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Design of a packed bed column for sulfur dioxide absorption considering three packing types

Amaury Pérez Sánchez[1a]; Yerelis Pons García[1]; Lennis Leidy Basulto Cruz[1]; Elizabeth Ranero González[1]; Eddy Javier Pérez Sánchez[2]; Lizthalía Jiménez Guerra[1]

[1]Facultad de Ciencias Aplicadas, Universidad de Camagüey "Ignacio Agramonte Loynaz", Camagüey, Cuba.
[2]Dirección Comercial, Empresa Servicios Automotores S.A., Cuba.

[a]amaury.perez84@gmail.com

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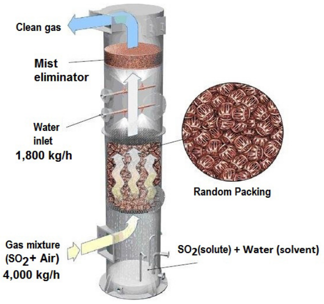
Graphical abstract



Key points

1. A packed bed absorption column is designed to carry out the absorption of sulfur dioxide using water as solvent.
2. Several parameters were calculated such as the column diameter, gas-phase pressure drop, liquid- and gas-phase volumetric mass transfer coefficients, total packed height and pumping power.
3. A sensitivity analysis was also performed to know how an increment in the gas inlet flowrate affects both the column diameter and total packed height for the three packing types considered.

Abstract

The design of packed absorbers is very important to calculate several parameters such as column diameter, gas-phase pressure drop and total packed height for a given gas absorption application. The aim of the present work was to design a packed bed column for sulfur dioxide absorption using water as the liquid solvent and evaluating three packing types, namely Hiflow, Nor-Pac and Pall rings. Several key design parameters were calculated such as the column diameter, gas-phase pressure drop, liquid- and gas-phase volumetric mass transfer coefficients, total packed height and pumping power for the three packing types evaluated. A sensitivity analysis was also carried out in order to examine how an increment in the gas inlet flowrate influences the column diameter and the total packed height for the three packing types evaluated. The Hiflow rings had the lower value of the column diameter (0.564 m) and gas-phase pressure drop (311.07 Pa/m), while Pall rings had the higher value of these parameters (0.727 m and 430.91 Pa/m). Likewise, Nor-Pac rings had the lower values of both mass transfer coefficients (liquid-phase: 0.00524 s^{-1} and gas-phase: 0.2489 kmol/m^3.s), while Pall rings had the higher values of these parameters (0.0104 s^{-1} and 0.3511 kmol/m^3.s). Finally, the total packed height and pumping power had lower values for the Pall rings (0.848 m, 479.09 W and 5.20 W), while the higher values of these parameters were obtained for the Hiflow rings (1.916 m, 781.12 W and 11.74 W). It's recommended to select the Hiflow rings for this mass-transfer system. The results of sensitivity analysis indicate that an increment of the gas inlet flowrate increases both the column diameter and total packed height for the three packing types considered.

Keywords: *Packed bed absorber; Column diameter; Gas pressure drop; Packed height; Mass transfer coefficients; Pumping power.*

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Diseño de una columna de lecho empacado para la absorción de dióxido de azufre considerando tres tipos de empaque

Resumen

El diseño de absorbedores empacados requiere calcular varios parámetros tales como diámetro de la columna, caída de presión de la fase gaseosa y altura total del empaque para una aplicación de absorción dada. El objetivo del presente trabajo consistió en diseñar una columna de lecho empacado para la absorción de dióxido de azufre usando agua como solvente líquido y evaluando tres tipos de empaques, llamados anillos Hiflow, Nor-Pac y Pall. Varios parámetros claves de diseño fueron calculados tales como el diámetro de la columna, caída de presión de la fase gaseosa, coeficientes de transferencia de masa de la fase líquida y gaseosa, altura total del empaque y potencia de bombeo para los tres tipos de empaque evaluados. También se llevó a cabo un estudio de sensibilidad con el fin de examinar cómo influye el incremento del caudal del gas de entrada en el diámetro de la columna y la altura total del empaque para los tres tipos de empaque evaluados. Los anillos Hiflow tuvieron el menor valor del diámetro de la columna (0,564 m) y la caída de presión de la fase gaseosa (311,07 Pa/m), mientras que los anillos Pall tuvieron el mayor valor de estos parámetros (0,727 m y 430,91 Pa/m). Asimismo, los anillos Nor-PAc tuvieron los menores valores de ambos coeficientes de transferencia de masa (fase líquida: 0,00524 s^{-1} y fase gaseosa: 0.2489 kmol/m^3.s), mientras que los anillos Pall tuvieron los mayores valores de estos parámetros (0,0104 s^{-1} y 0,3511 kmol/m^3.s). Finalmente, la altura total del empaque y potencia de bombeo tuvieron sus menores valores para los anillos Pall (0,848 m, 479,09 W y 5,20 W), mientras que los valores mayores de estos parámetros fueron obtenidos para los anillos Hiflow (1,916 m, 781,12 W y 11,74 W). Se recomienda seleccionar los anillos Hiflow para este sistema de transferencia de masa. Los resultados del análisis de sensibilidad indican que un incremento del caudal de alimentación del gas incrementa tanto el diámetro de la columna y la altura total de los tipos de empaque considerados.

Palabras clave: *Absorbedor de lecho empacado; Diámetro de la columna; Caída de presión del gas; Altura del empaque; Coeficientes de transferencia de masa; Potencia de bombeo.*

Projeto de coluna de leito empacotado para absorção de dióxido de enxofre considerando três tipos de empacotamento

Resumo

O projeto de absorvedores empacotados é muito importante para calcular vários parâmetros, como diâmetro da coluna, queda de pressão da fase gasosa e altura total do empacotamento para uma determinada aplicação de absorção. O objetivo deste trabalho foi projetar uma coluna de leito empacotado para absorção de dióxido de enxofre utilizando água como solvente líquido e avaliar três tipos de empacotamento, denominados anéis Hiflow, Nor-Pac e Pall. Vários parâmetros importantes de projeto foram calculados, como diâmetro da coluna, queda de pressão da fase gasosa, coeficientes de transferência de massa da fase líquida e gasosa, altura total do empacotamento e potência de bombeamento para os três tipos de empacotamento avaliados. Também foi realizado um estudo de sensibilidade para examinar como um aumento na vazão de entrada de gás influencia o diâmetro da coluna e a altura total do recheio para os três tipos de recheio avaliados. Os anéis Hiflow apresentaram o menor valor de diâmetro da coluna (0,564 m) e queda de pressão da fase gasosa 311,07 Pa/m), enquanto os anéis Pall apresentaram o maior valor desses parâmetros (0,727 m e 430,91 Pa/m). Da mesma forma, os anéis Nor-PAc apresentaram os menores valores de ambos os coeficientes de transferência de massa (fase líquida: 0,00524 s^{-1} e fase gasosa: 0,2489 kmol/m^3.s), enquanto os anéis Pall apresentaram os maiores valores desses parâmetros (0,0104 s^{-1} e 0,3511 kmol/m^3.s). Por fim, a altura total do empacotamento e a potência de bombeamento tiveram seus menores valores para os anéis Pall (0,848 m, 479,09 W e 5,20 W), enquanto os maiores valores desses parâmetros foram obtidos para os anéis Hiflow. É recomendado selecionar os anéis Hiflow (1,916 m, 781,12 W e 11,74 W) para este sistema de transferência de massa. Os resultados da análise de sensibilidade indicam que um aumento na taxa de alimentação de gás aumenta tanto o diâmetro da coluna quanto a altura total dos tipos de recheio considerados.

Palavras-chave: *Absorvedor de leito compactado; Diâmetro da coluna; Queda de pressão do gás; Altura do empacotamento; Coeficientes de transferência de massa; Potência de bombeamento.*

Introduction

Understanding the mass transfer mechanism during gas absorption involving droplets is essential for comprehending how trace gases are removed in wet scrubbers. The mass transfer between the gaseous phase and droplets is influenced by the physical and chemical characteristics of the gas that is diffusing, the size of the droplets, and the fluid dynamics that occur around and within the moving droplets. The transport of trace gases from the atmosphere into the descending droplet occurs due to molecular diffusion, in conjunction with the convective mass transfer occurring both outside and inside the descending droplets. The internal flow created by the aerodynamic forces acting on the droplet's surface aids in the even distribution of the absorbed gas [1].

Gas absorption refers to an operation where a gas mixture interacts with a liquid in order to selectively dissolve one or more specific components of the gas into the liquid [2]. This operation is used with various purposes, including the separation of gas mixtures; elimination of unwanted substances, toxins, or catalyst inhibitors from a gas; as well as the retrieval of valuable substances. Consequently, the components of interest within the gas mixture may include all the components, or those that are not transferred, or exclusively the components that are absorbed. The substances that move into the liquid absorbent are referred to as solutes or absorbates [3].

The two predominant types of high-efficiency absorbers are plate towers and packed towers. This equipment is widely utilized for controlling harmful gaseous emissions [3]. Packed columns are often the option of choice when (1) the necessary column diameter is less than 60 cm; (2) a minimal pressure drop is essential, particularly in vacuum applications; (3) materials that resist corrosion, such as ceramics or polymers, are suitable; and/or (4) maintaining low liquid holdup is preferable [2].

When utilizing water and hydrocarbon oils as absorbents, there are no major chemical reactions happening between the absorbent and the solute, which is typically called physical absorption [3]. Notable examples of physical absorption applications include the absorption of substances like acetone, ammonia, ethanol, formaldehyde, hydrochloric acid, and sulfur dioxide in water.

Absorption is a conventional mass transfer procedure. The design methods for both packed columns and tray towers are currently well established, and many commercial applications are frequently to encounter in the chemical industry. Complying with stringent environmental regulations related to air pollution caused by harmful gases from industrial activities has significantly advanced the implementation of gas absorbers, often referred to as scrubbers, over recent decades [2].

To maximize absorption effectiveness when designing absorbers, it is essential to: provide a considerable interfacial contact surface; ensure effective mixing of the gas and liquid phases; provide adequate residence time or contact duration between these phases; and select a liquid that has a high solubility for the targeted gaseous pollutant [4].

When developing a packed absorption system, specific parameters are set by either the conditions under which it operates, such as the gas inlet flow rate, or by regulations, including the permissible concentration of pollutants in the gas leaving the absorber. Typically, the gas that needs to be treated is the exhaust produced by a process within the facility. Consequently, the volume, temperature, and composition of the gas entering the absorber are established parameters. The composition of contaminants at the outlet is dictated by emission standards that have to be adhered to. Additionally, the flow rate, temperature, and inlet composition of the absorbent liquid are generally known as well. Furthermore, an accurate design of packed columns often needs an understanding of the hydraulic properties of the packing material within the entire operational range [5].

The primary uncertainties in designing the absorption system include the following features: the size of the vessel needed to handle both gas and liquid flow; the absorber's height necessary for sufficient removal rates; the pressure drop in the gas phase; and the coefficients for mass transfer between gas and liquid [4].

As stated by Maheswari *et al*. [6], the emission of sulfur dioxide (SO_2) from chemical manufacturing facilities is growing rapidly because of the increasing reliance on fossil fuels, leading to various negative impacts on the environment and public health. SO_2 predominantly appears in the exhaust gases from power generation plants, metal processing furnaces, sulfuric acid manufacturing facilities, or other chemical production plants. Several techniques for flue gas desulfurization (FGD) have been developed to help mitigate SO_2 emissions [7]. Given the harmful consequences of SO_2 on the environment, such as contributing to acid rain and ozone layer degradation, as well as serious health issues like irritation of the eyes and throat and the rise of cardiovascular diseases, international organizations have implemented restrictions on the amount of SO_2 released from industrial smokestacks [8].

Correspondingly, this subject has attracted increasing interest both from industry and academia [9], being necessary to implement the best methodology to reduce the SO_2 emissions, including the proper design of packed bed absorbers using water as solvent. The absorption method has the advantage of high SO_2 removal efficiency and the drawback of large consumption of fresh water. In industry, SO_2 emission reduction technologies comprise three main technologies: wet, dry, and semidry methods [9].

Also, it is crucial to eliminate sulfur dioxide and accurately forecast its presence in the flue gases released by diverse chemical sectors in a way that considers technological, economic, and environmental factors [10].

Amoresano *et al*. [11] indicated that when a droplet of liquid water comes into contact with a gas stream that has sulfur dioxide, a flow of SO_2 is created at the interface between the liquid and the gas due to its dissolution, as described by Henry's law. The sulfur dioxide that dissolves in water accumulates in the peripheral area of the droplet, resulting in its initial saturation. This buildup impedes the reception of new molecules into the droplet.

When sulfur dioxide is absorbed in water, the resulting equilibrium relations are written as [12]:

$$SO_2 + H_2O \leftrightarrow H_2SO_3$$
$$H_2SO_3 + H_2O \leftrightarrow H_3O^+ + HSO_3^-$$
$$HSO_3^- + H_2O \leftrightarrow H_3O^+ + SO_3^-$$

The absorption of sulfur dioxide in water has been studied by some authors [13,14], specifically to present a simple model for prediction of the SO_2 absorption and desorption by falling drops through air with low concentration of sulfur dioxide, where a model based on local scales, interfacial liquid friction velocity and drop size diameter was used for the liquid phase, while in the continuous gas phase the well-known Beard and Pruppacher model was applied [1]. Similarly, in Sarkar *et al*. [10] a residence time distribution (RTD) approach was used for developing a theoretical model for predicting the SO_2 removal efficiency in a horizontal co-current gas–liquid scrubber by water spray. Experimental result showed that a very high percentage removal of SO_2 could be achieved from air–SO_2 mixture without using any additives or pre-treatment. Experimental results agreed excellently with developed theoretical model and it shows that almost 75 - 99 % removal efficiency could be achieved by the approach presented in this study.

The absorption of SO_2 in water could lead to the formation of acidic solutions, especially at high gas concentrations where the water in equilibrium with SO_2 becomes strongly acidic, thus limiting the conversion of $SO_2 \cdot H_2O$ into HSO_3^- [13]. In Sarkar *et al*. [10] it was found that as the pH of the inlet liquid increases the removal efficiency increases and the outlet loading decreases in a SO_2–water scrubbing system. This means that the efficiency increases as the liquid becomes more basic, which is due to the affinity of the acidic SO_2 towards a basic solution.

Various researchers have designed packed columns for the purpose of absorbing SO_2. Maheswari *et al*. [6] showcased the physical modeling, computational fluid dynamics (CFD) assessment, and experimental evaluation of a packed column aimed at the flue gas desulfurization (FGD) process to significantly lower SO_2 emissions. Key parameters of the packed column such as the liquid/gas (L/G) ratio, diameter, packed height, and total height were calculated through physical modeling, using the two-film theory of gas-liquid absorption. A simulation model for the packed column was constructed using GAMBIT 2.2.30, and the analysis was performed with FLUENT 6.2.16. In the CFD analysis conducted in this research, hydrogen peroxide (H_2O_2) at various concentrations served as the absorbent.

Manyele *et al*. [4] investigated the design aspects of an absorber intended for extracting sulfur dioxide from a process gas stream to ensure environmental safety. This research involved calculating Henry's law constant from the y-x diagram's slope, while the minimum liquid-to-gas ratio was identified, which helped establish the minimum liquid flow rate and actual operational parameters, derived from mass balances through the absorber. By utilizing a generalized formula for flooding and pressure drop, along with the mass flow rates of both gas and liquid streams, the mass flow rate of gas per unit area of the tower was calculated. The required cross-sectional area and diameter of the absorption tower were determined based on the operating point, which varied between 50 to 75 % of the flooding velocity.

In the same way, in Chu *et al*. [9] a co-current rotating packed bed featuring a unique silicon carbide packing was explored as a potential way to improve current desulfurization methods. The study examined how factors such as rotation speed, gas flow rate, liquid flow rate, inlet concentration of SO_2, total salt concentration, and alkalinity influenced the efficiency of SO_2 removal, using an ammonia-based solution as the absorbent. Furthermore, the overall mass transfer coefficient for gas was derived from the mass balance equation, and a correlation related to it was also suggested.

Similarly, Darake *et al*. [8] examined how effectively seawater absorbs SO_2 in a packed-bed scrubber. These authors established a general mathematical model supported in thermodynamics to evaluate the performance of the scrubber tower. The experimental setup employed the Taguchi method, taking into account five different factors: the liquid flow rate, gas flow rate, gas temperature, concentration of SO_2, and pH of seawater.

On the other hand, Maheswari *et al*. [6] proposed a method for SO_2 removal utilizing H_2O_2 within a rotating packed bed (RPB). Their study began with the development of a mathematical model to illustrate the reaction and mass transfer between H_2O_2 and SO_2 in the RPB. They also analyzed how varying conditions such as RPB rotational speed, mass fraction of H_2O_2, gas-liquid volumetric flowrate ratio, gas flow rate, and initial SO_2 concentration impacted the desulfurization efficiency. Chavez *et al*. [14] conducted an experimental analysis of hydrodynamic and mass transfer phenomena within an absorption column featuring a diameter of 0.252 meters and a packed bed height of 3.5 meters, developed by the Mexican National Institute of Nuclear Research utilizing stainless-steel gauze corrugated sheet packing through SO_2–air–water systems. The findings from the experiments incorporated several metrics including pressure drop, flow capacity, liquid retention, SO_2 concentration, as well as global mass transfer coefficients and mass transfer unit height, assessed through a generalized performance model to understand the interaction between two-phase countercurrent flows and the assembly of the packed bed.

In Liu *et al.* [15], a method for designing a scrubber to remove SO_2 from flue gas produced during Oxy-fuel combustion was established, utilizing a kinetic modeling approach based in two film theory to design a packed bed. This design aimed to calculate parameters like the dimensions (diameter and height) of the packed bed, guided by the previously determined operational pH range (pH 5 - 6). Additionally, the impact of operational factors such as the initial pH of the absorbent and the liquid-to-gas (L/G) ratio on the column's design was explored. The ideal initial pH for the solutions and the optimal L/G ratio were consequently established.

Finally, Majeed *et al*. [16] conducted research on recuperating SO_2 from a SO_2/air mixture using a packed bed column at a pilot scale, with the objective of enhancing the absorption process's recovery efficiency. The study aimed to identify suitable operating parameters for the packed bed column, contributing to the industrial application of this method. The efficiency of SO_2 recovery was assessed while varying parameters like the flowrate of the gas mixture, the concentration of SO_2 at the inlet, the concentration of sodium carbonate solution, the temperature of the liquid, and the liquid hold-up according to the experimental design.

In a study carried out by some of the authors of the present work [17] a packed bed absorption column was designed to recover certain amounts of ethanol contained in a gaseous stream. Four packing types were considered in this study, namely Hiflow, Pall, Top Pak and VSP, while four key design parameters were calculated for each of the four packing types: 1) column diameter, 2) packing height, 3) overall mass-transfer coefficient and 4) gas pressure drop. This study concluded that the best packing type to employ in this mass transfer service was VSP rings.

In a chemical processing industry, a gaseous stream of SO_2 and air is generated which is required to be treated to reduce its SO_2 concentration before being emitted to the atmosphere. To carry out this treatment process, a packed bed absorber was proposed using pure liquid water as the solvent due to the availability of several packing types, water flowrate and space. In this context, the aim of this paper is to design of a packed bed absorption column to treat this gaseous mixture of SO_2/air, where several key design parameters were calculated such as the column diameter, gas-phase pressure drop, volumetric gas- and liquid-phase mass-transfer coefficients, packed height and pumping power for both the gas and liquid streams. Three packing types were considered to carry out this absorption process, i.e. 50 mm metal Hiflow rings, 35 mm plastic Nor-Pac rings and 50 mm ceramic Pall rings, to know which of them is the most appropriate from the geometrical, hydraulic and mass-transfer points of view. The calculation methodology and equations published in [2,3] were applied to carry out the design of this SO_2 packed bed absorber considering the three packing types available.

Methodology

Materials and methods

The main objective of this work is to know the geometrical dimensions, mass-transfer coefficients, pressure drop characteristics, and energy consumption of a gas-liquid absorption column to be designed to treat an air–SO_2 stream using liquid water as a solvent, where three packing types will be evaluated in order to select which of them is the most appropriate from the geometrical, mass-transfer, hydraulic and energy points of view, for this specific mass-transfer service.

Definition of the problem

A mixture of SO_2 and air is generated in a chemical processing industry due to the combustion of sulfur in air, and it's desired to absorb the SO_2 contained in this stream in a countercurrent absorption process using liquid water as solvent. The gas mixture has a flowrate, a temperature and a pressure of 4,000 kg/h, 298 K and 1.1 atm respectively, while liquid water is available at a flowrate of 1,800 kg/h and a temperature of 298 K. The molar composition of the inlet gaseous stream is 85 % air and 15 % SO_2, the required recovery of SO_2 is 97 %, while the allowable maximum pressure drop for the gas stream should not exceed 400 Pa/m of packed height. The objective is to design a suitable packed-bed absorption column for this mass transfer service working at 60 % of flooding (Figure 1), using the correlations and equations reported in [2,3], and evaluating the use of the following three packing types:

- 50 mm metal Hiflow rings.
- 50 mm ceramic Pall rings.
- 35 mm plastic Nor-Pac rings.

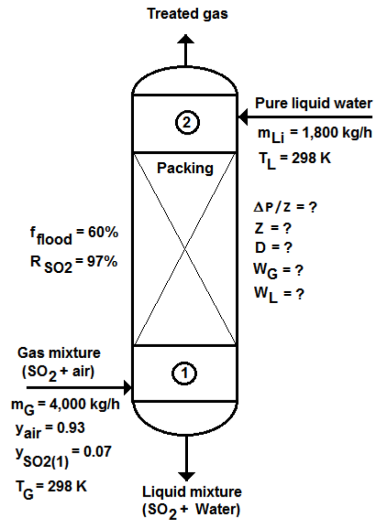

Figure 1. Scheme of the packed bed absorption column to be designed and its operating parameters.

Inlet data

- Gas mass flowrate (m_G): 4,000 kg/h.
- Inlet temperature of gas (T_G): 298 K.
- Inlet pressure of gas (P_G): 1.1 atm.
- Molecular weight of air (M_{air}): 28.96 kg/kmol.
- Molecular weight of sulfur dioxide (M_{SO2}): 64.06 kg/kmol.
- Molecular weight of water (M_w): 18.02 kg/kmol.
- Gravitational acceleration (g): 9.81 m/s^2.
- Ideal gas constant (R): 0.0821 m^3.atm/kmol.K [18].
- Molar composition of sulfur dioxide in inlet gas ($y_{SO2(1)}$): 0.07.
- Molar composition of dry air in inlet gas (y_{air}): 0.93.
- Viscosity of air at 298 K (μ_{air}): 0.00001845 Pa.s [18].
- Viscosity of sulfur dioxide at 298 K (μ_{SO2}): 0.00001292 Pa.s [18].
- Required recovery of sulfur dioxide (R_{SO2}): 97 %.
- Flooding factor (f_{flood}): 60 % = 0.6.
- Available mass flowrate of pure liquid water (m_{Li}): 1,800 kg/h.
- Inlet temperature of pure liquid water (T_L): 298 K.
- Molar volume of SO_2 at normal boiling point (V_{bSO2}): 44.8 cm^3/mol [2].
- Henry's law constant at 298 K for SO_2 dissolved in water (H): 0.02197 atm^{-1} [19].

Random packings to be evaluated

According to the previous epigraph, the random packings to be evaluated in this study, in order to design the packed bed column for SO_2 absorption, are:

- 50 mm metal Hiflow rings.
- 50 mm ceramic Pall rings.
- 35 mm plastic Nor-Pac rings.

The Hiflow ring represents a third-generation, high-efficiency tower packing that delivers an ideal design featuring excellent mechanical stability, a favorable void fraction, and enhanced mass transfer capabilities. This design enables the handling of greater volumes of gas and/or liquids compared to traditional packing designs, thanks to its open framework and optimized structure, all while maintaining mass transfer efficiency [20].

Pall ring is considered a second-generation tower packing, featuring a distinctive multi-blade structure that enhances the internal surface area and facilitates efficient fluid-gas interactions. The openings in the ring wall support a better distribution of both gas and liquid, while also enlarging the internal surface area [21].

Nor-Pac packing is specifically tailored for industrial applications, offering notable benefits over traditional tower packing materials, including low pressure drop rates (which conserve energy), the capability to handle high hydraulic loads (allowing for smaller column diameters), and the presence of overhanging fines that enhance droplet formation, continuously renewing the interfaces and ensuring high efficiency (suitable for low-height packed beds) [22].

Figure 2 shows the image of the three random packing types assessed in this study [5].

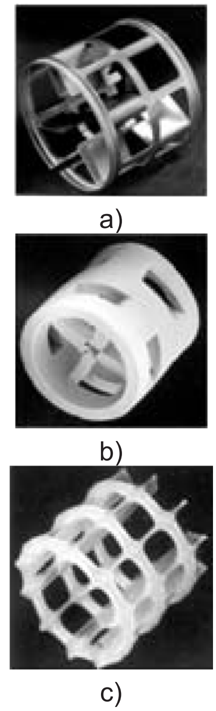

Figure 2. Random packing types evaluated in this study. a) Hiflow ring, metal. b) Pall ring, ceramic. c) Nor-Pac ring, plastic [5].

Hydraulic characteristics and mass-transfer parameters of the packing materials considered

According to Benitez [2] and Seader *et al*. [3], the random packing materials to be evaluated in this study have the hydraulic characteristics and mass-transfer parameters showed on Table 1.

Table 1. Hydraulic characteristics and mass-transfer of the random packings to be evaluated.

Packing	F_p (ft²/ft³)	a_0	ε	C_h	C_p	C_L	C_v
50 mm metal Hiflow	16	92.3	0.977	0.876	0.421	1.168	0.408
35 mm plastic Nor-Pac	21	141.8	0.944	0.587	0.371	0.756	0.425
50 mm ceramic Pall	43	116.5	0.783	1.335	0.662	1.227	0.415

Calculation procedure

Column diameter. Since the superficial gas velocity and pressure drop are highest at the bottom of the column, calculations are carried out for conditions there [2].

Step 1. Molecular weight of inlet gas (M_G):

$$M_G = y_{air(1)} \cdot M_{air} + y_{SO2(1)} \cdot M_{SO2} \quad (1)$$

Step 2. Density of the inlet gas (ρ_G) [2]:

$$\rho_G = \frac{P_G \cdot M_G}{R \cdot T_G} \quad (2)$$

Step 3. Viscosity of the inlet gas (μ_G) [23]:

$$\mu_G = \frac{M_G}{\frac{y_{air(1)} \cdot M_{air}}{\mu_{air}} + \frac{y_{SO2(1)} \cdot M_{SO2}}{\mu_{SO2}}} \quad (3)$$

Step 4. Volumetric flowrate of inlet gas (Q_G):

$$Q_G = \frac{m_G}{\rho_G} \tag{4}$$

Step 5. Molar flowrate of inlet gas (V_{mG}):

$$V_{mG} = \frac{m_G}{M_G} \tag{5}$$

Step 6. Sulfur dioxide absorbed (A_{SO2}):

$$A_{SO2} = V_{mG} \cdot y_{SO2(1)} \cdot \frac{R_{SO2}}{100} \cdot M_{SO2} \tag{6}$$

Step 7. Mass flowrate of liquid exiting the absorber (m_{Le}):

$$m_{Le} = m_{Li} + A_{SO2} \tag{7}$$

Step 8. Density of liquid water (ρ_L).
Step 9. Viscosity of liquid water (μ_L).
Step 10. Flow parameter (X) [2]:

$$X = \frac{m_{Le}}{m_G} \cdot \left(\frac{\rho_G}{\rho_L}\right)^{0.5} \tag{8}$$

Step 11. Pressure drop parameter under flooding conditions (Y_{flood}) [2]:

$$lnY_{flood} = -[3.5021 + 1.028 \cdot lnX + 0.11093 \cdot (lnX)^2] \tag{9}$$

Step 12. Coefficient at flooding conditions ($C_{S,flood}$) [2]:

$$C_{S,flood} = \left[\frac{Y_{flood}}{Fp \cdot \mu_L^{0.1}}\right]^{0.5} \tag{10}$$

Step 13. Gas velocity at flooding conditions (v_{GF}) [2]:

$$v_{GF} = \frac{C_{S,flood}}{\left[\frac{\rho_G}{\rho_L - \rho_G}\right]^{0.5}} \tag{11}$$

Step 14. Gas velocity (v_G):

$$v_G = v_{GF} \cdot f_{flood} \tag{12}$$

Step 15. Column diameter (D) [2]:

$$D = \left[\frac{4 \cdot \frac{Q_G}{3,600}}{\pi \cdot v_G}\right]^{0.5} \tag{13}$$

Gas-phase pressure drop

Step 16. Effective particle diameter (d_p):

$$d_p = 6 \cdot \left(\frac{1-\varepsilon}{a_0}\right) \tag{14}$$

Where a_0 and ε are hydraulic parameters specific for the type of random packing (Table 1).

Step 17. Wall factor (K_W):

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

Step 18. Gas-phase Reynolds number (Re_G):

$$Re_G = \frac{v_G \cdot d_p \cdot \rho_G \cdot K_W}{(1-\varepsilon) \cdot \mu_G} \tag{16}$$

Step 19. Dry-packing resistance coefficient (Ψ_0) [2]:

$$\Psi_0 = Cp \cdot \left(\frac{64}{Re_G} + \frac{1.8}{Re_G^{0.08}}\right) \tag{17}$$

Where Cp is a hydraulic parameter specific for the packing type (Table 1).

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

$$\frac{\Delta P_0}{Z} = \Psi_0 \cdot \frac{a_0}{\varepsilon^3} \cdot \frac{\rho_G \cdot v_G^2}{2} \cdot \frac{1}{K_W} \tag{18}$$

Step 21. Liquid mass velocity (G_L):

$$G_L = \frac{\frac{m_{Le}}{3,600} \cdot 4}{\pi \cdot D^2} \tag{19}$$

Step 22. Liquid-phase Reynolds number (Re_L):

$$Re_L = \frac{G_L}{a_0 \cdot \mu_L} \tag{20}$$

Step 23. Liquid-phase Froude number (Fr_L):

$$Fr_L = \frac{G_L^2 \cdot a_0}{\rho_L^2 \cdot g} \tag{21}$$

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

- For $Re_L < 5$:

$$\frac{a_h}{a} = C_h \cdot Re_L^{0.5} \cdot Fr_L^{0.1} \tag{22}$$

- For $Re_L \geq 5$:

$$\frac{a_h}{a} = 0.85 \cdot C_h \cdot Re_L^{0.25} \cdot Fr_L^{0.1} \quad (23)$$

Where C_h is a hydraulic parameter specific for the packing type (Table 1).

Step 25. Hydraulic, or effective, specific surface area of packing (a_h):

$$a_h = \frac{a_h}{a} \cdot a_0 \quad (24)$$

Step 26. 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 27. Gas-phase overall pressure drop per meter of packing height ($\frac{\Delta P}{Z}$):

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

Gas and liquid volumetric mass-transfer coefficients:
The Lennard-Jones constants for SO_2 and air are shown in Table 2 as reported by Poling *et al.* [24]:

Table 2. Lennard-Jones constants for SO_2 and air:

Compound	σ [Å]	$\frac{e}{k}$ [K]
Air	3.620	97.0
SO_2	4.112	335.4

Step 28. Parameter α:

$$\alpha = \frac{9.58}{V_{bSO2}} - 1.12 \quad (27)$$

Step 29. Liquid-phase diffusion coefficient (D_L):

$$D_L = 1.25 \times 10^{-8} \cdot (V_{bSO2}^{-0.19} - 0.292) \cdot T_L^{1.52} \cdot (\mu_L \cdot 1{,}000)^{\alpha} \quad (28)$$

Where μ_L is given in Pa.s.

Step 30. Average molecular weight of the gas-phase components (M_{AB}):

$$M_{AB} = 2 \cdot \left[\frac{1}{M_{air}} + \frac{1}{M_{SO2}}\right]^{-1} \quad (29)$$

Step 31. Parameter (T^*):

$$T^* = \frac{T_G}{\sqrt{\frac{e_{air}}{k} \cdot \frac{e_{SO2}}{k}}} \quad (30)$$

Step 32. Collision diameter (σ_{AB}):

$$\sigma_{AB} = \frac{\sigma_{air} + \sigma_{SO2}}{2} \quad (31)$$

Step 33. Diffusion collision integral (Ω_D):

$$\Omega_D = \frac{1.06036}{(T^*)^{0.15610}} + \frac{0.193}{\exp(0.47635 * T^*)} + \frac{1.03587}{\exp(1.52996 * T^*)} + \frac{1.76474}{\exp(3.89411 * T^*)} \quad (32)$$

Step 34. Gas-phase diffusion coefficient (D_G):

$$D_G = \frac{\left[3.03 - \left(\frac{0.98}{M_{AB}^{0.5}}\right)\right] \cdot (10^{-3}) \cdot T_G^{1.5}}{P_G \cdot M_{AB}^{0.5} \cdot \sigma_{AB}^2 \cdot \Omega_D} \quad (33)$$

Where P_G = 1.1 bar.

Step 35. Liquid velocity (v_L):

$$v_L = \frac{4 \cdot \frac{m_{Le}}{3{,}600}}{\rho_L \cdot \pi \cdot D^2} \quad (34)$$

Step 36. Liquid phase resistance (k_L):

$$k_L = 0.757 \cdot C_L \cdot \left[\frac{(D_L \cdot 0.0001) \cdot a_0 \cdot v_L}{\varepsilon \cdot h_L}\right]^{0.5} \quad (35)$$

Where C_L mass-transfer parameter specific for the packing type (Table 1) and D_L is given in cm^2/s.

Step 37. Volumetric liquid-phase mass-transfer coefficient (k_L^V):

$$k_L^V = k_L \cdot a_h \quad (36)$$

Step 38. Schmidt number for gas phase (Sc_G):

$$Sc_G = \frac{\mu_G}{\rho_G \cdot (D_G \cdot 0.0001)} \quad (37)$$

Where μ_G is given in Pa.s and D_G is given in cm^2/s.

Step 39. Gas phase resistance (k_G):

$$k_G = 0.1304 \cdot C_V \cdot \frac{D_G \cdot P_G}{R \cdot T_G} \cdot \frac{a_0}{[\varepsilon \cdot (\varepsilon - h_L)]^{0.5}} \cdot \left[\frac{Re_G}{K_W}\right]^{3/4} \cdot Sc_G^{2/3} \quad (38)$$

Where: C_V is a mass-transfer parameter specific to the packing type (Table 1); D_G is given in m²/s; P_G is given in atm and R = 0.0821 m³.atm/kmol.K.

Step 40. Volumetric gas-phase mass-transfer coefficient (k_G^V):

$$k_G^V = k_G \cdot a_h \quad (39)$$

Packing height

Because the absorption system operates at low pressure and temperature (1.1 atm and 298 K, respectively); the solute gas is very diluted in the liquid phase (that is, the liquid phase can be catalogued as a *dilute liquid solution*), and is assumed that there is no reaction between the dissolved solute (SO_2) and the solvent (water), it's established that the system obeys the *Henry's law* [2,3]. Thus, the proportionality constant (ϕ) is:

$$\phi = \frac{H}{P_G} \quad (40)$$

Where H is Henry's law constant = 0.02197 atm^{-1} [19].

Step 41. Molar flowrate of SO_2 absorbed (A_{SO2}^m):

$$A_{SO2}^m = V_{mG} \cdot y_{SO2(1)} \frac{R_{SO2}}{100} \quad (41)$$

Step 42. Inlet gas molar velocity (G_{My1}):

$$G_{My1} = \frac{V_{mG} \cdot 4}{3{,}600 \cdot \pi \cdot D^2} \quad (42)$$

Step 43. Outlet gas molar velocity (G_{My2}):

$$G_{My2} = \frac{(V_{mG} - A_{SO2}^m) \cdot 4}{3{,}600 \cdot \pi \cdot D^2} \quad (43)$$

Step 44. Average gas molar velocity (G_{My}):

$$G_{My} = \frac{G_{My1} + G_{My2}}{2} \quad (44)$$

Step 45. Inlet molar flowrate of liquid water (V_{mL}):

$$V_{mL} = \frac{m_{Li}}{M_W} \quad (45)$$

Step 46. Inlet liquid molar velocity (G_{Mx2}):

$$G_{Mx2} = \frac{V_{mL} \cdot 4}{3{,}600 \cdot \pi \cdot D^2} \quad (46)$$

Step 47. Outlet liquid molar velocity (G_{Mx1}):

$$G_{Mx1} = \frac{(V_{mL} + A_{SO2}^m) \cdot 4}{3{,}600 \cdot \pi \cdot D^2} \quad (47)$$

Step 48. Absorption factors at both ends of the column:

$$A_1 = \frac{G_{Mx1}}{\phi \cdot G_{My1}} \quad (48)$$

$$A_1 = \frac{G_{Mx1}}{\phi \cdot G_{My1}} \quad (49)$$

Step 49. Geometric average of absorption factors (A):

$$A = (A_1 \cdot A_2)^{0.5} \quad (50)$$

Step 50. Molar composition of SO_2 in outlet gas ($y_{SO2(2)}$):

$$y_{SO2(2)} = \left[1 - \left(\frac{R_{SO2}}{100}\right)\right] \cdot y_{SO2(1)} \quad (51)$$

Step 51. Overall number of gas-phase transfer units (N_{tOG}):

$$N_{tOG} = \frac{ln\left[\frac{y_{SO2(1)} - \phi \cdot x_{w(2)}}{y_{SO2(2)} - \phi \cdot x_{w(2)}} \cdot \left(1 - \frac{1}{A}\right) + \frac{1}{A}\right]}{1 - \frac{1}{A}} \quad (52)$$

Since pure water is used, $x_{w(2)}$ = 0.

Step 52. Total molar concentration in the liquid phase (c_L):

$$c_L = \frac{\rho_L}{M_w} \quad (53)$$

Step 53. Volumetric liquid-phase mass-transfer coefficient corrected (k_{Lc}^V):

$$k_{Lc}^V = k_L^V \cdot c_L \quad (54)$$

Step 54. Overall volumetric mass-transfer coefficient (K^V):

$$K^V = \frac{1}{\frac{1}{k_G^V} + \frac{\phi}{k_{Lc}^V}} \tag{55}$$

Step 55. Overall height of a gas-phase transfer unit (H_{tOG}):

$$H_{tOG} = \frac{G_{My}}{K^V} \tag{56}$$

Step 56. Total packed height (Z):

$$Z = H_{tOG} \cdot N_{tOG} \tag{57}$$

Pumping power

Step 57. Power required to force the gas through the tower (W_G):

$$W_G = \frac{\frac{Q_G}{3{,}600} \cdot \frac{\Delta P}{Z} \cdot Z}{E_{mf}} \tag{58}$$

Where E_{mf} is the mechanical efficiency of the motor-fan system = 0.60 [2].

Step 58. Power required to pump the liquid to the top of the absorber (W_L):

$$W_L = \frac{\frac{m_{Li}}{3{,}600} \cdot g \cdot Z}{E_{mp}} \tag{59}$$

Where E_{mp} is the isentropic efficiency of the pump = 0.80 [25].

Sensitivity analysis

A sensitivity analysis was carried out to determine how an increase of the inlet mass flowrate of the gaseous mixture influences in two design parameters, namely column diameter and total packed height, for the three packing types evaluated. In this case, the gas inlet mass flowrate was varied between 3,000 - 6,000 kg/h, keeping constant the rest of the inlet parameters. The numerical results were processed on MATLAB® software to obtain the corresponding graphs.

Results and discussion

Column diameter

The size of a packed column is governed by its cross-sectional area. Generally, the column will be designed to operate at the highest economical pressure drop, and also to guarantee good liquid and gas distribution [26].

Most packed columns consist of cylindrical vertical vessels. The column diameter is calculated to securely prevent flooding and operate in the preloading region with a pressure drop usually lower than 1.2 kPa/m of packed height [2].

Table 3 shows the results of the parameters calculated in steps 1 to 15 for the three packing types assessed.

The Hiflow rings had the lower value of the column diameter (0.564 m), while the Pall rings had the higher value for the column diameter (0.727 m) for the three packing types considered. A low value of the column diameter is obtained because the packing factor (F_p) has a lower value, which in turn increases the coefficient at flooding conditions ($C_{S,flood}$), the gas velocity at flooding conditions (υ_{GF}) and the gas velocity (υ_G), thus decreasing the column diameter (D). Therefore, when the value of the packing factor decreases, a lower value of the column diameter is obtained, maintaining constant the rest of the inlet parameters. These results agree with the findings reported by Walcek *et al.* [12], where four packing types were evaluated thus obtaining the higher value of the column diameter (1.221 m) for the packing type (Pall) with the higher value of the packing factor parameter (142 ft^2/ft^3), while the lowest value for the column diameter (0.921 m) was obtained for the packing type (Top-Pak) with the lowest value of the packing factor (46 ft^2/ft^3).

Table 3. Results of the parameters calculated in steps 1 to 15.

Step	Eq.	Parameter	Hiflow	Nor-Pac	Pall	Units
1	(1)	Molecular weight of inlet gas	31.417	31.417	31.417	kg/kmol
2	(2)	Density of the inlet gas	1.413	1.413	1.413	kg/m^3
3	(3)	Viscosity of the inlet gas	0.0000174	0.0000174	0.0000174	Pa.s
4	(4)	Volumetric flowrate of inlet gas	2,830.86	2,830.86	2,830.86	m^3/h
5	(5)	Molar flowrate of inlet gas	127.32	127.32	127.32	kmol/h

6	(6)	Sulfur dioxide absorbed	553.80	553.80	553.80	kg/h
7	(7)	Mass flowrate of liquid exiting the absorber	2,353.80	2,353.80	2,353.80	kg/h
8	-	Density of liquid water	997.052	997.052	997.052	kg/m^3
9	-	Viscosity of liquid water	0.00089	0.00089	0.00089	Pa.s
10	(8)	Flow parameter	0.0221	0.0221	0.0221	-
11	(9)	Pressure drop parameter under flooding conditions	0.3025	0.3025	0.3025	-
12	(10)	Coefficient at flooding conditions	0.1954	0.1705	0.1192	m/s
13	(11)	Gas velocity at flooding conditions	5.196	4.527	3.164	m/s
14	(12)	Gas velocity	3.118	2.716	1.898	m/s
15	(13)	Column diameter	0.564	0.607	0.727	M

Gas-phase pressure drop

In near-atmospheric applications, pressure drop typically needs to be reduced to decrease the cost of energy for compression of the feed gas.

In the countercurrent two-phase flow of gas and liquid, a pressure drop occurs in the packed column. It is imperative to know the pressure drop in the gas phase in single and two-phase countercurrent flow through random packings, to evaluate the operating mode of packed columns [4].

As reported by Benitez [2], absorbers and strippers are typically designed to accommodate gas pressure drops ranging from 200 to 400 Pa/m based on packed depth.

Generally, the design aims for the maximum economically viable pressure drop to optimize liquid and gas distribution. In the case of random packings, pressure drops usually do not exceed 80 mm of water per meter of packing height, equivalent to 785 Pa/m. At this threshold, the gas velocity is approximately 80 percent of the flooding velocity. Suggested design pressure drop values range from 15 to 50 mm water per meter of packing, or 147 to 490 Pa/m [26].

Table 4 presents the results of the parameters calculated in steps 16 to 27.

Table 4. Results of the parameters calculated in steps 16 to 27.

Step	Eq.	Parameter	Hiflow	Nor-Pac	Pall	Units
16	(14)	Effective particle diameter	0.0015	0.0024	0.0112	m
17	(15)	Wall factor	0.9284	0.9556	0.9549	-
18	(16)	Gas-phase Reynolds number	15,339.71	8,923.98	7,854.85	-
19	(17)	Dry-packing resistance coefficient	0.3523	0.3252	0.5887	-
20	(18)	Dry-gas pressure drop	257.96	298.94	380.76	Pa/m
21	(19)	Liquid mass velocity	2.6184	2.2578	1.5778	kg/m^2.s
22	(20)	Liquid-phase Reynolds number	31.87	17.89	15.22	-
23	(21)	Liquid phase Froude number	0.0000649	0.0000741	0.0000297	-
24	(23)	Ratio of specific areas[1]	0.6745	0.3965	0.790	-
25	(24)	Hydraulic specific surface area of packing	62.25	56.22	92.08	m^2/m^3
26	(25)	Specific liquid holdup	0.0223	0.0199	0.0245	-
27	(26)	Gas-phase overall pressure drop	311.07	337.50	430.91	Pa/m

[1]Equation 23 was used to calculate the ratio of specific areas since $Re_L \geq 5$.

The lower value for the gas-phase overall pressure drop was obtained for the Hiflow rings (311.07 Pa/m), while the higher value of this parameters was obtained for the Pall rings (460.91 Pa/m). The gas-phase overall pressure drop for the Pall rings exceeds the value recommended by Benitez [2] for absorbers and strippers (200 - 400 Pa/m). It should be noted that, in this study, the dry-gas pressure drop (and thus the gas-phase overall pressure drop) decreases with the column diameter, i.e. the packing type with the lower value of the column diameter(Hiflow, D = 0.564 m) has the lower value of the dry-gas pressure drop (257.96 Pa/m), thus coinciding with the conclusions reported by Manyele [4] which also indicates that the dry-gas pressure drop is lower in columns with small diameters than in large-diameter columns. The values of the gas-phase overall pressure drop for the Hiflow and Nor-Pac packing types are below the maximum value set for the mass transfer process (400 Pa/m), while is higher than 400 Pa/m for the Pall rings. Also, in this study the specific liquid holdup calculated for the Hiflow rings (0.0223) is lower than the liquid holdup calculated for the Pall rings (0.0245), which agrees with the results reported by Benitez [2].

Based on these results, the Hiflow rings have a greater capacity than the other packing types since the required diameter and gas-phase overall pressure drop have the lowest value for the same inlet parameters.

Gas and liquid volumetric mass-transfer coefficients

Table 5 displays the results of the parameters calculated in steps 28-39.

The packing type with the higher values of both the volumetric liquid-phase mass-transfer coefficient (k_L^V= 0.0104 s^{-1}) and the volumetric gas-phase mass-transfer coefficient (k_G^V= 0.3511 kmol/m^3.s) is Pall rings, while the packing type with the lower values of these mass transfer coefficients is Nor-Pac rings (k_L^V= 0.00524 s^{-1} and k_G^V= 0.2489 kmol/m^3.s, respectively). This is due to the higher value of the mass-transfer parameter (C_L) and the lower value of the hydraulic parameter (ε) for the Pall rings as compared to the Nor-Pac rings, which increments the value of the liquid phase resistance (k_L) and thus the value of the volumetric liquid-phase mass-transfer coefficient (k_L^V). Also, the higher value obtained of the hydraulic specific surface area of packing (a_h) for the Pall rings (92.08 m^2/m^3) with respect to the value obtained of this parameter for the Nor-Pac rings (56.22 m^2/m^3) also influences significantly in the calculated values of both k_L^V and k_G^V, irrespectively of the value obtained for the gas phase resistance. It is worth mentioning that in [17] the calculated values of both k_L^V and k_G^V are higher for the Pall rings as compared to the values of these mass-transfer coefficients for the Hiflow rings, which coincides with the results of this study.

Table 5. Results of the parameters calculated in steps 28-39.

Step	Eq.	Parameter	Hiflow	Nor-Pac	Pall	Units
28	(27)	Parameter α	-0.9061	-0.9061	-0.9061	-
29	(28)	Liquid-phase diffusion coefficient	0.0000155	0.0000155	0.0000155	cm^2/s
30	(29)	Average molecular weight of the gas-phase components	39.92	39.92	39.92	kg/mol
31	(30)	Parameter $T*$	1.652	1.652	1.652	-
32	(31)	Collision diameter	3.866	3.866	3.866	Å
33	(32)	Diffusion collision integral	1.1538	1.1538	1.1538	-
34	(33)	Gas-phase diffusion coefficient	0.1234	0.1234	0.1234	cm^2/s
35	(34)	Liquid velocity	0.0026	0.0023	0.0016	m/s
36	(35)	Liquid phase resistance	0.0001155	0.0000933	0.000113	m/s
37	(36)	Volumetric liquid-phase mass-transfer coefficient	0.00719	0.00524	0.0104	s^{-1}
38	(37)	Schmidt number for gas phase	0.9973	0.9973	0.9973	-
39	(38)	Gas phase resistance	0.0041	0.0044	0.0038	kmol/m^2.s
40	(39)	Volumetric gas-phase mass-transfer coefficient	0.2552e	0.2489	0.3511	kmol/m^3.s

Packing height

According to Equation 40, the proportionality constant (ϕ) is:

$$\phi = \frac{H}{P_G} = \frac{0.02197}{1.1} = 0.0199 \qquad (40)$$

Table 6 exhibits the results of the parameters calculated in steps 41 - 56. The lower value of the total packed height was obtained for the Pall rings (0.848 m), while the higher value for this parameter was obtained for the Hiflow rings (1.916 m). This is due to the higher value achieved for the parameter overall height of a gas-phase transfer unit (H_{tOG}) for the Hiflow rings (0.5371 m) as compared to the value of this parameter for the Pall rings (0.2377 m), which in turn is owed to the higher value obtained for the average gas molar velocity (0.1353 kmol/m^2.s) and the lower value obtained for the column diameter (0.564 m) for the Hiflow rings as compared to the values of these parameters (average gas molar velocity = 0.0842 kmol/m^2.s and column diameter = 0.727 m) for the Pall rings. That is, the column designed for the Hiflow rings has a lower cross-sectional area, which increments the average gas molar velocity, resulting in a higher overall height of a gas-phase transfer unit and thus a higher total packed height, regardless of the value obtained for the overall volumetric mass-transfer coefficient. This result agrees with that reported in Pérez *et al.* [17], where the value of the total packed height for Pall rings (0.8 m) is lower than the result of this parameter for Hiflow rings (2.0 m).

Table 6. Results of the parameters calculated in steps 41-56.

Step	Eq.	Parameter	Hiflow	Nor-Pac	Pall	Units
41	(41)	Molar flowrate of SO_2 absorbed	8.645	8.645	8.645	kmol/h
42	(42)	Inlet gas molar velocity	0.1401	0.1221	0.0853	kmol/m^2.s
43	(43)	Outlet gas molar velocity	0.1306	0.1138	0.0796	kmol/m^2.s
44	(44)	Average gas molar velocity	0.1353	0.1180	0.0842	kmol/m^2.s
45	(45)	Inlet molar flowrate of liquid water	99.89	99.89	99.89	kmol/h
46	(46)	Inlet liquid molar velocity	0.1099	0.0958	0.0670	kmol/m^2.s
47	(47)	Outlet liquid molar velocity	0.1194	0.1041	0.0728	kmol/m^2.s
48	(48)	Absorption factor A_1	42.82	42.82	42.82	-
	(49)	Absorption factor A_2	42.28	42.28	42.28	-
49	(50)	Geometric average of absorption factors	42.55	42.55	42.55	-
50	(51)	Molar composition of SO_2 in outlet gas	0.0021	0.0021	0.0021	-
51	(52)	Overall number of gas-phase transfer units	3.5673	3.5673	3.5673	
52	(53)	Total molar concentration in the liquid phase	55.33	55.33	55.33	kmol/m^3
53	(54)	Volumetric liquid-phase mass-transfer coefficient corrected	0.3978	0.2902	0.5779	kmol/m^3.s
54	(55)	Overall volumetric mass-transfer coefficient	0.2519	0.2447	0.3468	kmol/m^3.s
55	(56)	Overall height of a gas-phase transfer unit	0.5371	0.4821	0.2377	m
56	(57)	Total packed height	1.916	1.720	0.848	m

Pumping power

Table 7 presents the results of the pumping power for both the gas and liquid streams.

Considering the results of the Table 7, predictably the higher values obtained for the power required to force the gas through the tower, and the power required to pump the liquid to the top of the absorber, are for the Hiflow rings, due to the higher value obtained for total packed height (1.916 m) for this packing type as compared to the others. In this case, as the total packed height increases, a higher value will be required for both the power required to force the gas through the tower (irrespective of the value of the gas-phase overall pressure drop obtained and for a constant value of the inlet gas flowrate) and the power required to pump the liquid to the top of the absorber (for a constant value of the inlet liquid flowrate).

Table 7. Results of the pumping power for the gas and liquid streams.

Step	Eq.	Parameter	Hiflow	Nor-Pac	Pall	Units
57	(58)	Power required to force the gas through the tower	781.12	761.07	479.09	W
58	(59)	Power required to pump the liquid to the top of the absorber	11.74	10.55	5.20	W

According to the results, the Hiflow rings could be selected as the packing material for this mass transfer system if it is required to have the lowest values for the column diameter and gas-phase overall pressure drop, regardless the highest values obtained for the total packed height and the pumping power for both the gas and liquid phases, while the Pall rings could be selected if it needed to have the lowest values for the total packed height and pumping power, and the highest value for the volumetric mass-transfer coefficients, irrespective the highest results obtained for the gas-phase overall pressure drop, which is above the limit set by the process, and the column diameter. Finally, the Nor-Pac rings have intermediate values for the gas-phase overall pressure drop (which is lower than the limit value set by the process), total packed height, column diameter and pumping power, while it gives the lowest values for the volumetric mass-transfer coefficients. Thus, Nor-Pac rings could be also considered as a potential, prospective packing material for this mass transfer service due to the reasonable, acceptable results of its mass transfer, pressure drop, energy and geometrical design parameters. Considering the above, the authors of this work will select Hiflow rings as the packing material for this mass transfer system, because it has the lowest values for two of the most important design parameters taken into account when designing an absorption column, i.e., the column diameter and gas-phase overall pressure drop [2].

Results of the sensitivity analysis

Figure 3 shows the results of the sensitivity analysis carried out, where it was evaluated the influence of the increment of the gas inlet flowrate on the column diameter and the total packed height for the three packing types considered.

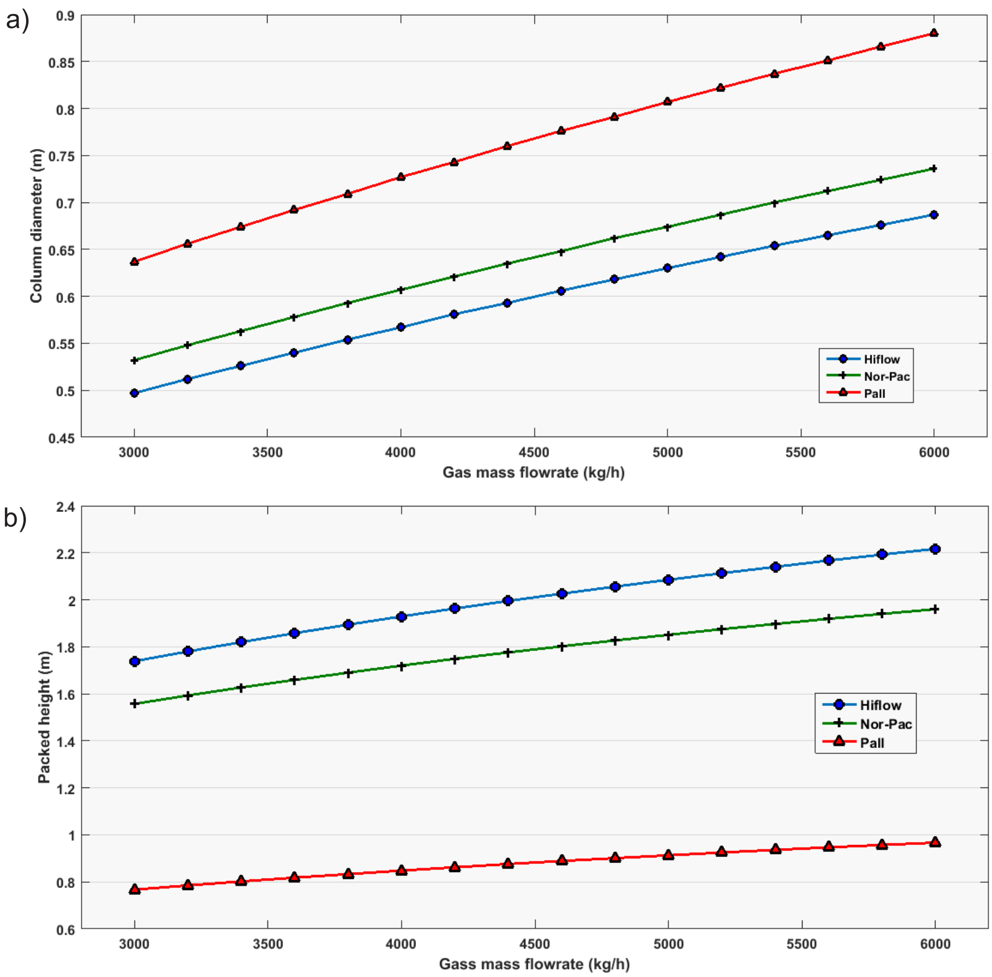

Figure 3. Results of the sensitivity study, corresponding to evaluate the effect of an increment of the inlet gas mass flowrate on a) column diameter and b) total packed height, for the three packing types considered.

It can be observed that the increment of the gas inlet mass flowrate increased the column diameter and the total packed height for the three packing types evaluated. The packing type with highest difference between the low and high limits for the column diameter (0.243 m) were Pall rings, while the packing type with the lowest variance between these limits were Hiflow rings (0.190 m). Likewise, the packing type with the highest and lowest difference between the low and high limits for the total packed height were Hiflow (0.478 m) and Pall (0.200 m) rings, respectively.

These results agree with that reported by [17], where an increment of the gas mixture feed flowrate also increases the column diameter and total packed height for the four packing types considered. Also, the Pall rings present a higher column diameter and a lower total packing height as compared to the Hiflow rings, which coincides with the results of the present study.

Conclusions

In this study, a packed bed absorber was designed using the methodologies and equations reported in [2,3], where several key design parameters were determined such as the column diameter, gas-phase pressure drop, volumetric mass transfer coefficients for both gas and liquid, total packed height and pumping power for three different packing types: Hiflow, Nor-Pac and Pall rings. Also, a sensitivity study was carried out to evaluate how an increment of the gas inlet flowrate influences in the column diameter and total packed height for the three packing types considered. The lower values of the column parameters as diameter (0.564 m) and gas-phase pressure drop (311.07 Pa/m) were obtained for the Hiflow rings, while the higher values of these parameters were obtained for Pall rings (diameter: 0.727 m; pressure drop: 430.91 Pa/m). The value of the gas-phase pressure drop for Pall rings is above the maximum value set by the process (400 Pa/m). Likewise, the packing type with the lower values of both the liquid- (0.00524 s^{-1}) and gas- (0.2489 $kmol/m^3.s$) volumetric mass transfer coefficients was Nor-Pac rings, while the packing type with the higher values of these coefficients was Pall rings (0.0104 s-1 and 0.3511 kmol/m3.s). Similarly, the higher value of the total packed height was obtained for Hiflow rings (1.916 m), while the lower value of this parameter vas obtained for Pall rings (0.848 m). Finally, the Pall rings had the lower values of the pumping power for both the gas (479.09 W) and liquid (5.20 m), while Hiflow rings had the higher values of these parameters (gas power: 781.12 W; liquid power: 11.74 W). According to the results of the sensitivity analysis, an increment in the gas inlet flowrate increases the column diameter and total packed height for the three packing types evaluated. In this case, the packing type with highest variance between the low and high limits for the column diameter was Pall rings, and the packing type with the highest difference between the low and high limits for the total packed height was Hiflow rings. The Hiflow rings have a greater capacity than the other packing types, while it is the packing type with the highest values of the total packed height (1.916 m) and the gas (781.12 W) and liquid pumping power (11.74 W). The Pall rings presented the higher value of the mass transfer coefficients (liquid-phase: 0.0104 s^{-1} and gas-phase: 0.3511 $kmol/m^3.s$) and the lower value for the total packed height (0.848 m), but its gas-phase pressure drop (430.91 Pa/m) exceeds the limit value established by the process. Taking into account the results, it's recommended to select the Hiflow rings for this absorption system because it has the lowest values for the column diameter (0.564 m) and gas-phase overall pressure drop (311.07 Pa/m), which are the most important design parameters to consider in an absorption system [2], as well as the second highest values for the volumetric liquid-phase mass-transfer coefficient (0.00719 s^{-1}), the volumetric gas-phase mass-transfer coefficient (0.2552 $kmol/m^3.s$) and the overall volumetric mass-transfer coefficient (0.2519 $kmol/m^3.s$), although this packing type has, as previously stated, the highest values for the total packed height and the pumping power for both the gas and liquid streams.

Nomenclature

a_0	Hydraulic parameter	-
a_h	Hydraulic, or effective, specific surface area of packing	m^2/m^3
$\frac{a_h}{a}$	Ratio of specific areas	-
A	Geometric average of absorption factors	-
A_1	Absorption factor at one end of the column	-
A_2	Absorption factor at one end of the column	-
A_{SO2}	Sulfur dioxide absorbed	kg/h
A_{SO2}^{m}	Molar flowrate of SO_2 absorbed	kmol/h
c_L	Total molar concentration in the liquid phase	kmol/m^3
C_h	Hydraulic parameter	-
C_L	Mass-transfer parameter	-
Cp	Hydraulic parameter	-
C_V	Mass-transfer parameter	-
$C_{S,flood}$	Coefficient at flooding conditions	m/s
d_p	Effective particle diameter	m
D	Column diameter	m
D_G	Gas-phase diffusion coefficient	cm^2/s
D_L	Liquid-phase diffusion coefficient	cm^2/s
E_{mf}	Mechanical efficiency of the motor-fan system	-
E_{mp}	Isentropic efficiency of the pump	-
f_{flood}	Flooding factor	-
Fr_L	Liquid-phase Froude number	-
g	Gravitational acceleration	m/s^2
G_L	Liquid mass velocity	kg/m^2.s
G_{Mx1}	Outlet liquid molar velocity	kmol/m^2.s
G_{Mx2}	Inlet liquid molar velocity	kmol/m^2.s
G_{My}	Average gas molar velocity	kmol/m^2.s
G_{My1}	Inlet gas molar velocity	kmol/m^2.s
G_{My2}	Outlet gas molar velocity	kmol/m^2.s
h_L	Specific liquid holdup	-
H_{tOG}	Overall height of a gas-phase transfer unit	m
H	Henry's law constant	atm^{-1}
k_G	Gas phase resistance	kmol/m^2.s
k_L	Liquid phase resistance	m/s
k_G^V	Volumetric gas-phase mass-transfer coefficient	kmol/m^3.s
k_L^V	Volumetric liquid-phase mass-transfer coefficient	s^{-1}
k_{Lc}^V	Volumetric liquid-phase mass-transfer coefficient corrected	kmol/m^3.s
K_W	Wall factor	-
K^V	Overall volumetric mass-transfer coefficient	kmol/m^3.s
m_G	Gas mass flowrate	kg/h
m_{Le}	Mass flowrate of liquid exiting the absorber	kg/h
m_{Li}	Available mass flowrate of pure liquid water	kg/h
M_{air}	Molecular weight of air	kg/kmol
M_{AB}	Average molecular weight of the gas-phase components	kg/mol
M_G	Molecular weight of inlet gas	kg/kmol
M_{SO2}	Molecular weight of sulfur dioxide	kg/kmol
M_w	Molecular weight of water	kg/kmol
N_{tOG}	Overall number of gas-phase transfer units	-
P_G	Inlet pressure of gas	atm
$\frac{\Delta P_0}{Z}$	Dry-gas pressure drop	Pa/m
$\frac{\Delta P}{Z}$	Gas-phase overall pressure drop per meter of packing height	Pa/m
Q_G	Volumetric flowrate of inlet gas	m^3/h
R	Ideal gas constant	m^3.atm/kmol.K
Re_G	Gas-phase Reynolds number	-
Re_L	Liquid-phase Reynolds number	-
R_{SO2}	Required recovery of sulfur dioxide	%
Sc_G	Schmidt number for gas phase	-
T^*	Parameter	-
T_G	Inlet temperature of gas	K
T_L	Inlet temperature of pure liquid water	K
v_G	Gas velocity	m/s
v_{GF}	Gas velocity at flooding conditions	m/s
v_L	Liquid velocity	m/s

V_{bSO2}	Molar volume of SO_2 at normal boiling point	cm^3/mol
V_{mG}	Molar flowrate of inlet gas	kmol/h
V_{mL}	Inlet molar flowrate of liquid water	kmol/h
W_G	Power required to force the gas through the tower	W
W_L	Power required to pump the liquid to the top of the absorber	W
$y_{air(1)}$	Molar composition of dry air in inlet gas	-
$y_{SO2(1)}$	Molar composition of sulfur dioxide in inlet gas	-
$y_{SO2(2)}$	Molar composition of SO_2 in outlet gas	-
Y_{flood}	Pressure drop parameter under flooding conditions	-
Z	Total packed height	m

Greek symbols

α	Parameter	-
ρ_G	Density of the inlet gas	kg/m^3
ρ_L	Density of liquid water	kg/m^3
ε	Hydraulic parameter	-
σ	Lennard-Jones constant	Å
σ_{AB}	Collision diameter	Å
$\frac{e}{k}$	Lennard-Jones constant	K
μ_{air}	Viscosity of air	Pa.s
μ_G	Viscosity of the inlet gas	Pa.s
μ_L	Viscosity of liquid water	Pa.s
μ_{SO2}	Viscosity of sulfur dioxide	Pa.s
ϕ	Proportionality constant	-
Ψ_0	Dry-packing resistance coefficient	-
Ω_D	Diffusion collision integral	-

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