RECyT
Year 27 / Nº 43 / 2025 /
DOI: https://doi.org/10.36995/j.recyt.2025.43.010

Designing a Packed Column for Ammonia Recovery: Evaluating Two Packing Types

Diseño de una columna empacada en la recuperación de amoníaco: evaluación de dos tipos de empaque

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Received: 01/02/2023; Accepted: 06/05/2025

Abstract
Gas absorption is a mass transfer operation that involves separating components from a gaseous mixture by contacting them with a suitable liquid, typically performed in packed columns. In this study, a packed column was designed for the absorption of gaseous ammonia using water as a solvent, and two types of packing were evaluated: ceramic Raschig rings and metallic Hiflow rings. The use of Hiflow rings resulted in a 30.35% reduction in column diameter compared to Raschig rings. Furthermore, the total pressure drop of the gas-liquid system at 70% flooding was 17.81% lower for Hiflow rings (522.16 Pa/m) than for Raschig rings (615.16 Pa/m). The calculated convective mass transfer coefficients for both liquid and gas phases were also higher when using Hiflow rings compared to Raschig rings. Based on these findings, Hiflow rings are recommended for this mass transfer application due to the smaller column internal diameter and lower pressure drop obtained, as well as the higher mass transfer coefficients achieved with this packing type compared to Raschig rings.

Keywords: Packed column; Internal diameter; Pressure drop; Mass-transfer coefficients; Design.

Resumen
La absorción gaseosa es una operación de transferencia de masa que consiste en la separación de componentes de una mezcla gaseosa mediante el contacto con un líquido adecuado, típicamente llevada a cabo en columnas empacadas. En el presente trabajo se diseñó una columna empacada para efectuar la absorción de amoníaco gaseoso usando agua como solvente y evaluando dos tipos de empaque, anillos Raschig cerámicos y anillos Hiflow metálicos. Los anillos Hiflow redujeron el diámetro de la columna en un 30.35% comparado con los anillos Raschig, mientras que la caída de presión total del sistema gas-líquido a 70% de inundación fue un 17.81% menor para los anillos Hiflow (522.16 Pa/m) que para los anillos Raschig (615.16 Pa/m). Los valores calculados de los coeficientes de transferencia de masa convectivos para las fases líquida y gaseosa fueron superiores para los anillos Hiflow en comparación con los anillos Raschig. Basado en estos resultados, se recomienda los anillos Hiflow para esta aplicación de transferencia de masa, debido a los bajos valores obtenidos para el diámetro interno de la columna y caída de presión, así como también los valores superiores de los coeficientes de transferencia de masa alcanzados para este tipo de empaque comparados con los anillos Raschig.

Palabras claves: Columna empacada; Diámetro interno; Caída de presión, Coeficientes de transferencia de masa; Diseño.

Introduction

Unit operation techniques in the chemical process industries (CPI) facilitate the separation of a mixture or mixtures into their individual components. These operations are commonly referred to as diffusional or mass transfer operations. The techniques employed in the CPI to achieve these separations include: distillation, absorption, liquid extraction, drying, leaching, crystallization, and gas adsorption [1].

In counter-current separation processes, such as distillation, extraction, and gas absorption, the separation relies on the transfer of one or more components between the contacting fluid phases [2]. Following distillation, gas/liquid absorption is arguably the second most crucial separation operation utilized in the chemical and related industries [3].

Gas-liquid absorption is a heterogeneous process that involves the transfer of a soluble component from a gas phase into a relatively non-volatile liquid absorbent [4]. There are instances where a solute diffuses through a vapor phase and is subsequently absorbed into an immiscible fluid phase, as exemplified by the absorption of ammonia from air using water [5].

To enhance the efficiency of this process by increasing mass transfer between the phases, the contact between these phases is intensified through the application of phase contactor devices, namely trays (plates) or packings. The contact between the phases is stagewise when using trays, and continuous when using packings [2].

One of the most prevalent and rapidly developing methods used to perform the absorption process on an industrial scale is the packed column (Figure 1).

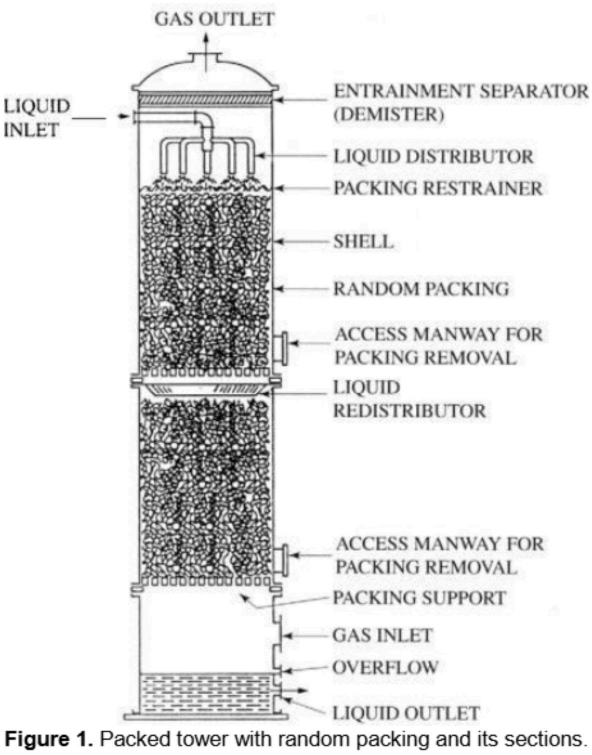


Figure 1. Packed tower with random packing and its sections.

A packed column is essentially a vertical pipe filled with an inert material, commonly known as packing materials [6]. Typically, a packed tower operates in a countercurrent manner, where the liquid enters from the top and wets the surfaces of the packing, while the gas stream containing the effluent enters from the bottom. As the two streams come into intimate contact, the effluent components are absorbed into the liquid. The liquid surface area available for mass transfer and the time available for the diffusion of gaseous molecules into the liquid are considered crucial factors affecting the process's performance. Mass transfer to the liquid continues until the liquid approaches saturation, at which point equilibrium is established between the two phases [7].

To meet the requirements of column size optimization (in terms of height and diameter) and pressure drop limitation, efficient and high-capacity packings, along with appropriate designs for the gas and liquid distributors, are essential [8]. The distribution of the liquid and gas phases within the packing is ensured by gas-liquid tray distributors located at the top of each packed bed and a bottom gas distributor at the column's base [8]. In a packed column, the packing section is responsible for providing the surface area where the liquid and gas phases contact, making it a critical component of the column [4].

The packing section plays a vital role in the absorption process by providing surface area for gas and liquid phases to interact. Broadly, two main types of packing materials are available for gas absorption: random packing (e.g., Pall rings, IMTP, Hiflow, Raschig rings) and structured packing (e.g., Flexipac, Mellapak, Gempak, BX) [9]. These are manufactured from a variety of construction materials, including polymers, plastics, ceramics, and metals [5].

Random packings, which are porous solids of various shapes such as spheres, coils, mesh, and cylinders, have been in use since the early 20th century. They consist of discrete structural elements randomly dumped into a column to form the absorption section. Typical sizes for random packings range from 1 to 10 cm. In contrast, structured packings are composed of corrugated metal sheets or wire mesh arranged vertically in the column as blocks of assembled layers. The corrugation sizes typically fall between 0.5

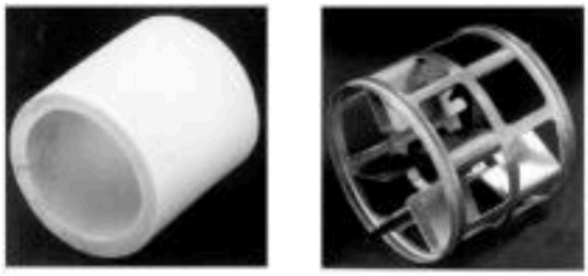
and 2 cm, with block sizes on the order of 25 cm [2].

The primary objective of any packing is to maximize efficiency for a given capacity at a reasonable cost. To achieve this, packing materials are designed with the following characteristics in mind [10]:

- Maximize the specific surface area: This maximizes the vapor-liquid contact area, thereby enhancing efficiency.
- Ensure uniform surface area distribution: This improves vapor-liquid contact and, consequently, efficiency.
- Maximize the void space per unit column volume: This minimizes resistance to gas up-flow, thereby increasing packing capacity.
- Minimize friction: This is facilitated by an open shape with favorable aerodynamic characteristics.
- Minimize cost.

According to [9], the two most critical factors for selecting packing material are surface area and void fraction. Additionally, the material should be chemically inert to the fluids being processed and possess sufficient structural strength for easy handling and installation [11].

The Raschig ring, first patented by Dr. Fritz Raschig in Germany in 1907, was the inaugural standardized packing. Until the 1960s, packed columns were predominantly filled with Raschig rings or Berl saddles, collectively known as first-generation packings. Raschig rings are hollow cylinders with diameters ranging from 6 to 100 mm or more (Figure 2a). They can be manufactured from metal, ceramic, or plastic [11]. Due to their high porosity, Hiflow rings (Figure 2b) are considered third-generation packings, making them suitable for high gas flow rates and thus well-suited for treating industrial gaseous effluents [12].



a) b)

Figure 2. Two common packing types used in packed columns.
a) Ceramic Raschig ring.
b) Metal Hiflow ring.

The selection of column internals necessitates a thorough understanding of the specific purpose of the gas/liquid absorption application, along with precise knowledge of the characteristics of the gas and liquid solvent flows throughout the packed bed. This includes their hydrodynamic behavior (e.g., pressure drop, flooding) and mass transfer properties (e.g., gas-side and liquid-side mass transfer coefficients) [8].

Despite their considerable industrial success, packed columns encounter various operational challenges, including flooding, channeling, entrainment, and foaming [13]. Nevertheless, their advantages include lower liquid holdup, reduced pressure drops [5], higher capacity, and increased interfacial area [2].

A comprehensive understanding of a gas absorption process hinges on several parameters. These include fluid stream analysis, the study of the packed column's hydrodynamic features, determination of fluid mass balance, calculation of mass transfer coefficients, and the calculation of drag and flooding flows. It also involves examining the physicochemical properties and composition of the fluids, component recovery from the fluid streams, industrial design, process simulation, evaluation of influencing factors (e.g., column diameter, packing height, mass transfer coefficient, molar flow rates), process design, countercurrent two-phase flow studies, optimization of the stream ratio (inert liquid to gas), effective packing surface area, the influence of packing type, and the assessment of column efficiency for fractionators, absorbers, and strippers [5].

Gas/liquid absorption is widely employed in recovering vapors from gas streams, treating gases in refineries, and for industrial waste treatment [5]. It also finds numerous industrial applications, such as acid gas removal, solvent-based post-combustion carbon dioxide (CO2) capture [8], sour gas scrubbing, and petroleum refining operations [7].

Packed columns are increasingly utilized across diverse applications within the chemical process industries. This trend is driven by an increase in the availability of design information, the development of higher-capacity and more efficient mass-transfer packings, and advancements in distributors and support plates. Today, packings can be considered for most services requiring a high number of theoretical stages for mass transfer [1].

Numerous studies have evaluated or investigated packed columns for various applications and services. These include:

- The absorption of sulfur dioxide from air into a sodium hydroxide solution using HelieR packing [14].
- CO2 absorption into aqueous solutions of single and blended alkanolamines in a bench-scale absorber packed with high-efficiency packings [15].
- The absorption of CO2 in monoethanolamine and 2-amino-2-methyl-1-propanol using a counter-current absorber containing DX structured packing [13].
- The determination of hydrodynamic characteristics and mass transfer in a pilot plant packed bed absorption column filled with Raschig rings for CO2 absorption from air using water [3].
- The absorption of CO2 into aqueous ammonia solution in a packed column containing 8-mm ceramic Raschig [16].
- Physical modeling, computational fluid dynamics analysis, and experimental analysis of a packed column containing 25-mm polypropylene Pall rings, used for flue gas desulfurization to reduce sulfur dioxide emissions [17].
- The absorption of CO2 into aqueous ammonia solution using a packed column containing 8-mm ceramic Raschig rings as packing material. This study experimentally evaluated the packed column's performance under various conditions to reveal the effects of several process parameters, including CO2 partial pressure in the gas phase, gas flow rate, liquid flow rate, ammonia concentration, and temperature [18].
- The evaluation of CO2 absorption into aqueous ammonia solution using a packed column with 8-mm ceramic Raschig rings to assess overall CO2 absorption rates. This revealed the effects of several process parameters, including ammonia concentration, liquid flow rate, CO2 inlet concentration, gas flow rate, and the temperatures of the ammonia solution and the gas [19].
- The development and validation of a model for CO2 absorption using 3 wt% dilute aqueous ammonia solution in both rotating packed beds and standard packed beds, utilizing experimental data. The resulting model was then employed to design absorbers for various throughput rates, ranging from 0.01 to 1,000 tons of CO2 capture per day [20].

The removal efficiencies for gas absorbers vary depending on the pollutant-solvent system and the type of absorber used. Most absorbers achieve removal efficiencies exceeding 90%, with packed tower absorbers potentially reaching efficiencies as high as 99.9% for some pollutant-solvent systems [7].

Currently, most modern industrial plants implement gas treatment systems to mitigate emissions of harmful air pollutants generated during their processes. Specifically, ammonia gas is a significant contributor to air pollution, leading to the deterioration of the atmospheric environment. Given that packed tower operation is considered cost-effective, ammonia-water absorption columns are increasingly popular today for addressing environmental issues linked to ammonia emissions [7].

Several authors have evaluated packed columns for gaseous ammonia absorption. For instance, [21] investigated the ammonia absorption rate from air by water in a 1-foot-diameter tower packed with carbon Raschig rings. They also examined the effect of gas rate, liquor rate, temperature, ring size, degree of inlet gas humidification, and the reproducibility of a given tower filling. Individual film coefficients were calculated using Sherwood and Holloway's liquid film correlation. Similarly, [22] explored the absorption of ammonia from an air stream in a multiple-stage crosscurrent packed column, suitable for gas-liquid mass transfer. Water served as the solvent in this study, Pall rings were selected as the packing material for all experimental runs, and the ammonia-air-water system was chosen due to its high commercial importance, relative safety, ease of handling with proper precautions, and readily available thermodynamic and physical data. The absorption column in this study consisted of a rectangular box constructed from Plexiglas and metal, with deflection baffles strategically placed at regular intervals on opposite sides of a central packed section to divert the gas phase into the packing, thereby creating a crisscross gas-liquid flow pattern.

Other authors also studied the absorption of ammonia from an air stream into water in a packed tower, publishing their findings in two papers. In the first [23], they measured pressure loss, holdup, and liquid distribution for a standard 10 mm glass Raschig ring packing contained in a Quickfit packed tower with a 10.2 cm inside diameter. In the second [24], they outlined a simple modification of gas absorption theory for this setup, enabling the determination of mass transfer coefficients in laboratory apparatus that have been successfully used in industrial equipment design. These authors concluded that the theory can be developed to an increasing degree of mathematical sophistication to address the most complex experimental situations. The general method derived in this study has clear applications to other mass transfer processes, particularly those employing packed towers.

Likewise, [7] described two new empirical models based on the composite desirability function methodology for predicting packed column diameter and packing height in physical ammonia absorption problems. A computational analysis encompassing a total of 131 absorption scenarios was conducted for six fundamental operating parameters: inlet gas flow rate (500-5000 m^3/h), solute concentration in the inlet gas (5-10%), desired removal efficiency (87-98%), operating temperature (10-60 °C), percentage of the minimal liquid-to-gas flow rates ratio (24-52%), and percent of flooding velocity (30-80%). Ceramic Raschig rings were chosen as one of the most common packing types for this study. The paper's aim was to provide a tool for researchers, students, engineers, and others, enabling rapid calculation of packing height and packed column diameter for physical ammonia absorption with Raschig rings, without requiring the full theoretical procedures detailed in the literature. It also aimed to offer a practical, novel reference for absorber designers, researchers, manufacturers, absorber-equipment engineers, and end-user industries for real-life packed tower design under varying ammonia absorption data using common operating parameters.

Furthermore, [4] reported an experimental evaluation of perlite from Lamba, Albay, Bicol, as a packing material for gaseous ammonia absorption using liquid water as a solvent, with the goal of subsequently designing a packed column based on the obtained results. Finally, [25] developed a model to predict the performance of a packed bed absorber for an ammonia-water absorption refrigeration system, evaluating two packing types: Raschig rings and Berl Saddles. The resulting model was used in a parametric study to investigate the effect of several design and operating parameters on the absorber's performance.

In the present work, a packed column is designed for the absorption of gaseous ammonia using water as a solvent. This study evaluates two different packing types: ceramic Raschig rings and metal Hiflow rings. Key parameters such as column inside diameter, total pressure drop of the gas-liquid system at 70% flooding, and the convective mass transfer coefficients for both phases are determined. The objective is to identify which packing type is most appropriate for this mass transfer service, considering the results obtained for the key parameters for both packings. To achieve this objective, the methodology proposed in [11] is applied.

Materials and methods

Problem definition

The objective is to recover ammonia from a dry air stream, where the ammonia concentration is 8% mol. The total inlet flow rate of the ammonia/air gas stream is 40 kmol/h, with an inlet temperature of 303 K and a pressure of 1 atm. The desired ammonia recovery is 90%, utilizing pure liquid water as a solvent. The available water flow rate is 1,700 kg/h, and its feed temperature and pressure are 298 K and 101.3 kPa, respectively. Two packing materials will be evaluated for this mass transfer service::

- 25-mm ceramic Raschig rings.
- 25-mm metal Hiflow rings.

For both packing materials, the following must be determined:

a) Column inside diameter.
b) Pressure drop for operation at 70% of flooding.
c) Mass transfer coefficients for both phases.

The total pressure drop of the gas-liquid system at 70% of flooding must not exceed 600 Pa/m for either packing.

Collection of initial data:

- Mole fraction of air in the gas phase (y_{air}) = 0.92.
- Mole fraction of ammonia in the gas phase (y_{NH3}) = 0.08.
- Molar flow rate of the gas phase (V) = 40 kmol/h.
- Inlet temperature of the gas phase (T_G) = 303 K.
- Inlet pressure of the gas phase (P_G) = 101.3 kPa = 1.013 bar = 1 atm.
- Inlet temperature of water (T_L) = 298 K.
- Inlet pressure of water (P_L) = 1 atm.
- Mass flow rate of the inlet liquid (L) = 1,700 kg/h.
- Ideal gas constant (R) = 8.314 J/mol.K = 0.08205 atm.m^3/kmol.K [10].
- Percentage of ammonia to be scrubbed ($\%S_{NH3}$) = 0.9.
- Molecular weight of ammonia (M_{NH3}) = 17.03 g/mol.
- Molecular weight of air (M_{air}) = 28.96 g/mol.
- Density of water at T_L and P_L (ρ_L): 997 kg/m^3 [10].
- Viscosity of water at T_L and P_L (μ_L): 0.000890 Pa.s [10].
- Packing factor for 25-mm ceramic Raschig rings (F_P) = 179 [11].
- Packing factor for 25-mm metal Hiflow rings (F_P) = 42 [11].
- Viscosity of dry air at 303 K and 1 atm (μ_{air}) = 0.00001869 Pa.s [10].
- Viscosity of ammonia at 303 K and 1 atm (μ_{NH3}) = 0.00001030 Pa.s [10].

Column inside diameter

Most packed columns consist of cylindrical vertical vessels. According to [7], if the gas velocity through the column is gradually increased by utilizing columns with progressively smaller diameters, a point is reached where the liquid flowing downwards over the packing begins to be retained within the void spaces of the packing. A further increase in gas velocity beyond this loading point causes the liquid to completely fill the packing's void spaces. Ultimately, the liquid forms a layer over the top of the packing, preventing any further downward flow through the tower. This condition is termed flooding, and the gas velocity at which it occurs is known as the flooding velocity. For this reason, standard practice dictates sizing a packed column diameter to operate below the flooding velocity, specifically at a certain percentage of it.

The column diameter is determined to safely avoid flooding and ensure operation in the preloading region, with a pressure drop not exceeding 1.2 kPa/m of packed height (equivalent to 1.5 in. of water head per foot of packed height) [11]. Flooding establishes the minimum possible diameter for the absorber column, and the typical design operates at 50 to 75 percent of the flooding velocity [7]. It is assumed that by operating within this range, the gas velocity will also remain below the loading point.

Step 1. Molecular weight of the inlet gas (ammonia-air mixture) (M_G):

$$M_G = M_{air} \cdot y_{air} + M_{NH3} \cdot y_{NH3} \quad (1)$$

Step 2. Mass flow rate of the gas phase (V'):

$$V' = \frac{V \cdot M_G}{3{,}600} \quad (2)$$

Step 3. Density of the gas phase (ρ_G):

$$\rho_G = \frac{P_G \cdot M_G}{R \cdot T_G} \quad (3)$$

Where P_G = 101.3 kPa.

Step 4. Volumetric flow rate of the gas phase (Q_G):

$$Q_G = \frac{V'}{\rho_G} \quad (4)$$

Step 5. Ammonia absorbed (A_{NH3}):

$$A_{NH3} = V \cdot y_{NH3} \cdot \%S_{NH3} \cdot M_{NH3} \quad (5)$$

Step 6. Mass flow rate of the exiting liquid (L'):

$$L' = \frac{L + A_{NH3}}{3{,}600} \quad (6)$$

Step 7. Flow parameter (X):

$$X = \frac{L'}{V'} \cdot \left(\frac{\rho_G}{\rho_L}\right)^{0.5} \quad (7)$$

Step 8. Pressure drop parameter under flooding (Y_{flood}):

$$lnY_{flood} = -[3.5021 + 1.028 \cdot lnX + 0.11093 \cdot (lnX)^2] \quad (8)$$

Step 9. Parameter Cs under flooding (Cs_{flood}):

$$Cs_{flood} = \left[\frac{Y_{flood}}{F_p \cdot \mu_L^{0.1}}\right]^{0.5} \quad (9)$$

Step 10. Superficial gas velocity at flooding (v_{GF}):

$$v_{GF} = \frac{Cs_{flood}}{\left[\frac{\rho_G}{\rho_L - \rho_G}\right]^{0.5}} \quad (10)$$

Step 11. Pressure drop at flooding (ΔP_{flood}):

$$\Delta P_{flood} = 93.9 \cdot F_p^{0.7} \quad (11)$$

Step 12. Superficial gas velocity at 70% of flooding (v_G):

$$v_G = 0.7 \cdot v_{GF} \quad (12)$$

Step 13. Column inside diameter (D)

$$D = \left[\frac{4 \cdot Q_G}{\pi \cdot v_G}\right]^{0.5} \quad (13)$$

Total pressure drop for operation at 70% flooding

The pressure drop (ΔP) through a packed bed accounts for frictional losses, kinetic energy losses through the packing, and the force exerted by the operating liquid holdup. At a constant ΔP, the packed bed exhibits less volumetric liquid holdup in systems with high liquid density. Conversely, with low-density liquids, the volumetric liquid holdup can be significantly greater than that for water at the same ΔP [1].

Step 14. Hydraulic parameters for both random packings:

According to [11], the two random packings evaluated in this study exhibit the hydraulic parameters presented in Table 1.

Table 1. Hydraulic parameters of the two random packings evaluated.

Parameter	Symbol	Units	Raschig	Hiflow
Mass-transfer surface area per unit volume	a	m^2/m^3	190	202.9
Porosity or void fraction	ε	-	0.680	0.962
Packing constant C_h	C_h	-	0.577	0.799
Packing constant C_p	C_p	-	1.329	0.689

Step 15. Effective particle diameter (d_p):

$$d_p = 6 \cdot \left(\frac{1-\varepsilon}{a}\right) \quad (14)$$

Step 16. Wall factor (K_W):

$$K_W = \frac{1}{1 + \frac{2}{3} \cdot \left(\frac{1}{1-\varepsilon}\right) \cdot \frac{d_p}{D}} \quad (15)$$

Step 17. Viscosity of the gas phase (μ_G):

$$\mu_G = \frac{M_G}{\frac{y_{air} \cdot M_{air}}{\mu_{air}} + \frac{y_{NH3} \cdot M_{NH3}}{\mu_{NH3}}} \quad (16)$$

Step 18. Reynolds number of the gas phase (Re_G):

$$Re_G = \frac{v_G \cdot d_p \cdot \rho_G \cdot K_W}{(1-\varepsilon) \cdot \mu_G} \quad (17)$$

Step 19. Dry-packing resistance coefficient (Ψ_0):

$$\Psi_0 = C_p \cdot \left(\frac{64}{Re_G} + \frac{1.8}{Re_G^{0.08}}\right) \quad (18)$$

Step 20. Dry-gas-pressure drop ($\frac{\Delta P_0}{Z}$):

$$\frac{\Delta P_0}{Z} = \Psi_0 \cdot \frac{a}{\varepsilon^3} \cdot \frac{\rho_G \cdot v_G^2}{2} \cdot \frac{1}{K_W} \quad (19)$$

Step 21. Liquid mass velocity (G_L):

$$G_L = \frac{4 \cdot L'}{\pi \cdot D^2} \quad (20)$$

Step 22. Reynolds number of the liquid phase (Re_L):

$$Re_L = \frac{G_L}{a \cdot \mu_L} \quad (21)$$

Step 23. Liquid Froude number (Fr_L):

$$Fr_L = \frac{G_L^2 \cdot a}{\rho_L^2 \cdot g} \quad (22)$$

Step 24. Ratio of specific areas ($\frac{a_h}{a}$):

- For $Re_L < 5$:

$$\frac{a_h}{a} = C_h \cdot Re_L^{0.5} \cdot Fr_L^{0.1} \quad (23)$$

- For Re_L ε 5

$$\frac{a_h}{a} = 0.85 \cdot C_h \cdot Re_L^{0.25} \cdot Fr_L^{0.1} \quad (24)$$

Step 25. Specific liquid holdup (h_L):

$$h_L = \left[12 \cdot \frac{Fr_L}{Re_L}\right]^{1/3} \cdot \left[\frac{a_h}{a}\right]^{2/3} \quad (25)$$

Step 26. Total pressure drop of the gas-liquid system at 70% flooding ($\frac{\Delta P}{Z}$):

$$\frac{\Delta P}{Z} = \frac{\Delta P_0}{Z} \cdot \left(\frac{\varepsilon}{\varepsilon - h_L}\right)^{1.5} \cdot exp\left(\frac{Re_L}{200}\right) \quad (26)$$

Mass transfer coefficients

Step 27. Lennard-Jones parameters for air and ammonia:

According to [26] the Lennard-Jones parameters for both the air and ammonia are as follows:

Air:

- σ_{air} = 3.620 Å
- ε_{air}/k = 97.0 K

Ammonia:

- σ_{NH3} = 2.900 Å
- ε_{NH3}/k = 558.3 K

Step 28. Mass-transfer parameters for both packings:

As stated by [11], the mass-transfer parameters for the two random packings evaluated are:

25-mm ceramic Raschig rings:

- C_L = 1.361
- C_V = 0.412

25-mm metal Hiflow rings:

- C_L = 1.641
- C_V = 0.402

Step 29. Molar volume for ammonia at normal boiling point [$V_{b(NH3)}$]:

As reported by [11], the molar volume of ammonia at its normal boiling point is $V_{b(NH3)}$ = 25.8 cm^3/mol.

Step 30. Parameter δ:

$$\delta = \frac{9.58}{V_{b(NH3)}} - 1.12 \quad (27)$$

Step 31. Liquid diffusion coefficient of ammonia in the aqueous solution (D_L):

$$D_L = 1.25 \times 10^{-8} \cdot \left(V_{b(NH3)}^{-0.19} - 0.292\right) \cdot T_L^{1.52} \cdot (\mu_L \cdot 1{,}000)^{\delta} \cdot 0.0001 \quad (28)$$

Step 32. Molecular weight of the gaseous mixture (M_{AB}):

$$M_{AB} = 2 \cdot \left[\frac{1}{M_A} + \frac{1}{M_B}\right]^{-1} \quad (29)$$

Step 33. Average collision diameter (σ_{AB}):

$$\sigma_{AB} = \frac{\sigma_{air} + \sigma_{NH3}}{2} \quad (30)$$

Step 34. Average Lennard-Jones parameter ($\frac{\varepsilon_{AB}}{k}$):

$$\frac{\varepsilon_{AB}}{k} = \sqrt{\frac{\varepsilon_{air}}{k} \cdot \frac{\varepsilon_{NH3}}{k}} \quad (31)$$

Step 35. Parameter T^*:

$$T^* = \frac{T_G}{\frac{\varepsilon_{AB}}{k}} \quad (32)$$

Step 36. Diffusion collision integral (Ω_D):

$$\Omega_D = \frac{1.06036}{(T^*)^{0.15610}} + \frac{0.193}{exp(0.47635 \cdot T^*)} + \frac{1.03587}{exp(1.52996 \cdot T^*)} + \frac{1.76474}{exp(3.89411 \cdot T^*)} \quad (33)$$

Step 37. Gaseous diffusion coefficient of ammonia in air (D_G):

$$D_G = \frac{\left[3.03 - \frac{0.98}{M_{AB}^{0.5}}\right] \cdot (10^{-3}) \cdot T_G^{1.5}}{P_G \cdot M_{AB}^{0.5} \cdot \sigma_{AB}^2 \cdot \Omega_D \cdot 0.0001} \quad (34)$$

Where P_G = 1,013 bar.

Step 38. Liquid velocity (v_L):

$$v_L = \frac{4 \cdot L'}{\pi \cdot \rho_L \cdot D^2} \quad (35)$$

Step 39. Convective mass-transfer coefficient in dilute liquid phase (k_L):

$$k_L = 0.757 \cdot C_L \cdot \left[\frac{D_L \cdot a \cdot v_L}{\varepsilon \cdot h_L}\right]^{0.5} \quad (36)$$

Step 40. Schmidt number for gaseous phase (Sc_G):

$$Sc_G = \frac{\mu_G}{\rho_G \cdot D_G} \quad (37)$$

Step 41. Convective mass-transfer coefficient in gaseous phase (k_G):

$$k_G = 0.1304 \cdot C_V \cdot \frac{D_G \cdot P_G}{R \cdot T_G} \cdot \frac{a}{[\varepsilon \cdot (\varepsilon - h_L)]^{0.5}} \cdot \left[\frac{Re_G}{K_W}\right]^{0.75} Sc_G^{0.667} \quad (38)$$

Where R = 0.08205 atm.m^3/kmol.K [10] and P_G = 1 atm.

Results and discussion

The numerical results obtained for the main parameters determined using the packed column design methodology for both evaluated packings are presented below. These parameters include the column inside diameter, the pressure drop of the gas-liquid system at 70% flooding, and the mass transfer coefficients for both the liquid and gaseous phases.

Column inside diameter

Table 2 displays the results of the parameters determined in Steps 1-13, which were ultimately used to calculate the packed tower diameter for both packings.

Table 2. Results of the parameters determined in steps 1-13 for both packings.

Step	Parameter	Symbol	Raschig	Hiflow	Units
1	Molecular weight of the inlet gas	M_G	28.01	28.01	g/mol
2	Mass flow rate of the gas phase	V'	0.311	0.311	kg/s
3	Density of the gas phase	ρ_G	1.126	1.126	kg/m^3
4	Volumetric flow rate of the gas phase	Q_G	0.276	0.276	m^3/s
5	Ammonia absorbed	A_{NH3}	49.05	49.05	kg/h
6	Mass flow rate of the exiting liquid	L'	0.486	0.486	kg/s
7	Flow parameter	X	0.052	0.052	-
8	Pressure drop parameter under flooding	Y_{flood}	0.238	0.238	-
9	Parameter Cs under flooding	Cs_{flood}	0.052	0.107	m/s
10	Superficial gas velocity at flooding	v_{GF}	1.547	3.184	m/s
11	Pressure drop at flooding	ΔP_{flood}	3,545.38	1,285.11	Pa/m
12	Superficial gas velocity at 70% of flooding	v_G	1.083	2.229	m/s
13	Column inside diameter	D	0.570	0.397	m

According to the values presented in Table 2, the calculated column inside diameter (D) for the Hiflow rings (0.397 m) is 30.35% lower than the value calculated for the Raschig rings (0.570 m). This difference is primarily attributed to the lower packing factor (F_P) of Hiflow rings compared to that of Raschig rings. Specifically, a lower F_P for Hiflow rings leads to an increased Cs_{flood} parameter, which in turn raises the superficial gas velocity under flooding (v_{GF}) as well as the superficial gas velocity at 70% flooding (v_G), ultimately resulting in a smaller column inside diameter.

Table 2 also indicates that 49.05 kg/h of ammonia are absorbed for each packing. Furthermore, the superficial velocity of the gas under flooding is 51.41% higher for Hiflow rings (3.184 m/s) compared to Raschig rings

(1.547 m/s). This difference causes the pressure drop at flooding to be 63.75% higher for Raschig rings (3,545.38 Pa/m) than for Hiflow rings (1,285.11 Pa/m).

Yetilmezsoy [7] investigated the physical absorption of ammonia from an air stream using water as a solvent in a packed column equipped with ceramic Raschig rings. He presented two new empirical models based on the composite desirability function methodology for predicting packed column diameter and packing height. According to Yetilmezsoy's findings, the packed column diameter was 0.799 m for an average inlet gas flow rate of 2,750 m³/h, an average ammonia concentration in the inlet gas of 7.5%, an average desired removal efficiency of 92.5%, an operating temperature of 35 °C, and a flooding velocity percentage of 55%. As reported by this author, increasing the flooding velocity percentage will decrease the column diameter for the same inlet gas flow rate.

Total pressure drop for operation at 70% flooding

Table 3 presents the results of the parameters calculated in Steps 15-26, which were used to determine the total pressure drop of the gas-liquid system at 70% flooding for both packings.

Table 3. Results of the parameters determined in Steps 15-26 for both packings.

Step	Parameter	Symbol	Raschig	Hiflow	Units
15	Effective particle diameter	d_p	0.010	0.001	m
16	Wall factor	K_W	0.965	0.958	-
17	Viscosity of the gas phase	μ_G	0.000018	0.000018	Pa.s
18	Reynolds number of the gas phase	Re_G	2043.02	3515.26	-
19	Dry-packing resistance coefficient	Ψ_0	1.341	0.658	-
20	Dry-gas pressure drop	$\frac{\Delta P_0}{Z}$	554.83	438.04	Pa/m
21	Liquid mass velocity	G_L	1.906	3.928	kg/m^2.s
22	Reynolds number of the liquid phase	Re_L	11.27	21.75	-
23	Liquid Froude number	Fr_L	0.000071	0.000321	-
24	Ratio of specific areas [using equation (24) since Re_L ε 5]	$\frac{a_h}{a}$	0.346	0.655	-
25	Specific liquid holdup	h_L	0.021	0.042	-
26	Total pressure drop of the gas-liquid system at 70% flooding	$\frac{\Delta P}{Z}$	615.16	522.16	Pa/m

According to the results presented in Table 3, the total pressure drop of the gas-liquid system at 70% flooding is 17.81% higher for Raschig rings (615.16 Pa/m) compared to Hiflow rings (522.16 Pa/m). This difference is attributed to several factors: the Reynolds number of the liquid phase (Re_L) is 48.18% higher for Hiflow rings (21.75) than for Raschig rings (11.27), and the porosity and void fraction (ε) of Hiflow rings are 29.31% higher than those for Raschig rings. This outcome is further influenced by the fact that the dry gas pressure drop is 21.05% lower for Hiflow rings (438.04 Pa/m) compared to Raschig rings (554.83 Pa/m). As can be observed, the calculated total pressure drop for the gas-liquid system at 70% flooding for the Raschig rings exceeded the maximum limit established for the process, which is 600 Pa/m. Consequently, it is concluded that Raschig rings cannot be employed for the desired mass transfer service due to the excessive pressure drop obtained.

Mass transfer coefficients

Table 4 displays the results of the parameters calculated in Steps 30-41, which were used to determine the mass transfer coefficients for both the liquid and gaseous phases for the two considered packings.

Table 4. Results of the parameters determined in Steps 30-41 for both packings.

Step	Parameter	Symbol	Raschig	Hiflow	Units
30	Parameter ™	δ	-0.749	-0.749	-
31	Liquid diffusion coefficient	D_L	1.94x10^{-9}	1.94x10^{-9}	m^2/s
32	Molecular weight of the gaseous mixture	M_{AB}	21.46	21.46	g/mol
33	Collision diameter	σ_{AB}	3.26	3.26	Å
34	Average Lennard-Jones parameter	$\frac{\varepsilon_{AB}}{k}$	232.71	232.71	K
35	Parameter $T*$	T^*	1.302	1.302	-
36	Diffusion collision integral	Ω_D	1.274	1.274	-
37	Gaseous diffusion coefficient of ammonia in air	D_G	2.34x10^{-5}	2.34x10^{-5}	m^2/s
38	Liquid velocity	v_L	0.002	0.004	m/s
39	Convective mass-transfer coefficient in dilute liquid phase	k_L	2.34 x10^{-4}	2.45x10^{-4}	m/s
40	Schmidt number for gaseous phase	Sc_G	0.683	0.683	-
41	Convective mass-transfer coefficient in gaseous phase	k_G	0.00347	0.00389	kmol/m^2.s

Considering the results presented in Table 4, the convective mass-transfer coefficient in the diluted liquid phase (k_L) is 4.49% higher for Hiflow rings (2.45x10^{-4} m/s) than for Raschig rings (2.34x10^{-4} m/s). This occurred because the values for the mass-transfer surface area per unit volume (a), liquid velocity (v_L), and the mass transfer parameter C_L are all higher for Hiflow rings compared to Raschig rings. On the other hand, the convective mass transfer coefficient in the gaseous phase (k_G) is 10.79% higher for Hiflow rings (0.00389 kmol/m²·s) than for Raschig rings (0.00347 kmol/m²·s). This is due to higher values for the parameters mass-transfer surface area per unit volume (a), mass transfer parameter C_V, and Reynolds number of the gas phase (Re_G) for Hiflow rings, while the wall factor (K_W) is lower.

From the numerical results obtained during the packed column design, we conclude that Hiflow rings should be used instead of Raschig rings. This is because Hiflow rings yield a smaller internal diameter, a lower total pressure drop, and higher mass-transfer coefficients. These conclusions align with findings reported in [11], which also indicated a lower column inside diameter and pressure drop for Hiflow rings compared to Raschig rings for a similar ammonia absorption mass-transfer service.

Conclusions

A packed column was designed for the absorption of gaseous ammonia using water as a solvent, with two packing types evaluated. The metallic Hiflow rings proved to be optimal for this mass transfer service, resulting in a column diameter 30.35% lower (0.397 m) and a pressure drop 17.81% lower (522.16 Pa/m) than the ceramic Raschig rings. Furthermore, Hiflow rings yielded higher mass-transfer coefficients for both the gaseous (0.00389 kmol/m²·s) and liquid (2.45x10^{-4} m/s) phases.

Nomenclature

$\frac{a_h}{a}$	Ratio of specific areas	-
A_{NH3}	Ammonia absorbed	kg/h
C_h	Packing constant	-
C_L	Mass-transfer parameter	-
C_p	Packing constant	-
Cs_{flood}	Parameter under flooding	m/s
C_V	Mass-transfer parameter	-
d_p	Effective particle diameter	m
D	Column inside diameter	m
D_G	Gaseous diffusion coefficient	m^2/s
D_L	Liquid diffusion coefficient	m^2/s
F_P	Packing factor	-
Fr	Froude number	-
G	Mass velocity	kg/m^2.s

h_L	Specific liquid holdup	-
k_G	Convective mass-transfer coefficient in gaseous phase	kmol/m^2.s
k_L	Convective mass-transfer coefficient in dilute liquid phase	m/s
K_W	Wall factor	-
L	Mass flow rate of the inlet liquid	kg/h
L'	Mass flow rate of the exiting liquid	kg/s
M	Molecular weight	g/mol
M_{AB}	Molecular weight of the gaseous mixture	g/mol
P	Inlet pressure	kPa/atm/bar
ΔP_{flood}	Pressure drop at flooding	Pa/m
$\frac{\Delta P}{Z}$	Total pressure drop of the gas-liquid system at 70% of flooding	Pa/m
$\frac{\Delta P_0}{Z}$	Dry-gas-pressure drop	Pa/m
Q	Volumetric flow rate	m^3/s
R	Ideal gas constant	J/mol.K or atm.m^3/kmol.K
Re	Reynolds number	-
Sc	Schmidt number	-
$\%S_{NH3}$	Percentage of ammonia to be scrubbed	-
T	Inlet temperature	K
T^*	Parameter	-
v_G	Superficial gas velocity at 70% of flooding	m/s
v_{GF}	Superficial gas velocity at flooding	m/s
v_L	Liquid velocity	m/s
V	Molar flow rate of the gas phase	kmol/h
V'	Mass flow rate of the gas phase	kg/s
X	Flow parameter	-
y	Mole fraction	
Y_{flood}	Pressure drop parameter under flooding	-

Greek symbols

δ	Parameter	-
ε	Porosity or void fraction	-
ρ	Density	kg/m^3
μ	Viscosity	Pa.s
σ	Collision diameter	Å
ε/k	Average Lennard-Jones parameter	K
Ψ_0	Dry-packing resistance coefficient	-
Ω_D	Diffusion collision integral	-

Subscripts

air	Air
G	Gas phase
L	Liquid phase
NH3	Ammonia

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