AN EQUIPMENT FOR MASS AND HEAT TRANSFER TO A FILM OF LIQUID FLOWING DOWN A PLANE SURFACE. III.*
THE MASS TRANSFER COEFFICIENT AND EFFICIENCY AT ABSORPTION OF AMMONIA IN WATER

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The paper deals with an experimental determination of the mass transfer coefficient between gas and liquid flowing down a flat packing in the ammonia–air–water system. The effect was examined of the flow rates of both phases and the length and the type of flat packing. The mass transfer coefficients obtained are compared with the values published in the literature for various types of packing. The efficiencies are compared involving the effects of the mass transfer coefficient, the through-put of gas and the pressure drop.

In the preceding paper of this series[1] the results were published of a study of absorption of carbon dioxide into a film of water flowing down a vertical flat packing. The carbon dioxide–water system is regarded from mass transfer viewpoint as one with principal resistance in the liquid phase.

The present study summarizes the results obtained on an identical equipment with the ammonia–air–water system, regarded as gas phase controlled. On the basis of results in these two systems it is possible to make a rough prediction of the efficiency of the flat packing for other systems.

The experimental studies of absorption of the ammonia–air mixture into a film of liquid published to date were carried out mostly in wetted wall columns. For instance, Chambers[2], who studied absorption of nitrogen dioxide in water solution, used ammonia as a "calibration system" with principal resistance in the gas phase. The author absorbed ammonia in water and sulphuric acid and from comparison of the results concluded that there is only a slight resistance on the liquid side at absorption in water. In a similar way determined the liquid phase resistance also other authors. Chertkov and coworkers[3] found that at gas velocity 1 m/s the liquid phase resistance amounts to 24% of the total resistance. Norman and Salomon[4] found from experiments on ceramic discs that the importance of the liquid phase resistance depends on the density of wetting and concentration. At high densities of wetting the liquid phase resistance is small owing to perfect wetting of the packing but it may become significant at low densities of wetting. Also at high concentrations of ammonia the resistance of the gas phase increases due to the increase of the Henry constant. For evaluation of the experimental data the authors used relations

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obtained by Stephens and Morris[5] at absorption of ammonia and carbon dioxide in water on discs. Finally, Walter and coworkers[6] found at absorption of carbon dioxide and ammonia in a bubble-cap column that the former has 98% of the resistance in the liquid phase and the latter 97% in the gas phase. From this survey it is evident that the ammonia–air–water system may be regarded as one with principal resistance on the gas side. As another advantage for our purposes appears that the experimental data published in the literature are numerous and were obtained on a variety of equipment providing thus standards for comparison and testing of the new equipment.

EXPERIMENTAL

A sketch of the experimental set-up is shown in Fig. 1. The column and the distributor are identical with those described in preceding communication[1]. Smooth metal sheets and expanded metals 10×5 mm mesh (0·6 mm thickness, 45·79% specific free surface), and $16 \times 5·5$ mm mesh (0·6 mm thickness, 52·25% specific free surface) were used as packings. The effective length of the packing was 500 and 750 mm; these distances indicate position of gas inlets *4* measured from the bottom of the distributor. Tap water thermostated to $20 \pm 0·2°C$ by a heater *5* controlled by a thermometer *6* was used as liquid. The water was then supplied into an overflow tank *7* and further into the column *1* via rotameter *8*, and into a column *29* for humidification of the gas phase which also ensures equal temperatures of both phases entering the absorption column. The humidification column was 100 mm diameter and 1000 mm long filled by Hyperfil. The air from
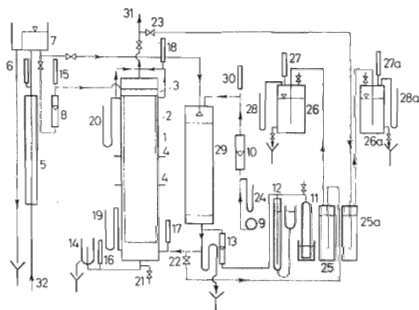

Fig. 1

Block Diagram of Experimental Set-Up

1 Jacket; *2* flat packing, *3* distributor, *4* gas inlet, *5* heater, *6* regulating thermometer, *7* overflow tank, *8* rotameter, *9* blower, *10* rotameter, *11* pressure cylinder — ammonia, *12* safety vessel, *13* rotameter, *14* adjustable overflow, *15—18* thermometers, *19*, *20* U-manometers, *21* sampling opening, *22* sampling opening (gas inlet), *23* sampling opening (gas outlet), *24* U-manometer, *25*, *25a* absorption flask, *26*, *26a* Marriotte bottles, *27*, *27a* thermometer, *28*, *28a* U-manometer, *29* humidification column, *30* thermometer, *31* gas exit, *32* tap water.

a pump *9* was brought into the humidification column *via* rotameter *10*; an orifice was used in case of higher flow rates. Ammonia was continuously added from a pressure cylinder *11 via* rotameter *13* to the air leaving the humidification column. The ammonia tubing was provided with a safety vessel *12*. The pressure cylinder was rinsed with water to prevent freezing and fluctuation of ammonia pressure particularly at high flow rates. The height of liquid in the column was adjusted by an overflow *14*. To prevent variations of the liquid head in the distributor following the fluctuations of gas velocity accompanied by changes of pressure in the column, the top of the column was interconnected with the space above the distributor. The temperatures of both phases at the inlet and exit of the column were measured by mercury thermometers *15— 18* with the accuracy $\pm 0.2°C$. The pressures were measured by U-manometers *19, 20* and *24* with the accuracy ± 1.0 mm of water head.

Sampling and analysis. The sampling of liquid on the exit from the column was carried out through a cock *21* directly into a pipette flushed for some time by the sampled liquid. The content of the pipete was then added to a known volume of a dilute solution of sulphuric acid and the excess acid was titrated by a solution of sodium hydroxide using methyl red. The gas for analysis was sampled on the exit and the inlet by cocks *22* and *23* and lead through bubblers *25* and *25a* filled with a known volume of dilute sulphuric acid and an indicator dye. Two bubblers in series were used in each branch, the second of which served as a check that all ammonia was absorbed quantitatively. It turned out that even at the highest flow rates of gas used all ammonia was absorbed in the first bubbler. The gas stripped of ammonia was collected above the level of water in Marriotte bottles *26, 26a* provided with thermometers *27, 27a* and manometers *28, 28a.*

Measurements. The flat packing was first perfectly rinsed with water and then a selected flow rate was adjusted. At the same time the requested flow rate of gas was set. By means of a throttle valve on the exit pipe the pressure necessary for blowing the gas through the bubblers and filling the Mariotte bottles was adjusted. Finally, the flow rate of ammonia was adjusted and the sampling began after 15 minutes. The respective ranges for flow rates of gas and liquid were $0.5—6.3$ l/min and $1.5—30$ kg/m min.

Data processing. The aim of this study was to find the dependence of the mass transfer coefficient on the flow rates of both phases and the length and the type of packing. A following relation was used for evaluation of the mass transfer coefficient

$$K_G = \dot{n}/F \, \Delta p_m, \tag{1}$$

where Δp_m is the log-average driving force expressed by means of partial pressures

$$\Delta p_m = [(p - p_{e1}) - (p - p_{e2})]/\ln [(p - p_{e1})/(p - p_{e2})]. \tag{2}$$

A relation provided by Ramm[7] was used to calculate the partial pressure of ammonia above its aqueous solutions

$$\log p_e = \left(-\frac{1750}{T} + 1.1 \log C + 7 \right). \tag{3}$$

The efficiency was defined as in the previous communication[1]

$$\eta = \frac{K_G a \cdot G}{\Delta p/l}. \tag{4}$$

RESULTS

From Fig. 2, depicting the dependence of the mass transfer coefficient on the velocity of gas on a smooth metal sheet and its comparison with the values obtained in a wetted-wall columns[3,8,9], it is seen that the mass transfer coefficient is practically independent of the density of wetting in the range $15-40$ kg/m min of our experiments. This result agrees well with those obtained on other types of equipment[3,8] with the exponents of the density of wetting reported to range between 0·068 and 0·079. Also the values of the exponent in the power expression for the effect of the gas velocity for a flat packing and wetted wall column are very close (0·76 for flat smooth packing and $0.732-0.780$ for wetted wall columns). A different value for wetted wall column is reported by Chertkov[3], namely 1·27. Since the mass transfer coefficient is independent of the density of wetting (or depends on it very slightly), its increase on smooth flat packing from the values found on wetted-wall columns (as it is apparent from Fig. 2) can be accounted only by more favourable hydrodynamic conditions for
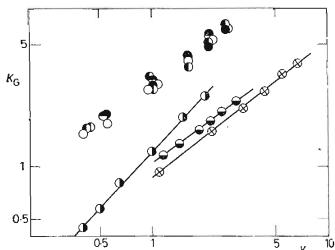
Fig. 2

Plot of the Dependence of the Mass Transfer Coefficient K_G (kg mol/m² h atm) on the Gas Velocity v (m/s) and the Density of Wetting L (kg/m min) on a Flat Sheet

○ Smooth sheet $L = 15$, $l = 0.75$ m; ● smooth sheet $L = 20$, $l = 0.75$ m; ◑ smooth sheet $L = 30$, $l = 0,75$ m; ◓ smooth sheet $L = 40$, $l = 0.75$ m; ◐ wetted wall[3] $L = 2.048$; ⊗ wetted wall[9] $L = 1.28$; ◒ wetted wall[8] $L = 3.33$.
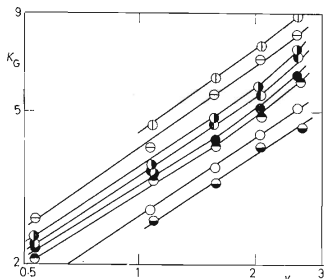
Fig. 3

The Dependence of the Mass Transfer Coefficient K_G (kg mol/m² h atm) of the Gas Velocity v (m/s), the Density of Wetting L (kg/m min) and the Type of Expanded Metal $l = 0.5$ m

◒ Expanded metal 16×5.5 mm, $L = 5$; ◒ expanded metal 16×5.5 mm, $L = 10$; ◐ expanded metal 16×5.5 mm, $L = 20$; ◑ expanded metal 16×5.5 mm, $L = 30$; ● expanded metal 10×5.0 mm, $L = 5$; ● expanded metal 10×5.0 mm, $L = 10$; ⊖ expanded metal 10×5.0 mm, $L = 20$; ⊕ expanded metal 10×5.0 mm, $L = 30$.

both phases. The lowest density of wetting on the smooth flat packing, characterized by the onset of film collapse, was 8 kg/m min. Increasing concentration of ammonia and the velocity of gas enhances the aptitude of the film to breakdown[10].

Fig. 3 shows a comparison of the results of absorption using two types of expanded metal of the effective length 500 mm. From this Fig. it is seen that the expanded metal with smaller mesh (10×5 mm) is more effective and accordingly this type was used for absorption in the following. From the same figure it is further seen that

FIG. 4

The Dependence of the Mass Transfer Coefficient K_G (kg mol/m^2 h atm) on the Density of Wetting L (kg/m min) for Expanded Metal $10 . 5$ mm and $l = 0.75$ at Various Gas Velocities v (m/s)

$\bigcirc v = 1.1$; $\bullet v = 1.5$; $\ominus v = 2.5$; $\ominus v = 3.1$; $\ominus v = 4.4$; $\ominus v = 5.3$.
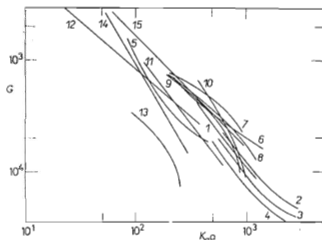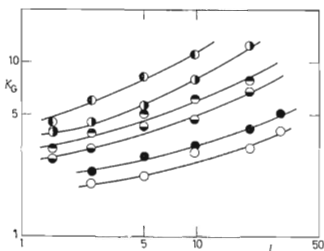

FIG. 5

A Comparison of the Dependence of $K_G a$ (kg mol/m^3 h atm) on the Gas Mass Velocity G (kg/m^2 h) for Various Equipments and Density of Wetting L(kg/m^2 h)

1 Smooth sheet $L = 90\,000$; 2 expanded metal 10×5 mm $L = 120\,000$; 3 expanded metal 10×5 mm $L = 60\,000$; 4 expanded metal 10×5 mm $L = 30\,000$; 5 1 in Raschig rings[14] $L = 2440$; 6 1 in Raschig rings[14] $L = 14\,760$; 7 bubble-cap plate[11] $L = 74\,760$; 8 bubble-cap plate[11] $L = 37\,300$; 9 bubble-cap plate[11] $L = 18\,600$; 10 sieve plate[17,20] $L = 5000-15\,000$; 11 turbogrid plate[16] $L = 16\,240$; 12 turbogrid plate[15] $L = 5250$; 13 bubble-cap plate[6] $L = 4810$; 14 1 in Raschig rings[13] $L = 2440$; 15 1 in Raschig rings[12] $L = 14\,700$.

in case of expanded metal the liquid flow rate does exert a significant effect. With increasing flow rate the value of the mass transfer coefficient increases as well.

Fig. 4 plots the resulting values of the mass transfer coefficient for expanded metal 10 × 5 mm mesh and 750 mm of effective length in dependence on both the gas and liquid flow rates. In this case too the effect of the liquid flow rate is clearly visible and it is enhanced by increasing flow rate of liquid. The last two Figs 5 and 6 serve to compare the results achieved on the flat packing with the results of other authors on different types on packing. Fig. 5 indicates that within the operating range of gas velocities for individual packings, the values of mass transfer coefficients related to a unit volume of equipment are comparable. It is the advantage of the flat packings, however, that they can be operated economically at higher velocities and the mass transfer coefficients significantly increase. Since the efficiency of plate columns is given in the literature mostly as Murphree's efficiency, the calculation of $K_G a$ from these values was performed similarly as in the last communication. It was assumed that the spacing of the flat packings is 10 mm which corresponds to $a = 200 \text{ m}^2/\text{m}^3$.
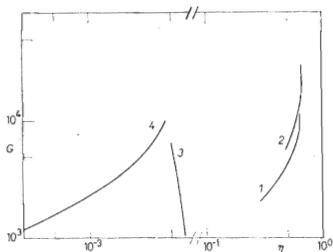

FIG. 6

The Dependence of η on the Gas Mass Velocity G (kg/m² h) on Density of Wetting L (kg/m² h) and Various Equipments

1 Smooth sheet $L = 90\,000$; *2* expanded metal 10 × 5 mm $L = 60\,000$; *3* 1 in Raschig rings[12] 1 in $L = 14\,700$; *4* bubble-cap plate[11] $L = 37\,300$.

The utility of flat packings stands out clearly from Fig. 6 plotting the efficiency defined by Eq. (*4*). This value is for flat packings two orders of magnitude greater than for other common types of packing, thanks to large through-put and mainly the low pressure drop.

LIST OF SYMBOLS

A	cross-sectional area	G	mass flow rate of gas per unit area
a	interfacial area per unit volume	K_G	total mass transfer coefficient
C	concentration per unit volume	L	density of wetting (per unit length or unit area)
F	surface of packing (2 times width times length)	l	effective length of packing

n absorbed amount per unit time   Subscripts
p partial pressure (in Eq. (3) in Torr)
Δp_m mean driving force   1   inlet
v superficial velocity of gas   2   outlet
η efficiency   e   equilibrium

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