}{2\pi}\frac{Q}{R\nu}\right)^{1/3}\left(\frac{\omega R^2}{\nu}\right)^{-1/6} \qquad (6)$$

where $\delta^+ = \delta\left(\omega/\nu\right)^{1/2}$ – the dimensionless thickness of the liquid film. In addition, it is indicated in [18] that the angular velocity of rotation of the liquid film is equal to the rotation speed of the disk, provided that $\delta^+ \le 0,5$. A similar result was also obtained in the study [19] when solving problems on the condensation of vapor on a rotating disk. The study [19] shows an insignificant effect of the surface tension on the film thickness and the shape of the free surface, which are mainly determined by the strength of the centrifugal forces. For calculations of the average thickness, equation (5) is recommended.

Aroesty *et al.* [20] obtained an approximate analytical solution, which extends to much larger radial distances. The final expression for the average film thickness according to [20] is similar to formula (5).

In the studies of Gasley and Charvat [21], the approximate solution by [20] was basically repeated and additional expression was obtained that allows one to determine the deviation of the circumferential velocity on the surface of the film u_c from the local velocity of the disk ωR:

$$\frac{\omega R - u_c}{\omega R} = 1,8\left(\frac{R}{L}\right)^{-8/3} \qquad (7)$$

Dependence (7) is more rigorous than that in study [20], which determines the length of the input section R_{in}, at which the circumferential velocity lags behind the surface of the film u_c from the local velocity of the disk ωR.

In the study [22], the dependence for δ was obtained by applying the Karman method for the solution of the Navier-Stokes equation for the axisymmetric flow of a laminar film over the surface of a rotating disc, and applying the assumptions similar to the ones used in the study [17]. Approximating the distribution of radial and circumferential velocities by a polynomial of the second degree, the authors in [22] obtained the equation:

$$Q^+ = \frac{1}{3}\left(\delta^+\right)^3 \qquad (8)$$

where Q^+ is the dimensionless flow, $Q^+ = Q/2\pi R^2\sqrt{\nu\omega}$. The transformation of the obtained dimensionless parameters gives the well-known formula (5).

A similar solution was presented in the study [23], however, in contrast to [22], polynomials of higher degree –third, fourth and fifth – were used to approximate the distribution of the axial, tangential, and radial velocities. It is shown (Fig. 2) [15] that for thin laminar films, when the dimensionless flow rate $Q^+ < 0,075$, and the dimensionless thickness coordinate $\delta^+ < 0,6$, all solutions for laminar flow give close values, which corresponds to the earlier conclusions of Sparrow [18] and Vachagin [17].

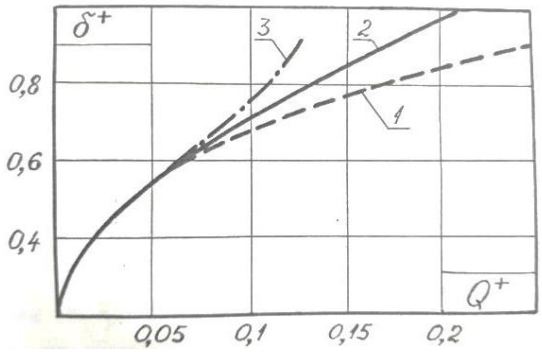

Fig. 2. Comparison of different theoretical dependencies for the thickness of a liquid film [15]: 1 - [16]; 2 - [24] and the approximation by a polynomial of the 4th, 5th degree according to [23]; 3 - approximation by a polynomial of the 3rd degree according to [23].

Thus, almost all theoretical studies on hydrodynamics of a fluid film on a rotating surface were conducted for the case of laminar flow. For thin laminar films, all solutions provide dependences for δ similar to Nusselt's solution [25] for a gravitational film, if g is replaced by $\omega^2 R$ in those solutions.

The experimental determination of the average film thickness at the time of the fluid flowing along the surface of a rotating disk is associated with certain technical difficulties due to the lack of reliable measurement methods and small measured thicknesses (up to $1 \cdot 10^{-6}$ m). Therefore, despite the widespread use of such film flows, at present there is a limited amount of studies describing the measurement of the average film thickness when the fluid moves in the field of centrifugal forces.

The contact method of measurements used in [23, 26-29] has a number of significant drawbacks - adhesion of liquid to the needle, presence of an extraneous element in the liquid flow, closure of the measuring circuit through the air layer which is saturated with water vapor, etc. Moreover, the method is not reliable in the case of rotation of the irrigation surface, since beating of the surface is possible, which, at small measured thicknesses (up to $1 \cdot 10^{-6}$ m), introduces significant errors in the measurements. As a result, essentially different results were obtained for approximately the same initial conditions in the different studies. In the study [26], a good agreement between the experimental data and formula (5) is noted. In [23, 29], there is a good coordination with the dependences that were obtained when the velocity distribution was approximated by polynomials of the fourth and fifth degree (see Fig. 2). An analysis of the results obtained in ref. [27] showed that the average film thickness is by 40% higher than the calculated one, and in ref. [28] the film thickness is 1.71 times higher than the calculated one.

Gasley and Charvat [21] measured the thickness of the film on a rotating disk by the optical method by absorbing infrared rays passing through the transparent disk. The results for the average thickness of the film are 2-3 times lower than those calculated using (5), with a greater deviation observed in the field of thin films. There is no proper explanation of this fact in ref. [21].

In the study [30], as our analysis showed, the average film thicknesses obtained are twice as high as the theoretical dependence.

In paper [15], experimental studies of the local parameters of a liquid film during its flow along a rotating disc were performed using the local electrical conductivity method. The experimental data on the average thickness of the liquid film (distillate, glycerin, surface-active substances) obtained in [15] are in qualitative agreement with the theoretical dependence (5) for a laminar film in the entire range of flow rate variation, disk rotation speed and its radius. The quantitatively obtained experimental data are by 18% lower than the theoretical ones. At the same time, the surface tension of the liquid did not affect the average film thickness. For the case $10^{-10} < Q\nu / \omega^2 R^5 < 10^{-8}$, a dependence is proposed for calculating the average film thickness:

$$\delta = 0,65R\left(\frac{Q\nu}{R^5\omega^2}\right)^{1/3} \qquad (9)$$

In Fig. 3 the dimensionless coordinates δ / R and $Q\nu / R^5\omega^2$ present all experimental data obtained on the average thickness of the fluid film on a rotating disk. The figure shows that the experimentally obtained character of the effect of the complex $Q\nu / R^5\omega^2$ on the dimensionless thickness δ / R corresponds to the theoretical dependence for the laminar flow (5) (curve 1) when $Q\nu / R^5\omega^2 > 10^{-10}$. At its lower values, the degree of influence of this complex increases, which can be explained by the turbulence of the liquid film.

Thus, as a result of an analysis of the actual data on the hydrodynamics of a film, it can be concluded that the calculation method to be used to determine the film thickness should be clarified.

Heat transfer during film condensation on the surface

One of the first fundamental works to deal with mathematical simulation on hydrodynamics and heat transfer during film condensation on a rotating surface was performed by Sparrow and Gregg in 1959 [31]. For the problem statement the authors used a system developed from five differential equations: three equations of a viscous fluid motion written as Navier-Stokes equations, a differential equation of energy and an equation of mass conservation.

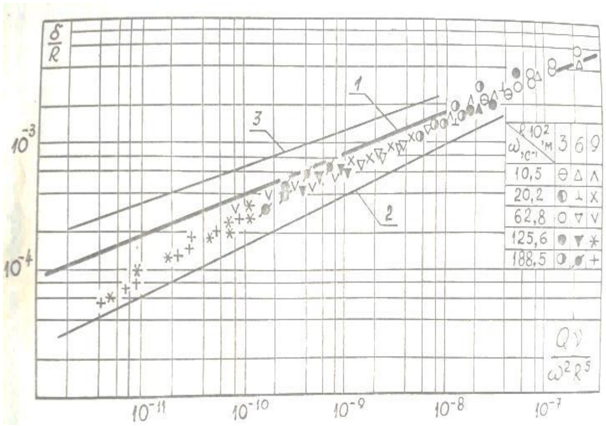

Fig. 3. Generalization of the experimental data on the average thickness of the liquid film on a rotating disk: points - experimental data [15]: 1 - calculation according to the theoretical dependence (5); 2 - calculation according to the empirical dependence of Gasley and Charvat [21]; 3 - experimental data of Povarov [30].

Sparrow and Gregg [31] have used a Karman's variable transformation which has been applied to the hydrodynamic problem solving for viscous liquid flow on the rotating disk in infinite space, simultaneous coordinates transformation with accepted assumptions have made it possible to reduce partial derivatives equations systems into a simple differential equation. For a number of Pr wide-band (from 10^{-3} up to 10) numerical solutions were obtained for the following dimensionless complexes:

$$Nu = \frac{h \cdot \left(\frac{\nu}{\omega} \right)^{0,5}}{\lambda} = 0,904 \left(\frac{\mathrm{Pr}}{c_p \Delta T / r} \right)^{0,25} \qquad (10)$$

The next step in theoretical analysis Sparrow and Gregg [18] made in 1960, performed theoretical analysis of the vapor braking effect on hydrodynamics and heat transfer of the rotating surface film condensation. The conclusion was drawn that the braking influence on heat transfer is restricted by several percent and can be neglected in the theoretical analysis.

In 1961 Sparrow and Hartnett [32] made a theoretical analysis of the heat transfer at film condensation on a rotating conic surface. When $\omega^2 R >> g \sin\varphi$ (φ is the taper angle), the hydrodynamics of the film and the heat transfer in case of condensation on both the inner and outer surfaces in the form of a cone will not differ from the case of flowing on a rotating disk.

One of the first experiments on the heat transfer at film condensation on the rotating surface was the report [33] published by Chernobylskiy and Schegolev in 1949. The device with a rotating surface was designed as a cylindrical steam camera with a rotating shaft placed coaxially to the camera‘s central axis. Taking into account the grounded assumption that the rotation radius *R* was considerably bigger than the tubes diameter and setting, thus for vertical parts the responsibility for film flow centrifugal forces and their density were approximately constant, the following equation was obtained:

$$h = const \frac{\lambda}{d} \cdot \sqrt[4]{\frac{d^3 R \omega r \rho}{\nu \lambda \Delta T}}. \qquad (11)$$

In 1960 Nandapurkar and Beatty [34] conducted experimentation on a horizontal water-cooled rotating disk. The experiments were performed at condensation of vapors of organic liquids such as spirits and refrigerants. The surface temperatures were measured at several points along the disk radius; the heat transfer coefficients for total surface were calculated on the base of these experimental temperatures. The experimental data demonstrated heat transfer coefficients values of 25-30% less in comparison with those predicted by the Sparrow and Greg [31] theory for laminar condensation on the rotation disk.

Heat transfer at steam film condensation experimentation and film flow parameters was also performed by Astafiev [28], Astafiev and Baklastov [35, 36]. Tests were performed on rotating horizontal disks with diameters of 80 and 105 mm. The shaft rotating velocity was varied from 0 up to 2500 rpm. It was assumed for flow patterns visualization in a special series of experiments a colouring substance in an amount not more than 7% of the condensate mass to be injected through the disks center. The fluid ring appearance on the disk edge was observed; detachment of the ring occurred at the moment when the centrifugal forces exceeded the surface forces.

The heat transfer coefficients data were generalized by the equation:

$$Nu = 1,38 \left(\mathrm{Pr} \cdot K \right)^{0,25} \left(Ga \right)^{0,215}. \qquad (12)$$

where: $Ga = \frac{\omega R^3}{\nu^2}$.

In dimensional form the authors [35] experimental data were generalized by the equation:

$$h = 1{,}18\left(\frac{\lambda^3 \rho r}{\nu \Delta T}\right)^{0{,}25} \omega^{0{,}43}. \qquad (13)$$

Butuzov and Rifert [37, 38] presented the experimental data on the inversed downwards condensing rotating surface. The steam condensation experimentation was performed on a horizontal rotating copper disk with a diameter of 0.3 m. The experimental measurements were performed for the disk angular velocity changes within 10 – 224 radian/s at heat flux densities from 20 up to 190 kW/m^2. The condensation had taken place in all experiments on the disks inversed downward surfaces.

The experiments demonstrated that at a constant disk angular velocity the average heat transfer coefficient at condensation decreased with both heat flux and temperature drop increasing, so for these conditions $h \sim \Delta T^{-0{,}25}$ which were typical for a condensate laminar film flow (fig. 4).

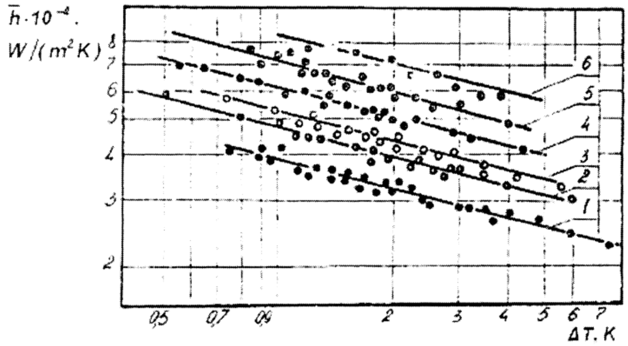

Fig. 4. The water steam condensation average heat transfer: T_s = 373K; R = 0.125 m; 1 – ω = 10.9 s^{-1}; 2 – 51.5 s^{-1}; 3 – 73.5 s^{-1}; 4 – 104 s^{-1}; 5 – 146 s^{-1}; 6 – 200 s^{-1}.

The dependence of h upon ω at ΔT = const in logarithmic coordinates (fig. 5) appears as a broken line with two zones: the first one extended from 10 to 40-52 radian/s. The second zone exceeded 52 radian/s. For the first one $h \sim \omega^{0{,}23}$, for the second $h \sim \omega^{0{,}5}$. The smaller influence of ω on heat transfer within the first zone was connected with the fact that at the slow rotation of the disk regions situated close to the rotation axis the gravitation forces influence on film flow was significant, so under these forces action, drops separation from a film took place. At ω > 52 radian/s a condensate film flow, as well as the heat transfer coefficients, were determined mainly by centrifugal forces and in this case the power index at ω was the same as in the Sparrow and Gregg equation (10).

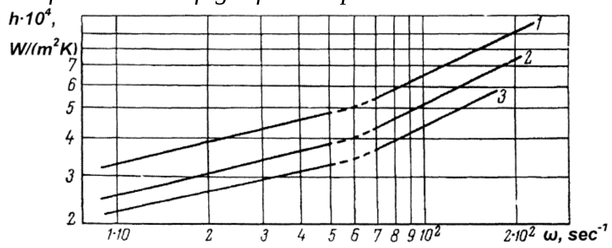

Fig. 5. The average heat transfer coefficient dependence from disks rotation velocity by the following different temperatures drops: 1 – ΔT = 1 K; 2 – ΔT = 2,5 K; 3 – ΔT = 4 K.

Yanniotis and Kolokotsa [39] experimentally studied heat transfer at film condensation of the steam on an aluminium disk inversed downwards with a smooth surface. The experiments were conducted on a disk with a diameter of 30 cm and thickness of 10 mm. The experiments were carried out at a saturated vapor temperature between 45 - 60°C.

The experimental results (fig. 6) show that the local heat transfer coefficient practically did not vary zonally on the disk surface. It agreed with the Sparrow and Gregg theory. The revolution rate in the experiments varied from 0 up to 1000 rpm.

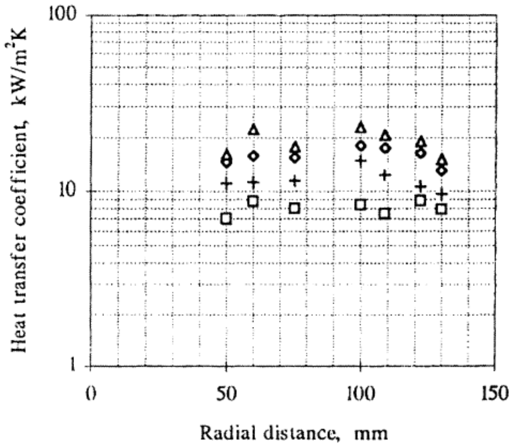

Fig. 6. Heat transfer coefficient for a temperature drop of 4 K between the steam and the disc wall.

It was established by authors experimentation, that the heat transfer coefficient increased with increasing angular velocity. So if the temperature drop (T_s – T_{wall}) was more than 20 K the heat transfer coefficient increase was approximately proportional to the angular velocity power of the $\omega^{0{,}25}$. When temperature drops decreased to 8 ºC by angular velocity, the influence increased and became proportional to $\omega^{0{,}42}$.

The temperature drops increase reduced the heat transfer coefficient in power ΔT^{-m} approximately, where m varied from 0.27 up to 0.18 with the rotation per minute increasing from 200 to 1000 rpm.

Heat transfer during evaporation of the liquid film on a rotating surface

The first studies that provided the formulas for calculating the heat transfer during evaporation of a liquid flow along a rotating surface, were conducted by Bromley [40]. The author accepts the laminar flow of a liquid film, which in those years and up to the present time is accepted (without proofs) when Re = $4G/P\mu < 200$ (P = $2\pi R$).

For the evaporators studied in ref. [40], the authors believe that for the equation Re = $4G/2\pi R\mu$ = 2000 there will be a laminar flow of the liquid film on the most part of the surface. Using the dependence (5) for determining the thickness for a laminar flow of a film, a well-known dependence is obtained in the dimensionless form:

$$Nu = 1{,}47\,\mathrm{Re}^{-1/3} \qquad (14)$$

Rahman and Faghri [41], using the well-known theoretical model of heat transfer for laminar condensation and evaporation of thin laminar films, obtained a dimensionless dependence:

$$Nu = Nu^{*} A\,\mathrm{Re}_{in}^{-1/3}\,E_{in}^{-2/3}\left(R/R_{in}\right)^{2/3} \qquad (15)$$

Substituting in (15) $Nu^{*} = h\delta/\lambda$, $A = \left(\nu^{2}/3gR_{in}^{3}\right)^{1/3}$, $\mathrm{Re}_{in} = u\delta/\nu$, $u = \omega^{2}R\delta^{2}/3\nu$, $E_{in} = \nu/\omega R^{2}$ the dependence (14) is obtained.

Theoretical solutions on how to calculate the heat transfer and general heat transfer at the time of the evaporation of a liquid in a film on a rotating conical surface are presented in ref. [42-44]. The following dependencies are obtained:

$$h = \frac{1}{x-L_1}\int_{L_1}^{x}\frac{\lambda}{\left[3\left(Q_f - Q_e\right)\nu\right]^{1/3}} \left\{2\pi g x\sin\beta\cos\beta\left(\frac{\rho-\rho_v}{\rho}\right) + 2\pi x^{2}\omega^{2}\sin^{3}\beta\right\}^{1/3} dx \qquad (16)$$

The novelty of the dependence (16) is in the presence of a term in the formula $2\pi g x\sin\beta\cos\beta\left(\frac{\rho-\rho_v}{\rho}\right)$. In real centrifugal evaporators, this term is smaller than the centrifugal acceleration term $2\pi x^{2}\omega^{2}\sin^{3}\beta$, even for small angles $\beta \approx 10^{o}$, which occur in ref. [42-44]. If we exclude the term $2\pi g x\sin\beta\cos\beta\left(\frac{\rho-\rho_v}{\rho}\right)$ from (16), we obtain (14).

The heat transfer coefficients measured at the experiments in [42-43] during evaporation and condensation for water, solutions of NaCl and sugar solution differed both in the values of *h* (by 15 ... 30%) and in the character of the effect of the fluid flow. The coefficient of heat transfer did not decrease with an increase in the fluid flow rate (Re_{in}), which follows from the authors' theory (formula (16)), but tended to increase (Fig.7).

In all studies presented [40, 42-44], as well as in [2, 3, 45, 46], the total heat transfer coefficient was measured.

The first measurements of the coefficients of heat transfer during the evaporation and boiling of water in NaCl solutions were performed in ref. [37, 47,48].

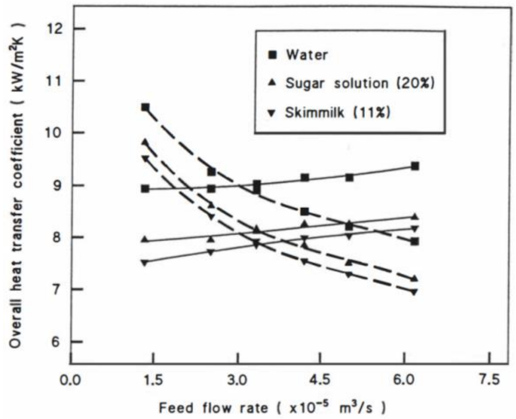

Fig.7. Effect of the feed flow rate on the overall heat transfer coefficient for water, 20% sugar solution and skimmilk in the Centritherm evaporator. Solid lines are experimental values while dashed lines are theoretical values. Evaporating temperature 60ºC, rotating speed 146.6 rad/s, temperature difference 10K.

In the experiments [47], the influence of the flow rate of liquid supplied to the center of the disk, the speed of rotation of the disk *ω*, the dimensions of the disk, the density of the heat flux and the evaporation temperature on the average coefficient of heat transfer during evaporation and boiling of liquids were studied. In our experiments, the temperature of the rotating surface was measured by thermocouples through a current collector. The temperature of the cold junctions was measured using a semiconductor thermistor fixed to the current collector rotor. Cold junctions together with the thermistor were qualitatively insulated. This ensured the possibility of obtaining reliable experimental data that are in good agreement with the theory for laminar and turbulent flows of a liquid film. Since only average heat flux could be measured in the experiments, it was not possible to evaluate experimentally the local (by the radius of the disk) heat transfer coefficient.

Figs. 8 and 9 [37] show the effect of *ω*, *G* and *q* on the average heat transfer coefficient. The main feature of these data is the absence of a laminar law of influence of *G* (Re) on *h*, which contradicts the models of a purely laminar film ($h \sim \mathrm{Re}^{-1/3}$), accepted in refs [40-42, 49]. This fact was noted in the study [50], in which the author assumes that given the certain rates of fluid consumption and the small disk sizes Re can reach values at which the film will be turbulent. Using the two-layer model of a turbulent film described in the studies of Kutateladze [51], the author of [50] presented a dependence for the average heat transfer during evaporation of a liquid film, which takes into account the effect of turbulence on a disk with a radius of $R < R_{cr}$ and laminar flow with a radius of $R > R_{cr}$ (formula (14)).

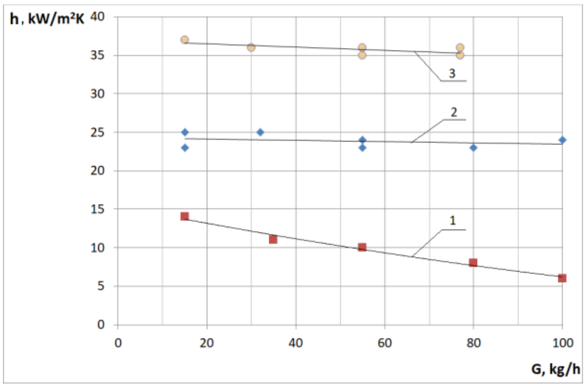

Fig. 8. Influence of the feedwater flow *G* on the heat transfer during the evaporation of the liquid film on a rotating disk at different rotation speeds ω: 1 - ω = 21 rad/s; 2 - ω = 52 rad/s; q = 6,6·10^4 W/m^2; 3 - ω = 105 rad/s; q = 9,6·10^4 W/m^2.

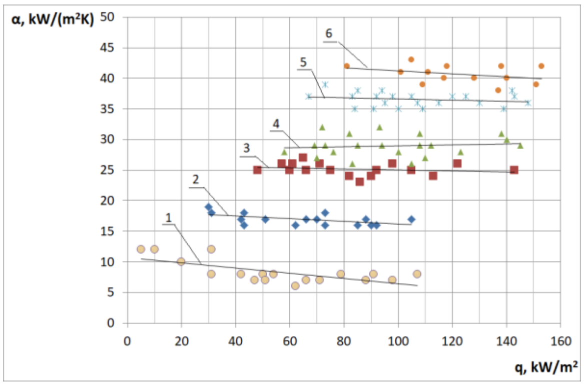

Fig. 9. The effect of the rotation speed of the disk and the heat flow on the average coefficient of heat transfer: 1 - ω = 21 rad/s; 2 - ω = 31 rad/s; 3 – ω = 52 rad/s; 4 - ω = 73 rad/s; 5 - ω = 105 rad/s; 6 - ω = 126 rad/s.

$$h = h_{lam}\frac{R^2 - R_{cr}^2}{R^2} + h_{turb}\frac{R_{cr}^2 - R_i^2}{R^2} \qquad (17)$$

Comparison of the experimental data from [48] with the calculations made using this formula showed satisfactory convergence.

However, our recent studies of the effect of turbulence in the film flow of a fluid [52] show a more accurate possibility to estimate the heat transfer coefficients for evaporation in a film on a rotating surface at high liquid flow rates (i.e. for large Re numbers).

CONCLUSIONS

A review and analysis of the state-of-the-art on the flow of a liquid film, its evaporation and condensation on a rotating surface of centrifugal evaporators is presented.

1. At present time, the characteristics of the liquid film in the field of a steady-state flow at $R >> R_i$ for laminar and wave flows have been well studied. It is necessary to pay attention to the question of justifying the criterion for the transition of a film on a rotating surface to a turbulent flow.

2. The flow of steam condensate on a rotating surface is well studied in the field of laminar flow and it also requires a refinement of heat transfer at low rotations of the rotating surface, when $\omega^2 R$ is close to g. Also the question of condensation on a liquid film, which, for example, takes place in centrifugal evaporators for space missions requires more research to be conducted.

3. The calculation of heat transfer during the evaporation of a liquid film on a rotating surface requires clarification, considering the real nature of the influence of the Re number on the processes of film condensation and evaporation.

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ХИДРОДИНАМИКА И ПРЕНОС НА ТОПЛИНА В ЦЕНТРОФУЖЕН ФИЛМОВ ИЗПАРИТЕЛ

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Постъпила на 20 март, 2018 г.; приета на 24 юли, 2018 г.

(Резюме)

Изпарители с въртяща се повърхност (диск или конус) се използват за концентриране на течности в хранителната, фармацевтичната индустрия и биоиндустрията. Намират приложение също за възстановяване на водата от течни отпадъци в системи за поддръжка на космически кораби и космически станции. В статията е направен преглед на работите върху изучаването на характеристиките на течен филм (дебелина, вълнови параметри), течащ под действието на центрофужна сила и пренос на топлина по време на кондензацията и изпаряването на филма. В повечето теоретични и експериментални изследвания филмовият поток е изследван при R/R_i (съотношение между радиуса на цялата повърхност и радиуса на струята) по-малко от 5, което е типично за инсталации с малък радиус на въртящата се повърхност. Авторите на статията представят нови данни за филмовите характеристики при $R/R_i > 5$, което е от значение в хранителната и фармацевтичната индустрия.