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Justification of the method for calculating heat transfer in film evaporators with a rotating surface

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The paper discusses a heat and mass transfer apparatus with a rotating surface of various shapes (disk, cone, etc.) for the treatment of liquids for which the residence time in the high-temperature region is critical (fruit juices, pharmacological preparations, etc.). In addition, such devices make it possible to create compact energy-efficient systems, including devices for microgravity conditions. Achieving the minimum dimensions and weight, the high quality of the distillate and the maximum level of concentration depends on the design of the rotation surface and on the accuracy of the calculation of heat transfer processes occurring in such devices. The paper discusses methods for calculating heat transfer during condensation and evaporation in a thin liquid film. The use of an analogy of the processes in a liquid film on a rotating surface and the gravity flow of a liquid film is justified. Experiments are performed to determine the average and local heat transfer coefficients on a rotating surface.

Keywords: centrifugal, film, condensation, evaporation

NOMENCLATURE

G – mass flow rate, kg/s, kg/h;
G_d – product rate, kg/s;
g – gravity, m/s^2;
h – heat transfer coefficient, W/(m^{2}K);
Nu – Nusselt number, $Nu = h\lambda^{-1}(\nu/\omega^2 R)^{1/3}$
n – rotating speed, rpm;
Pr – Prandtl number;
Q – heat flux, W;
q – heat flux, W/m^2;
R – radius, m;
r – latent heat, J/kg;
Re – Reynolds number, $Re = 4G/(2\pi R\mu)$;
t – temperature, °C;
Δt – temperature difference, °C;
U – overall heat transfer, W/(m^{2}K);

Greek symbols

β – half angle of the cone, measured from the vertical, °;
δ – thickness, m;
λ – thermal conductivity, W/(m·K).
μ – dynamic viscosity, kg/(m·s);
ν – kinematic viscosity, m^2/s;
ρ – density, kg/m^3;
τ – time, s;
ω – angular velocity, s^{-1};

Subscripts

c – condensate;
d – diameter, disk;
e – evaporated;
exp – experiment;
f – feed;
i – counting index;
w – water.

INTRODUCTION

The use of rotational motion to intensify heat transfer processes in liquid films was first implemented in practice at the first part of the twentieth century. The main advantage of concentrating thermolabile liquids during film flow on rotating surfaces is its short-term contact with the heating surface due to the high speed of the film flow (u > 10 m/s). It also reduces the probability of formation of solid deposits on the heat transfer surface and provides high heat transfer coefficients in such an apparatus.

There are numerous examples of successful applications of rotating surface-film evaporators. They can be used for evaporation of various aqueous solutions; they are used as distillation apparatuses in the production of fatty alcohols and acids, herbicides, etc. As a rule, these products have limited thermal stability [1].

In the food industry, where the problem of reducing the degree of thermal effect on processed products plays a primary role, there are also ample opportunities for their use: when condensing milk, concentrating fruit juices, obtaining extracts of instant coffee, tea, meat extract, for dehydration, etc. With the help of rotating film evaporators, derivatives of vitamins, a number of hormones, etc., are obtained [1]. The use of centrifugal evaporators is promising for the regeneration of water and wastewater from the life support system of astronauts in microgravity conditions [2-7].

The first description of the operation of a centrifugal apparatus was made by Hickman [8, 9]. In this apparatus, the product is distributed over the inner surface of a cone with a horizontal axis of rotation. Heating of the outer surface of the cone is carried out by steam obtained in the apparatus, which is compressed by a centrifugal compressor to create the required temperature difference (6...10 °C). For small pilot installations, the surface of revolution was chosen in the form of a disk with a diameter of 1.27 and 2.8 m.

Bromley and co-workers [10, 11] describe and study a multistage evaporator for sea water with a rotating surface in the form of a disk.

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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 = 0.4 kg/s, the heat transfer coefficient was about U = 8500 W/m^{2}K.

In [12, 13] the design of the heat exchange surface in a spinning cone column is described. It consists of a vertical succession of alternate rotating and stationary cones. Liquid flows as a film down the stationary cone, drains into the base of the rotating cone again as a film by the action of the centrifugal force. Gas flows up the column countercurrent to the flow of the liquid. Mass transfer from the liquid to the vapour phase in a spinning cone column takes place through the large surface area of the film (which may be less than 1 mm thick), and through the liquid spray in the regions between spinning and stationary cones. There may be several dozen of cone sets (stages) in a commercial column.

The Centritherm (CT) evaporator (Flavourtech, Griffith, Australia) is composed of multiple cones (1–12 depending on the evaporative capacity) that form a cone stack [14]. The centrifugal force of the rotating cones creates a thin layer and allows effective wettability of the heat-exchange surface. It is claimed that the CT evaporator is able to concentrate dairy products to concentrations unachievable with conventional designs of evaporator while maintaining product functionality. It can process viscous products at low temperature (50 °C). Moreover, the extremely short residence time, claimed to be around one second by the manufacturer, ensures very low thermal impact on the product.

In [3-6], the design and test results of a centrifugal multistage vacuum distiller (CMVD) are described for water recovery in a life-support system in microgravity. Evaporation occurs in a thin film (less than 0.02 mm) of a liquid (urine or a mixture of urine and water, etc.) inside a rotating rotor. Condensation of the produced steam occurs on the outer surface.

In all considered designs, the energy efficiency and quality of the product (distillate) in a centrifugal evaporator (distiller) depends mainly on two processes: condensation of heating steam on a rotating heat exchange surface and evaporation (sometimes boiling) of liquid. These processes take place in thin liquid films.

Heat transfer during film condensation in many works [9, 15] is calculated from the dependence obtained for the first time in work [16]:

$$\frac{h_c}{\lambda}\left(\frac{\nu}{\omega}\right)^{0,5} = 0,904\cdot\left(\frac{Pr}{c_p\Delta T}\right)^{0,25} \qquad (1)$$

For the case of a rotating cone, it was shown in [17] that

$$\frac{h_{cone}}{h_c} = \left(sin\,\beta\right)^{1/2} \qquad (2)$$

The formula (1) in empirical form is transformed into [18]:

$$Nu = \frac{h_c}{\lambda}\left(\frac{\nu^2}{\omega^2 R}\right)^{1/3} = 1,1\cdot Re^{-1/3} \qquad (3)$$

In this case, the local Reynolds number:

$$Re = \frac{4\cdot G_c}{2\pi R\mu}$$

Heat transfer during evaporation of a liquid film on a rotating disc and on conical surfaces was studied in [9, 10, 15, 19, 20]. However, the authors did not measure directly the coefficient of heat transfer during evaporation (h_e), but only the overall heat transfer coefficient U. In most papers, to calculate the heat transfer during evaporation of a liquid film on a rotating surface, a dependence based on a laminar model of liquid flow is used. But already in papers [21-23] it was shown that the nature of the influence of the liquid flow rate (Reynolds numbers) on the evaporation process cannot be described by the laminar theory

In the present study, the experimental values of the heat transfer coefficients during condensation h_c and evaporation h_e were determined. The method for calculating heat transfer using the results of numerical solutions of heat transfer in a liquid film flow (laminar and turbulent) was improved.

Experimental installation

In papers [21, 22] an experimental installation for studying the processes of evaporation and condensation on a rotating disk is described. The main element of this setup is shown in Fig. 1.

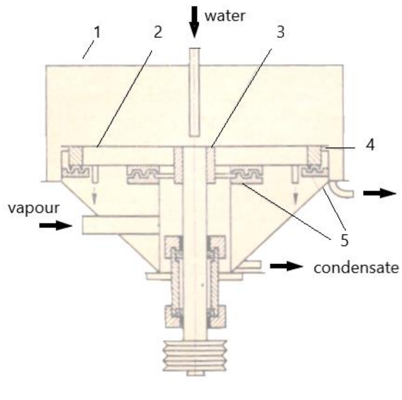

Fig. 1. Schematic diagram of the experimental installation

The centrifugal evaporator consists of a stainless steel housing 1, inside which a copper disk 2 (diameter is 300 mm and thickness is 1.5 mm) rotates on a shaft. The shaft is driven by a 0.5 kW DC motor (*n* = 0… 2500 rpm) using a V-belt transmission. The disk is rigidly connected to the flange 3 and the bronze ring 4 which is equipped with a labyrinth seal 5.

Steam was produced by boiling distilled water in a boiler and feeding it to the bottom surface of the rotating disk. The condensate was thrown by centrifugal force to the periphery of the disk and drained into the conical part of the apparatus. Then it entered the condensate measuring tank and returned to the boiler using a pump. To prevent air from entering the system, the steam pressure in the experiments was above atmospheric (about 1.1 bar) and was automatically maintained by an electronic pressure regulator, which changed the load of the electric heater in the boiler.

Water for cooling (evaporation) was supplied to the center of the disk. Its flow rate was measured with a rotameter. At the outlet of the apparatus, the condensate flow rate was determined by the volumetric method. The temperatures of steam and water were measured with mercury thermometers (graduation 0.1 °C). The vapor pressure was determined using a pressure gauge. The disk rotation speed was measured with a tachometer with an accuracy of ± 10%. To determine the temperature of the heat transfer surface, seven copper-constantan thermocouples with a diameter of 0.2 mm were embedded in the disk. Each thermocouple was placed in a 0.8×1.0 mm groove, first along the circumference, and then along the radius of the disk (every 30 mm). The thermocouples were connected to the measuring device through a slip-contact current collector.

Heat transfer during condensation of a liquid film on a rotating disk

In the first series of experiments, the local heat transfer coefficients were measured during condensation of water vapor at a temperature of t_c = 99.5 ... 99.8 °C and at a speed of *n* = 200, 500, 1000 and 1600 rpm. The consumption of cooling water G_w = 70 kg/h; inlet water temperature t_w = 20°C; the average heat flux was constant q = 125 kW/m^2.

The temperature of the cooling water at the outlet of the installation and the flow rate of the condensate were measured by the volumetric method. The difference between the heat balance on the condensation side $Q_c = G_c \cdot r$ and the water cooling side $Q_w = G_w \cdot c_p \cdot \Delta t_w$ did not exceed 3%. Fig. 2 shows the experimental data t_{wall} = f(*R*) at different disk revolutions. *n* – temperature of the wall. The process of calculating the local and average heat transfer coefficients h_c includes several steps.

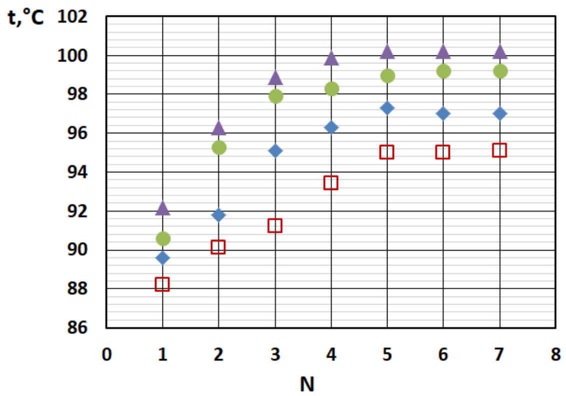

Fig. 2. Measured disk temperatures. N - thermocouple number; n = 200 (□), 500 (◊), 1000 (●), 1600 (▲) rpm.

1) Calculation of the disk area corresponding to the local radius $F_i = \pi R^2$, and the area of the surface corresponding to the ring where the thermocouple is installed:

$$\Delta F_i = \pi R^2_N - \pi R^2_{N-1} \quad (4)$$

where *R* – local radius, m; *N* – installed thermocouple number.

2) Determination of local temperature difference

$$\Delta t_c = t_c - t_N \quad (5)$$

where t_c – condensation temperature of water vapor, °C. It is a function of the condensing pressure.

3) Determination of the calculated local heat transfer coefficient during condensation by the formula (1)

4) Determination of the calculated total heat flux

$$\sum Q_c = \sum_1^N \left(h_c \cdot \Delta t_c \cdot \Delta F_i \right) \quad 6)$$

5) Comparison of the obtained total heat flux with the amount of heat taken by the cooling water and as a result of measuring the amount of condensate obtained

$$Q_w = G_w \cdot c_p \cdot \Delta t_w \quad (7)$$

$$Q_c = G_c \cdot r \quad (8)$$

As a result of the calculations, a coincidence between the calculated and measured amounts of heat was obtained $Q_c = Q_w$. The maximum difference was 7%.

Fig. 3 shows the local heat transfer coefficients. Comparison with the theoretical dependence is shown in Fig. 4.

Thus, the experimental data showed once again that in the case of condensation on a rotating surface, it is possible to use the well-known dependence for the laminar flow of a liquid. The gravitational component *g* is replaced by a complex ($\omega^2 R$). In the performed experiments, the Reynolds number of the film did not exceed Re = 60.

In this case, it can be noted that already starting from Re > 40, a slight deviation from the laminar theory is observed. A similar effect was also noted in [34].

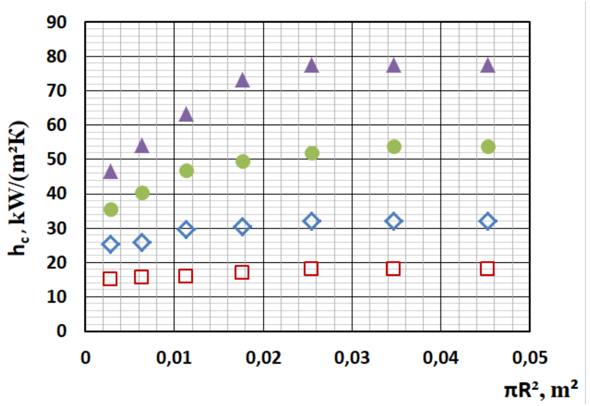

Fig. 3. Local heat transfer coefficient during vapor condensation at atmospheric pressure. n = 200 (□), 500 (◊), 1000 (●), 1600 (▲) rpm.

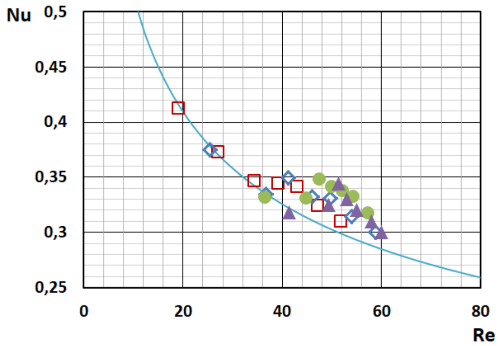

Fig. 4. Local Nu *versus* Reynolds number (condensate flow rate). Solid line - calculated by formula (1)

Heat transfer during evaporation from a liquid film on a rotating disk

In the second series of experiments, the local heat transfer coefficients were measured during evaporation of a liquid flowing down in the form of a film over a rotating disk surface at atmospheric pressure.

The liquid was supplied for evaporation to the center of the disk. Before being fed to the disk, the liquid was heated to boiling point. The evaporation temperature was equal to the saturation temperature and was t_e = 101.5 °C. The thermal power changed as a result of a change in the heating steam flow rate, which condensed on the back side of the disk (d = 0.3 m). After reaching the required temperatures, the specified disk rotation speed n and the evaporated water flow rate G_w were selected. Experiments were carried out with the following parameters: disk rotation speed n = 100...1900 rpm, average heat flow density q = $20 \cdot 10^3 ... 10^5$ W/m², feed water consumption G_w = 15 ... 96 kg/h, $\Delta t = t_e - t_{wall}$ = 1.3 ... 12 °C.

The experiments were carried out in the range of variation of the heat flux density $q < 10^5$ W/m², when there is no nucleate boiling in the film of an evaporating liquid [24]. It was assumed that the heat transfer coefficient from the condensation side h_c is known and can be determined from dependence (1) or (3).

The local coefficient h_e is determined as follows.

1) From the known temperatures of the disk and vapor condensation, the local heat transfer coefficient h_c during condensation, local heat transferred q_i and total heat transferred Q were determined.

2) Determine the local temperature difference

$$\Delta t_e = t_e - t_i \qquad (9)$$

where t_e is the temperature of evaporation, °C. It is a function of the condensing pressure.

3) Using the known local heat transferred and temperature difference, we find the local heat transfer coefficient during evaporation

$$h_e = \frac{q_i}{\Delta t_e} \qquad (10)$$

4) Determine the total heat transferred

$$\sum Q_e = \sum_1^N \left(h_e \cdot \Delta t_e \cdot \Delta F_i \right) \qquad (11)$$

5) Compare the obtained total heat transferred with the heat of phase transition using the formula (8) as a result of measuring the amount of obtained condensate.

As a result of the calculations, a coincidence of the calculated and measured amounts of heat was obtained $\Sigma Q_e = Q_c$. The maximum difference was 10%.

In the experiment, a weak dependence of the average and local heat transfer coefficients on the flow rate of the evaporated liquid was obtained (see Fig. 5), in contrast to the case of film condensation (see Fig. 4).

Thus, the experimental data showed that it is impossible to use the laminar theory when evaporating from a liquid film on a rotating surface. At the considered liquid flow rates, turbulization of the liquid film occurs, which leads to a change in the effect of flow rate (Re number) on the heat transfer coefficient.

Generalization of heat transfer during condensation and evaporation of a liquid film on a rotating disk

The processes of film condensation and surface evaporation of a liquid film heated to the saturation temperature occur at an almost constant heat flux along the thickness of the film. Therefore, local heat transfer coefficient in both cases submits to practically the same laws. In the case of gravitational and forced flow it was investigated in many theoretical [25-27] and experimental works [28-31]. In most of such works, heat transfer coefficient is expressed as a dependence of the form Nu = f (Re).

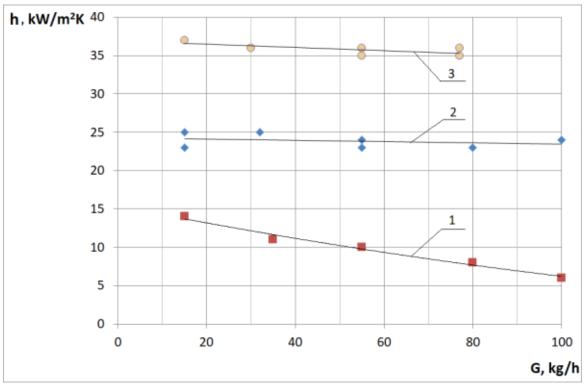

Fig. 5. Influence of the feedwater flow G on the heat transfer during the evaporation of the liquid film on a rotating disk at different rotation speeds ω: 1 - ω = 21 rad/s; 2 - ω = 52 rad/s; q = 6,6·104 W/m²; 3 - ω = 105 rad/s; q = 9,6·104 W/m².

In the case when the heat flux is the same over the entire film thickness, in the theoretical analysis of the evaporation process it is necessary to take into account the structure of the film surface (its turbulization). For this purpose, in [31], a semiempirical technique is proposed. The results of such calculation can be generalized using the following equation:

$$Nu_i = 1{,}1 Re^{-1/3}\left(1 + 0{,}02\, Re^{0{,}2} + 0{,}0009\, Re^{0{,}2} \cdot Pr^{0{,}65}\right) \quad (12)$$

If we drop the expression in parentheses in equation (12), then it becomes a theoretical equation for a laminar flow of a liquid film. Therefore, the expression in parentheses can be regarded as a correction factor that takes into account the increase in heat transfer during turbulization of the film flow as compared to the laminar flow.

It should be noted that Eq. (12) is valid only in those cases when the generated steam flow does not have a noticeable mechanical effect on the film.

Figure 6 shows the graphs Nu = f (Re) (solid lines) for two values Pr = 1.75 and Pr = 2.77 according to formula (12) [31]. The dashed line shows a graph for a strictly laminar flow of a liquid film according to formula (3).

The obtained experimental data on the evaporation and condensation on a rotating disk are shown by dots. In the range of Reynolds numbers Re < 60, heating steam condensed from the lower side of the disk (t_c ≈ 102 °C; Pr = 1.77) - see Section 1 of this paper. On the upper side of the disk, a liquid film (Re = 130...1100) evaporated at atmospheric pressure (t_e ≈ 100 ° C; Pr = 1.75) - see Section 2 of this work.

The graph also shows the experimental data for the evaporation of a liquid film in a vacuum (t_e ≈ 65 °C; Pr = 2.77) from paper [32].

As can be seen from Fig. 6, the theory of heat transfer is in qualitative agreement with experimental data on the evaporation and condensation of a liquid film on a rotating disk, which makes it possible to use it to calculate not only for the gravitational flow of a liquid film, but also for rotating systems, when ($\omega^2 R$) >> g.

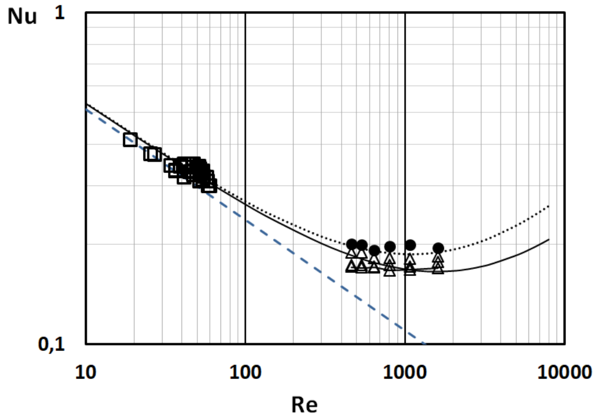

Fig. 6. Comparison of experimental data of the local Nusselt number with theoretical calculation: Solid line - theory (Pr = 1.75); Line to point - theory (Pr = 2.77); Dashed line - Nusselt's laminar theory (3); (□) - condensation, (▲) - evaporation at atmospheric pressure; (●) - evaporation in vacuum [32]

Comparison of experimental results with theory during evaporation

a) Rotating disc

One of the first works where heat transfer was measured during evaporation of water on a rotating disk, was the paper [8]. In this work, as well as in [9-11], a laminar model of liquid evaporation is used to determine h_c. According to this approach, the heat transfer coefficient depends on the flow rate of the liquid supplied to the rotating surface, $h_c \sim G^{1/3}$. As a result, the authors present in their works an empirical formula for calculating the heat transfer coefficient U (see, for example, formula (11) in [9]). It takes into account the deviation of the obtained data from the laminar model. The formula has a complex view, which is not very convenient for engineering calculations.

In experiments [33], the total heat transfer coefficient U was measured during water evaporation: t_e = 102.7...105.6 °C and an evaporating liquid flow rate G_e = 45.4 ... 68.1 kg/h. Total temperature difference $\Delta t = t_c - t_e$ = 2.78… 5.55 °C. Rotating speed n = 690 ... 1700 rpm. The evaporating liquid was fed in the center of a copper disk d = 0.3 m, δ = 1.6 mm. Analysis of the data shows that for the same ω(n) and Δt, the heat transfer coefficients are the same within ± 5%.

Calculation of the theoretical values of U and comparison of the experimental and calculated values was carried out as follows:

1) The local values of Re_c and Re_e at different radii R_i = 0.03; 0.045; etc., are found from the known flow rates of the condensate G_c and the evaporating liquid G_e.

2) According to Fig. 6 or according to the calculation formula (12), we find the local values of the numbers Nu_c, Nu_e and, accordingly, local h_c and h_e.

3) Using the known area $F_i = \pi R^2$ and the known temperature difference $\Delta t = t_c - t_e$, we find the local heat flux Q_i.

4) Find the total calculated heat flux through the disk ΣQ_i and compare it with the experimental Q_{exp}. (see Table 1).

The results of the comparison of some experimental and calculated values are presented in Table 1, from which it can be seen that the calculated values of the total heat flux are by 12...22% higher than the experimental ones. Thus, the proposed technique describes the experimental data with good accuracy.

b) Rotating cone

The most detailed study of heat transfer during the evaporation of various liquids in the rotating cone was studied in [15, 35-36]. In all these studies the total heat transfer coefficient U was measured.

Experimental measurements in [15, 36] of the total heat transfer coefficient were made for three liquids (water, 20% sugar solution and skim milk) at different evaporation temperatures and feed flow rate 1.5... 6.0·10^{-5} m^3/s.

Table 1. Comparison of calculated results and experimental data [33]

№	n, rpm	G_e, kg/h	G_c, kg/h	Δt, °C	U_{exp}, kW/(m²K)	Q_{exp}, kW	R_i, m	h_e, kW/(m²K)	h_c, kW/(m²K)	U_i, kW/(m²K)	Q_i, W	ΣQ_i, W	ΔQ, %
1	720	46.5	3.22	2.6	13.9	2.5	0.03	14.6	25.4	8.9	65	3.1	18
							0.045	17.4	32.7	10.9	98		
							0.06	20.0	39.3	12.6	159		
							0.075	22.4	45.3	14.1	230		
							0.09	24.6	51.0	15.6	309		
							0.105	26.8	56.3	17.0	397		
							0.12	28.8	61.4	18.2	493		
							0.135	30.8	66.3	19.4	595		
							0.15	32.7	71.0	20.5	705		
2	1010	46.4	3.58	2.4	16.6	2.9	0.03	18.3	30.8	11.0	72	3.5	19
							0.045	21.8	39.7	13.3	115		
							0.06	25.0	47.7	15.4	186		
							0.075	28.0	55.0	17.3	268		
							0.09	30.9	61.8	19.0	360		
							0.105	33.5	68.3	20.6	462		
							0.12	36.1	74.4	22.1	572		
							0.135	38.6	80.3	23.6	691		
							0.15	41.0	86.0	24.9	817		
3	1390	46.2	4.0	2.3	19.2	3.2	0.03	22.7	37.0	13,3	88	4.1	22
							0.045	27.0	47.6	16.1	133		
							0.06	31.0	57.1	18.6	214		
							0,075	34.7	65.8	20.8	308		
							0.09	38.2	73.9	22.9	414		
							0.105	41.5	81.6	24.8	530		
							0.12	44.7	89.0	26.6	656		
							0.135	47.8	96.0	28.3	791		
							0.15	50.8	102.8	29.9	934		
4	1700	46.7	4.4	2.2	24.3	3.8	0.03	25.9	41.0	14.9	93	4.3	12
							0.045	30.8	52.7	18.0	140		
							0.06	35.4	63.1	20.8	226		
							0.075	39.6	72.7	23.2	325		
							0.09	43.6	81.7	25.5	436		
							0.105	47.4	90.2	27.6	557		
							0.12	51.0	98.3	29.5	689		
							0.135	54.5	106.1	31.4	830		
							0.15	57.9	113.5	33.2	979		

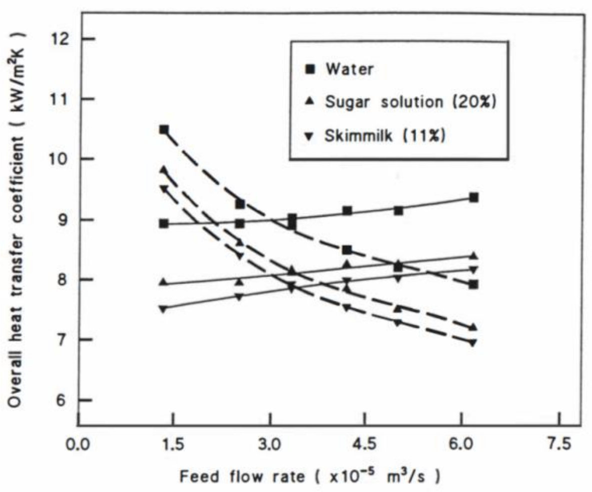

Fig. 7. Effect of the feed flow rate on the overall heat transfer coefficient for water, 20% sugar solution and skim milk in the Centritherm evaporator. Solid lines are experimental values while dashed lines are theoretical values. Evaporation temperature 60ºC, rotating speed 146,6 rad/s, temperature difference 10K.

Fig. 7 shows a comparison of the experimental (solid lines) and heat transfer coefficients calculated by the model for the laminar flow of an evaporating liquid film (dashed lines).

In [36], an attempt was made to explain the reasons for the discrepancy between the calculated and experimental data in Fig. 7. According to this model, the authors assume (without experimental justification) that vapor bubbles are formed inside the cone and an additional temperature drop appears on the side of evaporation. As a result, the overall temperature difference will increase, which will lead to a decrease in heat transfer.

The authors of [36] provide a formula for calculating these differences and a table with some of the results. But it should be noted that the main advantage of centrifugal film evaporators is that nucleate boiling in them at $\omega > 10^4$ s^{-1} occurs at a heat flux density $q > 2\cdot10^5$ W/m^2 [24, 32], which is approximately 4...5 times higher than the experimental values according to the data tests [15].

In our opinion, the influence of the liquid flow rate on the total heat transfer coefficient is associated with the characteristic of heat transfer during the evaporation. If we calculate the local Reynold number for water at 60 °C from Fig. 7, then it will lie in the range Re_i = 300 ... 2500. Figure 6 shows that in this range of Reynolds numbers the dependence Nu = *f* (Re) deviates significantly from the laminar theory and has a form similar to that in Fig. 7. The performed calculations for water according to Figs. 6 and 7, using formula (2), showed the convergence of the calculation of heat transfer coefficient h_e within 30% without invoking additional explanations.

CONCLUSIONS

Experimental studies of heat transfer processes during condensation and evaporation in liquid films made it possible to significantly refine the physical picture of the processes. These processes occur at an almost constant heat flux density across the film thickness; therefore, the local heat transfer in both cases obeys the same laws. At the same time, the effect of turbulization of a liquid film on the heat transfer coefficient during its flow on a rotating disk is shown for the first time. Comparison with the theory for the gravitational flow showed satisfactory agreement, which indicates a similar effect of the film flow on the heat transfer process under the action of centrifugal forces.

The considered calculation method using local heat transfer coefficients and semiempirical dependences for the gravitational flow makes it possible to accurately predict the value of the total heat transfer coefficient and to compare the experimental data of different authors obtained on disks of different diameters, including cones, when $\beta \neq 90$ °.

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