AN EQUIPMENT FOR MASS AND HEAT TRANSFER TO A FILM OF LIQUID FLOWING DOWN A PLANE SURFACE. II.*

THE MASS TRANSFER COEFFICIENT AND THE EFFICIENCY AT ABSORPTION OF CO_2 IN WATER

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The paper deals with experimental determination of the mass transfer coefficient at absorption of CO_2 in water flowing down a flat packing. The effect was examined of the liquid flow rate, the length of the packing and the type of the packing. A comparison is given in the paper of various types of packings used for absorption of gases in liquids.

A majority of studies dealing with mass transfer between a liquid film and a gas or vapour phase was carried out on wetted wall columns. To our knowledge, there are only a few papers dealing with this problem in systems where the liquid flows down a flat vertical surface, although the advantage of such systems are unquestionable (low pressure drop, large effective surface per unit volume, high through-puts of both phases, simple design, high porosity and low weight per unit surface).

Adolphi and coworkers[1] have used flat packing consisting of smooth metal sheets enabling the rectification process to be analyzed theoretically (they assumed a defined interfacial area). The experiments were carried out on an equipment 350 mm diameter and 6000 mm high. The distance of the sheets was 7, 12 and 24 mm. A methanol–water mixture was rectified. The results of experiments have shown that the number of theoretical plates was lower than that expected theoretically. The authors explain this discrepancy by imperfect wetting of the sheets. Yet, the low pressure drop, according to the authors, is very attractive from the viewpoint of practical utilization. The efficiency of the equipment, defined by the author as $\eta = (nw)/\Delta p$, is for a flat packing about an order of magnitude higher than that of Raschig rings 24 mm in diameter. Švarcštejn[2] has used flat packing at absorption of nitric oxide gas (0·1—1·8%) in 76·5% sulphuric acid. The column was 350 mm in diameter and 3000 mm high. The spacing of the sheets was 15 mm. From comparison with 50/50/5 Raschig rings given by the author it follows that the flat packing is economicaly 3·5 times more effective as a consequence of 10 times smaller volume of the equipment and 3·7 times smaller weight. Bancroft and coworkers[3] experimented on an equipment 6 × 6 in and 50 ft high. The spacing of the flat packing was 3/16, 1/4, 1/8 and 1/2 in. They used H_2O–HDO and ethanol—isopropyl alcohol systems. According to the authors, the pressure drop and the height of a transfer unit were higher than those expected from comparison with a small

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diameter wetted-wall column. Fleicher[4] gives a comparison of the efficiency of a column with flat packing with a bubble-cap column used for distillation of the cyclohexane–cyclohexanol mixture. From comparison it follows that the performance of the flat packing column per unit volume is 6·5 times greater and the total pressure drop is considerably smaller than that of the bubble-cap column; this enabled distillation to be carried out at a temperature 40°C lower. For the same system as the previous authors, Olevskii and coworkers[5] have used an equipment with flat sheets. The column was 150 mm in diameter and 3400 mm high. The sheets were 7 mm apart. The height of a transfer unit achieved at the Reynolds number ranging between 3000—4000 was 0·8 to 1·3 m The authors stress the necessity of perfect wetting of the packing. Maljusov and coworkers[6] have used sheets as a packing for rectification of water in a column 500 mm in diameter and 15 700 mm high. They conclude that as to the efficiency the flat packing is superior to comparable packings and recommend it for vacuum rectification. They also stress the necessity of a uniform wetting of the packing and provide an auxiliary construction of the liquid distributor.

From the review of the literature it follows that flat packing do have their advantages and that one of the preconditions is a perfect distribution of liquid over the packing.

The aim of the study to be presented was to verify the suitability of a new type of liquid distributor[7], and, furthermore, by proper choice of the type of flat packing to achieve intensive mixing of the liquid flowing down the packing with an increase of the driving force of the process while retaining other advantages of this type of equipment.

The equipment would thus gain on importance for various mass and heat transfer processes between two fluids of which at least one is liquid.

EXPERIMENTAL

Apparatus. A block diagram of the experimental set-up is shown in Fig. 1. The column itself *1* was of rectangular 105 × 15 mm cross-section and 1200 mm high. The material of the column was methylmethacrylate permitting visual observation of the uniformity of distribution of liquid over the flat packing *2*. The dimensions of the packing itself were 100 × 1100 mm. Smooth and perforated metal sheets and expanded metal were used as packings. Additional data on the packing are summarized in Table I. The upper part of the sheet was mounted between two spacers forming together with the top of the packing the bottom of liquid distributor *3*. In case of the smooth and perforated metal sheets the spacers were provided with ridges to leave slots for liquid entering the packing. In case of the expanded metal, the spacers were without ridges because the spatial structure of the metal replaced their function. A detailed description of the distributor is given in preceding communication[8]. There were four openings along the height of the column at the distance 250, 500, 750 and 1000 mm for sampling the liquid *4* and gas inlet *5*. These distances determine also the effective length of the packing, the effect of which on mass transfer was examined. This length could be changed by altering the height of the overflow *6*. The space above the liquid in the distributor *3* was connected with the space in the upper part of the column by a tube *7* to suppress the variations of the height of liquid level in the distributor accompanying the changes of pressure brought about by fluctuations in the gas flow rate. Both phases were at 20 ± 0·2°C before entering the column. Temperature was measured at the inlet and outlet by mercury thermometers *8—11* with the accuracy ±0·2°C, pressure by U-manometers with the accuracy ±1 mm of water head. The flow rates of both phases were measured by calibrated rotameters *14—16* with the accuracy of 1% for liquid and 2% for gas. The gas was supplied from a pressure cylinder *17* and was saturated in gas bubblers *18* placed in a thermostat

TABLE I
Packing Characteristics

Type of packing mm	Thickness of sheet mm	Specific free cross-section at 10 mm spacing of sheets	Type of packing size of mesh in mm	Thickness of sheet in mm	Specific free cross-section at 10 mm spacing of sheets
Smooth metal sheet 0	1·0	90·0	expanded metal 28 × 8	0·9	97·0
Perforated metal sheet 8	1·1	95·3	expanded metal 16 × 7·3	0·6	97·4
Perforated metal sheet 4 × 4	1·0	93·2	expanded metal 16 × 5·5	0·6	97·1
Perforated metal sheet 6·7 × 6·7	0·6	96·9	expanded metal 10 × 5	0·4	97·8

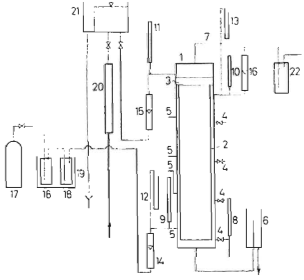

FIG. 1

Block Diagram of Experimental Set-Up

1 Jacket, *2* flat packing, *3* distributor, *4* sampling openings, *5* gas inlets, *6* adjustable overflow, *7* tube for equalizing pressure, *8—11* thermometers, *12—13* U-manometers, *14—16* rotameters, *17* pressure cylinder, *18* gas bubbler, *19* thermostat for gas, *20* thermostat for liquid, *21* overflow tank, *22* bubbler.

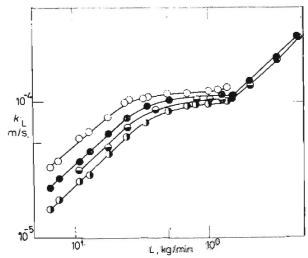

FIG. 2

Plot of the Mass Transfer Coefficient on the Density of Wetting of a Flat Smooth Sheet of Packing

Effective length of packing, mm: ○ 250, ● 500, ◒ 750, ◑ 1000.

19. The saturation was to eliminate evaporation of liquid from the flowing film. Tap water was supplied *via* thermostat into an overflow tank *21*. The flow rate of carbon dioxide was kept at a level well above the rate of absorption in order to keep the relative concentration of possible impurities constant. The content of impurities of the gas from the cylinder could reach as much as 1·5%. The flow rate of the excess gas was measured by a rotameter *16* on one hand and visually checked in a bubbler *22*.

Analysis. The sample of the exiting liquid was taken through one of the tubes *4* (at the end of the effective length of the packing) by a pipete. The pipete was rinsed for 5 minutes by the sampled liquid. The tip of the sampling tube was about 5 mm below the level of liquid in the apparatus. The sample was transferred and discharged below the level of 0·1N solution of barium hydroxide and after adding a few drops of phenolphtalein solution the surplus was titrated by 0·1N solution of oxalic acid. Since the formation of H_2CO_3 from CO_2 is slow, several equivalent points appear which change colour slower and slower. Accordingly, after first fading of the phenolphthalein dye the sample was left for 5 minutes and only then the titration of the pale solution completed. This point was considered as final for titration. The quality of the inlet water was checked similarly.

Processing of the experimental data. The length and the type of packing were taken as variables for experiments in addition to the flow rate of liquid. Each experiment was repeated five times on average under identical conditions. The value of the over-all mass transfer coefficient was calculated from experiments using the relation

$$K_L = 2{\cdot}3 \frac{L}{\varrho_l F} \log \frac{C_r - C_P}{C_r - C_k} \qquad (I)$$

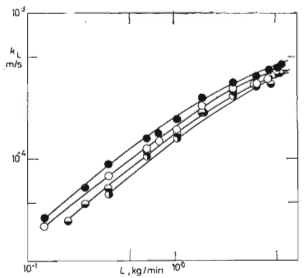

FIG. 3

Plot of the Mass Transfer Coefficient on the Density of Wetting of Perforated Metal Sheets with Openings 8 mm in Diameter

Effective lengths of packing, mm: ● 250, ○ 500, ◒ 750, ◑ 1000.

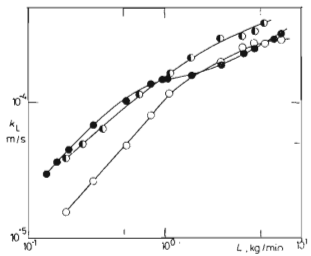

FIG. 4

A Comparison of the Dependence of the Mass Transfer Coefficient on the Density of Wetting for Perforated Metal Sheets with Square and Circular Openings and l = = 750 mm

Size of openings ● 4 × 4 mm, ○ 6·75 × × 6·75 mm, ◐ 8 mm in diameter.

and the efficiency was defined as

$$\eta = \frac{K_L a G/A}{\Delta p/l}, \tag{2}$$

assuming that 100 sheets of 1000 × 1000 mm packing can be accommodated in 1 m^3, *i.e.* 200 m^2/m^3. It is further assumed that the coefficient $K_L a$ is independent of the gas flow rate and of concentration in a wide range[9,10] as well. The average values of the coefficients obtained are plotted in Figs 2—6. Fig. 7 shows the coefficients $K_L a$ related to a unit volume of the apparatus (assuming again that 100 sheets of 1000 × 1000 mm packing can be accommodated in 1 m^3, *i.e.* 200 m^2/m^3) together with these coefficients for various types of packings and plates. For plate columns $K_L a$ was calculated from Murphree's efficiency by means of the number of transfer units from the relation

$$N_{OL} = -\ln (1 - E_{OL}) \tag{3}$$

based on a piston flow and constant equilibrium concentration, and from

$$\frac{L/\varrho_l A}{K_L a l} = N_{OL}. \tag{4}$$

The total distance between two plates was taken for l, not only the height of the froth, which is necessary if the value of $K_L a$ is to be comparable with that for the packings.

Finally, Fig. 8 gives the efficiency defined by Eq. (2) for various packings in dependence on the liquid flow rate. In some cases the dependence is given for several gas flow rates.

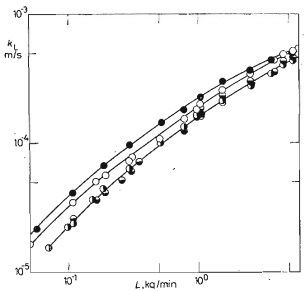

FIG. 5

Plot of the Mass Transfer Coefficient on the Density of Wetting for Expanded Metal 16 × 5·5 mm

Effective length of packing, mm: ● 250, ○ 500, ◒ 750, ◑ 1000.

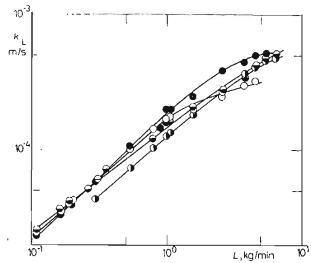

FIG. 6

A comparison of the Dependence of the Mass Transfer Coefficient on the Density of Wetting for Various Types of Expanded Metal and l = 750 mm

● 10 × 5 mm, ○ 16 × 5·5 mm, ◒ 16 × × 7·3 mm, ◑ 29 × 8 mm.

DISCUSSION

Firstly, from Fig. 2 it can be seen that the course of the dependence of the mass transfer coefficient is analogous to that found in wetted wall columns 26 mm in diameter[11] and the same system, and also the values of the mass transfer coefficients are approximately equal. It is interesting to note that the region of constant mass transfer coefficient corresponds from hydrodynamic standpoint to the transition region[12] of the flow. From Fig. 2 it can be further seen that the effect of the effective length of the packing is significant only at low densities of wetting; at higher densities it almost vanishes.

An increase of the mass transfer coefficient in the whole region of liquid flow rates from the values for smooth sheets is evident from Figs 3–6 plotting the mass transfer coefficient on flat packings providing continuous mixing of trickling liquid (perforated sheets, expanded metal). The difference is most conspicious in the region of constant mass transfer coefficient for smooth packing which for perforated sheets and expanded metal does not appear at all. The increase of the mass transfer coeffi-

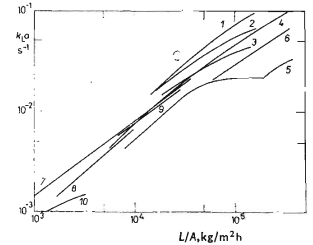

FIG. 7

A Comparison of the Dependence of the Mass Transfer Coefficient per Unit Volume on the Density of Wetting and the Velocity of Vapours for Various Packing

1 Bubble plates[16], overflow 2 in, w = = 0·96 m/s; *2* bubble plates[16], overflow 2 in, $w = 0{\cdot}65$ m/s; *3* bubble plates[16], overflow 2 in, $w = 0{\cdot}32$ m/s; *4* expanded metal 10 × 5 mm; *5* smooth sheet; *6* Raschig rings[15] 2 in; *7* Raschig rings[14] 1 in; *8* Raschig rings[19] 2 in; *9* Raschig rings[13] 1 in; *10* Raschig rings[17] 1 in.

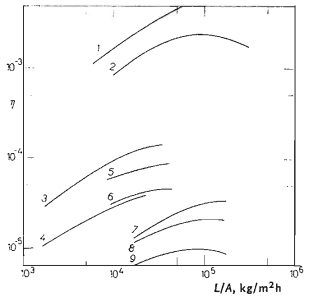

FIG. 8

The Efficiency of Various Packings in Dependence on the Density of Wetting and the Velocity of Vapours

1 Expanded metal 16 × 5 mm, w = = 1 m/s; *2* smooth sheet $w = 1$ m/s; *3* Raschig rings[19] 2 in, $w = 0{\cdot}65$ m/s; *4* Raschig rings[19] 1 in, $w = 0{\cdot}65$ m/s; *5* Raschig rings[13] 1 in, $w = 0{\cdot}3$ m/s; *6* Raschig rings[13] 1 in, $w = 0{\cdot}65$ m/s; *7* bubble plates[16], overflow 2 in, $w = 0{\cdot}96$ m/s; *8* bubble plates[16], overflow 2 in, $w = 0{\cdot}64$ m/s; *9* bubble plates[16] overflow 2 in, $w = 0{\cdot}32$ m/s.

cient is comparable on average with that achieved by artifical turbulisation of the film on the wall[11]. For this type of packing one can also observe certain effect of the length of the packing, particularly at low densities of wetting.

From comparison of the mass transfer coefficients for various packings in Fig. 7 it is seen that for the spacing of the sheets used in this work (10 mm) the coefficients for given liquid flow rate are practically identical (excepting the smooth sheet). As another advantage of the new type of packing appears the possibility of increasing the load of phases per unit area and hereby the mass transfer coefficient. In some cases also the built-in surface can be enlarged by as much as a factor of two ($400\ m^2/m^3$) which doubles the value of the mass transfer coefficient per unit volume.

One of the most significant advantages, however, is the low pressure drop. From Fig. 8 it is seen that the criterion defined in Eq. (2) is almost two orders of magnitude greater than that for other arrangements, mainly as a consequence of the low pressure drop and high through-put.

Expanded metal which has appeared as the most effective of the packings used has still additional advantages. From a unit of area of metal sheet a several times larger area of expanded metal can be manufactured with no scrap, and owing to the spatial structure of the expanded metal the mechanical strength of the packing is relatively high even when a fairly thin sheet is used. Thus the weight of the packing, in contrast to standard ones, can be considerably reduced. Furthermore, with the liquid distributor of our design, which has proved efficient, the spacers need not have protruding ridges because the spatial structure of the expanded metal suffices for bringing the liquid onto the packing.

LIST OF SYMBOLS

A cross-sectional area
C concentration
E_{OL} Murphree's efficiency
F gas–liquid interfacial area
G mass flow rate of gas
K_L over-all mass transfer coefficient
$K_L a$ mass transfer coefficient per unit volume
L mass flow rate of liquid
l effective length of packing
N_{OL} number of transfer units
n number of plates
Δp pressure drop
w velocity of vapours
η efficiency
ϱ density

Subscripts

r equilibrium
p initial
k final
l liquid

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