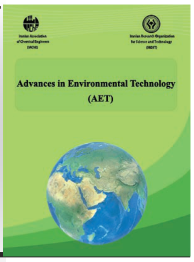
Advances in Environmental Technology 1 (2015) 25-30

Advances in Environmental Technology

journal homepage: http://aest.irost.ir



CO_2 removal from air in a countercurrent rotating packed bed, experimental determination of height of transfer unit

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ARTICLE INFO

Article history:
Received 22 September 2014
Received in revised form
21 December 2014
Accepted 26 December 2014

Keywords:
Rotating Packed Bed
Height of Transfer Unit
Mass Transfer
Absorption
Carbon Dioxide

ABSTRACT

Carbon dioxide capture is a key issue in climate change mitigation. For decades the removal of carbon dioxide has been an essential step in many industrial processing operations such as the synthesis of ammonia, natural gas purification, and oil refining. In this study, a rotating packed bed has been designed for absorption of carbon dioxide from an air stream. The rotating packed bed is a compact device which can be used to replace the conventional absorption technology because of its high efficiency, compact size, and reduced weight. Experiments have been done for carbon dioxide absorption and the effect of parameters such as rotational speed, gas and liquid flow rates, and concentration of the MEA solution on the height of transfer unit investigated for different packing types. The results show that the height of transfer unit values for carbon dioxide absorption were 2.4~ 4 cm depending on the rotational speed, absorption solution concentration, and gas and liquid flow rates.

1. Introduction

In recent years, the need to improve mass and heat transfer equipment has prompted engineers and scientist to search for new methods and techniques to achieve this aim. The challenges involved designing novel equipment and implementing new methods. Economic concerns also influenced this movement and led to the development of reliable, safe, and more efficient technologies that use smaller components. A result of adopting new methods such as miniaturisation and decentralisation of plants led to the distribution of these components to onsite facilities instead of large plants. Process Intensification (PI) was first highlighted by Ramshaw [1]. It is a novel concept which aims to achieve a significant reduction in the size of individual plant modules, by a factor of ten or more, resulting in cost reduction, efficiency enhancement, and inherent safety. The concept of PI is to improve heat and mass transfer characteristics, hence generating better contacts between media. The advantage of fast mixing properties can create improved heat and mass transfer rates. Thus, systems with limitations in mixing, reaction times, and heat and mass transfer could significantly benefit from PI [2]. A rotating packed bed, which replaces gravity with centrifugal force up to several hundred times of gravity to enhance mass transfer efficiency, plays an important role in the field of process intensification. Under the rotating packed bed operation, thin films and tiny droplets generated by a rigorous centrifugal acceleration (2000 ~ 10000 m s^{-2}) could provide an enhancement in the gas-liquid mass transfer. Furthermore, the rotating packed bed could process higher gas and/or liquid flow rates owing to the low tendency of flooding relative to that in the conventional packed bed. Therefore, the gas-liquid mass transfer would frequently be enhanced by a factor of 10 ~ 100 and a dramatic reduction in the size of the equipment would be achieved, thereby reducing the capital and operating costs. A countercurrent-flow rotating packed bed has applications in the absorption, stripping, distillation, adsorption, and nanoparticles preparation processes [3-16]. In our previous works, experiments and modeling have been done for volatile organic compounds and carbon dioxide. The results have been shown as a function of absorption efficiency and mass transfer coefficient [17, 18]. In this work, a comprehensive experiment regarding the influence of various parameters on the absorption process was carried out. The objective of this work is to describe a novel technology and its working methodology for CO_2 capture. Consequently, a rotating packed bed was designed and the absorption of carbon dioxide was investigated

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using different MEA wt% solutions. The results are represented by the Height of Transfer Unit (HTU) as a function of the rotor speed, gas flow rate, and liquid flow rate for different packing types.

2. Experiments

The experimental setup for carbon dioxide absorption in the countercurrent rotating packed bed is shown in Fig.1. The liquid enters the packed bed from a liquid distributor and sprays onto the inner edge of the packed bed. The liquid distributor used in this study had four vertical sets of holes spaced 90° apart. Each set had four 1 mm holes. Inside the bed, the liquid moves outward through the packing as a result of the centrifugal force. The liquid is then splashed on the stationary housing and is collected at the bottom. The gas is introduced from the stationary housing, flows inward through the packing, and leaves the rotor through the center pipe. Thus, the gas and the liquid contact countercurrently in the rotating packed bed. The bed can be operated in the range of 400-1600 rpm. Under a centrifugal field, thinner liquid films and smaller droplets could be obtained. This system can be operated at higher gas liquid^{-1} ratios because of the decreased tendency for flooding. The most important feature of this design is that it increases the mass-transfer coefficient by up to an order of magnitude; thus, it dramatically reduces the equipment size as compared with a conventional packed column. The axial height of the bed is 4 cm while the inner and outer radiuses of the bed are 3 cm and 6 cm, respectively.

In this process, the MEA solution was pumped into the rotating packed bed. The flow rate of the MEA was from 0.2 to 0.8 L min^{-1}. A CO_2-air stream introduced from the stationary housing flows inward through the packing. The CO_2 concentration in the inlet gas stream was maintained at 5000 ppm; the gas flow rate and liquid flow rate were from 10 to 40 L min^{-1} and 0.2 to 0.8 L min^{-1}, respectively. The CO_2 concentration in the inlet and outlet gas streams was measured by a CO_2 meter (model: AZ 77535). During the experimental runs, it typically required 5–10 min to obtain a steady state by monitoring the concentration in the outlet flow. All experiments were conducted at an average temperature of 25 °C with atmospheric pressure. The specifications of the packing types used in this work are summarized in Table 1.

Table 1. Specifications of packing types.

Packing Type		Material	Porosity	Specific Surface Area (m^2 m^{-3})
Type A	wire mesh	Stainless Steel	0.9	1800
Type B	Expamet	Aluminium	0.9	1300

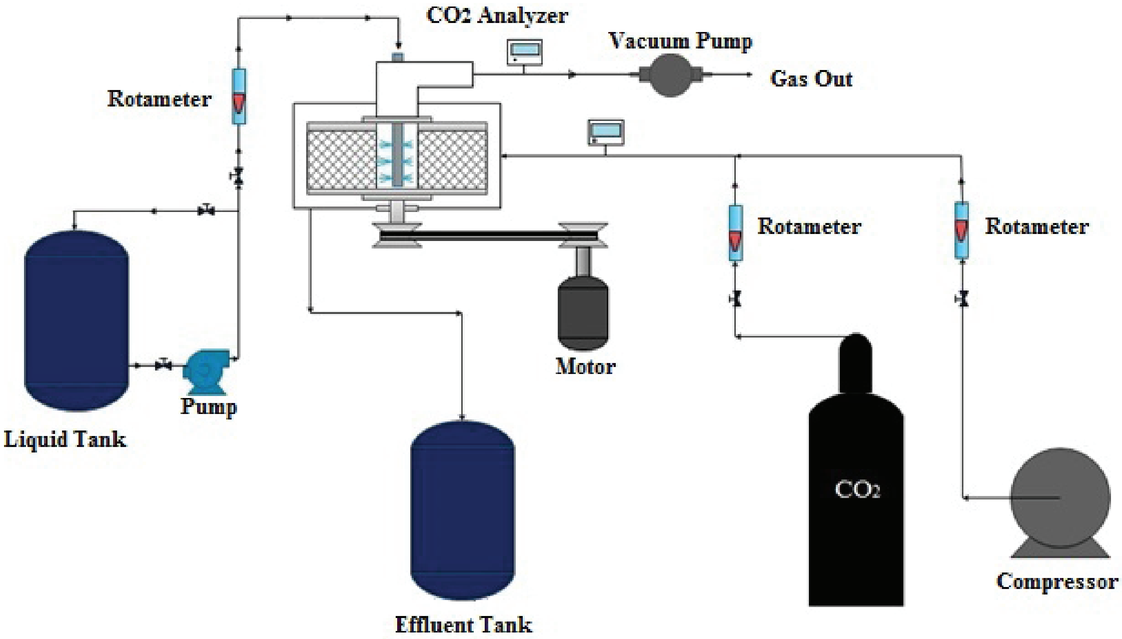
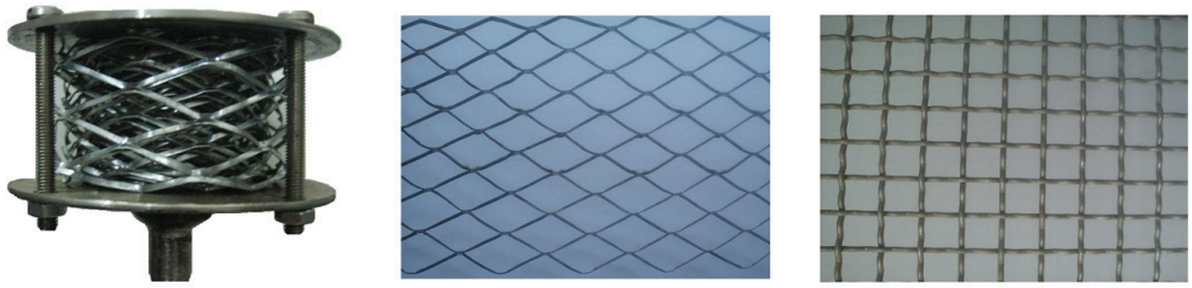


Fig. 1. Rotating packed bed diagram.



(a) (b) (c)

Fig. 2. (a) Rotor. (b) Expamet Packing. (c) Wire Mesh Packing.

Due to the small size of the bed, the design and preparation of the packing is difficult. Wire mesh and Expamet packing are prepared and mounted rather than other types. Another concern of this study was finding which one of these two packings has more mass transfer efficiency. Rotor and packing types used in this work are shown in Fig. 2.

3. Results and discussions

To derive the HTU equation for a rotating packed bed, the first consideration is a differential volume with a cross-sectional area of $2\pi r$ dr and a thickness dz, shown in Fig. 3.

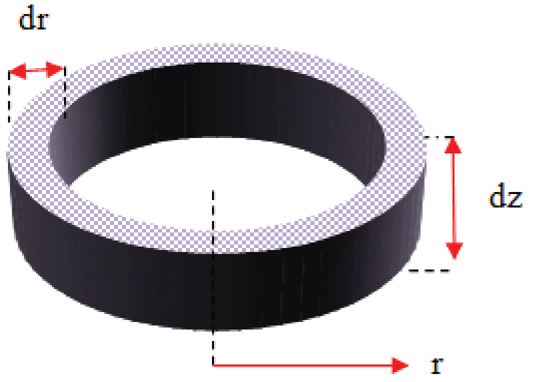


Fig. 3. Differential volume of rotating packed bed.

The differential volume is:

$$dV = 2\pi r dr\, dz \tag{1}$$

The rate of mass transfer of gas to liquid is:

$$d\left(Q_G C_G\right) = k_G a\left(C_G^* - C_G\right)dV \tag{2}$$

The mass balance of solute in this volume is:

$$\frac{Q_G}{\pi\left(r_o^2 - r_i^2\right)} 2\pi r\, dr\, dC_G = k_G a\, \left(C_G^* - C_G\right) 2\pi r\, dr\, dz \tag{3}$$

Then the mass transfer coefficient can be obtained by integrating the equation from $r=r_i$ to $r=r_o$ with the boundary conditions $C=C_{G,i}$ and $C=C_{G,o}$, respectively.

$$Q_G \int_{C_{G,i}}^{C_{Go}} \frac{dC_G}{C_G^* - C_G} = k_G a\ .2\pi z \int_{r_i}^{r_o} r\, dr \tag{4}$$

So, the overall volumetric gas-phase mass transfer coefficients (k_G a) of the rotating packed bed can be evaluated by the following equation:

$$k_G a = \frac{Q_G}{\pi\left(r_o^2 - r_i^2\right)z} Ln\ \left(\frac{C_{G,i}}{C_{G,o}}\right) \tag{5}$$

Where, Q_G Gis the gas volumetric flow rate, *Z* is the axial length of the rotating packed bed, r_i and r_o are the inner and outer radii of the rotating packed bed, respectively. $C_{G,i}$ and $C_{G,o}$ are the concentrations of CO_2 in the inlet and outlet streams, respectively. C_G^* is the equilibrium concentration associated with the liquid concentration.

The HTU values of the rotating packed bed can be estimated using the following equation, based on the HTU definition of a conventional packed bed:

$$\mathrm{HTU} = \frac{V_G}{k_G a} \tag{6}$$

Where V_G is the average gas superficial velocity.

3.1. Effect of Rotational Speed

It can be seen that at constant liquid and gas flow rates, the height of transfer unit decreases with an increase in rotational speed; hence, this observation would demonstrate that the separation performance was improved as a result of using higher centrifugal acceleration. The dependence of HTU on rotational speed at constant liquid flow rate and gas flow rate is shown in Fig. 4. As expected, the k_G a values increased with increasing rotational speed, implying that centrifugal force could effectively reduce the mass transfer resistance for the CO_2 absorption process in a countercurrent flow rotating packed bed. Higher values of the volumetric mass transfer coefficients and thus lower HTU values can be achieved at higher centrifugal acceleration.

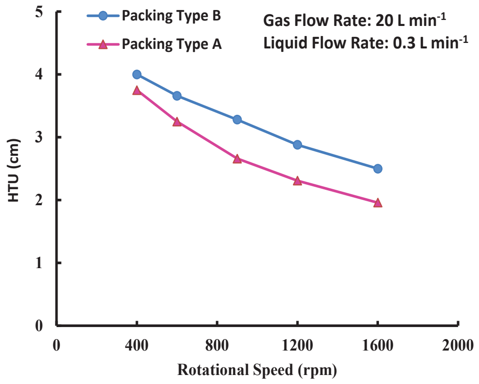


Fig. 4. Dependence of HTU on rotational speed for different packing types and 30 wt% MEA.

Figure 4. Dependence of HTU on rotational speed for different packing types and 30 wt% MEA

The experimental data indicated that HTU are proportional to rotational speed to the power of 0.16 ~ 0.18. The lower HTU values would contribute to the significant reduction of the equipment size. The higher centrifugal acceleration environment was not only enhancing the mass transfer coefficient, but it also enhanced the effective surface area thus producing higher volumetric mass transfer coefficients. This also tends to imply that better mixing was achieved within the packing as a result of higher centrifugal acceleration.

3.2. Effect of gas flow rate

The experimental HTU values indicated that the height of transfer units varies with different gas flow rate at constant rotational speed and liquid flow rate for the two packings tested. The HTU values increased with the increases of gas flow rate for a given liquid flow rate and rotor speed. Owing to that, an increasing gas flow rate reduces the contact time, so mass transfer decreases. Fig. 5 shows that as the gas flow rate increases, the height of the transfer unit increases at constant liquid flow rate and rotational speed. The results showed that HTU are proportional to the gas flow rate to the power of 0.33 ~ 0.36.

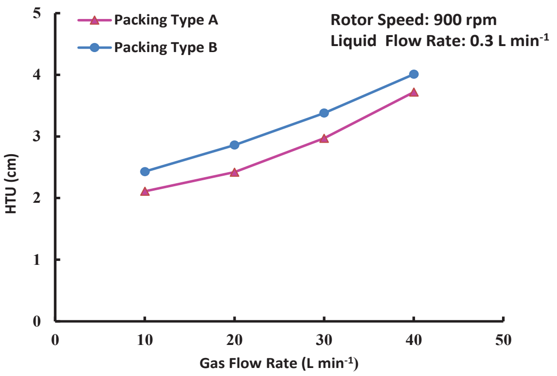


Fig. 5. Dependence of HTU on gas flow rate for different packing types and 30 wt% MEA.

3.3. Effect of liquid flow rate

Fig. 6 shows the dependence of HTU on the liquid flow rate. Increasing the liquid flow rate increased the k_G a values, therefore lowering the HTU values. This is probably due to the existence of more gas–liquid interfacial area, including the films on the packing surface and the droplets in the bed porosity, when the liquid flow rate increased. Under a rigorous centrifugal field, thin liquid films and tiny liquid droplets are generated, resulting in a dramatic increase in mass transfer. Thus, substantial enhancement in the magnitude of mass transfer can frequently be observed in the rotating packed bed. The results indicated that HTU are proportional to the liquid flow rate to the power of -0.8 ~ -0.92.

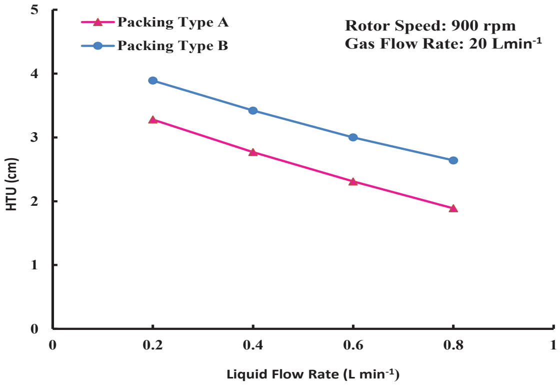


Fig. 6. Dependence of HTU on liquid flow rate for different packing types and 30 wt% MEA.

3.4. Effect of MEA concentration

The effect of MEA concentration on HTU is shown in Fig. 7. The results show that the dilution of the MEA solution leads to an increase in the HTU values. Increasing the MEA concentration increases the absorption of CO_2 and indicates a higher value of an overall mass transfer coefficient and a lower HTU. At a given gas and liquid flow rate, the mass transfer increased with an increasing MEA concentration. This characteristic was caused by the fact that increasing MEA concentration could give higher amounts of hydroxide ions per unit volume for reacting with more CO_2 at a given gas flow rate and liquid flow rate. The experimental data indicated that HTU are proportional to the MEA concentration to the power of 0.21 ~ 0.25.

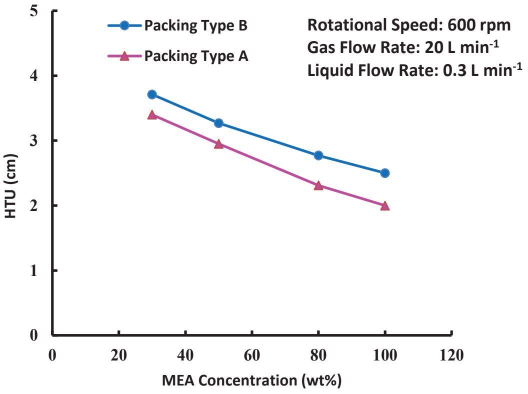


Fig. 7. Dependence of HTU on MEA solution concentration for different packing types.

3.5. Effect of packing type

The effects of the packing type on the HTU seem to be significant. By comparing HTU values between wire mesh (Type A) and Expamet (Type B) on previous figures, we found that the magnitude of the specific surface area of the packing is effective on HTU. The results show that the wire mesh packing has better mass transfer performance and leads to lower HTU values because the gas– liquid contacting area generated by the wire mesh packing was higher than the Expamet type. In Table 2, the specification of the present rotating packed bed system and HTU results were compared with other reported works. The HTU values of 2.4 ~ 4 cm for the absorption of carbon dioxide from air were obtained in the present work, suggesting that such a system could provide a more efficient mass transfer relative to that of a conventional packed bed. Furthermore, the HTU values of the other systems such as the stripping process indicate the high feasibility of applying the rotating packed bed to the gas-liquid separation processes.

4. Conclusion

In this study, the HTU of a countercurrent – flow rotating packed bed for carbon dioxide absorption by different MEA wt% concentration has been examined. The HTU were investigated as a function of rotational speed, liquid flow rate, gas flow rate, and liquid concentration. Two different packing types were used. The results show that the HTU values for CO2 absorption were 2.4 ~ 4 cm depending on the rotational speed, gas and liquid flow rates, and absorption solution concentration. The high centrifugal acceleration in rotating packed beds generates high shear forces in the liquid, resulting in very thin liquid films. Accordingly, these films can yield very large surface areas when fine packing is used for a given value of throughput. In addition, centrifugal acceleration may cause rapid and continuous renewal of the interfacial surface. These factors coupled with the turbulence generated by the gas, e. g. in gas/liquid countercurrent flow, offer great mass transfer enhancement potential in the rotating packed beds. Also, a very low height of transfer units is achieved compared to those of the conventional packed beds. This reduction in HTU was attributed to the higher values of volumetric mass transfer coefficients. Furthermore, when high centrifugal accelerations are applied to a countercurrent flow in packed beds, the usual flooding restrictions are relaxed. This allows the achievement of high mass fluxes for packing with large surface area per unit volume. The results showed that HTU values decrease by increasing rotational speed, liquid flow rate, and MEA concentration, whereas increasing gas flow rate leads to higher values of HTU. The experiments showed that using wire mesh packing has better mass transfer performance than the Expamet type, leading to lower HTU values because the gas– liquid contacting area generated by the wire mesh packing was higher than the Expamet type. The results of this study can be used to design the absorption process on

Table 2. Comparison of present system specification and HTU results with other reported works.

Authors	Experimental system	Rotating packed bed specification (cm)			Packing used			HTU range (cm)
		r_i	r_o	z	type	porosity	$a_{t\,(1/m)}$	
Chia-Chang Lin and Wen-Tzong Liu[19]	O_2- H_2O (stripping)	3.8	8	2	wire mesh	0.956	803	1.9 ~2.3
Haitem Mustafa Hassan-Beck[2]	Air- water (stripping)	8	20	6	Knitmesh	0.95	2300	3.7 ~6.3
Present work	CO_2 – MEA (absorption)	3	6	4	wire mesh	0.9	1800	1.9 ~3.5
					Expamet	0.9	1300	2.4 ~ 4

an industrial scale or even to optimize the effective parameters on the absorption process in a rotating packed bed leading to higher performance. It is recommended that in future works, the absorption of CO2 from different gas stream mixtures be investigated to provide an appropriate model to predict HTU values.

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