Chemical Engineering Journal 81 (2001) 9–14

Chemical Engineering Journal

www.elsevier.com/locate/cej

Film wiping in the molecular evaporator

Ján Cvengroš*, Štefan Pollák, Miroslav Micov, Juraj Lutišan

Faculty of Chemical Technology, Slovak Technical University, Radlinského 9, Bratislava 81237, Slovak Republic

Received 10 December 1998; received in revised form 4 January 2000; accepted 19 January 2000

Abstract

This study deals with a wiper for a molecular evaporator. Its wiping element has the shape of a cylinder with a screw thread with coarse pitch (lead) on its surface. The wiping element bears on the evaporating cylinder due to centrifugal force and rolls over it, bringing the liquid on the evaporating cylinder into an intensive complex movement. The screw thread on the wiping element surface increases the permeability of the liquid through the element, while restricting the formation of a longitudinal wave which develops in front of the element. An analysis of residence time distribution curves shows that there are three different liquid flow regimes on the evaporating cylinder. In this study, conditions of the formation of these regimes and their consequences are discussed. Optimum conditions for distillation can be reached at peripheral speeds of the wiper at which increased retention of a liquid on the evaporator occurs. This leads to an increased residence time. The increased residence time is a positive factor which makes efficient evaporation under gentle conditions at a lower evaporating temperature possible.

Keywords: Molecular evaporator; Wiper; Liquid film; Residence time distribution

1. Introduction

Wiping of a liquid film on the evaporating area of a molecular evaporator is a key operation implicating efficient, powerful and also gentle distillation of a treated heat-sensitive substance without thermal hazard.

In a wiped film evaporator, the liquid in the film on the evaporating surface is continuously mixed and evenly distributed over the whole evaporating cylinder. Advantageous conditions for the heat and mass transfer are created, thermal gradients in the film formed as a result of intense evaporation are compensated, cleaning of the evaporating surface from deposits and resinous substances is ensured, the whole evaporating surface utilisation is reached, and a sufficient quantity of the liquid is ensured even in cylinder's lower parts. Favourable effects of wiping will be manifested at high evaporation rates up to $100\,kg\,m^{-2}\,h^{-1}$ without thermal degradation, while the separation power is close to a theoretical value [1]. However, the evaporator's design remains simple (Fig. 1). It is also possible to construct big apparatuses with evaporating areas up to $40\,m^2$ [2]. The wiped film average thickness is ranging from 0.1 to 0.5 mm depending on the viscosity, liquid load, wiper's peripheral speed and the type of wiper. In evaporators with appropriately designed wipers, it is possible to treat liquids of a viscosity of 5–10 Pa s at operating temperature.

Experimental results [3] as well as model study results [4,5] show that the significant resistance for the mass transfer is in the liquid film on the evaporating cylinder. It is necessary that the next development of evaporators and the endeavour to increase their output should be aimed at the improvement of hydrodynamic conditions on the evaporating cylinder. For the time being, the distillation space geometry in molecular evaporators, particularly in those of greater diameters (evaporating cylinder above 200 mm), tends to a concave evaporating area (evaporating area formed on the inner side of an externally heated cylinder), and the centrifugal force is utilised for a vigorous and defined bearing of wiping elements on the evaporating surface. The wiper is made up of a massive basket construction which rotates around the evaporator's axis together with the wiping elements placed on supports in regular intervals parallel to the evaporator's axis and relatively close to the evaporating area.

There are more design solutions for molecular evaporator wipers with a concave evaporating area, comb wipers used in evaporators manufactured by GEA Canzler, Dueren (Fig. 2a) and tube wipers made by UIC, Alzenau (Fig. 2b) are the best known ones.

Comb wipers made of PTFE, electrographite, etc. are freely placed on U-shaped supports along the evaporating

* Corresponding author. Tel.: +421-7-59325-531; fax: +421-7-393-198.
E-mail address: cvengros@chtf.stuba.sk (J. Cvengroš).

1385-8947/01/$ – see front matter
PII: S1385-8947(00)00195-9

Nomenclature

$C(t)$	time distribution function of tracer concentration ($\mathrm{mol\,m^{-3}}$)
t	time (s)
v	peripheral speed of the wiper ($\mathrm{m\,s^{-1}}$)

Greek letters

Γ	peripheral liquid load ($\mathrm{l\,h^{-1}\,dm^{-1}}$)
τ	mean residence time (s)

cylinder. On the side of contact with the evaporating area, they have oblique slots for the liquid to flow through. When the wiping basket is rotating, the comb wipers partially put out due to centrifugal force and bear on the evaporating area. The liquid flowing in the film downward on the evaporation cylinder is captured by the comb wiper and forced to flow at a higher speed through the passage channels of the screw thread downward. This leads to optimum film mixing, and good conditions for the mass transfer are reached. Under some conditions (high viscosity, high liquid load), a roulade-shaped longitudinal wave with intense rotary motion, where the liquid flows downward at a high speed, can be formed before the comb wiper. The peripheral speed ranges from 6 to $8\,\mathrm{m\,s^{-1}}$ [6].

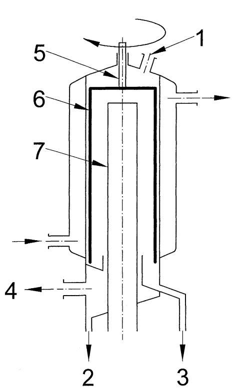

Fig. 1. Scheme of a wiped film molecular evaporator. 1 — feed, 2 — distillate, 3 — residue, 4 — vacuum source, 5 — wiper frame, 6 — wiper, 7 — condenser.

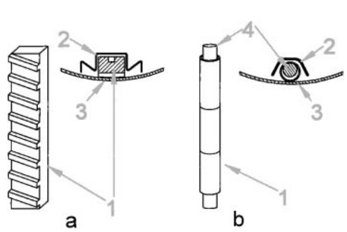

Fig. 2. Comb wiper by GEA Canzler, Dueren (a) and tube wiper by UIC, Alzenau (b). 1 — wiping element, 2 — bearing channel, 3 — evaporating cylinder, 4 — bearing rod.

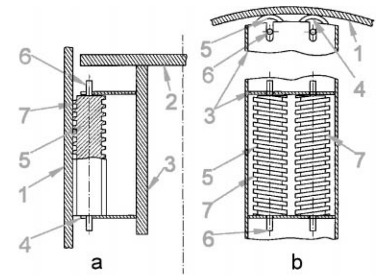

Fig. 3. Profiled-surface roller wiper, simple (a) and twinned (b). 1 — evaporating cylinder, 2 — wiping basket, 3 — bearing channel, 4 — locating groove, 5 — wiping element, 6 — pin, 7 — screw thread.

Tube wipers are made of PTFE tubes that are put on bearing rods the diameter of which is smaller than the inner diameter of the tube wipers (see Fig. 2b). During rotation of the wiping device, tube wipers bear on the evaporating area, leaving a thin film behind themselves. This film is appropriate for efficient evaporation. The wiper creates an intensive longitudinal wave in front of itself allowing parts of the liquid in the wave to escape from the evaporating surface without distillation. Liquid film is restored by the liquid from the longitudinal wave. The tube wiper peripheral speed ranges from 0.3 to $1\,\mathrm{m\,s^{-1}}$ [7]. The liquid scraped away by the tube wipers is captured in the bearing trough and returned by centrifugal force on the evaporating surface.

Our development of a molecular evaporator wiper with concave evaporating surface resulted in a roller wiper [8] (Fig. 3) seated on pins in locating grooves of a bearing trough. There is a deep screw thread with a great lead on the PTFE roller wiper. During the rotation of the wiping basket, the roller wiper bears on the evaporating surface due to centrifugal force. The wiper does not gather the liquid in front of it into a longitudinal wave, but it orients the liquid, forms it into strand-like structures, allows it to pass through the thread openings, bringing it into a complex intense motion. The role of the screw thread on the wiping element surface is to substantially increase the wiping element's permeability for the liquid to minimise the longitudinal wave formation in front of the wiper. This should result in increased hold-up of the liquid on the evaporating surface and in prolonged residence time. According to the thread lead orientation (upward or downward), the particles of a liquid obtain speed components oriented either upward or downward. The liquid possibly captured by threads is returned from the bearing trough by centrifugal force onto the evaporating surface. Increased effect of the process of mixing the liquid in the film can be obtained via a couple of closely placed roller wipers on the support, particularly if the thread lead orientations are different (Fig. 3b). Roller wiper peripheral speed is ranging from 1 to $3\,\mathrm{m\,s^{-1}}$.

The aim of this study is to investigate the function of the developed roller wiper at different liquid loads of the evaporator's perimeter and at different wiper peripheral speeds.

2. Experimental details

2.1. Evaporator and wiper

Measurements were performed in a MO 150 molecular evaporator of own construction. The evaporator's diameter and height are 150 and 600 mm respectively.

The wiper is made of two sets of wiping rollers on two pins relatively shifted by 180°. The number of wiping rollers on one pin is five, the height of one roller is 108 mm, its diameter is 18 mm. The screw thread on its surface is clockwise with a pitch of 4 mm per a thread, the gap width is 2.5 mm, the ridge thickness is 1.5 mm and the thread depth is 2 mm. The free crossectional area for liquid flow is 62%.

The wiper is driven by an electric motor of 1360 rpm at 50 Hz with a 1:4 gear ratio towards slowdown, while motor revolutions can be adjusted by a frequency converter. The wiper can rotate in both directions. The measurements presented in this study were performed on a right-handed screw thread rotating from right to left.

2.2. Residence time distribution curves

When investigating film wiping conditions, residence time distribution curves (RTD curves) of tracer concentration were used [9]. These curves were obtained from conductivity measurements after transformation into concentration functions. The conductivity sensor was made up of a ring with an oblique outer edge just under the wiper. The second electrode was the evaporator's jacket. Conductivity was measured by a conductometer linked to a PC. The computer program evaluates mean value of 10 measurements, minimum sampling interval is 1 s.

The testing liquid was a mixture of tri- and tetraethylene glycols with a dynamic viscosity of 50 mPa s at the measurement temperature (22°C). The measurements were performed in the opened evaporator without distillation. When the feed reached steady state, 1 ml of a tracer (saturated solution of NaCl in water) was injected into the liquid flow in the inlet tube within about 0.5 s. The outlet of this tube is above the plate on the top of the rotating wiper. The beginning of the measurement was derived from the logic signal from the tracer sampler.

Mean residence time τ defined as the first momentum of residence time distribution around the onset was determined from the following equation:

$$\tau = \frac{\int_0^\infty tC(t)\,\mathrm{d}t}{\int_0^\infty C(t)\,\mathrm{d}t}$$

Basic measurement were performed at four different wiper peripheral speeds ν and at three different liquid loads Γ. For each value of the specified parameters, five to six measurements were performed.

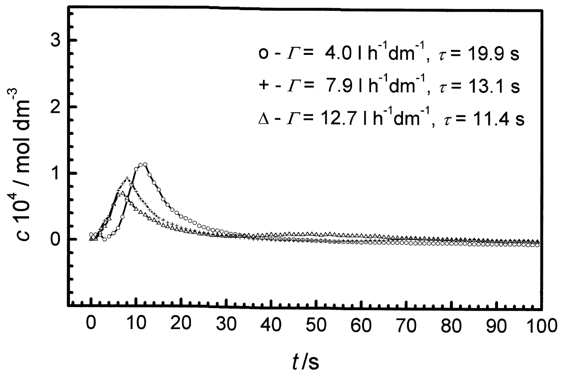

Fig. 4. Residence time distribution curves for wiper peripheral speed of 0.64 m s^{-1} and different liquid loads.

3. Results and discussion

Fig. 4 shows RTD curves for the lowest wiper peripheral speed measured at three different liquid load values. There is an evident shift of the curves towards shorter times with increasing liquid load, while the curves have an expected shape for which the peak position and the half-width are primarily determined by the mean convective speed of liquid and the diffusion coefficient respectively. The curve shift towards shorter times at higher liquid loads is related to the higher film thickness, higher mean speed inside the film that results in the shorter residence time.

Analogical RTD curves for increased wiper peripheral speed are shown in Fig. 5. An evident broadening of the RTD curves can be seen, particularly for lower liquid loads, as well as their non-conventional shape. This curve shape is not accidental, several times repeated measurements at this regime show a high reproducibility of the RTD curve shapes. This non-standard phenomenon disappears if the wiper peripheral speed is considerably increased at a given feed (Figs. 6 and 7). It can be seen in Figs. 6 and 7 that all the curves have the usual shape again and their relative position is as expected – the biggest feed is related to the lowest mean residence time. The wiper peripheral speed has

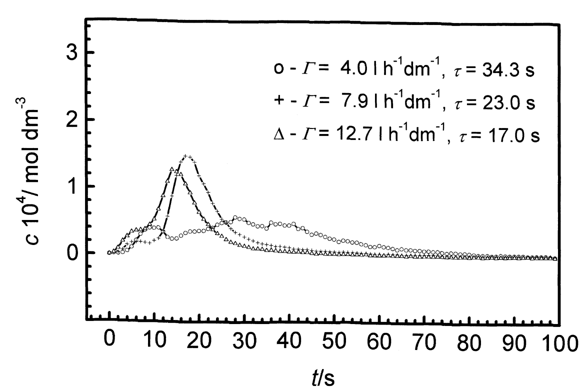

Fig. 5. Residence time distribution curves for wiper peripheral speed of 1.14 m s^{-1} and different liquid loads.

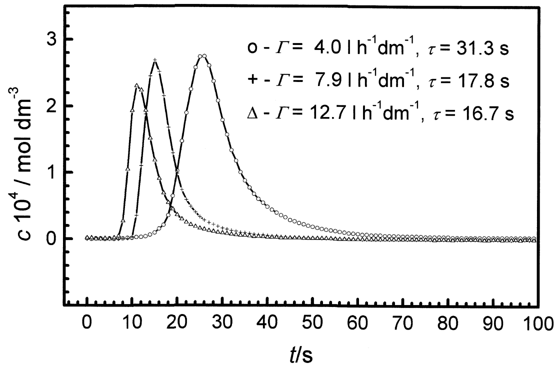

Fig. 6. Residence time distribution curves for wiper peripheral speed of 1.92 m s^{-1} and different liquid loads.

a dominant influence on the shape of RTD curves, while the liquid load effect is lower.

The comparison of RTD curve shapes, e.g. in Figs. 4 and 6, for the same liquid loads and equal volumes of the tracer shows different integral areas of relevant RTD curves. It can be caused by the fact that the angular concentration distribution of the tracer after entering the evaporating cylinder is not uniform. This unevenness is maintained during the whole process of the liquid flow through the evaporator. These concentration differences are equalised with increasing wiper peripheral speed due to the wiping of the liquid. Therefore, higher peripheral speed regimes will result in more uniform angular distribution of the tracer in the detector and in higher conductivity.

Unusual shape of RTD curves at the given combination of feed, wiper peripheral speed and liquid viscosity according to Fig. 5 initiated us to investigate the effect of wiper peripheral speed on the behaviour of the liquid on the evaporating cylinder in detail. This resulted in a set of six measurements (see Fig. 8) at a liquid load of 4 l h^{-1} dm^{-1} indicating complex hydrodynamic conditions in the film wiped with a profiled surface roller wiper.

At low wiper peripheral speeds (Fig. 8, curve 1), the RTD curve has a shape of a bell with elongated tail as expected. At a higher speed (Fig. 8, curve 2), the curve shape qualitatively changes. This indicates that the curve can be construed considered superimposition of a small number of elementary distribution curves the peaks of which are close to each other. This tendency is more markedly demonstrated on increasing the peripheral speed (Fig. 8, curve 3) when the RTD curve is made up of a linear combination of a considerably higher number of elementary curves as in the previous case. Further increase of the peripheral speed (Fig. 8, curve 4), the situation with augmented number of extremes indicates a similar multimodal case, but with a smaller half-width of the curves, i.e. the slopes of curves are steeper. Further peripheral speed increase leads to a decrease in the number of peaks (Fig. 8, curve 5), but the differences between maxima and minima are becoming more distinct what can be related to disappearance of some elementary curves. This process continues by additional peripheral speed increase, resulting in an only marked peak on the RTD curve (Fig. 8, curve 6).

The mean residence time of the liquid continually grows, particularly in the curve 3 in Fig. 8, but it decreases with further peripheral speed increase until it reaches steady state (approximately 30 s) which is considerably higher than in the previous one-peak RTD curve (30.1 s compared to 19.9 s).

The analysis of RTD curves at various wiper's frequencies shows that there are three different hydraulic regimes in the wiped film on the evaporating cylinder.

For the first low peripheral speed regime, an RTD curve with one peak with an extended tail is characteristic. For the wiper studied and a 50 mPa s viscosity testing liquid used, this process is observed at peripheral speeds up to about 0.6 m s^{-1} at a liquid load of 4 l h^{-1} dm^{-1}. The profiled surface wiping element directs the liquid to pass through its passage channels, thus forming it into strands having increased thickness. The liquid strands disappear relatively shortly after the wiping element passage because of surface

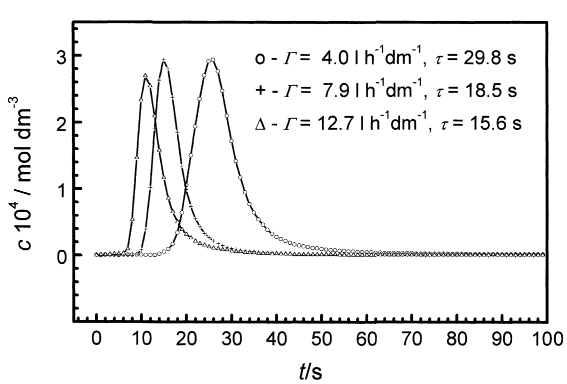

Fig. 7. Residence time distribution curves for wiper peripheral speed of 2.68 m s^{-1} and different liquid loads.

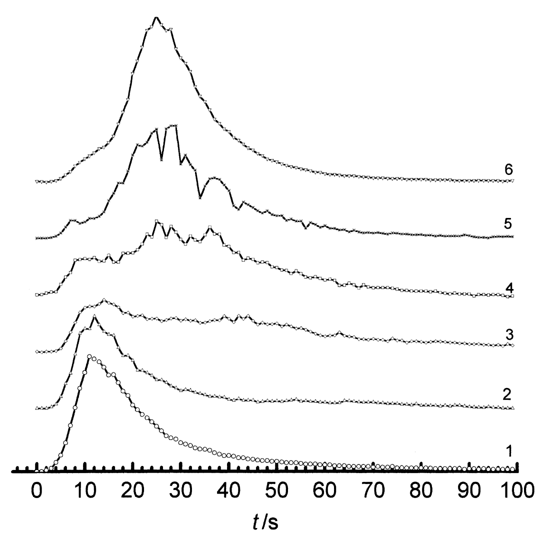

Fig. 8. Residence time distribution curves for liquid load of 4 l h^{-1} dm^{-1} and selected wiper peripheral speeds. 1: v=0.64 m s^{-1}, τ=19.9 s; 2: v=0.92 m s^{-1}, τ=25.1 s; 3: v=1.01 m s^{-1}, τ=39.1 s; 4: v=1.21 m s^{-1}, τ=34.8 s; 5: v=1.41 m s^{-1}, τ=32.3 s; 6: v=1.63 m s^{-1}, τ=30.1 s.

tension effects, and a continuous, more or less undulated laminar liquid film flowing downward is created.

The character of wiping changes with the peripheral speed. There is a certain peripheral speed interval where, at a given liquid load, liquid viscosity and wiper's design, the liquid moves on the evaporation cylinder mostly in the form of liquid strands. These strands which tend to deflect downward after leaving the passage channels do not have enough time to level, merge and disappear, and they are captured at a lower level in the passage channels of the subsequent wiping element. Small portion of the liquid from a higher strand flows to a lower one, but major part of the liquid makes an intricate movement in the strands downward along the screw thread. This is manifested by an increase of the liquid residence time and by an increase of liquid hold-up on the evaporating cylinder. In this regime, the RTD curve loses its typical shape, changing it in an elongated one with several small peaks. This corresponds to a gradual output of the tracer at the screw thread end at the evaporator's bottom. The mean residence time is longer at the beginning of the strand regime than at its end. The strand regime occurred within the peripheral speed range from 0.6 to 1.9 $m\,s^{-1}$.

In general, the strand regime of the liquid movement on the evaporator can be considered favourable from the point of view of molecular distillation. The liquid dwells on the evaporating cylinder for a prolonged period of time, and there is enough liquid to be mixed during the increased hold-up on the evaporating cylinder. Moreover, the wiper mixes the liquid at a high rate in the direction of the evaporator's axis in the strand regime, what enables to enrich also lower evaporator's parts with the volatile component. This regime shows the biggest deviation from plug flow. Relatively long residence times indicate high wiping element's permeability for the liquid.

The third hydrodynamic regime on the evaporating cylinder is indicated by the existence of the only one smooth and narrow peak on the RTD curve after passing the multiple-peak area on increasing the wiper peripheral speed. In the event of sufficiently high wiper peripheral speed, the liquid is not able to form strands, or these strands are not stable, and a continuous downward-moving turbulent film is created on the evaporating area. A sharp and relatively narrow peak on the RTD curve indicates non-significant vertical mixing of the liquid in the film.

The shorter mean residence time in this turbulent regime compared to the mean residence time in the strand regime may also be related to the increased manifestation of a longitudinal wave (roulade) before the wiping element. At higher liquid loads, higher wiper peripheral speed and higher viscosity, the liquid is not capable of entering the wiping element's passage channels, and part of it flows down at increased speed as a longitudinal wave before the wiping element. The liquid in the roulade rotates [10] and serves as a reservoir for replenishing the evaporated liquid in evaporator's lower parts. The wiping element design with the helical channel on its surface and with its rolling movement over the evaporating cylinder should restrict the longitudinal wave formation. An evident longitudinal wave before the wiping element is created at higher liquid loads and higher peripheral speeds. This can be seen in pictures of a wiped coloured liquid on the glass evaporating cylinder obtained by a trick 35 mm Mitchell camera (128 pictures per second).

When comparing RTD curve shapes at constant feed and various peripheral speeds, it is obvious that the residence time of the liquid on the evaporating area grows with increasing wiper peripheral speed within a certain range of values. The wiper is capable of prolonging the liquid hold-up on the evaporating area at increased peripheral speed. From the viewpoint of gentle distillation of thermolabile substances, the prolonged residence time is a positive factor. Heat transfer is a dynamic process depending on time, among other factors. During the prolonged optimum residence time of a liquid on the evaporating cylinder, an increased amount of heat which is necessary to compensate the enthalpy of evaporation can be transferred into the liquid under more gentle conditions at a lower evaporating cylinder temperature [11]. Intensive mixing of the liquid on the evaporating cylinder helps compensate concentration and temperature gradients that are formed in the film as a result of intense evaporation.

Experimental RTD curves corresponding to wiping elements with opposite screw thread orientation on their surfaces were obtained as well. The comparison shows that the effect of thread orientation on the RTD curve shape and the mean residence time is only small. It is obviously connected to the small pitch between screw threads and to the relatively high degree of the wiper's permeability.

The optimum operating regime of the evaporator with a profiled-surface roller wiper of specified geometry for a liquid of 50 mPa s dynamic viscosity at evaporator perimeter liquid load of 4 $l\,dm^{-1}\,h^{-1}$ is found at wiper peripheral speed ranging from 0.7 to 1.9 $m\,s^{-1}$. For these operating and design parameters, favourable conditions for heat and mass transfer are created, and no simultaneous degradation of heat-sensitive compounds occurs.

4. Conclusion

Measured relations between the residence times of the liquid on the film evaporator with a profiled surface roller wiper show that there are three different hydrodynamic regimes created in the film depending on the wiper peripheral speed. For distillation processes, the regime connected with increased hold-up of the liquid on the evaporator is advantageous. The increased hold-up and prolonged residence time enable to utilise evaporator's lower temperatures while maintaining a high evaporation output without thermal hazard for the distilled liquid. The wiping roller with a screw thread on its surface ensures good stirring effect when rolling over the evaporating area. Therefore, the rotary profiled-surface roller wiper combines the advantages of today's wipers of similar types, and, in addition, it minimises the longitudinal wave formation while ensuring high permeability for the liquid.

References

[1] P.R. Watt, Molecular Stills, Chapman & Hall, London, 1963, p. 182.
[2] N. Kukla, Chem. Eng. World 32 (1997) 33.
[3] J. Cvengroš, A. Tkáč, Ind. Eng. Chem. Process Des. Dev. 17 (1978) 246.
[4] J. Lutišan, J. Cvengroš, Chem. Eng. J. 56 (1995) 39.
[5] J. Lutišan, J. Cvengroš, Sep. Sci. Technol. 30 (1995) 3375.
[6] Data sheet of GEA Canzler, GmbH, Dueren, Germany.
[7] Data sheet of UIC, GmbH, Alzenau, Germany.
[8] J. Cvengroš, J. Ďurčanský, Pat. SK 279 (1998) 347.
[9] J. Cvengroš, V. Badin, Š. Pollák, Chem. Eng. J. 59 (1995) 259.
[10] F. Widmer, A. Giger, Chem. Proc. Eng. 51 (1970) 63.
[11] J. Cvengroš, Chem. Eng. Technol. 18 (1995) 49.