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Raschig Rings Versus PVC as a Packed Tower Media in Scrubbing Ammonia from Air

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Abstract: The selection of the packing media is concerned when ammonia is going to be scrubbed through a packed tower. In this study, a packed tower with two types of packing including raschig rings and PVC were used to remove the ammonia gas from air stream. Three gas flow rates as well as three ammonia concentrations and three pH of scrubbing liquid were applied. The level of ammonia at the inlet and out let of the packed tower was measured through a direct reading device. The removal efficiency of column significantly increased in both modes, packed with raschig rings and PVC ($p<0.001$) as the inlet concentration of ammonia gas was increased. With decreasing pH of scrubbing liquid from 7 to 5, the removal efficiency of the tower packed with raschig rings significantly increased ($p< 0.01$). The head loss across the bed was significantly increased ($p< 0.001$) as air flow rate increased from 5 to 10 and 10 to 15 l/s. The head loss across the bed was also higher when column was packed with raschig rings rather than packed with PVC. The lower ammonia removal efficiency of PVC rings could be ignored considering their other advantages such as light weight, low headlosses, low initial and operating costs.

Key words: Raschig rings · PVC · Packed tower · Ammonia removal · Efficiency · pH

INTRODUCTION

Ammonia (NH_3) is a colorless gas with a sharp odor. It is soluble in water and very irritant gas. Exposure to ammonia gas can cause skin and eye irritations. Long term exposure to ammonia may cause lung injuries. Ammonia may be absorbed through skin rapidly because of its' high water solubility. Ammonia reacts with water leading to a highly irritant and caustic hydroxide [1]. Ammonia is an explosive gas when mixed with air in appropriate reaction rate. Explosion is the main risk dealt with ammonia gas [2]. The Environmental Protection Agency (EPA) classified ammonia in National Priorities List (NPL). EPA stated that the source of human exposure to ammonia may increase in future and evaluation program is needed to identify the source of exposure [3].

Ammonia can be removed from polluted air by several methods. The most common methods include biofiltration, condensation or distillation method, adsorption and gas scrubbing (absorption) method [4]. Absorption is a mass-transfer operation in which pollutant transfers from gas into liquid phase. That is, concentration is varying between gas and liquid phase [5].

Water is the most widely used liquid to clean polluted air in wet scrubbers [6]. In spite of very high water soluble quality of ammonia gas, scrubbing by water

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depends on physical absorption [7]. It is the case that acidic solution such as sulfuric acid (H_2SO_4) and the like has been known as scrubbing liquids for ammonia gas. These put forward the further benefit of chemical absorption [7]. Sulfuric acid was added to the scrubbing liquid in the present study expecting the following results when it is contacted with ammonia in the tower [8].

$$2NH_3 + H_2SO_4 \rightarrow (NH_4)_2SO_4 \quad (1)$$

Ammonium sulfate ($(NH_4)_2SO_4$) formed in this reaction is soluble in water and it could be easily removed by the blow down [7]. Packed columns provide continuous contact between the scrubbing liquid and the polluted gas. The countercurrent packed column is the most widely used device in air pollution control techniques. This type of column is commonly used in the chemical and pollution control industries [9]. Erosion and corrosion are the major drawbacks in wet scrubbers [10]. Packing is the mass transfer unit. It is important to ensure from appropriate operation of mass transfer media. Selection of packing material should be accurate in features such as in stability, resistance to corrosion and efficiency. The basic requirement for choosing the packing material is the ability to carry out the required gas and liquid flow rates. Besides, it needs to be affordable [11]. Ceramic packed beds with various porosities are usually used in the chemical and petrochemical industries. Ceramic tower packing is very efficient in contact with a number of scrubbing liquid [12]. The existing accounts showed that the ceramic packing material can be used in the corrosive atmosphere.

PVC packing is cheaper than metal and ceramic packing materials [13]. In compare to ceramic raschig rings, PVC is often preferred because of its light weight and great resistance to breakage. Its low resistance to high temperatures is the major drawback of PVC. The maximum operating temperature of PVC is 150 °F (66°C) [14]. The main objective of this paper was to compare the removal efficiency of ammonia gas from contaminated air using two kinds of packing material including ceramic raschig rings and PVC in a packed column.

MATERIAL AND METHODS

General Description of Experiment: A counter flow packed column in laboratory scale with 20 cm diameter was used to remove ammonia gas from contaminated air.

Table 1: Characteristics of studied packed column

parameter	value
Column diameter (m)	0.20
Column height (m)	1.80
Packing depth (m)	0.30
Size of packing materials (in)	0.25 , 0.44
Air flow rate (l/s)	5, 10, 15
Gas mass flow rate (lb/ft² hr)	140.88, 281.77, 422.66
Gas temperature (?C)	25
Injected ammonia gas (ppm)	25±3, 42±3, 57±3
Liquid flow rate (l/min)	0.21, 0.43, 0.64
Liquid mass flow rate (lb/ft² hr)	84.13, 168.27,252.41

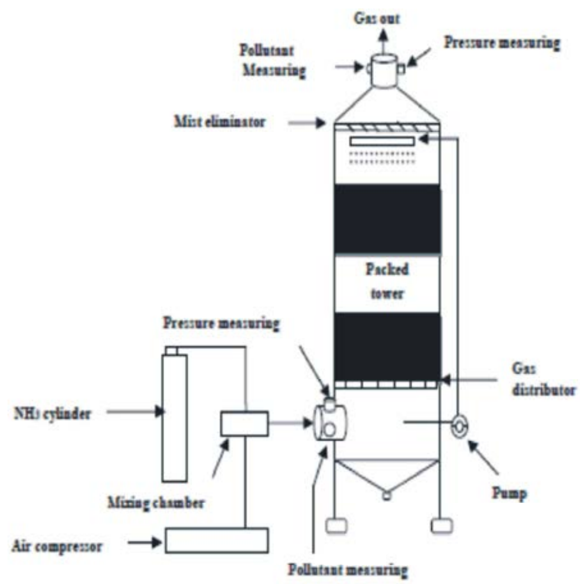

Fig 1: Packed column with auxiliary equipment

The column was randomly packed in 30 cm depth with 0.25 inch ceramic raschig rings and 0.44 inch PVC rings. Ammonia laden air was injected into the column at three air flow rates including 5, 10 and 15 l/s. Ammonia gas was applied to the column in three concentration ranges including 25±3, 42±3 and 57±3 ppm. A caustic scrubbing liquid at three pH including 5, 6 and 7 were used to scrub the polluted gas. Ammonia gas was measured with a direct reading instrument. Ammonia direct reading sensor used to measure ammonia gas in contaminated air [15]. All measuring instrumentation was calibrated prior to their use. The tower was operated at atmospheric pressure and room temperature. The results were analyzed by SPSS version 16 software package. Multi-way ANOVA test was used to analyze the data. Tukey's test was applied for multiple comparisons between variables. Table 1 shows the characteristics of packed column used in this study. Fig. 1 shows the packed column with auxiliary equipment.

Air Flow Rate and Pressure Drop: Required air flow rate for experiments were 5, 10 and 15 l/s. These air flow rates were supplied by a variable flow rate fan model HVDLT-MK2[1], UK air flow Company. A venture meter (G type) was used to measure air flow rate. The accuracy of venture was ± 5%. A monometer- Type 504 manufactured by UK air flow Company was used to measure the pressure losses. The measurement range of manometer was 0-5000 pa with an accuracy of ±10 pa.

Scrubbing Liquid Flow Rate and pH: The scrubbing liquid was free from ammonia at the beginning but it was recirculated by a pump with a maximum capacity of 6 l/min. The optimum volume of injected liquid was based on the exhaust gas flow rate defined in literature [16, 17]. The liquid-to-gas mass flow ratio $(L/G)_m$ was 0.6 based on ACGIH recommendations which is in the range of 0.6 to 1.2 for packed columns [18]. The pH values of scrubbing liquid were controlled by applying sulfuric acid and monitored with a pH meter. A Sartorius Basic Meter PB-11 with an accuracy of ±0.01 was used to measure the pH of scrubbing liquid.

Ammonia Supply and Measurement: A 45 kg gas cylinder was used to supply ammonia gas supply. Ammonia was blended with air prior to its injection to the packed tower. Ammonia concentration was measured through a direct reading using Crowcon Gasman single gas detector at the inlet and outlet of the column. This instrument had a measuring range of 0-100 ppm and detecting accuracy of ±1 ppm. All measuring instrumentations were calibrated prior to their application.

Ammonia removal efficiency (% eff.) was calculated based on given Eq. 2. The results were then averaged and reported [8].

$$\%\,Ammonia\ Eff. = \frac{InletConc. - OutletConc.}{InletConc.} \times 100 \qquad (2)$$

RESULTS AND DISCUSSION

Air Flow Rate versus Removal Efficiency: Three air flow rates including 5, 10 and 15 l/s were introduced to the tower packed with ceramic raschig rings as well as PVC while other parameters were kept constant. The results of 162 experiments showed that the column packed with raschig rings had higher removal efficiency in all air flow rates than the column packed with PVC (Table 2).

In air flow rates variation, the results showed that the tower packed with ceramic raschig rings has higher ammonia removal efficiency than PVC rings. Higher gas flow rates leads to higher turbulent flow, introducing higher energy to the gas which consequently leads to higher removal efficiencies [18]. In present study, increasing the air flow rate from 5 to 10 l/s decreased the removal efficiency of ammonia gas in a tower packed with both packing materials but such decreases was not significant. These results are not consistent with results reported by Jafari *et al.* [16]. They used this packed column to remove sulfuric acid mist by scrubbing with caustic solution. Their results showed that increasing the air flow rate increased the removal efficiency of sulfuric acid mists. It seems that since the volume of the column was constant, an increase in air flow rate resulted in lower retention time [19] and decreases the removal efficiency of ammonia gas in the column. The retention time plays an important role in the absorption of pollutant into scrubbing solution [20]. However, in studied tower packed with both packing materials, by increasing the air flow rate from 10 to 15 l/s, the removal efficiency of ammonia gas was increased although the quantity was not significant.

Inlet Ammonia Concentration Versus Removal Efficiency: Three ranges of ammonia concentration including 25±3, 42±3 and 57±3 ppm were applied to investigate the influences of input concentration on

Table 2: Removal efficiency at different air flow rates

Q_{air} (l/s)	V (m/s)	Type of packing	Test NO.	Removal efficiency (%) Ave± std	Min	Max
5	0.16	Raschig rings	27	95.38± 2.14	91.09	98.15
		PVC	27	92.43± 3.91	86.09	96.91
10	0.32	Raschig rings	27	92.24± 3.22	88.37	98.48
		PVC	27	92.11± 4.63	83.91	96.73
15	0.48	Raschig rings	27	94.35± 3.72	88.37	98.99
		PVC	27	93.80± 2.65	88.26	97.30

[1]High velocity ductwork leakage tester MK2

Table 3: Removal efficiency at different input ammonia concentration

C_{in} (ppm)	Type of packing	Test NO.	Removal efficiency (%) Ave± std
25±3	Raschig rings	27	91.09± 1.98
	PVC	27	87.93± 1.42
42±3	Raschig rings	27	95.73± 1.01
	PVC	27	94.27± 2.34
57±3	Raschig rings	27	97.23± 1.12
	PVC	27	96.11± 0.72

Table 4. Removal efficiency at different pH of scrubbing liquid

			Removal efficiency (%)		
pH	Packingtype	Test NO.	Ave± std	Min	Max
5	Raschig rings	27	96.23± 2.55	91.89	98.99
	PVC	27	93.78± 3.64	86.96	97.09
6	Raschig rings	27	94.44± 2.8	89.53	97.3
	PVC	27	93± 3.6	86.09	96.36
7	Raschig rings	27	93.38± 3.08	87.98	96.29
	PVC	27	91.54± 4.07	83.91	95.82

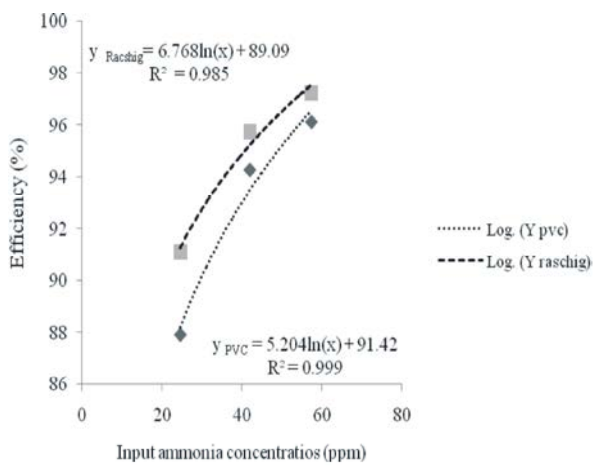

Fig 2: Removal efficiency versus input concentration

removal efficiency. The results revealed that the removal efficiency of column packed with ceramic raschig rings was higher than it when packed with PVC rings. The result of Tukey post-hoc test showed that with increases in the input concentration of ammonia gas, average removal efficiency in both media significantly increased (P-value <0.001). Table 3 shows the influences of inlet concentration of ammonia gas on packed tower removal efficiency. Fig. 2 shows the trend of ammonia removal efficiency of the tower at different ammonia input concentrations while packed with ceramic and PVC rings.

According to the results, increasing inlet ammonia concentration can increase tower removal efficiency. This is mainly because of high concentration of ammonia leads to a high driving force between gas and liquid phase which consequently increases the removal efficiency. A positive significant relationship (P-value<0.001) was observed between inlet ammonia concentration and the removal efficiency when using both packing materials. In a tower packed with ceramic raschig rings, increasing inlet ammonia concentration from 25±3 to 42±3 then to 57±3 the removal efficiency increased by 5.09% and 1.55% respectively. In similar situations for PVC packing materials, an increase in inlet concentration from 25±3 to 42±3 and then to 57±3 ppm, the removal efficiency increased by 7.9 and 1.94%, respectively.

The Scrubbing Liquid pH Versus Removal Efficiency: Sulfuric acid was added to water to have a caustic scrubbing liquid for better removal efficiencies. Three pH of scrubbing liquid including 5, 6 and 7 was used to scrub the ammonia gas. Table 4 shows the effect of pH of scrubbing liquid on removal efficiency of ammonia by the tower packed with ceramic raschig rings and PVC rings. Fig. 3 shows the trend of ammonia removal efficiency at different pH of scrubbing liquid in similar cases.

The result of Tukey post-hoc test showed that the removal efficiency of column packed with raschig rings significantly increased (P< 0. 01) as the pH of scrubbing liquid was reduced from 7 to 5. With decreasing the pH of scrubbing liquid from 7 to 5 in column packed with PVC, its removal efficiency increased but not significant quantities (P = 0.081). The trend is almost the same for both packing material.

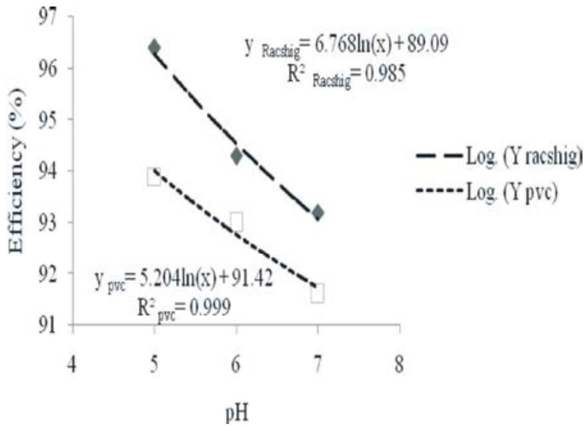

Fig 3: Removal efficiency versus scrubbing liquid pH

The acidity of scrubbing liquid plays a key role in chemical absorption. In such an absorption, the removal efficiency of a packed tower is expected to increase by decreasing the pH (increasing the acidity) of scrubbing liquid [8]. This is expected to be independent from the type of packing material. The results of the present study well agree with this fact. The results showed that removal efficiency of tower packed with raschig rings at studied pHs of 5, 6 and 7 was more than PVC by 1.95, 0.97 and 0.5%, respectively. That is not seems to be due to acidity of scrubbing liquid. At lower pH of 5, higher concentration of sulfuric acid more effectively reduces the ammonia gas from polluted air in packed column. The removal efficiency was consequently decreased with the increasing of pH of scrubbing liquid [8, 21].

The ammonia removal efficiency was independent from G/L ratio and inlet ammonia concentration when H_2SO_4 was applied as the absorbent. Adding H_2SO_4 to the scrubbing solution is recommended in order to have higher ammonia removal efficiencies in a packed tower which is consistent with Bunyakan *et al.* findings [21]. While the handling of scrubbing solutions with high acidity (e. g. pH of less than 4) is more difficult and expensive, the present study shows that at lower concentrations of H_2SO_4 (pH > 5), acceptable average removal efficiency of up to 96.23% is obtainable. This is in the range of removal efficiencies obtained by Melse and Ogink [22]. They have reported an average ammonia removal efficiency of 91 to 99% at pH of 4 [22].

The Influences of Air Flow Rates on Pressure Loss: As it was expected, head losses of packed tower were increased with increases in the air flow rate in both packing materials. Higher head loss was observed when the tower was packed with ceramic raschig rings rather than packed with PVC in all three air flow rates. Fig. 4 shows the effect of air flow rates on head losses of the tower with two types of packing material. The maximum head loss of 788 (pa) was observed at the air flow rate of 15 l/s when the column was packed with ceramic raschig rings.

Table 5: Head losses at different air flow rates

Type of packing	Q, l/s	ΔP, Pa	P-value
Raschig rings	5, 10	153.2	P<0.001
	10, 15	115.2	P<0.001
	5, 15	268.42	P<0.001
PVC	5, 10	7.41	P<0.001
	10, 15	6.07	P<0.001
	5, 15	13.48	P<0.001

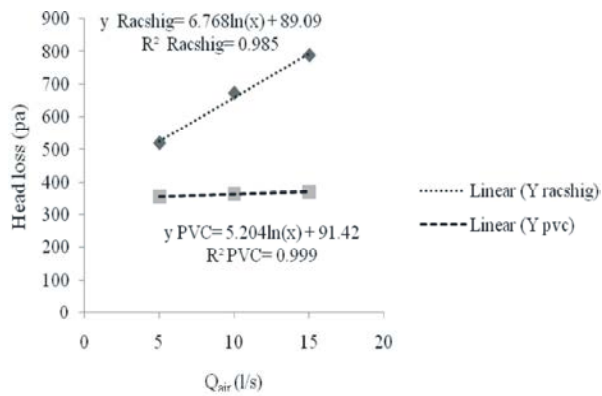

Fig 4: Tower head losses versus air flow rates

The results of Tukey post-hoc test indicated that changing air flow rates from 5 to 10 and 10 to 15 l/s caused a significant increase (P-value<0.001) in tower head loss with both packing materials. Table 5 shows the Tukey post- hoc analysis test to compare the effect of different air flow rates on the head loss of tower packed with two types of packing material.

By increasing air flow rate, the head loss across the bed packed with both packing materials significantly (P-value<0.001) increased which his in consistent with results of many investigations reported in literature [9, 11 and 16]. As the air velocity increases in the column, the head loss which depends on air velocity is expected to increase. The trends of head loss versus air flow rates in Fig. 4 show that the type of air flow in the column packed with Raschig rings is turbulent while it seems to be laminar flow when it is packed with PVC rings. This could be mainly due to smaller sizes of raschig rings in compare to PVC rings. Smaller packing sizes offer a larger surface area, thus enhancing absorption. However, smaller packing fits more tightly, which decreases the open area or void volume between packing, leading to high head losses across the packing bed [6, 9].

By increasing the air flow rate from 5 to 15 l/s, the head loss across the bed packed with Raschig rings increased by 51.63%, while it increased by only 3.79% when it was packed with PVC rings. This is a significant advantage of PVC rings over raschig rings. It may be concluded that the operating costs of air cleaning with packed towers using raschig rings will be much higher than PVC. Packed towers with 500 to 2500 Pascal pressure drops classified as medium-energy scrubbers [17]. The head loss of the studied packed tower packed with raschig rings was two times higher than PVC for the same removal efficiency which is a considerable credit for PVC rings.

CONCLUSION

Lower concentration of H_2SO_4 (pH > 5) is recommended to remove ammonia from polluted air. The lower ammonia removal efficiency of PVC rings could be ignored considering their other advantages of having less weight, low head loss, low initial and operating costs.

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Conflict of Interest: The authors announce no conflict of interests.

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Persian Abstract

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چکیده

انتخاب بستر پرکننده برای حذف گاز آمونیاک در ستون پرشده اهمیت زیادی دارد. در این مطالعه یک برج پرشده با دو نوع ماده پرکننده شامل حلقه‌های راشیگ سرامیکی و PVC برای حذف گاز آمونیاک از جریان هوا مورد استفاده قرار گرفت. هوا در سه گذر حجمی، گاز آمونیاک در سه دامنه‌ی تراکم، و مایع شستشو در سه pH بکار گرفته شد. غلظت گاز آمونیاک در ورودی و خروجی برج پرشده توسط تجهیزات قرائت مستقیم اندازه‌گیری گردید. راندمان حذف ستون پرشده با افزایش غلظت آمونیاک ورودی در هر دو نوع بستر پرشده بوسیله‌ی حلقه‌های راشیگ سرامیکی و PVC بطور معنی‌دار افزایش یافت (P< 0.001). با کاهش pH مایع شستشو از ۷ به ۵ راندمان حذف ستون پرشده با حلقه‌های راشیگ سرامیکی بطور معنی‌دار افزایش یافت (P< 0. 01). با افزایش گذر حجمی هوا از ۵ به ۱۰ و از ۱۰ به ۱۵ لیتر بر ثانیه، افزایش معنی‌داری (P< 0.001) در افت فشار ستون در هر دو نوع بستر پرکننده مشاهده گردید اما این افت فشار افزایش یافته در ستون پر شده بوسیله‌ی حلقه‌های راشیگ سرامیکی بیشتر بود. با وجود راندمان حذف کمتر ستون پر شده توسط حلقه‌های PVC نسبت به حلقه‌های راشیگ سرامیکی، سایر مزایای این نوع پرکننده از قبیل وزن پایین‌تر، افت فشار کمتر و هزینه‌ی اولیه و نگهداری پایین‌تر سبب می‌شود بیشتر مورد پذیرش و استفاده قرار گیرد.