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Study on chemical absroption absrober with polypropylene packing for Guohua Jinjie CCS demonstration project

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A R T I C L E I N F O

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A B S T R A C T

The hydrophilic modified polypropylene structured packing could lower the absorber investment in carbon capture process with chemical absorption method. While the pressure drop of the polypropylene packing is higher than that of the stainless steel packing with the same specific surface area. The optimal absorber with polypropylene and stainless steel structured packing for Guohua Jinjie CCS demonstration project was studied in this paper. The contact angle, effective surface area and pressure drop of the hydrophilic modified polypropylene packing 250Y are measured firstly. The economic analysis model which includes absorber investment (shell, packing and other internals) and operating cost (blower and lean solution pump operating expense) is built.

The minimum total cost of the absorber with polypropylene packing 250Y and stainless steel packing 125–500Y are obtained. The absorber with stainless steel packing 250X/Y exhibits the lower investment and operating cost among the stainless steel packing. The minimum total cost of the absorber with stainless steel packing 250X/Y is about 0.955 \$/t CO_2 under 48% flooding. For the CO_2 absorber of the Jinjie CCS project, the absorber with polypropylene 250Y is just about 59.5% of that with SUS304 250Y. In addition, the absorber investment, blower and pump cost with polypropylene 250Y is 27.37% lower than that with SUS304 material. The hydrophilic modified polypropylene packing 250Y can replace the stainless steel packing from the economic analysis.

1. Introduction

Carbon dioxide capture and storage (CCS) is one of the effective measures for reducing CO_2 emitted from fossil fuel. For existing fossil-fuel power plants, chemical absorption is considered as one of the most feasible CO_2 capture technologies. However, the amine absorption method still faces the challenge of high energy penalty and costly. The solvent regeneration duty accounts for more than 60% of the total energy consumption required by CCS (Raksajati et al., 2017). It results in approximately 10% efficiency penalty for a typical coal fired power plant (Goto et al., 2013). CO_2 avoided cost from post-combustion power plants using mono-ethanolamine (MEA) solution is about US\$70/ton CO_2~~avoided~~ (Raksajati et al., 2013). The high investment and operating cost are supposed to be the major obstacle to current large-scale implementation of carbon capture and storage (CCS). The economics of the CO_2 capture design in a 630 MWe power plant, and the repartition of the investment cost were taken in account (Raynal et al., 2013). The amine and the dissolved CO_2 gas in the solution have a strong corroding effect on the carbon steel, so absorber (shell, packing and internals) is generally made of stainless steel SUS304 or SUS316L material. Absorber investment accounts for about 37% - 46% of total equipment investment in CO_2 capture system (Li et al., 2016). Concrete material may reduce the absorber investment which had been applied in SaskPower Boundary Dam ICCS project (Stéphenne, 2014). From the minimum cost ~~results~~ analysis of the CO_2 absorber with stainless 250Y structured packing, packing accounts for about 63% of the total absorber (Wang et al., 2015).

The mass transfer performance of the packing in the column is

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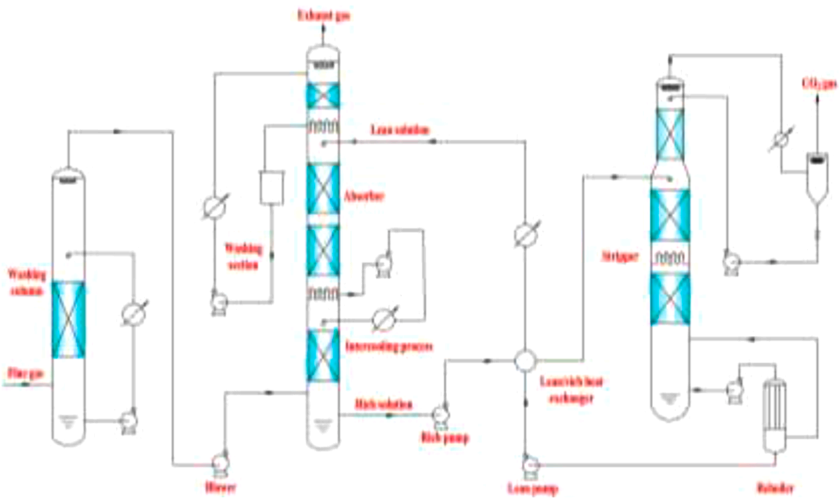


Fig. 1. Process diagram of the post-combustion carbon capture process with advanced absorber.

Fig. 2. Design parameters of the CCS demonstration project at Jinjie power plant.

primarily characterized by the volumetric overall mass trasnfer coefficient (K_Ga_v), which is The mass transfer performance of the packing in the column packing height. The volumetric overall mass trasnfer coefficient K_Ga_v for CO_2 absorption with amine solutions of absorber with stainless random and structured packing were summarized (Afkhami-pour et al., 2017). However, the gas mass transfer coefficient for CO_2 absorption into amine solutions ~~of absorber~~ is several order than liquid mass transfer coefficient in the absorber. The effective the absorber. of the structured packing directly impacts the overall mass transfer coefficient (Razi et al., 2012; Rahmanian et al., 2018). Polypropylene structured packing (Lehner et al., 2011) can further reduce the absorber investment. While the total free surface energy of polypropylene material is just about 30 MJ/m^2, which leading to higher water static contact angle (usually about 90–110°). The rivulet flow over polypropylene plate is worse than that of stainless plate(Singh et al., 2016) (Singh et al., 2017), and the effective surface area of the polypropylene structured packing is about 30% - 40% of that of stainless structured packing (Rajesh et al., 2016, 2017).

This article illustrates the hydrodynamics and mass transfer performance of the hydrophilic modified polypropylene structured packing 250Y in detailed. The main purpose of this paper is to search the optimal absorber with stainless steel structured packing and polypropylene structured packing 250Y for Jinjie CCS demonstration project.

Fig. 3. Testing hydrophilic modified polypropylene structured packing.

2. Carbon capture demonstration project description

Guohua Jinjie carbon capture and storage (CCS) demonstration project is under construction. It is the first domestic post-combustion CO_2 capture - salt water layer sequestration project ~~at~~in the coal-fired power plant. Guohua Jinjie CCS demonstration project is erected in the Jinjie power plant with 600 MW subcritical coal-fired units. The design carbon capture scale of the CCS demonstration project is 150,000 tons/a. Fig. 1 shows the main process of the Guohua Jinjie carbon capture and storage (CCS) demonstration project. This project was designed based on blended amine solvents, biphasic solvents and ionic liquid. The design solution regeneration duty was 2.4 GJ/t CO_2. In order to achieve this goal, inter-cooling process (Rehan et al., 2017), fully welded plate heat exchanger with low terminal temperature difference, rich split process and lean solution compression process are used in this project.

Fig. 2 shows the pretreater, absorber, stripper and design parameter of Shenhua carbon capture and storage (CCS) demonstration project. CO_2 concentration of the flue gas is about 11.1 vol%. The flow rate of the flue gas is 100,000 Nm^3/h. The carbon capture rate is set as 90%. To reduce the investment of the absorber, the abosrber with hydrophilic modified polypropylene structured packing 250Y was adopted. The carbon absorber has a diameter of 5.5 m and a height of 52 m, where the structured packing height was 20 m. The stripper has a diameter of 4.0 m and a height of 34.5 m, where the structured packing height was 12 m.

3. Methods

3.1. Experimental

The hydrophilic modified polypropylene structured packing 250Y with porous structure on the corrugated surface was developed to improve the gas/liquid mass transfer coefficient. The contact angle meter (Dataphysics, OCA 20) was used for measuring the modified plate water contact angle. The hydrodynamics and mass transfer coefficient of the hydrophilic modified polypropylene packing were conducted in the acrylic column as shown in Fig. 3. The testing platform consisted of a centrifugal fan, acrylic column, polypropylene structured packing, circulating pump, solution tank and ball valve. The acrylic column diameter was 300 mm, and the packing height was about 2000 mm.

The hydrodynamics of the polypropylene packing in air/water process was tested at first, which including dry pressure drop and wet pressure drop. F factor, $F_s = \sqrt{\rho_G} \times u_{SG}$, ranged from 0.7 to 3.0 $Pa^{0.5}$, and solution loading ranged from 10 to 30 $m^3/(m^2{\bullet}h)$.

The chemical method (CO_2 absorption from air with 0.1 mol/L NaOH solution, (Tsai and Frank, 2011)) was employed for the measurements of effective mass transfer area of the structured packing, which reflected the actually mass transfer area. During the effective area testing, the superficial gas velocity of the absorber was kept at 1.5 m/s. The CO_2 concentration of the inlet and outlet of the absorber was measured by LI-840A infrared gas analyzers (0–20,000 ppm). The gas mass transfer coefficient for CO_2 absorption into amine solutions of absorber was several orders lower than liquid mass transfer coefficient. The gas-phase mass-transfer resistance was negligible, so the effective mass transfer area could be calculated as follows (Tsai et al., 2008).

$$a_e = \frac{u_G \ln\left(\frac{y_{CO_2,in}}{y_{CO_2,out}}\right)}{ZRT} \times \frac{H_{CO_2}}{\sqrt{k_{OH^-}[OH^-]D_{CO_2,l}}} \quad (1)$$

3.2. Economic analysis model

3.2.1. Absorber parameters

The absorber diameter, packing type, packing height and pressure drop are the critical parameters in the designing of the absorber. The superficial gas velocity determines the absorber diameter,

$$D_{absorber} = \sqrt{\frac{4Q_{gas}}{\pi \rho_{gas} u_{SG}}} \quad (2)$$

Where, ρ_G was the air density; u_{SG} was the superficial gas velocity; Q_{gas} was the flue gas flow rate, m^3/s; $D_{absorber}$ was the absorber diameter, m.

The dimensionless mass transfer models (Robert et al., 2011;Wang et al., 2016) had developed for predicting the effective area ratio a_e/a_p of different stainless steel structured packing. Eq. (3) shows the effective surface area of different stainless steel structured packing from the (Robert et al., 2011; Wang et al., 2016). Table 2 shows the constant C_{eff} of the effective surface area ratio equation. The a_e/a_p of the polypropylene structured packing 250Y can be calculated by Equation 15.

Table 1
Absorber internals height.

Internals	Sump	Gas distributor	Support	Liquid distributor	Outlet duct
mm	3500	2200	600	1300	3650

Table 2
Constant of the effective area ratio equation (Wolf-Zöllner et al., 2019).

Packing type	125Y	250X	250Y	PP 250Y	350Y	500Y
C_{eff}	1.42	1.30	1.34	1.74	1.27	1.10

$$\frac{a_e}{a_p} = C_{eff}\left[\left(\frac{\rho_L}{\sigma}\right)g^{1/3}\left(\frac{Q}{L_P}\right)^{4/3}\right]^{0.116} \quad (3)$$

The wet pressure drop of stainless steel and polypropylene structured packing was calculated with Eq. (4), 5 and 6 (Wolf-Zöllner et al., 2019). Table 3 shows the constant of the pressure drop calculation in Equation 4.

$$CP = C_S F_P^{0.5} \nu_{solvent}^{0.05} = C_1(\Delta P)^{C_2}\left[1 - e^{C_6 F_{LV}^{C_7}}\right] \Big/ \left[1 + C_3(\Delta P)^{C_2 C_4} F_{LV}^{C_5}\right]^{C_4} \quad (4)$$

$$C_S = u_{gas}\sqrt{\rho_{gas}/\rho_{solvent} - \rho_{gas}} \quad (5)$$

$$F_{LV} = Q_{solvent}/Q_{gas}\sqrt{\rho_{gas}/\rho_{solvent}} \quad (6)$$

Where, $\nu_{solvent}$ is the kinetic viscosity of liquid phase, cSt; ΔP is the pressure drop of structured packing, in H_2O/ft; u_{gas} is the superficial gas velocity, m/s; ρ_{gas} and $\rho_{solvent}$ are the gas and liquid density, kg/m^3; $Q_{solvent}$ and Q_{gas} are the mass flow rate of liquid and gas flows, kg/s; F_P is the packing factor, ft^{-1}.

The total height of the absorber is calculated with Eq. (7) and 8. The height of each packing section is no more than 5000 mm. The other internals includes sump, gas distributor, structured packing support, liquid distributor and outlet duct. The internals height is shown in Table 1.

$$n = \left|H_{packing}/h_{packing}\right| + 1 \quad (7)$$

$$H_{absorber} = h_{sump+G-distributor+outlet} + n\left(h_{L-distributor} + h_{Packing} + h_{support}\right) \quad (8)$$

Where, $H_{packing}$ is the total packing height, m; $h_{packing}$ is the packing height of each section.

3.2.2. Absorber investment

The absorber investment consists of shell, structured packing and other internals. The shell cost is calculated with Eq. (10). The thickness of the shell is set as 10 mm. The internals of the absorber is set as 0.3 times of the shell cost.

$$C_{absorber} = C_{packing} + C_{shell} + C_{internals} \quad (9)$$

$$C_{shell} = 575 \times (\pi \rho_{steel} D_{absorber} H_{absorber} \delta)^{0.609} \quad (10)$$

$$C_{internals} = 0.3 C_{shell} \quad (11)$$

Where, ρ_{steel} is the density of the shell material SUS304, lb/m^3; δ was the thickness of the shell, m;

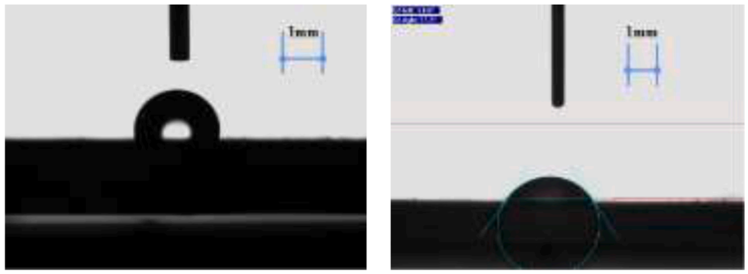
The stainless steel structured packing cost is calculated based on specific surface area by Eq. (12) (Wang et al., 2015). The polypropylene structured packing 250Y was set as 675 \$/m^3.

$$C_{packing} = \frac{\pi}{4} D_{absorber}^2 H_{packing}\left(7.31 + \frac{203.05}{a_p}\right) \quad (12)$$

Where, a_p was the specific surface area, m^2/m^3;

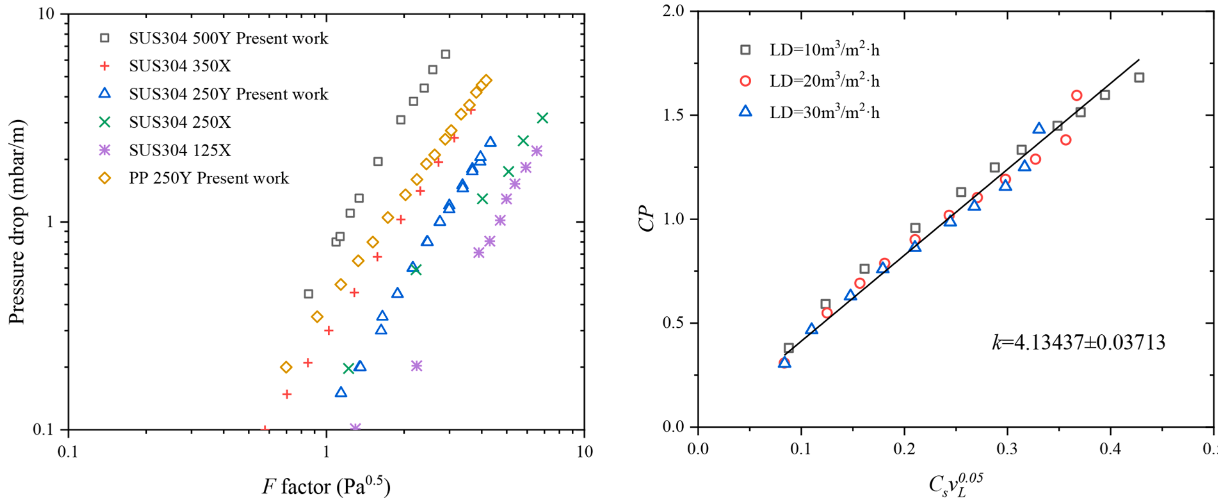
Table 3
Constant of the pressure drop equation (Wolf-Zöllner et al., 2019).

GPDC type	C_1	C_2	C_3	C_4	C_5	C_6	C_7
In H_2O/ft	3.8617	0.6609	6.3763	0.7206	0.2898	−0.9093	−0.6819



(a) Origin polypropylene plate (b) Hydrophilic modified plate

Fig. 4. Water contact angle of polypropylene plate.



(a) Dry pressure drop (b) Wet pressure drop

Fig. 5. Testing pressure drop of different structured packing.

3.2.3. *Operating cost*

The blower and lean solution pump operating cost should be taken into account in the designing of the absorber. The blower and pump operating cost is calculated by Eq. (13) and 14 (Wang et al., 2015). The electricity price is set as 41.4 \$/MW•h.

$$C_{blower} = C_{electricity}\frac{\Delta P_{packing} Q_{gas}}{1000\eta_{blower}} \quad (13)$$

$$C_{pump} = C_{electricity}\frac{\rho g H_{absorber} Q_{solvent}}{\eta_{pump}} \quad (14)$$

Where C_{blower} is the blower operating cost, \$/h; $C_{electricity}$ is the electricity price, \$/kW•h; $\Delta P_{packing}$ is the pressure drop of the total structured packing, Pa. Q_{gas} is the flow rate of the blower, m^3/s; η_{blower} is the blower efficiency. C_{pump} is the lean solution pump operating cost, \$/h; ρ is the lean solution density, Kg/m^3; $H_{absorber}$ is the total height of the absorber, m; $Q_{solvent}$ is the flow rate of the lean solution; η_{pump} is the lean solution pump efficiency.

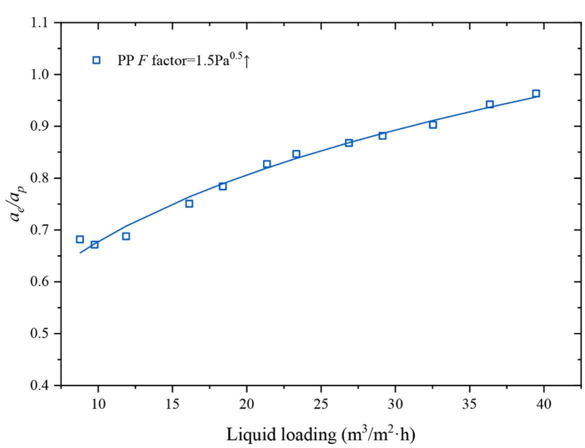


Fig. 6. Effective surface area of polypropylene structured packing.

4. Results and discussion

4.1. *Polypropylene structured packing performance*

Fig. 4 shows the water contact angle of the origin and hydrophilic modified polypropylene plate. The water contact angle of origin polypropylene plate is about 100–110° due to low free surface energy. The

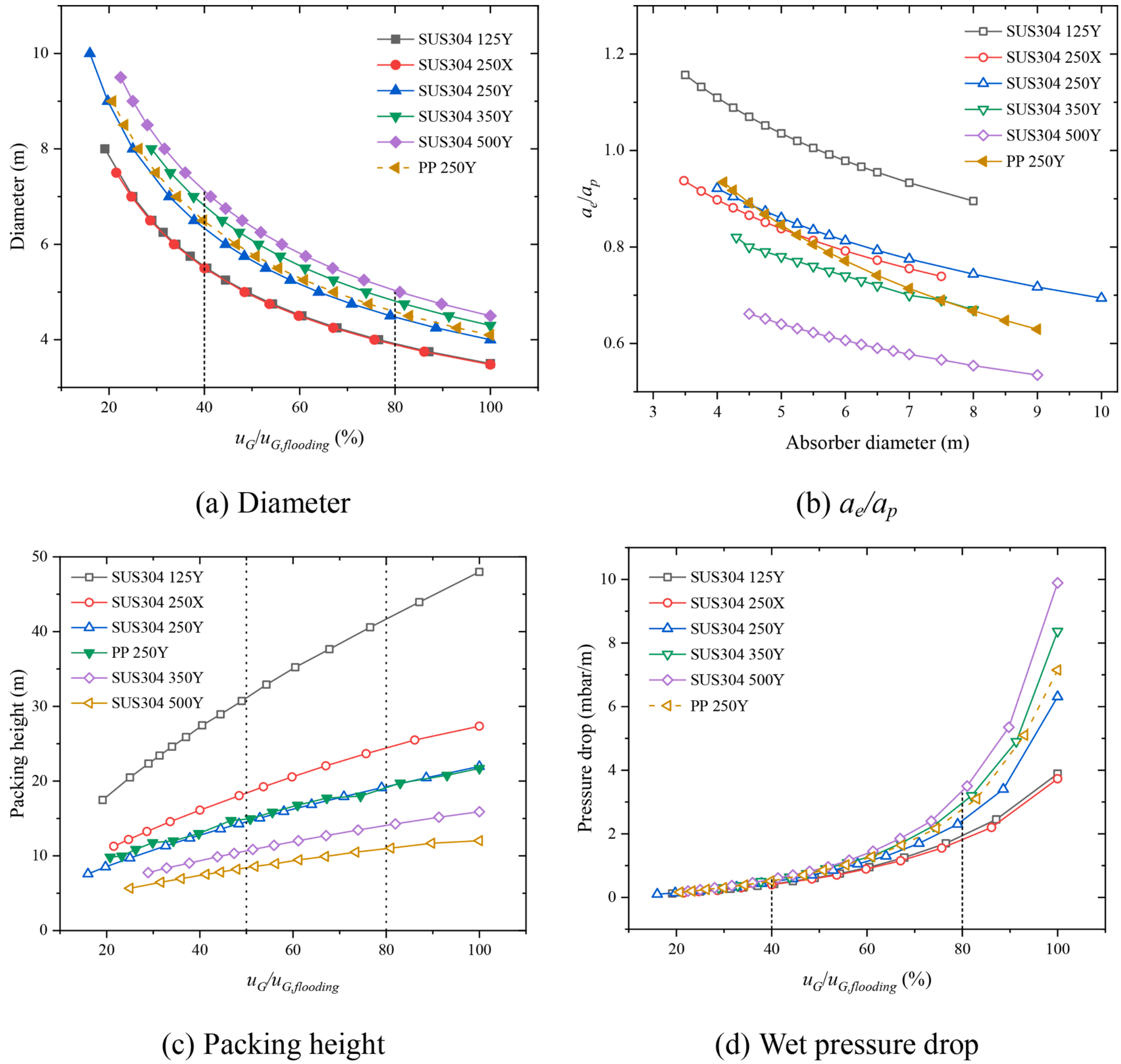


Fig. 7. Absorber diameter, effective area, packing height and pressure drop.

water contact angle of hydrophilic modified polypropylene reduced to 55–60° by constructing the porous surface on the origin polypropylene plate.

Fig. 5a shows the dry pressure drop of polypropylene 250Y and other stainless steel structured packing. The dry pressure drop data of stainless steel packing from other researchers (Lassauce et al., 2014). The dry pressure drop of polypropylene 250Y is higher than stainless steel 350X due to its thicker plate. To calculate the wet pressure drop for polypropylene structured packing, Kister GPDC correlation of stainless steel random and structured packing is applied(Kister et al., 2007). The constant $F_p=17.1$ for polypropylene packing is derived from the testing data under different liquid loading as shown in Fig. 5b.

Fig. 6 shows the testing data of a_e/a_p of polypropylene packing 250Y under different liquid loading. The effective area of polypropylene packing 250Y increases with increasing liquid loading. The fitting equation of a_e/a_p for polypropylene packing 250Y is shown in Eq. (15). In addition, Eq. (15) is adopted in Aspen plus for calculating effective surface area of polypropylene packing 250Y.

$$\frac{a_e}{a_p} = 1.74\left[\left(\frac{\rho_L}{\sigma}\right)g^{1/3}\left(\frac{Q}{L_P}\right)^{4/3}\right]^{0.1884} \tag{15}$$

4.2. Absorber investment

The diameter, packing type, packing height and pressure drop are the critical parameters ~~in the design~~ of the absorber. The flooding velocity of the structured packing are calculated with Eq. (2) and 3. The flooding velocity of SUS304 and polypropylene 250Y are 2.87 m/s and 2.73 m/s, respectively. As shown in Fig. 7a, the absorber diameter with polypropylene 250Y is higher than that of SUS304 250Y and lower than that of SUS304 350Y. The lean solution loading was set as 0.26 mol CO_2/mol solution. The results demonstrates that the polypropylene packing 250Y is more likely to have less effective area ratio than the SUS304 packing with the same specific surface area, as shown in Fig. 7b. When the absorber diameter over 5.25 m, the a_e/a_p of the polypropylene 250Y is lower than that of SUS304 250X/Y. The packing height of SUS304 and polypropylene structured packing is calculated in Aspen plus software

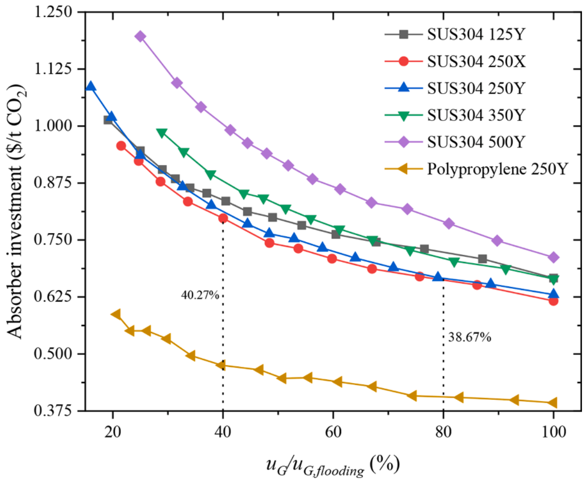


Fig. 8. Absorber investment of shell, packing and other internals.

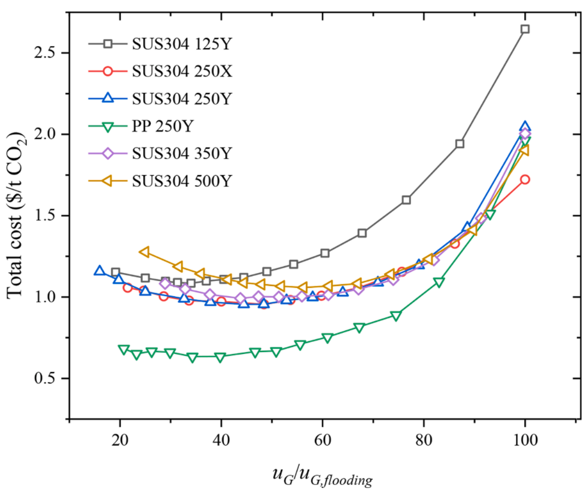


Fig. 9. Total cost of the absorber with stainless steel and polypropylene packing.

based on the effective area Eq. (3) and 15, respectively. The lean solution loading is set as 0.49 mol CO_2/mol MEA solution. Fig. 7c shows that the height of the polypropylene packing 250Y is very close to that of SUS304 packing 250X.Fig. 7d displays that the wet pressure drop of

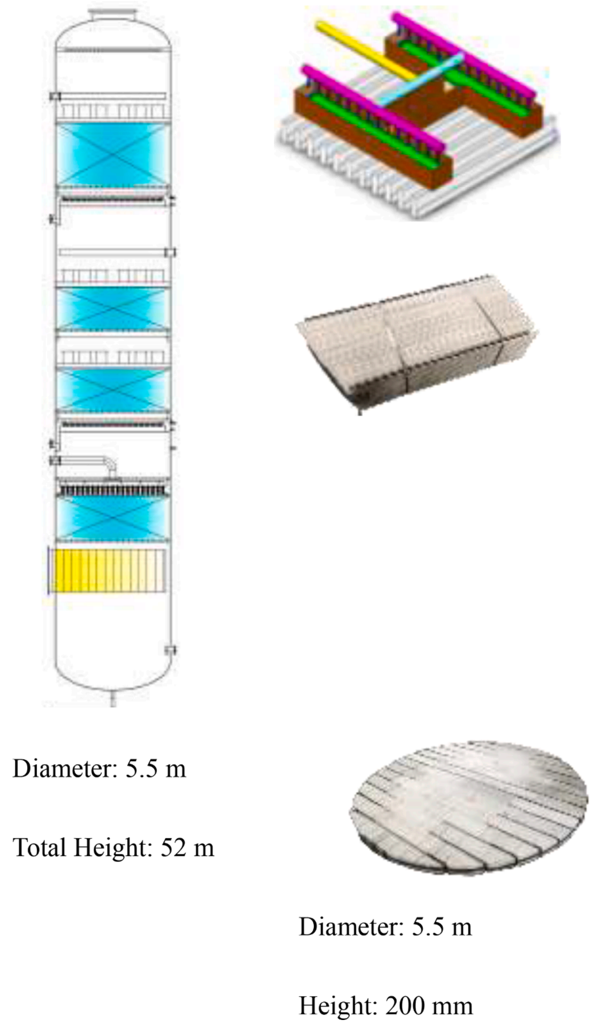


Fig. 11. Absorber with polypropylene structured packing 250Y.

polypropylene 250Y was higher than that of SUS304 250Y and lower than that of SUS304 350Y under the same flooding rate.

Fig. 8 shows the investment of the absorber with SUS304 packing 125Y, 250X/Y, 350Y, 500Y and polypropylene packing 250Y. The absorber investment decreases with increasing of the flooding rate. For stainless steel structured packing, the absorber with packing 250X/Y

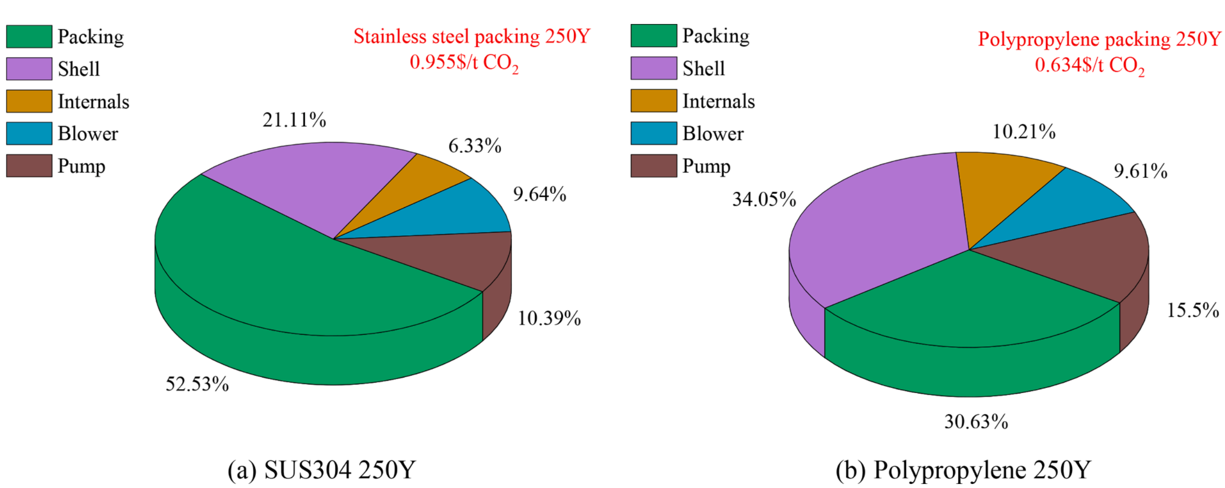


Fig. 10. Absorber cost distribution with stainless steel and polypropylene packing.

Table 5
Absorber parameter and cost of SUS304 and polypropylene 250Y.

Items	SUS304 250Y	Polypropylene 250Y	Units
Absorber parameter			
Diameter	5.5	5.5	m
Flooding	52.9	55.57	%
Packing height	15.06	15.84	m
Pressure drop	85	102	Pa/m
Total height	32.01	33.840	m
Investment and operating cost			
Investment	0.753	0.448	\$/t CO_2
Blower	0.118	0.149	\$/t CO_2
Pump	0.108	0.114	\$/t CO_2
Total	0.979	0.711	\$/t CO_2

had the lowest investment under 40%−80% flooding. In this range, the investment of the absorber with polypropylene packing 250Y is about 38.6%−40.2% of that with SUS304 packing 250X.

4.3. Investment and energy cost

Fig. 9 shows the investment and operating cost of the absorber with stainless steel and polypropylene structured packing under different flooding ~~rate~~. The total cost decreases with increasing of flooding at first, and then increases. For the stainless steel packing, the absorber with packing 250X/Y has the lower investment and operating cost. The minimum total cost of the absorber with stainless steel packing 250X/Y is about 0.955 \$/t CO_2 under 48% flooding. For the hydrophilic polypropylene packing 250Y, the absorber has the lowest total cost under 40% flooding. Compared with the investment and operating cost of the absorber with stainless steel 250Y, the polypropylene packing 250Y has lead to a 33.6% reduction of the total cost.

Fig. 10 shows the distribution of the packing, shell, internals, blower and pump cost of the absorber with stainless steel and polypropylene packing 250Y. For the stainless structured packing 250Y, the packing cost accounts for 52.53% of the total cost. As a consequence, the cost-effective polypropylene structured packing can reduce the absorber total cost. The packing proportion of the total cost drops down to 30.63% due to the polypropylene structured packing.

4.4. Absorber for Jinjie CCS project

The absorber for the carbon capture demonstration project consists of the two-stage trough liquid distributors, two-line vane gas distributor, enhanced hydrophilic modified polypropylene structured packing 250Y and support structure, as shown in Fig. 11. The hydrophilic modified polypropylene packing is reinforced by using welded stainless steel corrugated plate.

The wet pressure drop of polypropylene 250Y was about 1.2 times of that of SUS304 250Y under the same operating conditions. The column design parameter, investment, blower and pump cost of the demonstration absorber are summarized in Table 5. The investment of the absorber with polypropylene 250Y is just about 59.5% of that with SUS304 250Y. In addition, the absorber investment, blower and pump cost with polypropylene 250Y was 27.37% lower than that with SUS304 packing 250Y.

5. Conclusion

The hydrophilic modified polypropylene packing 250Y has the similar effective surface area and flooding velocity of that of the stainless steel packing 250Y. The wet pressure drop of the polypropylene packing 250Y is slight higher than that of the stainless steel packing 250Y. The absorber with polypropylene 250Y was just about 59.5% of that with SUS304 250Y. In addition, the absorber investment, blower and pump cost with polypropylene packing 250Y was 27.37% lower than that with SUS304 packing 250Y. As a consequence, the cost-effective polypropylene structured packing can replace the stainless steel packing.

The strength of polypropylene packing is lower than that of stainless steel packing, so the actual hydrodynamics and mass transfer performance should be tested over a prolonged period of time.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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