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Mass and Heat Transfer During Thin-Film Evaporation of Liquid Solutions

Janusz Dziak
Wroclaw University of Technology
Poland

1. Introduction

Thin-film evaporation is applied in heat exchangers called thin-film or thin-layer evaporators. Actually thin-layer evaporators may be considered as heat and mass exchangers, since molecules from liquid phase are transferred to gas phase during process of vaporization and the movement of molecules from gas phase to liquid phase is probable during process of condensation. This kind of devices are commonly applied in chemical, pharmaceutical and food industries since 1950. Vertical thin-layer evaporator, example of which is presented in Fig.1, is characterized by small pressure drop and short residence time of the phases in the apparatus, which means also that there is short contact time of the liquid with hot surface of the evaporator wall. These features of the evaporator cause that it is applied for the concentration of heat sensitive liquid solutions especially with high viscosity. Because of low value of pressure drop during gas flow inside the evaporator the boiling temperature of liquid, which is evaporated, depends only on its composition and does not depend on liquid position in the evaporator, which is of great importance in case of evaporation at low pressure.

There are two main types of the thin-layer evaporator, which will be considered below, namely: static type thin-layer evaporator and mechanically agitated thin-layer evaporator. All types are constituted by vertical cylinder heated from the outside, inside which liquid flows off gravitationally on the heated surface. During that flow vaporization of liquid takes place.

If liquid flows off freely, by means of gravity force, without any disturbance, it means, without any mechanical action on flowing liquid inside the evaporator, then such an apparatus is called static type thin-layer evaporator.

If the evaporator is equipped with blades that mix the liquid flowing inside the evaporator, then such an apparatus is called mechanically agitated thin-layer evaporator or mechanical thin-layer evaporator. The blades applied in the evaporator distribute liquid uniformly on the evaporator wall, which prevents the appearance of dry places on the heated surface of the evaporator. The blades could be fixed rigidly to the shaft of the mixer (Fig.1.) or they could be mounted to the rotating shaft in such a way that the blades swing freely and scrape the surface of the evaporator wall. The pressure exerted by the blade on the surface of evaporation depends on revolution speed of the shaft equipped with moving blades. This kind of evaporator is especially suitable for evaporation of liquid solutions that produce crystals during the process of evaporation (Dziak & Skoczylas, 1996).
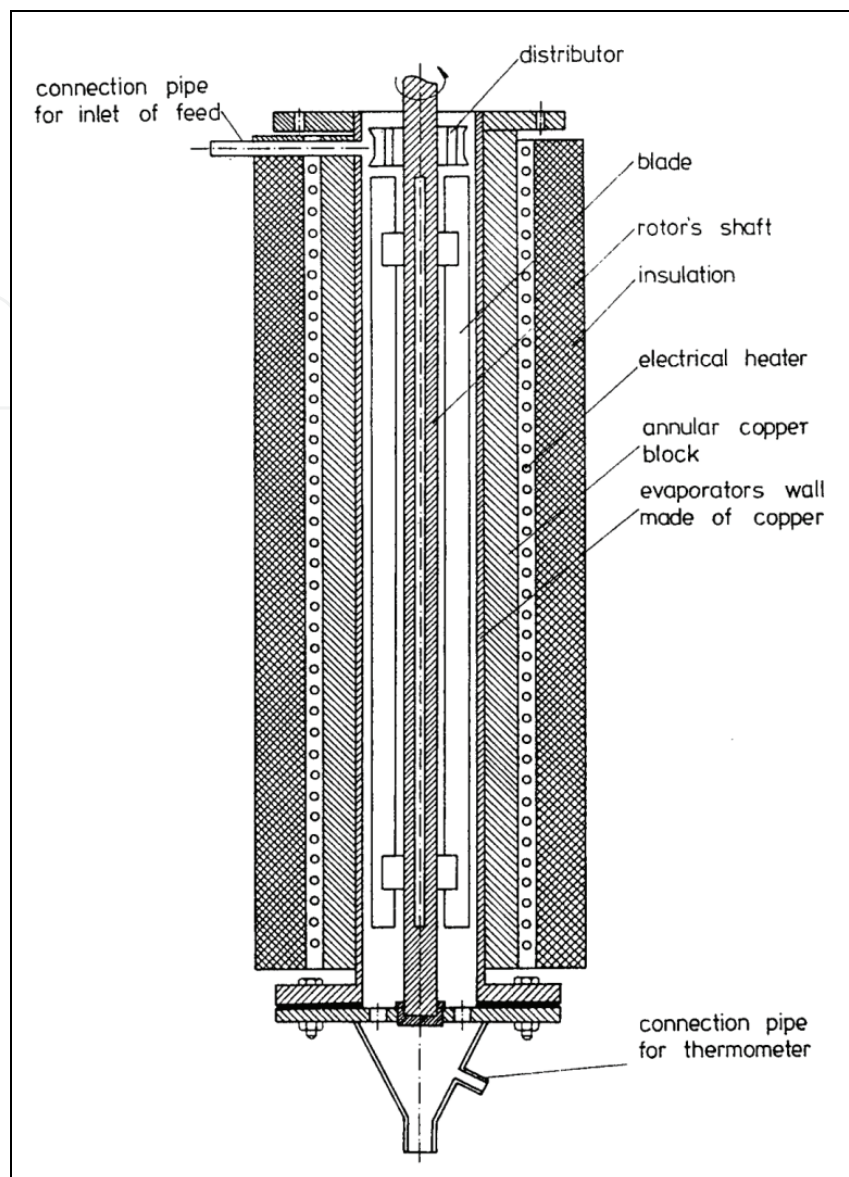
Fig. 1. Vertical section of the mechanical thin-layer evaporator equipped with rotor possessing rigidly fixed blades

One can find in the literature mathematical models of hydrodynamics of thin layer flow of liquid over a vertical wall (El Haj Assad M. & Lampinen M. J., 2002; Chen F.C. & Gao Z., 2004; Ludwig et al., 2008).

There are many works that deal with heat transfer during the process of heating and evaporation of liquids in thin-layer evaporators. Most of them are devoted to individual heat transfer coefficients determination in case of one component liquid treating (Chun K.R. & Seban R.A., 1971; Skoczylas A., 1978; Alhusseini A. et al., 1998). There are mathematical equations that allow determination of individual heat transfer coefficients depending on the conditions of heat transfer. Mechanism of evaporation is quite complicated and depends on many factors such as: liquid physical properties, the roughness of the surface (where vapour bubbles are formed), heat load. Because of that the equations, presented by different authors, for calculation of the individual heat transfer coefficients could give the results that sometimes differ substantially and one should be careful applying them.

Even more complicated is the process of evaporation of liquid solutions i.e. liquid that contains more than one component. At some circumstances during the process of liquid solution evaporation the gradient of concentration in liquid phase appears and it causes some additional difficulties in heat and mass transfer analysis of the process of evaporation. There are not so many works that deal with this problem (Leuthner S. et al., 1999; Krupiczka R. et al., 2004). Some experimental results, ideas and theoretical considerations will be presented below.

2. Theories of mass transfer during the process of thin-layer evaporation

The fundamental theory applied for determination of separation efficiency of the thin-layer evaporator was presented by Billet (Billet R., 1957). Billet presumed that the vapor generated during vaporization of the liquid mixture is removed from the evaporator without any contact with the liquid phase flowing down the tube. Similar point of view was presented by Dieter (Dieter K., 1970), who analyzed the evaporation process both in mechanical thin-layer and molecular evaporators. Molecular evaporator is an apparatus in which the distance between vaporization surface and condensation surface is smaller than mean free path between molecules collision in the gas phase.

Billet's theory is based on the mass balance of more volatile component in differentially small element of dh-length in the evaporator (Fig.2), which is constituted by a pipe, heated from the outside, inside which the process of evaporation takes place. Assuming that for this element the liquid and generated vapor are in equilibrium ($y=y^*$) one can write the equation:

$$L \cdot x = (L-dV) \cdot (x-dx) + y^* dV \tag{1}$$

where: L - liquid molar flow at the inlet to the element of dh length, x – more volatile component concentration in liquid at the inlet to the dh element, $(L-dV)$ - the liquid molar flow at the outlet of the dh element, $(x-dx)$ - more volatile component concentration in liquid at the outlet of the dh element, dV- molar flow of vapor produced in the element of dh length of evaporator, y^* - vapor concentration, which is in equilibrium with liquid concentration of more volatile component.
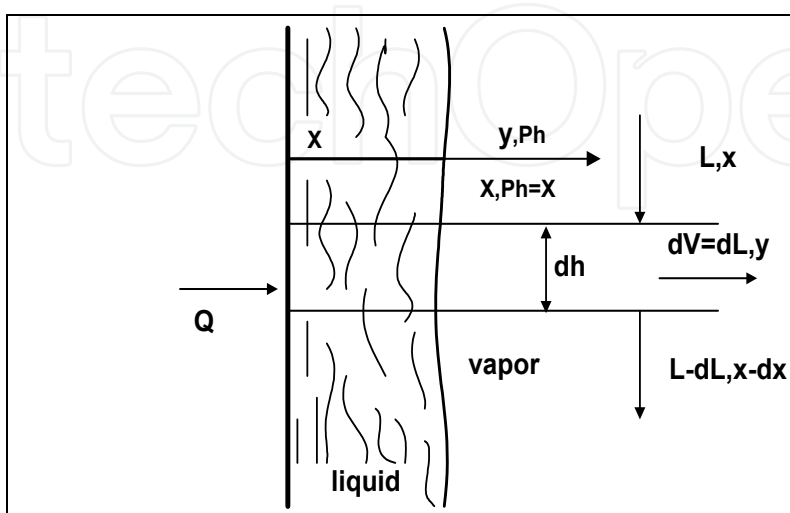

Fig. 2. Scheme of the two-component liquid thin-layer evaporation. Billet's theory

The solution of equation (1) is the integral:

$$\ln\frac{L_F}{L_R} = \int\limits_{x_R}^{x_F} \frac{dx}{y^* - x} \tag{2}$$

Integral (2) can be solved numerically. This equation allows calculation of the residue flowrate from the evaporator L_R, knowing the values of the feed flowrate L_F, its concentration x_F as well as the concentration of residue x_R. It is also necessary to have the vapor-liquid equilibrium data [$y^*= f(x)$].

The average composition of the distillate can be determined from the mass balance equation:

$$D = L_F - L_R \tag{3}$$

$$x_D = \frac{L_F \cdot x_F - L_R \cdot x_R}{D} \tag{4}$$

Mannheim and Passy (Mannheim C.H. & Passy N., 1974) stated that during evaporation process of liquid mixtures, in the vertical thin-layer evaporators, the rectification could appear as an effect of countercurrent flow of liquid and vapor phases inside the evaporator. Similar point of view presented Billet in his later work (Billet, 1983). He also noticed that distillation of liquid mixtures in a thin-layer evaporator could lead to significantly better separation than that obtained in corresponding simple batch distillation. According to him this effect is caused by intimate contact of liquid and gas phases in the evaporator. Anybody of those authors presented experimental verification of their hypothesis.

3. Experimental work on thin-layer evaporation of two-component liquid solutions

An extensive experimental work was proceeded by the author of this chapter to establish the results of thin-layer distillation of two component liquid solutions in mechanical thin-film evaporator (Skoczylas A. & Dziak J., 1990). The investigation was carried out in the mechanical thin-layer evaporator, which some details are presented in Fig.1.

The liquid feed was supplied from the connection pipe to the distributor and then it was distributed uniformly over the surface of the evaporator. Inside the evaporator the liquid was spread over the inner surface of the tube by means of four rotating blades. The clearance between the inner surface of the tube and the edge of the rotor blades might be set continuously in the range 0.5-2.5 mm.

The main geometric dimensions of the evaporator were: inner diameter d=0.04 m, height of the evaporator h=0.57 m, heat transfer area A=0.0716 m².

The experimental installation, which was applied in the investigation, is presented in Fig.3. Two component liquid solution from the feed tank (V_1) was pumped to the thin-layer evaporator (T.L.E.) through the rotameter and double pipe heat exchanger (in which the liquid was heated up to the boiling point). The vapor phase flowed up to the condenser (CND) and liquid distillate was collected in the receiver of distillate (V3). The bottom product was collected in the receiver of residue (V2). The evaporator was heated by an electrical heater and the power supplied was regulated by means of changing the input voltage.

The following systems were applied in the experimental work: water-ethylene glycol, methyl alcohol-water. The concentrations of examined liquids were determined by
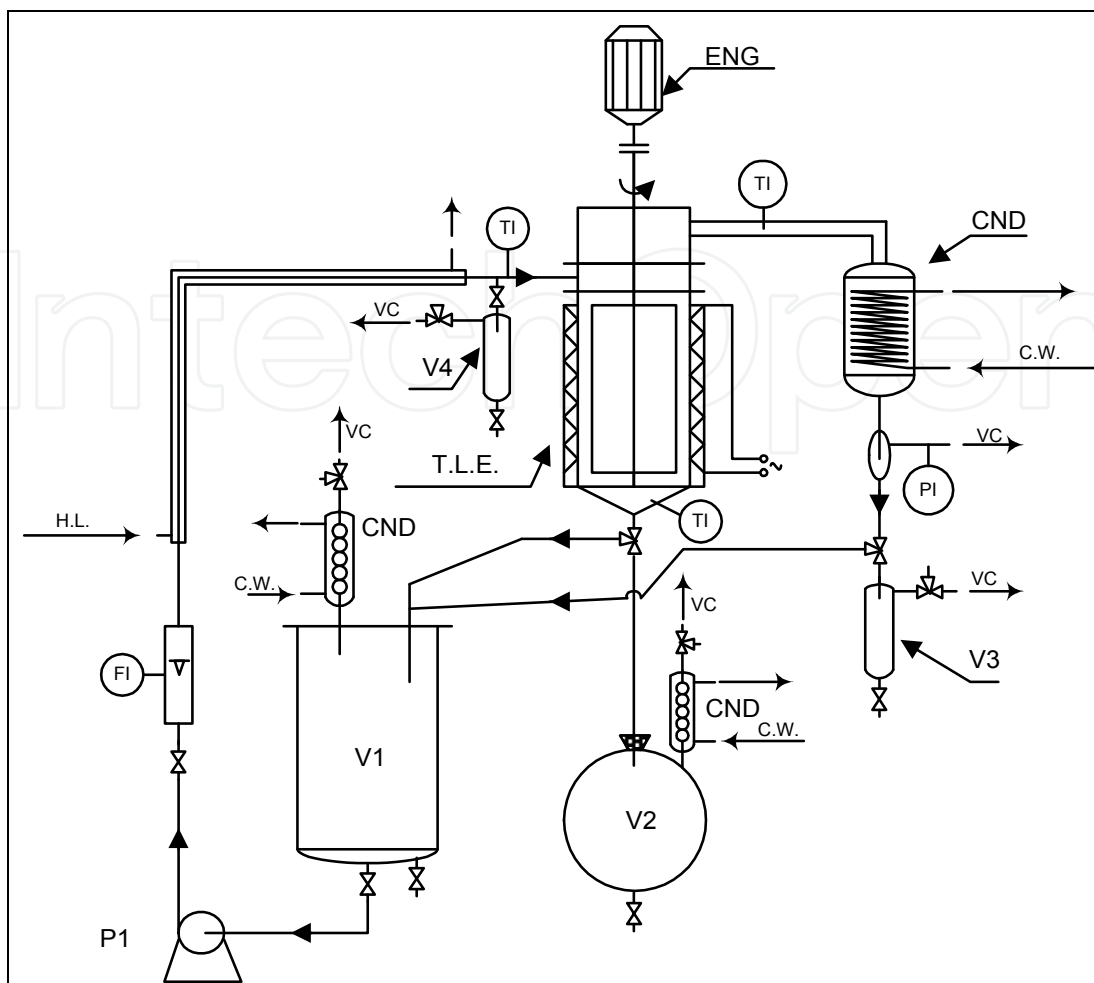
Fig. 3. Scheme of installation for heat and mass transfer examination in thin-layer evaporator. CND-condenser, C.W.-cooling water, H.L.- heating liquid, P1- pump, V1- feed tank, V2- residue tank, V3- distillate tank, V4- feed sample receiver, VC- to vacuum, T.L.E.- thin-layer evaporator, FI- flow indication, PI- pressure indication, TI- temperature indication

measuring density. Altogether 118 measurements of separation efficiency of the mechanical thin-layer evaporator were carried out, which included 77 measurements on a methyl alcohol-water system and 41 measurements on a water-ethylene glycol system. When selecting the systems, the coefficients of relative volatility α_{AB} were considered. The numerical values of these coefficients, at the applied working conditions, amounted to: α_{AB} =5 for methyl alcohol-water system and α_{AB}=120 for the water-ethylene glycol system. The ranges of the experimental conditions are presented in table 1.

The purpose of the work was confrontation Billet's theory results with reality and to establish whether the rectification effect exists during the process of thin-film evaporation. In each experiment the following magnitudes were measured: -moles of feed, distillate and residue per unit time; compositions of feed, distillate and residue; temperatures of liquid at the inlet and outlet of the evaporator; temperature of vapor at the outlet from the evaporator; pressure inside the evaporator. Having these data one could get both experimental and calculated values of separation efficiency.

The vapor-liquid equilibrium data applied in calculations using Billet's theory were taken from the literature (Gmehling J. & Onken U., 1977).

	Methyl alcohol-water system	Water-ethylene glycol system
Moles of feed per unit time (kmol/s)	$1.18 \cdot 10^{-5} - 3.71 \cdot 10^{-4}$	$6.35 \cdot 10^{-5} - 8.29 \cdot 10^{-4}$
Mole fraction of the more volatile component in the feed	0.181-0.605	0.048-0.418
Rate of heat flux (kW/m²)	4.25-13.36	3.18-14.97
No. of rotor's revolutions (rev./min.)	200,600,1000	200,600
Pressure (hPa)	1013	33

Table 1. Ranges of the experimental conditions for thin-layer evaporation of two component liquid solutions

The results of experimental investigation are presented in Fig.4 and Fig.5.

Fig.4 shows the dependence between water concentration in distillate x_D and its average concentration in liquid phase x_L , calculated as an arithmetic average of water concentration in the feed and in the residue, obtained in the process of thin-layer evaporation. The dependence was obtained in water-ethylene glycol system. The solid line in this figure describes the theoretical relationship $x_D = f(x_L)$, obtained according to Billet's theory, whereas experimental data are represented by individual points.

If the process of evaporation was accompanied with rectification effect then the experimental results would be above the corresponding theoretical results. Actual concentrations of more volatile component in the distillate would then be higher than corresponding concentrations calculated applying equations 2-4. Figure 3 shows that it is not the case for the process of evaporation in mechanical thin-layer evaporator.
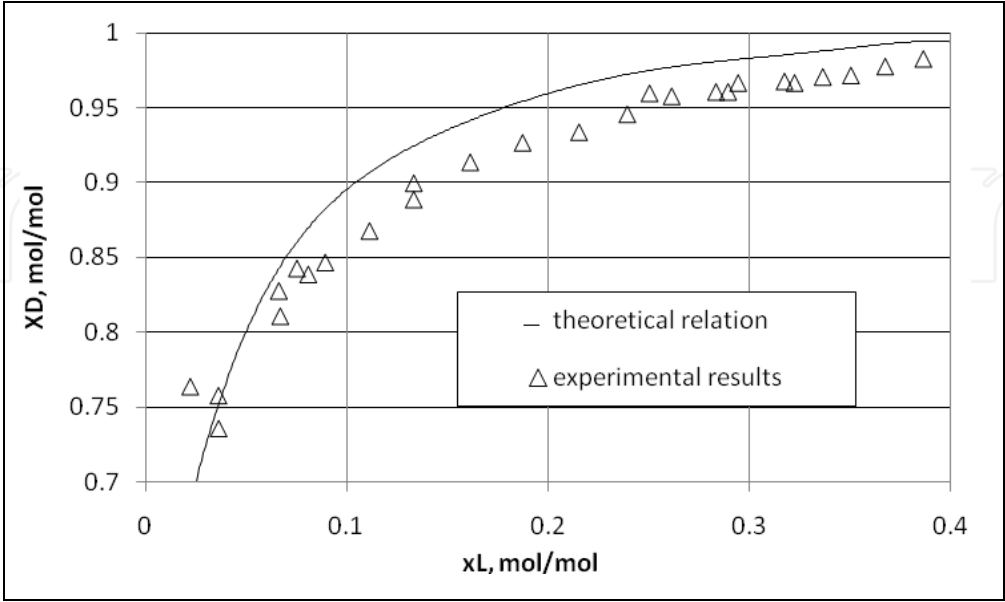

Fig. 4. Concentration of more volatile component in distillate x_D as a function of average concentration of that component in liquid $x_L = (x_F + x_R)/2$. Water-ethylene glycol system

The sets of curves in Fig.5, obtained in methyl alcohol-water system, illustrates the relation between the average mole fraction of methyl alcohol in distillate x_D and the ratio of distillate to feed flowrates D/F for different values of methyl alcohol concentration in the feed. The ratio D/F constitutes the degree of evaporation, obtained in the thin-layer evaporator. Solid lines show theoretical relationships and individual points represent experimental results. It can be seen from Fig.5 that the agreement between theoretical and experimental results is very good. For all measurements, which were performed on methyl alcohol-water system, the mean deviation between x_D data, obtained experimentally, and the theoretical ones amounted to 1.86% and the maximum deviation was 7.94%.

From the comparison of the experimental results and theoretical calculations presented above one can conclude that in the thin-layer evaporators, similar to the design that was used by the author of this work, there is no rectification effect despite countercurrent flow of vapor and liquid phases through the evaporator. Even more, one can notice that in water-ethylene glycol system some phenomenon took place, causing that experimentally obtained values of more volatile component concentration in the distillate are lower than those calculated theoretically.

4. Explanation of the absence of rectification effect during evaporation of liquid solution in the thin-layer evaporator

The absence of the rectification effect during distillation of liquid solutions in the thin-layer evaporator can be explained on the grounds of detailed analysis of hydrodynamics as well as heat and mass transfer. The mechanism of flow of both phases in the thin-layer evaporator is quite different to that in the rectification column. This difference is a consequence of different way of supplying energy to the apparatus. One can compare the way of working of both apparatus: rectification column and thin-layer evaporator taking the advantage of Fig.6.
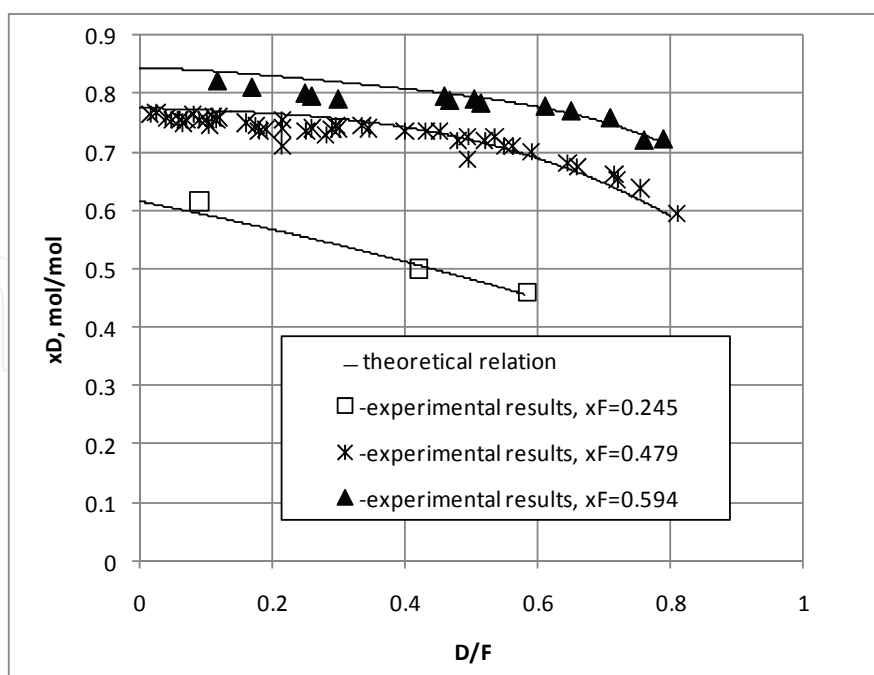

Fig. 5. Relationship between distillate concentration x_D and the ratio of distillate and feed flowrates D/F for different values of the feed concentration x_F. Methyl alcohol-water system

In the case of the rectification column the vapor phase generated in the conventional evaporator is fed to the lower part of the rectification column, whereas the liquid phase generated in the condenser is fed on the top of the column. The cylindrical surface of the rectification column ought to have an adiabatic jacket, whereas in the case of thin-layer evaporator this surface is heated by means of steam or by electrical heater.

Let's examine in detail the mechanism of heat and mass transfer during vaporization of a two component liquid system, both in the rectification column and in the thin-layer evaporator.

In case of rectification column, if the molar heat of vaporization of both components is the same and the column has an adiabatic jacket, then equal-molar flow of the liquid and vapor phases is achieved.

The vapor phase from the lower part of the column, having temperature t_V and concentration of the more volatile component y_V flows up and contacts with the liquid, which flows down. The temperature of liquid t_L is lower than the temperature of the vapor $t_V > t_L$. The concentration of the more volatile component in gas phase y_V is lower than the concentration of more volatile component in gas phase y_V^*, which is in equilibrium with liquid phase (possessing concentration x_L) that contacts with gas. Because of thermodynamic state of the liquid and gas phases, that are in contact, there are conditions for heat and mass transfer. The vapor flowing near by the liquid layer is being cooled and the drop of vapor temperature brings about that part of it is being condensed, mainly the
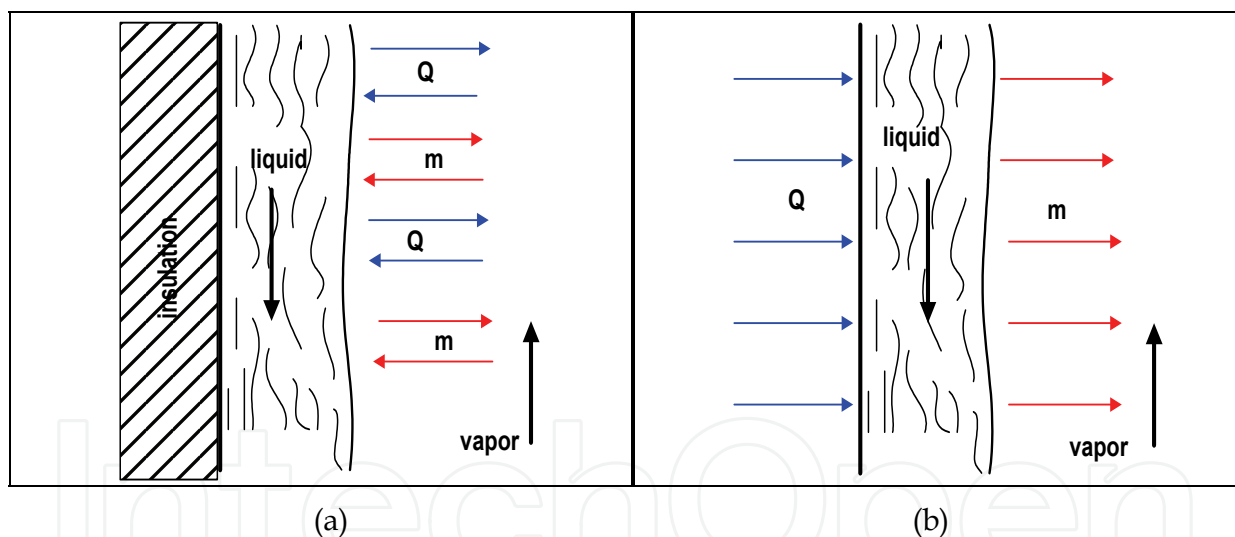

Fig. 6. Comparison of the work of rectification column (a) and thin-layer evaporator (b)

less volatile component. The liberated heat of condensation causes evaporation of an equivalent amount of the liquid phase, mainly the more volatile component. If the molar heat of vaporization of components are the same, and the column has an adiabatic jacket, then during the process of heat and mass transfer no volume changes of liquid and vapor phases occur.

In case of thin-layer evaporator, there is no adiabatic jacket, and its cylindrical wall is just a heating surface of the evaporator. The liquid phase at boiling temperature t_b flows down on the inner surface of the vertical tube, which temperature t_w is higher than the liquid temperature $t_w > t_b$. In the time of liquid flowing down, part of it evaporates, mainly the more volatile component. The volume of vapor created V_V is much greater than the volume of

disappearing liquid V_L and the ratio V_V/V_L is in the range 10^3-10^5. Such a considerable increase of volume accompanying the evaporation process of a liquid on the vertical wall of the tube brings about the increase of pressure in the immediate neighborhood of the liquid layer. As a result, the motion of vapor particles is mainly unidirectional, from the liquid layer to the centre of the tube, and only on the liquid-vapor surface one can expect the existence of equilibrium conditions.

The dynamic pressure exerted by vapor generated during process of evaporation in the thin-layer evaporator could be calculated from equation (5):

$$\triangle p = \frac{w^2 \cdot p_v}{2} \tag{5}$$

and the linear velocity of the vapor phase, perpendicular to the tube's wall can be calculated from equation (6):

$$w = \frac{q}{p_v \cdot r} \tag{6}$$

Where: q is the rate of heat flux, kW/m^2; ρ_V- density of the vapor phase, kg/m^3; r- heat of vaporization, kJ/kg.

The numerical values of w and Δp for applied, by the author, working conditions were in the range:

$$w = 3 \cdot 10^{-3} \div 0.25 \text{ m/s}$$

$$\Delta p = 6 \cdot 10^{-6} \div 7.7 \cdot 10^{-4} \text{Pa}$$

The above presented mechanism explains the absence of rectification effect in the thin-layer evaporator, but it does not explain why the concentration of more volatile component in vapor phase is lower than that obtained from theoretical calculations applying Billet's theory, as it is illustrated in Fig.3. This could be explained considering in detail what is going on in liquid phase during two component liquid solution thin-layer evaporation.

5. Gröpp and Schlünder theory of simultaneous heat and mass transfer during thin-layer evaporation of two-component solutions

The process of liquid solution evaporation in thin-layer evaporator is more complex than evaporation of one component liquid. It is connected with the fact of mass transfer resistance arise at some conditions of two-component liquid thin-layer evaporation.

Gröpp and Schlünder (Gröpp U. & Schlünder E.S., 1986) presented theory that allows understanding the process of mass transfer in liquid phase during thin-layer evaporation of liquid solution.

Fig.1 shows schematically the temperature and concentration profiles in the thin-layer of liquid during surface evaporation in the vertical thin-layer evaporator. Two-component liquid (with components A and B) flows along the heated surface and is partially evaporated. Mole fraction of more volatile component in gas phase y_{Aph} and in liquid phase x_{Aph} at interface, as well as temperature at interface t_{ph} are established according to thermodynamic equilibrium conditions. If it is assumed that the vapor generated on liquid surface is directly discharged to the condenser, and there is no mass transfer resistance in the

gas phase, then the distillate concentration equals the gas concentration y_{Aph} at the interface. The mole flowrate of more volatile component in the direction to the interface on liquid side $n_A^\bullet$ could be determined from the equation concluded from boundary layer theory:

$$n^\bullet{}_A = -\rho_L \cdot \delta_L \cdot \left(\frac{\partial x_A}{\partial s}\right) + n^\bullet \cdot x_A \tag{7}$$

Where: ρ_L- liquid density, kmol/m³; δ_L- liquid diffusivity, m²/s; x_A- mole fraction of more volatile component in liquid phase; s- boundary layer thickness, m; $n^\bullet$- overall mole flowrate, kmol/s
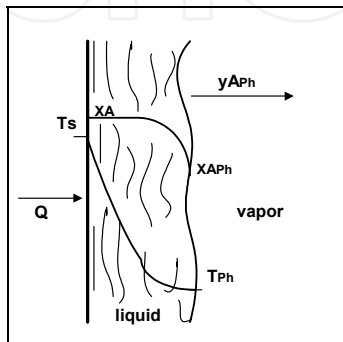
Fig. 7. Thin-layer evaporation accompanied with mass transfer resistance in liquid phase

$$n^\bullet = n^\bullet{}_A + n^\bullet{}_B \tag{8}$$

Mole flowrate of more volatile component could be determined from equation (9):

$$n^\bullet{}_A = n^\bullet \cdot y_{Aph} \tag{9}$$

Taking advantage of the equation (9) in equation (7), one obtains:

$$n^\bullet \cdot y_{Aph} = -\rho_L \cdot \delta_L \cdot \left(\frac{\partial x_A}{\partial s}\right) + n^\bullet \cdot x_A \tag{10}$$

And then:

$$-\rho_L \cdot \delta_L \cdot \frac{\partial x_A}{\partial s} = n^\bullet \cdot \left(y_{Aph} - x_A\right) \tag{11}$$

Integrating the equation (11) gives:

$$-\frac{\rho_L \cdot \delta_L}{n^\bullet} \cdot \int_{x_A}^{x_{Aph}} \frac{dx_A}{y_{Aph} - x_A} = \int_0^s ds$$

$$-\frac{\rho_L \cdot \delta_L}{n^\bullet} \cdot [-\ln(y_{Aph} - x_A)]_{x_A}^{x_{Aph}} = s$$

$$-\ln\left(y_{Aph} - x_{Aph}\right) + \ln\left(y_{Aph} - x_A\right) = -\frac{n^\bullet}{\rho_L} \cdot \frac{s}{\delta_L} \tag{12}$$

If we define mass transfer coefficient by the equation (13):

$$\beta_L = \frac{\delta_L}{s} \tag{13}$$

and linear velocity in the interface direction by the equation (14):

$$v_L = \frac{\overset{\bullet}{n}}{\rho_L} = \frac{q}{\rho_L{}' \cdot r} \tag{14), (15}$$

Where: q- heat load, W/m²; r- heat of vaporization, J/kg; $\rho_L{}'$-liquid density, kg/m³
Introducing equations (13) and (14) into equation (12) one obtains:

$$\ln \frac{y_{Aph} - x_A}{y_{Aph} - x_{Aph}} = -\frac{v_L}{\beta_L} \tag{16}$$

The equations presented above allow determination of mass transfer coefficient value for specific thin-layer evaporation conditions. Knowing the values of liquid heat of vaporization (r), heat load (q) and liquid density (ρ_L')one can calculate the value of v_L from equation (15). After that, knowing the value of v_L and the values of concentrations in liquid and vapor on the interface boundary y_{Aph}, x_{Aph}, as well as the average concentration in liquid phase x_A, one can determine the value of mass transfer coefficient β_L from relationship (16).

6. Experimental investigation of mass transfer in liquid phase during liquid solution evaporation in thin-layer evaporator

The purpose of the work, carried out by the author, which results are presented below, was checking whether the mass transfer resistances exist during the process of thin-layer evaporation of liquid solutions, and if they do, finding values of mass transfer coefficients for specific conditions of thin-layer distillation. Another objective of the work was determination, if there is a way of mass transfer resistance lowering, if such resistance exists. Isopropanol-water and propylene glycol solutions were chosen for the examination. Both systems possess the components that significantly differ in volatility, which is essential considering the possibility of mass transfer resistance appearance. Additionally the water-propylene glycol solutions possess relatively high viscosity.
The scheme of installation applied in an experimental work is presented in Fig. 2. Two kind of evaporators were used in experiments: one of static type (without blades that mix liquid) and the second equipped with mixer, which blades swing freely and scrape the surface of the evaporator. The main dimensions of both evaporators are presented in table 2.
Ranges of changeability of magnitudes applied in experiments are presented in table 3.

	Static thin-layer evaporator	Thin-layer evaporator equipped with mixer
Heated height h, m	0.56	0.266
Evaporator diameter d, m	0.04	0.06
Heat transfer area A, m²	0.07	0.05

Table 2. Main dimensions of thin-layer evaporators used in experiments

Magnitude	Isopropanol-water system	water-propylene glycol system
External pressure, Pa	$1,013 \cdot 10^5$	3332
Volatility=$P_{more\ volatile}/P_{less\ volatile}$ (t,^{o}C)	2 (82°C)	47 (74°C)
Feed concentration-X_F, mol/mol	0.0678-0.133	0.1788- 0.2475
Sprinkle intensity-m', kg/(ms)	0.0531-0.213	$6.839 \cdot 10^{-3}$- $9.9882 \cdot 10^{-2}$
Heat load-q, W/m^2	8087.9-32809.5	7216.8- 19752
Liquid density-ρ, kg/m^3	878.4-921.4	989.2-1008.4
Liquid viscosity-η, mPa·s	0.3106-0.3449	3.4- 4.8
Mixer revolutions, rev./min.	-	200-800

Table 3. Ranges of changeability of magnitudes applied in experiments

Intensity of heated surface sprinkle by the liquid was calculated from relation (17):

$$m'=m^{\bullet}/O \tag{17}$$

Where: $m^{\bullet}$- average mass flowrate of liquid, kg/s; O- evaporator perimeter, m
Heat load of evaporator heated surface was determined from equation (18):

$$q=Q^{\bullet}/A \tag{18}$$

Where: $Q^{\bullet}$- heat exchanged in the evaporator, kW; A-heat exchange surface area of the evaporator, m^2

The concentrations of examined liquids were determined by measuring density for isopropanol-water system and refractive index for water-propylene glycol system. The vapor-liquid equilibrium data were taken from the literature (Gmehling J.& OnkenU., 1977).
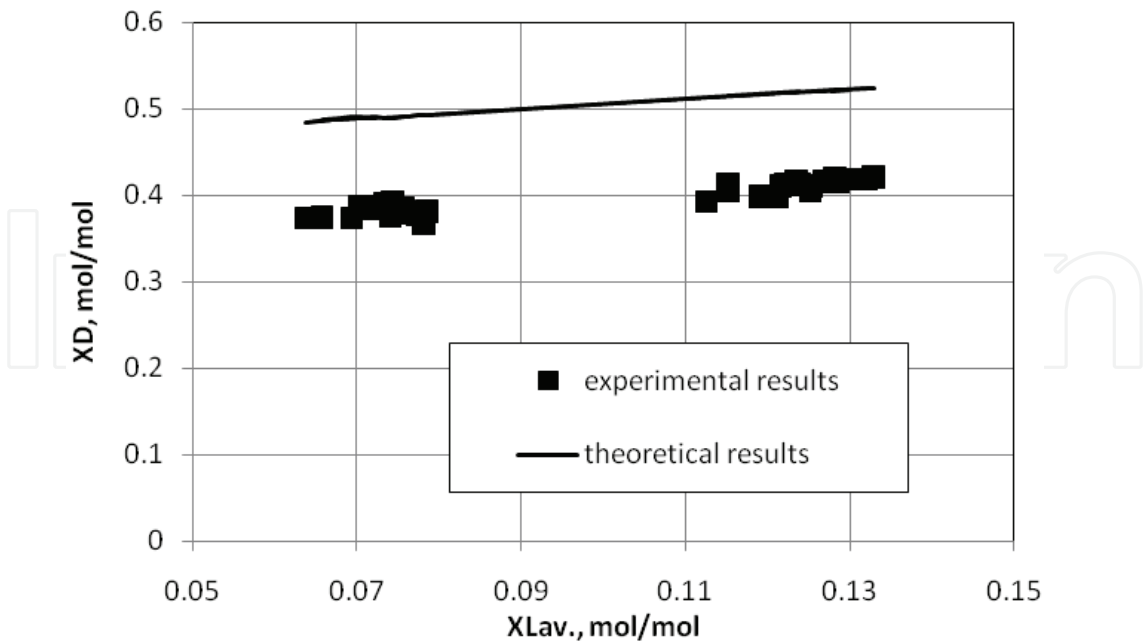

Fig. 8. Results of distillation of isopropanol-water liquid solutions carried out in static type thin-layer evaporator. Dependence between more volatile component concentration in distillate and its average concentration in evaporated liquid
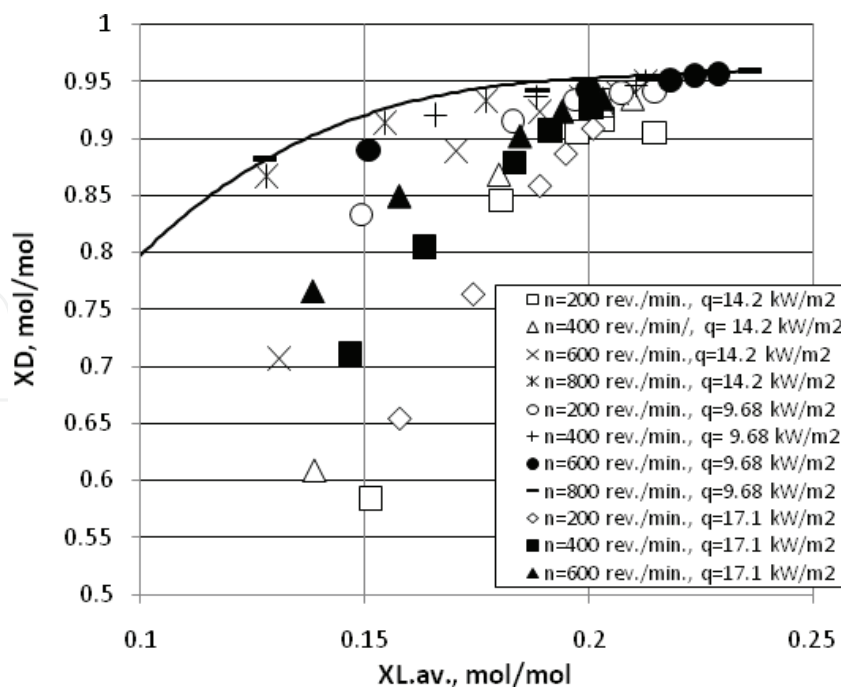
Fig. 9. Results of distillation of water-propylene glycol solutions carried out in wiped-film thin-layer evaporator. Dependence between more volatile component concentration in distillate and its average concentration in evaporated liquid. Solid line represents theoretical calculations
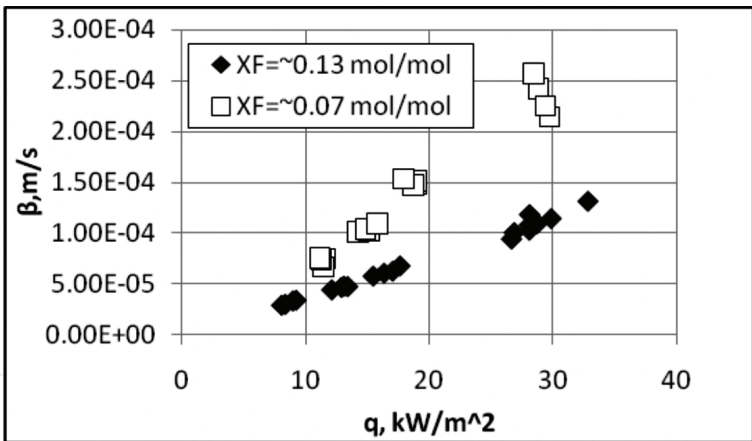

Fig. 10. Individual mass transfer coefficient dependence on process variables. Static type thin-layer evaporator. Isopropanol-water system

In Fig.8 and Fig.9. there is a comparison of the results of distillation in thin-layer evaporator, calculated theoretically (Billet's theory) and determined experimentally. Fig.8 describes results obtained in static type thin-layer evaporator for isopropanol-water system and Fig.9 represents the results obtained applying wiped thin-film evaporator for water-propylene glycol system. As one can see in Fig.8 and Fig.9 mass transfer resistance during distillation of liquid solutions in the thin-layer evaporator significantly influences the results of distillation. Theoretically calculated compositions of distillate (solid line in Fig. 8 and Fig.9) are not in line with experimental results (individual points). Experimental results are much worse than those anticipated theoretically. It can be also noticed from Fig.9 that mass transfer resistance could be substantially reduced by the action of blades that mix the evaporated liquid film.

One can read in Fig.10 and Fig.11 the values of mass transfer coefficients determined with the use of Gröpp and Schlünder theory.

The dependency of individual mass transfer coefficient on liquid concentration and heat load was noticed in the case of isopropanol-water system.

On the other hand, in case of water-propylene glycol system, clear dependence of individual mass transfer coefficient on liquid flowrate and mixer number revolutions per minute was
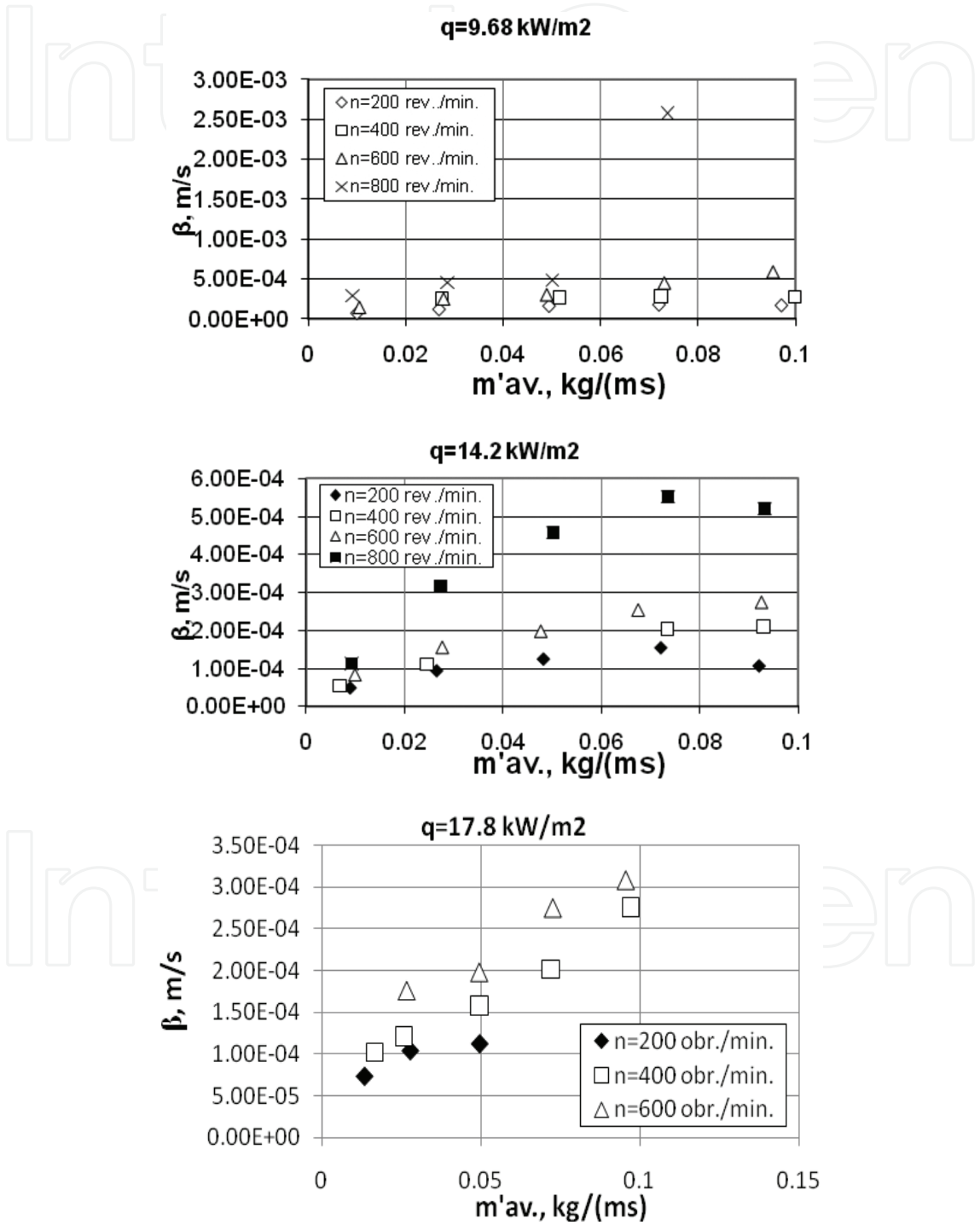
Fig. 11. Individual mass transfer coefficient dependence on process variables. Wiped thin-layer evaporator. Water-propylene glycol system

confirmed. One can notice significant growth of individual mass transfer coefficient with the growth of speed of the mixer rotation. Especially high values of individual mass transfer coefficient were obtained for heat load q=9.68 kW/m² and n=800 rev./min.. It could be expected that for low value of heat load and suitable mixer action mass transfer resistance, in liquid phase, could be eliminated.

7. Conclusions

As one can see, from the above presented considerations, the process of liquid solution evaporation, carried out in the thin-layer evaporator, is complicated. The processes of heat and mass transfer, which proceed simultaneously, influence to each other. Simple theory that does not take into account the mass transfer resistance in liquid phase during the process of thin-layer evaporation, becomes unrealistic, especially in the case of evaporation carried out in the evaporator without liquid film mixing. Mass transfer resistances in liquid phase arising during the process of liquid solution thin-layer evaporation could be lowered by applying of liquid-film mixing. Mixing is generally helpful for intensification of mass and heat transfer.

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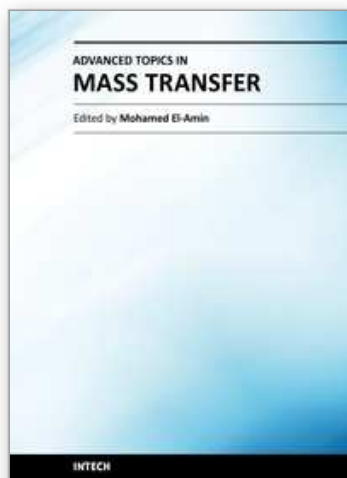
Advanced Topics in Mass Transfer

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This book introduces a number of selected advanced topics in mass transfer phenomenon and covers its theoretical, numerical, modeling and experimental aspects. The 26 chapters of this book are divided into five parts. The first is devoted to the study of some problems of mass transfer in microchannels, turbulence, waves and plasma, while chapters regarding mass transfer with hydro-, magnetohydro- and electro- dynamics are collected in the second part. The third part deals with mass transfer in food, such as rice, cheese, fruits and vegetables, and the fourth focuses on mass transfer in some large-scale applications such as geomorphologic studies. The last part introduces several issues of combined heat and mass transfer phenomena. The book can be considered as a rich reference for researchers and engineers working in the field of mass transfer and its related topics.

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