

GAS ABSORPTION WITH WETTED-WICK COLUMN

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Abstract—The newly designed wetted-wick column was constructed by using fiber glass and wire mesh and studied to investigate its feasibility as an alternative to the conventional packed tower in gas purification processes.

Absorption of carbon dioxide in water for physical absorption and in aqueous mono-ethanolamine (MEA) solution for chemical absorption were employed for this investigation. A comparison with the packed tower, based on overall mass transfer coefficients (K_{OGa}) and height of transfer units (HTU_{OG}) at the same range of operating conditions, feed gas compositions, and gas retention time was made. High mass transfer coefficients (K_{OGa}) and low heights of transfer unit (HTU_{OG}) were obtained for the wetted-wick column. The high efficiency of mass transfer was caused by a number of factors: the separate passage of liquid and gas flow, an increased wetting surface, a longer period of residence time of the liquid and gas stream, and an increased interfacial area.

The present study shows that the wetted-wick column is a highly recommendable device as an alternative to the packed tower in gas purification processes, either for physical gas absorption or for chemical gas absorption.

INTRODUCTION

Gas absorption into liquid is probably the most important gas purification technique and is common to a great number of processes[1]. It is required in natural gas processing, in refining operations, in synthesis gas production, or in the production of chemicals to avoid catalyst poisoning. The types of absorbers used for gas purification operations are packed, plate, or spray towers. The packed towers are, in general, preferred, due to a number of advantageous characteristics. In spite of the many features of the packed tower, there still remain several inherent limitations.

1. Inherent Limitations of Packed Tower

The traditional packed tower has many inherent limitations which cause poor performance: low liquid-gas interfacial area (low wetting surface), non-uniform liquid distribution (channeling), flooding, backmixing, and excess wall flow of liquid, which causes a high liquid-to-gas ratio and requires high energy (steam) consumption for absorbent regeneration.

To avoid the flooding phenomenon, absorption tower operation must maintain a high liquid-to-gas

ratio. For conventional absorption at large liquid-to-gas ratios, the concentration of the transferring component in the liquid phase is low due to the excess liquid. Most gas purification plants, however, require the regeneration of solvent. Hence, the greater the amount of excess liquid, the greater the amount of excess energy (steam) that must be consumed for solvent regeneration. The essential utilities of gas absorption plants consists of the steam consumption for solvent regeneration, the cooling water requirement at the column overhead, electric energy consumption for the pump, and solvent loss[2]. Buttwell et al.[3] have reported that for an ammonia plant using the so-called Amine Guard III system, 88% of the total annual utility cost represents the steam needed for solvent recovery. Steam consumption of the regeneration column depends primarily on the amount of solvent to be regenerated.

An important factor in efficient packed tower operation is the maximum wetting of packing materials. Even though many kinds of tower packing[4-7] and packing supports[8] have been studied for good contact between liquid and gas, Chen and Jain[9], Niranjana et al.[10] have reported that the efficiency of screen and wire gauze packing was two to four times higher than that of the conventional ring or saddle packing.

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The liquid distributed over the top of the packing tends to flow along localized paths through the packing because a certain path through a packed bed offers less resistance to gas flow than others. The dynamic pressure of the gas in the path of lower resistance will tend to push the liquid flow to neighboring paths, which causes liquid channeling. Especially at low liquid rates, much of the packing surface may be dry or covered by a stagnant film of liquid (channeling phenomena). Low liquid rates lead to incomplete wetting, thus decreasing the contact efficiency. Manning and Cannon[11] reported that the seriousness of the channeling effect is illustrated in the following example: without the channeling phenomena, 56 theoretical plates are required to give a certain degree of separation, but 1% of the liquid channeling requires 100 theoretical plates. This means that 1% of the liquid channeling has resulted in an apparent loss of 44 theoretical plates for their example.

Another significant factor for efficient packed tower operation is the proper distribution of liquid over the bed cross section. Platt[12], and Ryan[13] have shown that, no matter how uniform the distribution of the liquid at the top of the packing, there is marked maldistribution at lower levels.

There is another factor in the packed tower which influences the spread of liquid and liquid distribution within the packed bed itself. Roblee et al.[14], Ridgeway and Tarbuck[15], and Pillai[16] observed that the interface of wall and packing material in the packed tower represents a region of higher voidage as well as a discontinuity in packing structure. Once liquid has entered the interface of wall and packing material, the liquid is less likely to leave this region. The result will increase liquid flow along the wall and force the gas stream to flow up the center of the bed. A considerable proportion of the liquid runs down along the wall of the column, due to a high voidage at the bed-to-wall border. Hence, this liquid is not very effectively exposed to the gas. The excess wall flow has been experimentally measured by Porter and Templeman[17]. Porter and Templeman[17] reported that up to 50% of the total liquid fed to the 6 inch diameter packed tower appeared on the wall, depending upon the liquid flow rate and the column-to-packing diameter ratio. The effect of maldistribution on mass transfer efficiency has been studied by Manning and Cannon[11] and Huber and Hiltbrunner[18]. For the reduction of wall flow, various types of redistributors[19] have been used. There are, however, some disadvantages associated with the use of redistributors[19]. Some redistributors induce flooding at the redistribution level. At high gas rates, liquid can be entrained around redistributors,

decreasing the efficiency of mass transfer. Moreover, redistributors require an elaborate design of the column and redistributor supports, which increase investment cost.

Packed towers are also subject to axial mixing, so called back mixing, because the downward movement of liquid induces downward movement of gas, and there is relative movement within each fluid stream parallel to the tower [19,20]. The transport of solute by axial mixing tends to reduce the concentration difference for interface mass transfer, which severely reduces the absorption rates. The poor performance requires larger equipment resulting in a larger excess liquid flow and excess energy for regeneration. The state-of-the-art on back-mixing effects in gas-liquid reactors, including packed towers, was reviewed by Shah et al.[21]. A design problem illustrating the detrimental effects of axial dispersion is presented by Sherwood et al.[22]

2. Features of Wetted-Wick Column

The wetted-wick absorption column provides many features which improve the inherent drawbacks of the conventional packed tower, which has been described above. The wetted-wick column provides a 100% wetted surface, owing to the capillary action which spreads liquid over the wick material, in contrast to the partially wetted surface of a conventional packed tower. The main advantage of the wetted-wick column is that a 100% wetted surface can be sustained even at very low liquid flow, whereas much of the packing surface in the packed tower may be dry. Thus, a high wetted surface may be maintained at any liquid-to-gas flow ratio. A high wetted surface at low liquid flow rate offers a low liquid-to-gas flow ratio, which results in no excess liquid flow, and, therefore, saves steam (energy) for regeneration.

In addition, this device does not create the back mixing which causes the poor mass transfer. Most of the conventional mass transfer devices, such as spray towers, baffle towers, packed towers, and tray towers, suffer from the backmixing phenomena in absorption, distillation, and extraction[20].

Another feature of the wetted-wick column is that it can be operated in the absence of gravity, even in reverse direction to gravity. In a gravity-free environment, the liquid is transported through the wick via capillary action, which enables the wetted-wick column to be utilized in space technology for gas purification processes.

In summary, the newly designed wetted-wick column has many advantages over the conventional mass transfer devices: a high interfacial area, 100% wetted surface, no wall flow of liquid, uniform distribu-

tion of liquid, no back mixing, and low liquid-to-gas ratio. All of these will contribute to low energy consumption for regeneration, low electric power consumption for pumping liquid absorbent, and smaller equipment size. However, certain engineering problems associated with the wetted-wick column must be addressed. One major problem is the fabrication of the wetted-wick column; that is, how uniformly the column should be lined with wick material to increase the interfacial area. The lining of wick materials on the column might require a more complicated and elaborate design than manufacturing of the packed towers.

DESCRIPTION OF WETTED-WICK COLUMN

The inner surface of the wetted-wick column is covered with a layer of capillary-porous materials and is wetted with a liquid phase of solvent. The capillary-porous materials are supported with wire clothes, as shown in Figure 1. Various porous materials (cotton, fiber glass, gauzes or sintered porous structures, etc.) can serve as the wick. For more liquid flow and higher liquid-gas interfacial area, it is better to put arteries,

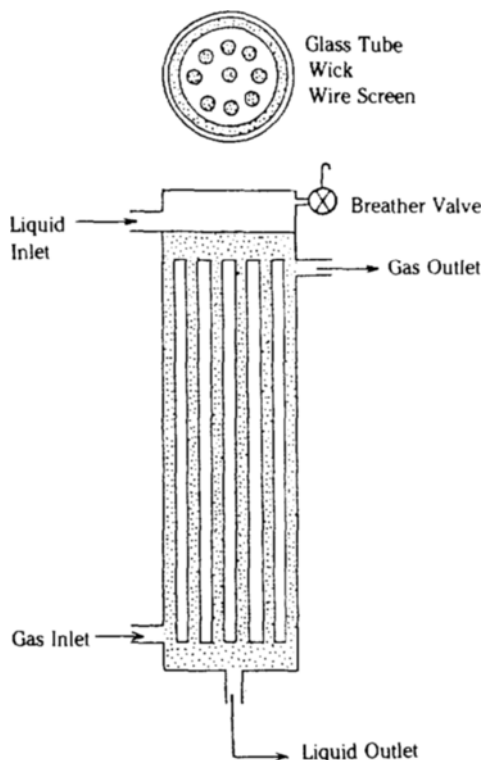


Fig. 1. Schematic diagram of wetted-wick absorption column for higher efficiency.

which are composed of wick and are supported with stainless steel wire screen, into the gas space. How much liquid-gas interfacial area is needed at a given volume of column depends mainly on how many arteries can be put into the gas space. More arteries provide more interfacial area per-unit-volume and higher capacity of the absorption column.

The wetted-wick column offers: a very high gas-liquid interfacial area per-unit-volume of bed, no back mixing, uniform distribution of liquid, and a fairly low pressure drop. The wick lined inside of the absorption column tends to spread liquid over the wick material, due to their capillary action, giving a 100% wetting surface as well as liquid transport along the axial direction. The conventional gas-liquid contact devices, as well as liquid-liquid contactors, are designed based on gravitational force, which allows the liquid to flow downward. In the wetted-wick absorption column, the main force establishing the gas-liquid interface and liquid flow is the capillary force in addition to the gravitational force.

Capillary force has been used in heat pipes, which were developed for application in temperature control systems of spacecraft in the early 1960's and have been successfully applied to other fields, such as energy conservation, heat recovery, electronics and solar energy utilization [23,24].

Recently, Seok and Hwang[25] applied the principle of the heat pipe to the distillation for liquid separation. They demonstrated that for comparable separations to those in packed columns the equivalent height was only one-ninth the length of conventional packed towers.

The wetted-wick absorption column uses wick materials for liquid flow as in a heat pipe. However, there are many differences in the operating principles. Absorption is an open system in which a liquid absorbent passes the absorption column once-through and is then sent to the regeneration tower, while the heat pipe is a closed system in which the working fluid is circulated inside.

THEORY

Modeling of Wetted-Wick Column

The model of the wetted-wick column was developed for mass transfer process between the liquid and gas phase, with absorption from gas phase to liquid phase.

The governing equations are a differential mass balance over an infinitesimal column segment in each phase. Material balance for a soluble component in gas phase is given by

$$\frac{d(Gy)}{dz} = K_{oc}aP(y - y^*) \quad (1)$$

The corresponding material balance in the liquid phase for a soluble component is

$$\frac{d(Lx)}{dz} = K_{ol}aP(x - x^*) \quad (2)$$

In gas absorption processes, the mechanism is a unidirectional diffusion from the gas phase to the liquid phase; the transfer of a soluble component from one phase to the other is not accomplished by any other transfer in the reverse direction, so that the liquid flow rate and the gas flow rate are no longer constant between every segment dz .

According to the characteristics of unidirectional diffusion,

$$\frac{d(Gy)}{dz} = \frac{d(Lx)}{dz} \quad (3)$$

and

$$\frac{dG}{dz} = \frac{dL}{dz} \quad (4)$$

Since the solute is the only component being transferred,

$$\frac{dG}{dz} = \frac{d(Gy)}{dz} \quad (5)$$

$$= G \frac{dy}{dz} + y \frac{dG}{dz} \quad (6)$$

Therefore, differential forms of governing equations for each phase can be written as:

$$\frac{dG}{dz} = K_{oc}aP(y - y^*) \quad (7)$$

$$\frac{dy}{dz} = \frac{K_{oc}aP(y - y^*)}{G} - \left(\frac{y}{G}\right) \frac{dG}{dz} \quad (8)$$

$$\frac{dx}{dz} = \frac{K_{ol}aP(x - x^*)}{L} - \left(\frac{x}{L}\right) \frac{dL}{dz} \quad (9)$$

The above equations can be solved simultaneously using the fourth-order Runge-Kutta method, and the values of an over-all absorption coefficient would be obtained by the equation $K_{OG}a = W/(V\Delta p)$.

Numerical simulation provides the profiles of compositional variation in the gas phase and the liquid phase, which vary with axial position of the column. It also enables to predict the column length required to achieve the desired gas purification with certain initial and boundary conditions, as well as flow rate distribution of gas and liquid streams along the column. Determining the driving forces at each step of integration requires a knowledge of the equilibrium vapor pressure of a soluble gas over the solution.

EXPERIMENTAL

The experimental part of this investigation consists of two portions: the absorption of carbon dioxide in water and in aqueous mono-ethanolamine(MEA) solutions, which are operations of considerable industrial importance. The former is for the case of physical absorption and the latter for chemical absorption. In each, the mass transfer rate of carbon dioxide in the wetted-wick column was obtained under controlled conditions.

The column was made of a glass tube (19.2 mm O.D. \times 150 mm long), which was lined with fiber glass (Owens-Corning) to act as a wick. This wick was held firmly against the wall by stainless-steel screen. For higher interfacial area per unit volume, 6 arteries are installed inside space of column as shown in Figure 1 (3mm \times 150mm long). The gas flow rates at the inlet and outlet were measured, using mass flow meters (Matheson model 8160). These flow meters were calibrated with a soap bubble meter. The feed liquid was introduced using a Masterflex pump (Cole-Parmer Co.) to control the liquid flow rate. Gas was sampled from the gas outlet and also taken at the gas inlet for checking the feed gas composition. The entire column was wrapped with a heating tape or with a circulator coil to control the column temperature. The temperatures of the absorption column were measured with a Centigrade Thermometer (Cole Parmer Co., Cat. no 8502-25). A circulator equipped with a temperature controller (Brinkman RM6) was used for controlling the column temperature and the inlet liquid temperature.

Runs were made at constant gas flow rate and constant column temperature, but the liquid flow rate was varied. Absorption of the soluble gas (carbon dioxide) was carried out by passing a gas stream counter-currently through the absorbing liquid. The liquid flow rate, gas flow rate, and system temperature were recorded, since the performance of the column depends mainly on these factors. When this series of runs was completed, the gas flow rate was adjusted to a new value and another set of runs was carried out at this new gas flow rate at a constant temperature.

The amount of the carbon dioxide absorbed per unit time was calculated from the material balance based on the analysis of the inlet and outlet gas and the measured gas flow rate, instead of direct analysis of the liquid. This was done in all runs because the analysis of the inlet and outlet concentrations of the liquid would generate more error and the gas flow rate could be more accurately measured and controlled than the liquid flow rate, also because of the easy and accurate

analysis of the gas composition by the gas chromatography.

Gas inlet and outlet streams were analyzed by gas chromatography (Hewlett-Packart, 5840A Gas Chromatography). The chromatograph system was equipped with a thermal conductivity cell and integrator. The carbon dioxide-nitrogen mixture was separated by a porapak-S column (Supelco, Inc.). Helium was used as a carrier gas.

RESULTS AND DISCUSSION

1. Absorption of Carbon Dioxide in Water (Physical Absorption)

Experimental data of the wetted-wick column operation were taken and compared with those of the packed tower. The results of the experimental data on the absorption of carbon dioxide in water showed that the wetted-wick column gave higher efficiency than the conventional packed tower. The dependence of K_{OGa} and HTU_{OG} upon the gas flow rate, composition of gas, and flow rate of absorbing liquid has been investigated by experiments in which carbon dioxide was employed as a soluble component and nitrogen as an inert carrier. Equilibrium data of carbon dioxide in water were those of Buch[27] and Morgan and Maass[28] of which data are assembled in the study of Dodds et al.[29].

1-1. Comparison with Packed Tower

To make a proper comparison, experimental data were collected in almost the same range of retention

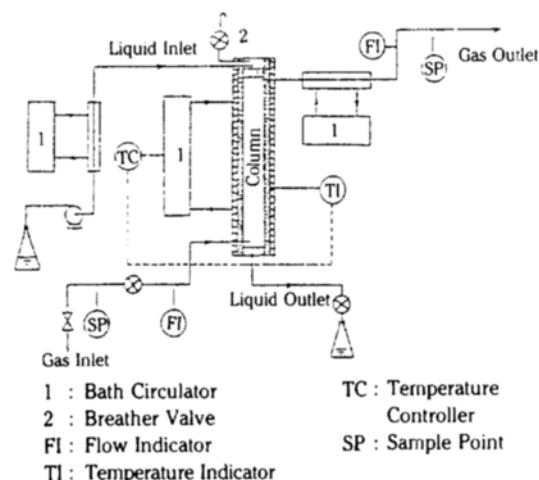


Fig. 2. Experimental apparatus of wetted-wick absorption column.

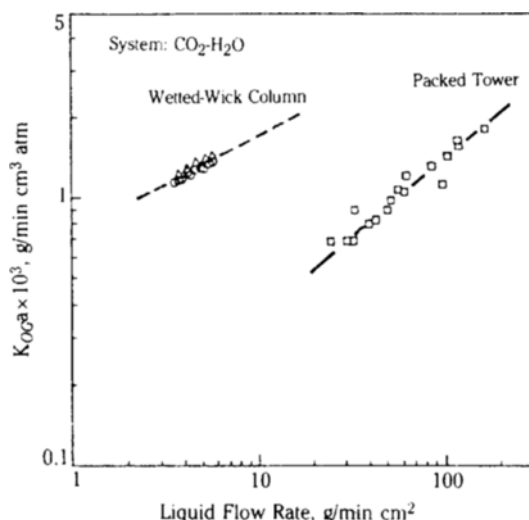


Fig. 3. Comparison of K_{OGa} between the wetted-wick column and the packed tower in $\text{CO}_2\text{-H}_2\text{O}$ system.

- Wetted-Wick: (Δ) 11.06% CO_2 , R.T. = 1.03–1.52 min, (\odot) 18.44% CO_2 , R.T. = 0.91–1.58 min
- Packed Tower: (\square) 11.80–26.4% CO_2 , R.T. = 1.16–1.36 min

time of gas flow in the absorption column, as well as at the same operating conditions as the packed tower; the range of velocity of the gas stream based on the superficial velocity was 0.91–1.58 minutes for the wetted-wick column and 1.16–1.36 minutes for the packed tower. The operating temperature was 6.6°C for the wetted-wick column and 6.4–9.2°C for the packed tower. The inlet gas composition was 11.06% and 18.44% carbon dioxide for the wetted-wick column and 11.8% to 26.4% carbon dioxide for the packed tower. As indicated in Figure 3, due to the higher K_{OGa} values and lower liquid flow rates, the wetted-wick column has great advantages over the packed tower in terms of size and power consumption.

According to Figure 4, HTU_{OG} values of the wetted-wick column are one-tenth that of the packed tower, with about one-tenth of the liquid flow rate. Hence, it is obvious that the size of the equipment and the energy to regenerate the solvent can be reduced to one-tenth that of the packed tower by employing the wetted-wick column for treating the same amount of gas. With regard to the power consumption for pumping the absorbing liquid from absorber to stripper and pumping back from stripper to absorber one-tenth of the packed tower operation is sufficient for the wetted-wick column operation.

One of conditions unfavorable to conventional packed tower is the pressure drop of a gas flowing upward

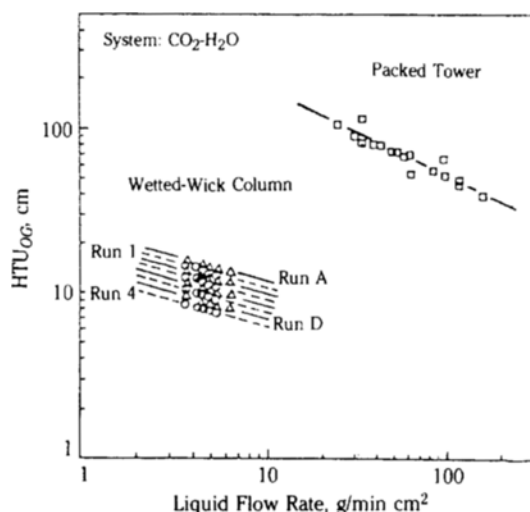


Fig. 4. Comparison of HTU_{OG} between the wetted-wick column and the packed tower in CO_2 - H_2O system.

- Wetted-Wick: (Δ) 11.06% CO_2 , Run A: R.T. = 0.88 min, Run D: R.T. = 1.52 min, (\circ) 18.44% CO_2 , Run 1: R.T. = 0.91 min, Run 4: R.T. = 1.58 min
- Packed Tower: (\square) 11.80–26.4% CO_2 , R.T. = 1.16–1.36 min.

through a packing. The pressure drop is caused by the channels of liquid flow which is in common with the route of gas flow. In contrast to the packed tower, the pressure drop was, as expected, not observed over the range of this experiment. The negligible pressure drop is owing to the liquid channels isolated from the gas flow.

1-2. Effect of Water Flow Rate

Figures 3 and 5 show a variation in $K_{OG}a$ with a variation in the water rate with a parameter of the gas flow rate. From Figure 5, it is evident that $K_{OG}a$ increases with an increase in the liquid flow. However, experimental data for 11.06% carbon dioxide and for 18.44% carbon dioxide show that the variations in the inlet gas composition give no noticeable effect on the value of $K_{OG}a$.

1-3. Effect of Feed Gas Composition and Gas Flow Rate

Experiments were carried out for 11.06% carbon dioxide and for 18.44% carbon dioxide in the feed gas stream, in which the gas flow rate was varied over the range of 4.843 to 16.88 $cc/min\ cm^2$, with variation in the liquid flow rate of 3.713 to 5.417 $g/min\ cm^2$. The results indicate a constant value of $K_{OG}a$ with variation in the gas flow rate and gas composition, as shown in Figure 5 for 18.44% carbon dioxide, which means that carbon dioxide has so low a solubility in water that the gas phase resistance is negligible and, therefore, the

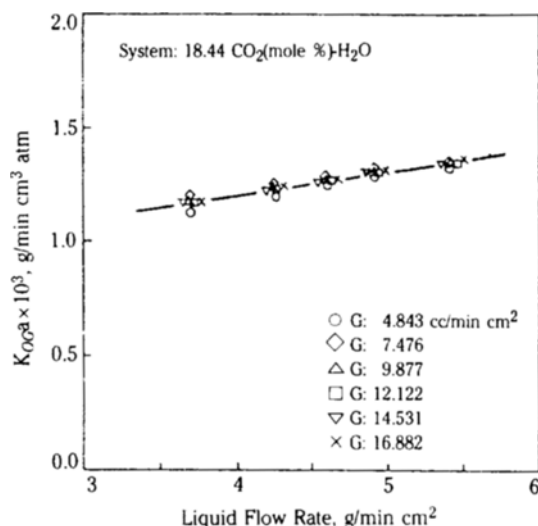


Fig. 5. Effect of liquid rate on $K_{OG}a$ in CO_2 (18.44%)- H_2O system, with gas flow rate as parameter.

overall transfer coefficient is essentially controlled by the liquid film. A negligible effect on $K_{OG}a$ of the gas flow rate in the carbon dioxide absorption process is consistent with the results of Allen[30], Sherwood et al.[31], and Cooper et al.[32].

It is noted that $K_{OG}a$ is constant with varying inlet gas composition, as shown in Figure 3. It follows from the facts of a low solubility of carbon dioxide in water and constant $K_{OG}a$ with varying gas flow.

1-4. HTU

HTU_{OG} vs. the gas flow rate indicates a high degree of linearity, as shown in Figure 6. HTU_{OG} is increased with the gas flow rate, which is as expected, since an increased gas flow rate gives a larger load to the absorption column. As expected from the results, that $K_{OG}a$ is constant with a varying gas flow rate and with a varying gas composition, HTU_{OG} is not varied with a varying gas composition for 11.06% carbon dioxide and for 18.44% carbon dioxide.

The effect of the liquid flow rate on HTU_{OG} is illustrated in Figure 6. The HTU_{OG} is diminished with an increase in the liquid flow, as expected. The variation of HTU_{OG} with liquid velocity was relatively small over the range of 3.713–5.417 $g/min\ cm^2$ of the liquid flow rate. But the effect of the gas flow rate on HTU_{OG} is remarkably greater, as indicated in Figure 6. It is believed that the relatively small effect of the liquid flow rate, as compared to the gas flow rate, on HTU_{OG} is due to such a low solubility of carbon dioxide in water, and the high degree of linearity is due mainly to the linearity of the equilibrium curve.

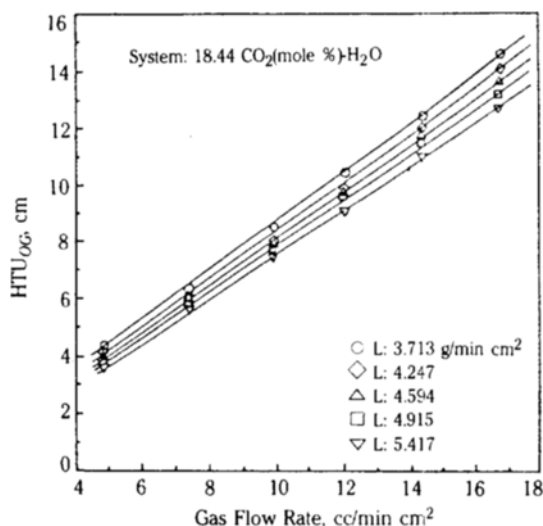


Fig. 6. Effect of gas rate on HTU_{OG} in $CO_2(18.44\%)$ - H_2O system, with liquid flow rate as parameter.

2. Absorption of Carbon Dioxide in Aqueous MEA Solution (Chemical Absorption)

Series of the tests for 10.4 mole % carbon dioxide in 20 wt% aqueous MEA solution were conducted, in which the liquid rate varied from $L = 0.880$ g/min cm^2 to $L = 1.988$ g/min cm^2 and the gas rate varied from $G = 281.5$ cc/min cm^2 to $G = 499.5$ cc/min cm^2 . The data were collected over the same ranges of gas flow and liquid flow for 16.95 mole % carbon dioxide. Experimental results of the absorption of carbon dioxide in aqueous mono-ethanolamine solution illustrated that the wetted-wick column would give higher values of $K_{OG}a$ with less liquid flow than the conventional packed tower. The effects of gas flow rate, liquid flow rate, and composition of the gas flow rate on $K_{OG}a$ and HTU_{OG} are discussed with experimental data. The data of equilibrium between carbon dioxide and MEA solutions are available from Kent and Eisenberg[33], and Mason and Dodge[34].

2-1. Comparison with Packed Tower

For the sake of comparison with the packed tower, experiments were carried out at the same operating conditions as in the work done by Teller and Ford[35]: operating temperature was 114°F, aqueous solution of 20 wt% mono-ethanolamine. 10.4 mole% carbon dioxide in the feed gas stream. To compare the performance more properly, the overall mass transfer coefficient ($K_{OG}a$) and height of transfer unit (HTU_{OG}) were obtained and compared at the same retention time of the gas flow based on superficial gas velocity in the absorption column, as well as the same operating conditions, because the values of $K_{OG}a$ are strongly dependent on gas retention time in the absorption column.

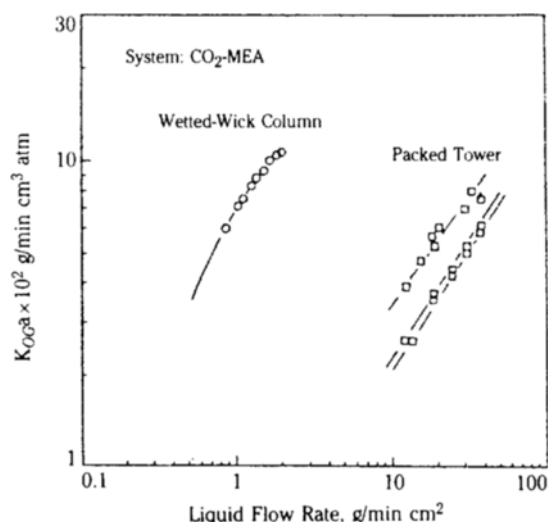


Fig. 7. Comparison of $K_{OG}a$ between the wetted-wick column and the packed tower in CO_2 (10.4%)-MEA(20 wt%) system.

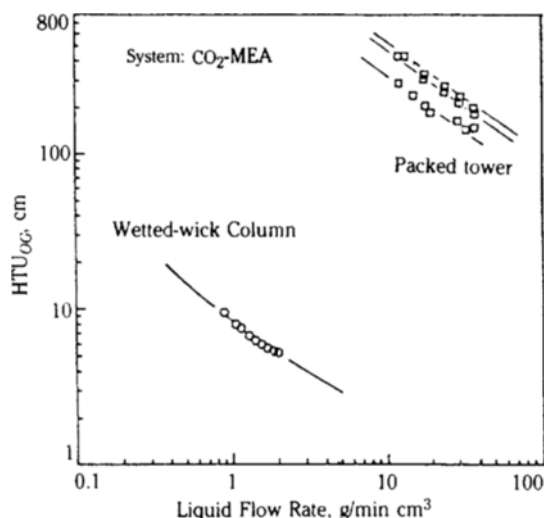


Fig. 8. Comparison of HTU_{OG} between the wetted-wick column and the packed tower in CO_2 (10.4%)-MEA (29 wt%) system.

dent on gas retention time in the absorption column.

As shown in Figure 7, the overall mass transfer coefficients ($K_{OG}a$) of the wetted-wick column are about 2 times greater than that of the packed column at one-fifteenth of the liquid flow rate. From Figure 8, the height of the transfer unit (HTU_{OG}) in the wetted-wick column is about one-thirtieth smaller than that of the packed tower at one-fifteenth of the liquid flow rate. In other words, the wetted-wick column is about 30 times as efficient as a packed tower, with one-fif-

teenth of the cost of energy (steam) in the regeneration unit.

It is believed that the wetted-wick column would result in high efficiency of mass transfer for four reasons. First, the wetted-wick materials would cause the liquid to remain in the column for a longer period of time than in the conventional packed-tower for the same throughput of gas stream. Thus, the contact time of liquid for material transfer would increase. Second, more interfacial area and a higher wetting surface, owing to the capillary force spreading the liquid over the wick material, provides higher efficiency for gas absorption. Third, the effective open cross-section of the wetted-wick column for the gas stream is larger than that of the packed tower because of separate passages of liquid and gas flow and an absence of packing materials. The larger effective open cross-section gives the gas stream a longer period of residence time. A longer residence time of the gas stream gives a longer contact time of the gas stream with the liquid phase at the same superficial velocity of gas flow as the packed tower, thus resulting in a higher efficiency. Fourth, in the packed tower, the packing surface is discontinuous in nature, making the gas phase and liquid phase discontinuous. In the wetted-wick column, however, the gas stream is regularly continuous, due to the separate passage of liquid through the wick. Thus, the increase in efficiency may be attributed to increased wetting, increased interfacial area, and increased contact time.

The wetted-wick column, therefore, can be employ-

ed in place of the packed tower for gas absorption processes, with several advantages, as stated above.

2-2. Effect of Gas Flow Rate

The negligible effect of the gas flow rate on the absorption coefficient $K_{OG}a$ is shown in Figure 9 for 10.4 mole% carbon dioxide and Figure 10 for 16.95 mole% carbon dioxide in feed gas, which illustrates that $K_{OG}a$ is essentially independent of the gas rate, indicating that the liquid film is the controlling resistance. This behavior indicates that the gas film resistance to mass transfer is negligible compared with the liquid phase resistance under the test conditions. No noticeable effect on $K_{OG}a$ of the gas flow rate in carbon dioxide absorption processes is consistent with the results of Cryder and Moloney[36], and Teller[35].

Experimental results for the concentration of 10.4 mole% carbon dioxide in feed gas show the same trend of $K_{OG}a$ values against the gas flow rate as for that of the 16.95 mole% carbon dioxide; that is, the gas flow rate has little effect on the mass transfer coefficient ($K_{OG}a$). This merely confirms the fact that, no matter what concentration of carbon dioxide is in the gas stream to be treated, the absorption of carbon dioxide by aqueous MEA solutions is controlled by the conditions in the liquid phase. It should be noted, however, that $K_{OG}a$ value is varied with varying inlet gas composition; the values of $K_{OG}a$ for 10.4% carbon dioxide are about 1.6 times greater than those for 16.95% carbon dioxide, as illustrated in Figure 9 and Figure 10.

2-3. Effect of Liquid Flow Rate

Fig. 9. Effect of liquid rate on $K_{OG}a$ in CO_2 (10.4%)-MEA(20 wt%) system, with gas flow rate as parameter.

Fig. 10. Effect of liquid rate on $K_{OG}a$ in CO_2 (16.95%)-MEA(20 wt%) system, with gas flow rate as parameter.

The liquid flow rate has a considerable effect on the coefficient, as illustrated in Figure 9 and Figure 10, which show $K_{OG}a$ vs. the liquid flow rate with a parameter of different gas flow rates. It has been found that $K_{OG}a$ increases with increased liquid loading. In the range of liquid flow employed, $K_{OG}a$ increased linearly with an increasing liquid flow rate. It was commonly assumed that the increase in the $K_{OG}a$ with an increased liquid rate might be due to a decrease in the effective liquid film thickness[36].

However, the effect of the liquid flow rate might be more reasonably explained based on the following considerations. An increase in the rate of liquid flow increases the thickness of the liquid layer on the wick, and in any given section of the column, more liquid is available to take up a given quantity of free carbon dioxide. Hence, the concentration gradient of free carbon dioxide in the liquid will be greater and this will result in a greater absorption rate. Especially in chemical absorption, a rapid chemical reaction in the liquid can lead to a very large increase in the mass transfer coefficient[37]. The rapid reaction consumes much of the CO_2 very close to the gas-liquid interface, which makes the gradient for CO_2 steeper and enhances the process of mass transfer in the liquid.

2-4. Effect of Partial Pressure

$K_{OG}a$ was compared with different concentrations of carbon dioxide (10.4 mole% and 16.95 mole%) in the feed gas against the liquid flow. In contrast to the carbon dioxide absorption in water, in which the values of $K_{OG}a$ are not affected by the gas composition for treating, the values of $K_{OG}a$ for carbon dioxide absorption in MEA solution are significantly changed for 10.4% carbon dioxide and 16.95% carbon dioxide in the feed gas. These results would be attributed to the much higher solubility of carbon dioxide in MEA solution than in water.

From the comparison of Figure 9 and Figure 10, it can be seen that the $K_{OG}a$ value of higher concentrations of carbon dioxide (16.95% CO_2) in the feed gas is smaller than that of lower concentrations of carbon dioxide (10.4% CO_2). This phenomenon might be explained by considering the variation of the driving force and the amount of carbon dioxide absorbed with varying partial pressure of carbon dioxide. It is obvious that the partial pressure of carbon dioxide in the gas phase increased with an increased concentration of carbon dioxide in the feed gas. The amount of carbon dioxide absorbed in the liquid also increased with an increase in concentration of carbon dioxide. The lower $K_{OG}a$ observed in the case of a higher concentration of carbon dioxide in the feed gas might be explained based on the fact that the ratio of the increased partial

Fig. 11. Effect of gas rate on HTU_{OG} in $CO_2(10.4\%)-MEA(20\text{ wt}\%)$ system, with liquid flow rate as parameter.

pressure of carbon dioxide over the solution is greater than the ratio of the increased amount of carbon dioxide absorbed in the solution.

2-5. HTU_{OG}

As can be seen from the Chilton and Colburn[38] equation, HTU_{OG} increased with the gas flow rate and decreased with an increase in the liquid flow rate, as shown in Figure 11.

It was found that low concentration of gas stream causes a small value of HTU_{OG} , and an increase in the rate of HTU_{OG} with varying gas flow is larger for a high concentration (16.95%) of carbon dioxide than for a low concentration (10.4%). It was as expected that the higher concentration of the gas stream would give more load, which causes larger value of HTU_{OG} .

With a varying liquid flow rate, a smaller value of HTU_{OG} was obtained in a lower concentration of carbon dioxide than in a higher concentration of carbon dioxide.

CONCLUSIONS

This work demonstrates that the newly designed wetted-wick column gives higher efficiency with less liquid flow rate (than the conventional packed tower) for both physical absorption and chemical absorption. Due to the high and rising energy cost involved in the operation of gas treatment plants, the higher efficient wetted-wick column might be applicable as an alternative to the conventional one in a large number of industrial gas purification or recovery processes.

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NOMENCLATURE

a	: interfacial area per volume, cm^{-1}
G	: gas flow rate, g/min cm^2
HTU_{OG}	: height of overall gas-phase transfer unit, cm
K_{OG}	: overall gas-phase mass transfer coeff., $\text{g/min cm}^2 \text{ atm}$
K_{OGa}	: overall gas-phase absorption coeff., $\text{g/min cm}^3 \text{ atm}$
K_{OL}	: overall liquid-phase mass transfer coeff., g/min cm^2
K_{OLa}	: overall liquid-phase absorption coeff.
L	: liquid flow rate, g/min cm^2
P	: total pressure, atm
S	: cross sectional area, cm^2
W	: weight of CO_2 absorbed per unit time, g/min
x	: the composition of CO_2 in liquid phase
x^*	: the composition of CO_2 in equilibrium with gas phase
y	: the composition of CO_2 in gas phase
y^*	: the composition of CO_2 in equilibrium with a solution
z	: column length, cm

Subscripts

G	: gas phase
OG	: overall in gas phase
OL	: overall in liquid phase

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