Research Article

Experimental Evaluation of Sulfur Dioxide Absorption in Water Using Structured Packing

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An experimental study of hydrodynamic and mass transfer processes was carried out in an absorption column of 0.252 m diameter and 3.5 m of packed bed height developed by Mexican National Institute of Nuclear Research (ININ by its acronym in Spanish) of stainless steel gauze corrugated sheet packing by means of SO2-air-water systems. The experiments results include pressure drop, flows capacity, liquid hold-up, SO2 composition, and global mass transfer coefficient and mass transfer unit height by mass transfer generalized performance model in order to know the relationship between two-phase countercurrent flow and the geometry of packed bed. Experimental results at loading regimen are reported as well as model predictions. The average deviation between the measured values and the predicted values is ±5% of 48-data-point absorption test. The development of structured packing has allowed greater efficiency of absorption and lower pressure drop to reduce energy consumption. In practice, the designs of equipment containing structured packings are based on approximations of manufacturer recommendations.

1. Introduction

The modelling and study of the beds of structured packing, geometrically ordered, have played scientific and technological challenges, motivated by the urgent need to increase the separation efficiency of separation processes and efficient use of energy and in compliance with environmental legislation [1].

The development of structured packing has allowed greater efficiency of absorption and lower pressure drop to reduce energy consumption [2]. In practice, the designs of equipment containing structured packings are based on approximations of manufacturer recommendations. Conventional structured packing offers the highest efficiency versus other devices. However, it is less resistant to particulate fouling versus grid style packing and there is less experience with conventional packing in this particular service. This is considered a viable option but requires a design that mitigates the potential for particulate fouling [3].

The main feature of the process plant is its large size, handling large quantities of products. These result in specific problems related to equipment efficiency, energy consumption, and transportation of materials, which affect directly on manufacturing costs.

The high cost per unit volume of the structured packing is a disadvantage [2]; however, economic research in separation processes indicates that they generate a greater contribution to energy savings, so that its design is mainly focused on the reduction of pressure drop per theoretical stage at high-load stages.

The aim of this paper is the experimental evaluation of sulfur dioxide absorption in water with high-efficiency packings, manufactured at the Mexican National Institute of Nuclear Research (ININ), and operation behavior based on hydrodynamic and mass transfer models. These models describe fluid dynamic relationship in packed columns with countercurrent flow of gas and liquid phases [4–6]. The Billet model was made by considering void fraction in bed of packing of multiplicity of vertical channels through which the liquid flows downwards in the form of a film countercurrent to the ascending gas stream.
2. Materials and Methods

The methodology was divided in two parts: (i) the use of hydrodynamic and mass transfer models to determine the column diameter and height, respectively, and (ii) the use of other packing, as liquid-gas contactor, in order to determine the absorption column dimensions, one manufactured at the ININ and the other by Sulzer Brothers Limited.

2.1. Hydrodynamic Behavior and Mass Transfer Models. Equations that were known for calculating mass transfer process during two-phase countercurrent flows in packed columns were those that apply to the range extending up to the loading points. At loading regimen, the shear stress in gas stream supports an increasing quantity of liquid in the column, with the result that the liquid hold-up greatly increases. At flooding points, the liquid accumulates to such an extent that column instability occurs. Mass transfer in this upper loading regimen can be described if these fluid dynamic relationships are taken into consideration [4–6]. The equations take due account of geometric, hydrodynamic and system-related parameters that they govern the fluidity behavior and mass transfer [4–6]. The fluid dynamics and mass transfer description take into account the great diversity in the geometry, structure and materials for packings in industrial columns, which normally entails differences in the fluid dynamics under operation conditions and thus in the packing performance. Mass transfer calculation allows for the continuous decrease in the average effective liquid load at gas velocities above the loading point.

2.2. Hydrodynamic Model for Hazardous and Structured Packings. The pressure drop per unit packed height $\Delta P/H$, the liquid hold-up $h_{L,S}$ and the model flow factor $\xi$ [4–6] have been used for the packed columns prediction. The load point is described by (1):

$$h_{L} = 4.5803 \left( \frac{Re_{L}}{Fr} \right)^{0.3507}$$

$$\frac{\Delta P}{H} = \xi \left( \frac{a_{g}}{2} + \frac{d_{c}}{d_{l}} \right) \left( \frac{1}{\varepsilon - h_{L}} \right) u_{L}^{2} \rho_{V}$$

$$\xi = 0.45 W \left( \frac{64}{Re_{V}} + \frac{3}{Re_{V}^{3/2}} \right) \left( \frac{\varepsilon - h_{L}}{\varepsilon} \right)^{3-x},$$

where $Re_{L}$ and $Re_{V}$ are the Reynolds numbers for the liquid and gas phases film flow, respectively, $Fr$ is the Froude number, $\xi$ is the resistance coefficient, $a_{g}$ is the geometric packing area ($m^{2}/m^{3}$), $d_{l}$ is the column diameter ($m$), $\varepsilon$ is the void fraction ($m^{3}/m^{3}$), $u_{V}$ is the superficial vapor velocity ($m/s$), $\rho_{V}$ is the gas (or vapor) density ($kg/m^{3}$), $C_{P}$ and $x$ are constants determined from experiment data, and $W$ is the wetting function.

2.3. Mass Transfer Model for Structured Packings. The two-resistance model [4–6] is used with the assumption of thermodynamic equilibrium at the phase interface. This is useful for either rate-based or equilibrium stage-based computational routines. It is assumed that the mass transfer follows the laws of stationary diffusion valid for short periods of contact between the phases involved and is described by the following relation, formulated by Higbie. The basic parameters of the model are the gas (or vapor) and liquid phases mass transfer coefficients $\beta_{V}$ and $\beta_{L}$, respectively, and the effective interfacial area $a_{ph}$:

$$\beta_{V} a_{ph} = 1.02 \frac{u_{L}^{2.15}}{D_{V}^{0.67}},$$

$$\beta_{L} a_{ph} = \frac{u_{L}}{HTU_{L}} = C_{L} \left( \frac{\rho_{L} g}{\eta_{L}} \right)^{1/6} \left( \frac{D_{L}}{l_{t}} \right)^{1/2} \frac{a_{g}^{2/3}}{u_{L}^{1/3}} \left( \frac{a_{ph}}{a_{g}} \right),$$

$$\frac{a_{ph}}{a_{g}} = 1.5 \left( \frac{a_{ph} d_{h}}{u_{L}} \right)^{-0.5} \left( \frac{u_{L} d_{h}}{v_{L}} \right)^{-0.2} \left( \frac{u_{L} d_{h}}{a_{L}} \right)^{0.75} \left( \frac{u_{L} d_{h}}{g d_{h}} \right)^{-0.45}.$$  

The quantity $a_{g}$ is the geometric packing area ($m^{2}/m^{3}$); $\beta_{V} a_{ph}$ and $\beta_{L} a_{ph}$ the gas and liquid phase (1/h) volumetric mass transfer coefficient, respectively; $u_{L}$ the liquid load, ($m^{2}/m^{3}/s$); $d_{h}$ the hydraulic diameter of the packing ($m$); $\eta_{L}$ the dynamic viscosity ($kg/ms$); $a_{L}$ the surface tension; $g$ the gravitational constant, 9.8 m/s$^{2}$; $\nu_{L}$ the cinematic viscosity ($m^{2}/s$); $D_{L}$ the liquid phase, ($m^{2}/s$) solute diffusivity; $C_{L}$ a constant determined from experiment data; $l_{t}$ the characteristic length of the path of contact.

The two-film model is based on the number of gas and liquid resistance transfer global units (NTUs) that are related to the mass transfer efficiency in terms of the height of a mass transfer global unit ($HTU$) [7–9].

The packed column height $Z$ for the gas and liquid is:

$$Z_{G} = HTU_{OG} \times NTU_{OG},$$

$$Z_{L} = HTU_{OL} \times NTU_{OL}.$$  

The application of the two-film model is frequently used to relate the height of the transfer global unit ($HTU_{OG}$ or $HTU_{OL}$) to the height of the gas $HTU_{G}$ and liquid $HTU_{L}$ transfer units to the absorption:

$$HTU_{OG} = HTU_{G} + \lambda HTU_{L},$$

$$HTU_{OL} = HTU_{L} + \frac{1}{\lambda} HTU_{G}.$$  

The height of the transfer global units is determined by (5):

$$HTU_{OV} = HTU_{V} + \lambda NTU_{L} = \frac{u_{V}}{\beta_{V} a_{ph}} + \left( \frac{m}{L/V} \right) \frac{u_{L}}{\beta_{L} a_{ph}}.$$  

The quality $\lambda$ is given by

$$\lambda = m \frac{V}{L}.$$  


where \( m \) is the ratio of the slope of the equilibrium line to the operation line, and \((L/V)\) is known as the removed factor. The absorption factor is the inverse of \( \lambda \).

### 2.4. Absorption Column

Countercurrent contact in a structured packed column of the lean solvent with the process gas transfers the \( \text{SO}_2 \) to the liquid, producing the rich solvent. The absorption factor is the inverse of \( \alpha \).

The use of \( \text{Di} \) in equilibrium.

\[ \text{NTU}_{av} = \frac{\int_{y_{in}}^{y_{out}} \frac{dy}{y^\ast - y}}{\left( (y_{out} - y_{out}^\ast) - (y_{in} - y_{in}^\ast) \right) / \ln\left( (y_{out} - y_{out}^\ast) / (y_{in} - y_{in}^\ast) \right)} \]

where \( y_{in} \) and \( y_{out} \) are the concentrations of \( \text{SO}_2 \) at inlet and outlet gas stream, respectively, and \( ^\ast \) is the concentration of \( \text{SO}_2 \) in equilibrium.

### 2.5. Use of Different Packings

Table 1 shows the geometric characteristics of the two structured packings, where \( a \) is the corrugated angle with respect to vertical axis of the column, \( n_t \) is the gauze threads number per square foot, \( B \) is the long of the channel flow, \( S \) is the side corrugated wide, \( \theta \) is the corrugated angle, \( \rho_p \) is the packing density, \( \epsilon \) is the void fraction, and \( d_g \) is the geometric area of the packing.

### 3. Results and Discussion

The mass transfer results and \%Re\(_{c}\) are the recuperation percentages like \( \text{SO}_2 \) absorbed or removed in the water presented in Table 3. Table 2 shows experimental data, where \( y_{in} \) and \( y_{out} \) are the inlet and outlet mol fraction concentration, respectively, and the \( \text{SO}_2 \) concentrations were determined by chromatography analysis. The experiments were conducted to loads less than 70% of flood; in this case the resistance to mass transfer is located in gas phase. Equations allow the determination of the quantities, on the basis of which are the efficiencies of the test system. Furthermore the research can be applied for absorption system.

Figure 2 shows the liquid hold-up with respect to the gas capacity factor \( F_v \). If the gas velocity is larger than \( U_V = U_{\text{VLS}} \), the liquid hold-up increases rapidly above the value at the loading point, that is, \( h_L > h_{\text{L,FS}} \) until the flood point is reached, that is, \( h_L = h_{\text{L,FI}} \). At this point, all the liquid is forced upwards by the stream of gas in the bed. The liquid hold-up of \( \text{ININ}18 \) is greater than that of Sulzer BX by 44 to 63\%, depending upon the values of \( \alpha, B, S, \epsilon, \) and \( a_g \). This percentage variation depends on the operation regimen. The angle of inclination of the flow channels \( a \) of \( \text{ININ}18 \) is lower compared to the Sulzer BX; this causes the residence time of liquid phase is greater than the second packing. Figure 3 shows the pressure drop per unit packed height with respect to the gas capacity factor, from 49 to 84.5 \( \text{m}^3/\text{m}^2\text{h} \) of liquid velocity. The Sulzer BX pressure drop per unit packed height is less than \( \text{ININ}18 \) packing. This result is a consequence of their geometry parameters. The Sulzer BX has its maximum flow capacity of 0.83 \( \text{kg}^{1/2}\cdot\text{m}^{-1/2}\cdot\text{s}^{-1} \) (0.927215 \( \text{m/s} \)) and the \( \text{ININ}18 \) at 1.4369 \( \text{kg}^{1/2}\cdot\text{m}^{-1/2}\cdot\text{s}^{-1} \) (1.6051 \( \text{m/s} \)), which is attributed to the difference in the diameter of the columns used, corresponding to 0.07 m and 0.252 m, respectively. Sulzer BX packing generates lower pressure drop compared to \( \text{ININ}18 \). Figure 3 shows liquid flow at \( U_L = 84.5 \) and 82.34 \( \text{m}^3/\text{m}^2\text{h} \), loading zone \( \text{ININ}18 \) at \( F_v = 0.85 \text{kg}^{1/2}\cdot\text{m}^{-1/2}\cdot\text{s}^{-1} (U_V = 0.9495 \text{m}^3/\text{m}^2\text{s}) \), and flooding at 1.3 \( \text{kg}^{1/2}\cdot\text{m}^{-1/2}\cdot\text{s}^{-1} (U_V = 1.45226 \text{m}^3/\text{m}^2\text{s}) \), while Sulzer BX loading zone at \( F_v = 0.62 \text{kg}^{1/2}\cdot\text{m}^{-1/2}\cdot\text{s}^{-1} (U_L = 0.6926 \text{m}^3/\text{m}^2\text{s}) \) and flooding at \( F_v = 0.93 \text{kg}^{1/2}\cdot\text{m}^{-1/2}\cdot\text{s}^{-1} (U_L = 1.0389 \text{m}^3/\text{m}^2\text{s}) \). Although the pressure drop \( \text{ININ}18 \) is greater than that of Sulzer BX, this is not as great as conventional random packings. It is expected that the greater capacity of operation of \( \text{ININ}18 \) is dependent on the geometry of the packing, the porosity, and diameter of column.

Figure 4 shows the volumetric mass transfer coefficient, of \( \text{ININ}18 \) packing, with respect to the gas capacity factor,
whereas Figure 5 presents the global mass transfer unit height with respect to the gas capacity factor. Both graphs show the experimental data as well as the tendency predicted from Billet model [4–6] and equivalent behavior for other mass transfer system [7, 10]. The average deviation between the measured and predicted values is ± 5%.
### Table 3: Mass transfer results.

<table>
<thead>
<tr>
<th>NTUOV</th>
<th>HTUOV [m]</th>
<th>( \beta )</th>
<th>aPh</th>
<th>%Re</th>
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<tr>
<td>3.9048</td>
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<td>0.85</td>
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<td>1.94</td>
<td>99</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2: Liquid hold-up versus the gas capacity factor.

Figure 3: Pressure drop versus the gas capacity factor.

Figure 4: Global mass transfer coefficient versus the gas capacity factor.

Figure 5 shows the trend of lower height per unit of mass transfer, when the gas flow increases. This is the result of the mass transfer efficiency increases with increasing gas flow (Figure 4), promoting the formation of the uniform liquid film on the entire surface of the packing and that the flow channel is sufficiently large to allow a homogeneous mixed phases.

This paper highlights the benefit of identifying and evaluating pressure drop in a \( \text{SO}_2 \)-air-water system; this new way of using existing models can complement the assessments made in an equivalent system as developed by Kuntz and Aroonwilas, [7]; Aroonwilas et al., [10] in the \( \text{CO}_2 \) absorption using MEA, in which they determined mass transfer coefficients through the use of processes, which, although different, are found to be comparable to the process discussed in this paper by trends in the parameters under study.

### 4. Conclusions

(i) The ININ18 packing was higher capacity and lower geometric area than Sulzer BX, due to the type of mesh they were built with, with 18 mesh and 60 mesh, respectively.

(ii) ININ18 packing allowed better distribution of liquid than the Sulzer BX packing on the surface and larger residence time of the liquid on the surface of the packing, as a result of a greater angle of the flow channel about the vertical axis of the column, which increases the separation efficiency.

(iii) The ININ18 packing liquid hold-up was higher than Sulzer BX packing, as a result of the flow channel dimensions and porosity of the last one are lower.
(iv) The pressure drop $\Delta P/H$ generated by the packing ININ18 was greater than the Sulzer BX due to increased liquid hold up $h_L$.

(v) ININ18 packing efficiency was high performance, since the removal of SO$_2$ was obtained, of the gaseous mixture from 97 to 98%. The lower height of a mass transfer unit by the gas side is achieved at higher gas flow.

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References


