Hydrodynamic and Mass Transfer Model Adjusted to Sulphur Dioxide Absorption in Water

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ABSTRACT

In this work we report experimental results at loading points and compare them with hydrodinamic and mass transfer model predictions in order to determine the adjusted parameters and to know the relationship between a two-phase countercurrent flow and the geometry of the bed of the packing column. The bed of the packing is essential for the design of rectification and absorption columns. A study of hydrodynamic processes was carried out in an absorption column of 0.252 metre diameter with stainless steel gauze corrugated sheet packing by means of air-water and SO_2-water systems. The experiment results include capacity, liquid hold-up and composition. The absorption test produced a total of 48 data points. The average deviation between the measured values of liquid hold-up to the predicted values is 3 time higher than the experimental data.

Keywords: Structured packing, SO_2, absorption, hydrodynamic performance.

NOMENCLATURE

Symbol	Process data	Unit
a	surface area per unit packed volume	m^2/m^3
a_g	geometric area of the packing	m^2/m^3
a_{Ph}	interfacial area per unit packed volume	m^2/m^3
B	long of the channel flow	m
C	constant	
d_h	hydraulic diameter	m
D	diffusion coefficient	m^2/s
g	gravitational constant	m/s^2
h_L	liquid holdup	m^3/m^3
HTU	height of a mass transfer unit	m
L	mass flow of liquid	kg/h
m	slope of the equilibrium line	
n	exponent	
n_t	gauze threads number per squared foot	
NTU	number of transfer units	
S	side corrugated wide	m
u	superficial load	m/s
$\tilde{u}$	average effective velocity	m/s
V	mass flow of gas	kg/h
Z	Column total packed height	m

Greek symbols

α	corrugated angle with respect to vertical axis of the column	
β	mass transfer coefficient	m/s
ε	void fraction	m^3/m^3
θ	corrugated angle	$^\circ$
μ	dynamic viscosity	$kg/m\,s$
λ	stripping factor	
ξ	resistance coefficient	
ρ	density	kg/m^3
σ	surface tension	kg/s^2

Subscripts

Fl	flood point
L	liquid
o	overall
S	loading point
V	gas
w	water

1. INTRODUCTION

Atmospheric contamination in cities with a large population is a significant problem. The contamination comes from the burning of heavy oil that releases energy into the atmosphere. The burning of the heavy oil, as a primary source of energy, has high pollution effects due to the formation and expulsion of gases and particles that contaminate the atmosphere. Although new laws control atmospheric contamination, there are no solutions that adapts to each country characteristics [1].

Heavy oil is used in diverse productive activities such as the electric power generation, cements, ceramics, glass and bricks for the construction industry [2].

The main purpose of this paper is the experimental evaluation of the absorption of Sulphur Dioxide in water with high efficiency packings, made in the *Mexican National Institute of Nuclear Research* (ININ) and using hydrodynamic and mass transfer models.

2. MATERIALS AND METHODS

The methodology was divided in two parts: The use of hydrodynamic and mass transfer models to determine the column diameter and height, respectively [3, 4, 5] and the use of one type of packing made by the ININ (for its acronym in Spanish) [6, 7].

Hydrodynamic and mass transfer models

The bed flow is upward for the gas and downward for the liquid. Under stationary conditions, we assume that gravity and shear forces in the liquid film of the density and the dynamic viscosity are in equilibrium at a point representing any given thickness in a coaxial layer within the liquid film, and the frictional force exerted by the vapor of the density acts at the surface of the film. Operating parameters are the liquid load and the gas velocity, which also affects the liquid hold-up. As expected the differential equation solution depends upon the flow pattern.

Up to now, the only equations that were known for calculating mass transfer during two phase countercurrent flow in packed columns were those that apply to the range extending up to the loading point [8].

The gas and liquid streams flow separately through the column below but not above this point. Above it, the shear stress in the gas stream supports an increasing quantity of liquid in the column, with the result that the liquid holdup greatly increases. Finally, at the flood point, the liquid accumulates to such an extent that column instability occurs. Mass transfer in this upper loading range can be described if these fluid dynamic relationships are taken into consideration.

Hydrodynamic model for hazardous and structured packings

A model that describes the fluid dynamic relationships in packed columns with countercurrent flow of the gas and liquid phases was developed in a previous work by Billet and Schultes. It allows the flow conditions to be described up to the flood point. The assumption made was that the void fraction in a bed of packing could be represented by a multiplicity of vertical channels through which the liquid flows downwards in the form of a film countercurrent to the ascending gas stream. This model also permits mass transfer in the loading range up to the flood point to be determined [8].

The liquid hold-up $h_{L,S}$ and the model flow factor ξ_S [9] have been used for the packed columns prediction. The load point is described by the equations:

$$u_{V,S} = \sqrt{\frac{1}{\xi_S}}\left(\varepsilon - h_{L,S}\right)\sqrt{\frac{h_{L,S}}{a_p}}A \tag{1}$$

$$h_{L,S} = \left(12\ \frac{1}{g}\ \frac{\mu_L}{\rho_L}\ u_{L,S}\ a_p^{\,2}\right)^{1/3} \tag{2}$$

$$\xi_S = \frac{g}{C_S^2\left[\frac{L}{V}B\left(\frac{\mu_L}{\mu_V}\right)^{0.4}\right]^{2\,n_S}} \tag{3}$$

Where:

$$A = \sqrt{\frac{\rho_L}{\rho_V}}\ ,\ B = \sqrt{\frac{\rho_V}{\rho_L}}$$

The liquid holdup at the flood point $\mathrm{h}_{\mathrm{L,Fl}}$ must be determined by iteration from Eq. (5) for the mass flow ratio $\frac{L}{V}$ that relates to the problem in question. In this case, the only values of physical significance are those in the $\frac{\varepsilon}{3} \le \mathrm{h}_{\mathrm{L,Fl}} \le \varepsilon$.

$$u_{V,Fl} = \sqrt{2}\sqrt{\frac{g}{\xi_{Fl}}}\ \frac{\left(\varepsilon - h_{L,Fl}\right)^{3/2}}{\varepsilon}\ \sqrt{\frac{h_{L,Fl}}{a_p}}A \tag{4}$$

$$h^3_{L,Fl}\left(3\ h_{L,Fl} - \varepsilon\right) = \frac{6}{g}a_p^{\,2}\ \varepsilon\ \frac{\mu_L}{\rho_L}\ \frac{L}{V}\ B\ u_{V,Fl} \tag{5}$$

$$\xi_{Fl} = \frac{g}{C_{Fl}^2\left[\frac{L}{V}B\left(\frac{\mu_L}{\mu_V}\right)^{0.2}\right]^{2\,n_{Fl}}} \tag{6}$$

The gas stream exerts a strong effect on the liquid holdup above the loading point. The liquid holdup $h_{L,S}$ up to the loading point can be calculated from Eq. (2); and that at the flood point $h_{L,Fl}$ from Eq. (5) [8].

The Eq. (7-11) for calculating the liquid holdup at the loading point and loading capacity and liquid holdup at the flooding point and the flooding capacity are:

$$u_V = 70\% Flooding \;\; u_{V,FI} \tag{7}$$

$$u_L = \frac{L}{V}\frac{\rho_V}{\rho_L}u_V \tag{8}$$

$$h_{L,S} = \left(12\,\frac{1}{g}\,\frac{\mu_L}{\rho_L}\,u_L\,a_p^{\,2}\right)^{1/3} \tag{9}$$

$$h^3_{L,Fl}\left(3\,h_{L,Fl} - \varepsilon\right) = \frac{6}{g}a_p^{\,2}\,\varepsilon\,\frac{\mu_L}{\rho_L}\,\frac{L}{V}\,A\,u_V \tag{10}$$

$$h_L = h_{L,S} + \left(h_{L,Fl} - h_{L,S}\right)\left(\frac{u_V}{u_{V,FI}}\right)^{13} \tag{11}$$

The increase in h_L with the gas load, can be expressed by Eq. (11).

Mass transfer model for structured packings.

The two-resistance model [9] is used, with the assumption of thermodynamic equilibrium at the phase interface. This makes it useful for either rate based or equilibrium stage based computational routines. The basic parameters of the model are the gas (or vapor) and liquid phases mass transfer coefficients β_V, β_L, respectively, and the effective interfacial area a_{Ph}:

$$\frac{a_{Ph,S}}{a} = 1.5\left(a_P d_h\right)^{-0.5}\,\mathrm{Re}_L^{-0.2}We_L^{0.75}Fr_L^{-0.45} \tag{12}$$

Where:

$$\mathrm{Re}_L = \frac{u_L\,d_h}{\mu_L}$$

$$We_L = \frac{u_L^2\,\rho_L\,d_h}{\sigma_L}$$

$$Fr_L = \frac{u_L^2\,\rho_L\,d_h}{\sigma_L}$$

$$\frac{a_{Ph,FI}}{a} = 7\left(\frac{\sigma_L}{\sigma_W}\right)\frac{a_{Ph,S}}{a} \tag{13}$$

$$\frac{a_{Ph}}{a} = \frac{a_{Ph,S}}{a} + \left(\frac{a_{Ph,FI}}{a} - \frac{a_{Ph,S}}{a}\right)\left(\frac{\mathrm{u_V}}{\mathrm{u_{V,FI}}}\right)^{13} \tag{14}$$

$$\tilde{u}_L = \frac{\mathrm{u_L}}{h_L}\left\{1 - \left(\frac{\mathrm{u_V} - \mathrm{u_{V,S}}}{\mathrm{u_{V,FI}} - \mathrm{u_{V,S}}}\right)^2\right\} \tag{15}$$

If $\mathrm{u_{V,S}} \le \mathrm{u_V} \le \mathrm{u_{V,FI}}$

$$\tilde{u}_L = \left(\frac{g\,\rho_V^2\,U_V^2}{12\,\mu_L\,a_p\,\rho_L}\right)^{1/3}\left(\frac{L}{V}\right)^{2/3}\bar{C} \tag{16}$$

$$\bar{C} = 1 - \left(\frac{u_V - u_{V,S}}{u_{V,FI} - u_{V,S}}\right)^2$$

$$\beta_L a_{ph} = C_L\,12^{1/6}\,\tilde{u}_L^{1/2}\left(\frac{D_L}{d_h}\right)^{1/2} a\,F \tag{17}$$

$$\beta_V a_{ph} = C_V\,\frac{1}{\left(\varepsilon - \mathrm{h_L}\right)^{1/2}}\frac{a^{3/2}}{d_h^{1/2}}D_V G^{3/4}E^{1/3}F \tag{18}$$

Where:

$$F = \frac{a_{Ph}}{a},\; G = \frac{\mathrm{u_V}}{a\,\mu_V},\; E = \frac{\mu_V}{D_V}$$

All the constants were determined by the experiments reported in this work, using an absorption column of 0.252 metre diameter with stainless steel gauze corrugated sheet packing, named ININ, by means of the air-water and SO_2-water systems.

The two-film model is based on the number of gas and liquid resistance transfer global units, NTU that are related to the efficiency in terms of the height of a transfer global unit HTU [10, 11, 12].

The column total packed height Z for the gas and liquid are:

$$Z_V = HTU_{OV} * NTU_{OV} \tag{19}$$

$$Z_L = HTU_{OL} * NTU_{OL} \tag{20}$$

The application of the two-film model is frequently used to relate the height of the transfer global unit (HTU_{OV} or HTU_{OL}) with the height of the gas HTU_V and liquid HTU_L transfer units to the absorption:

$$HTU_{OV} = HTU_V + \lambda\,HTU_L \tag{21}$$

$$HTU_{OL} = HTU_L + \frac{1}{\lambda}HTU_V \tag{22}$$

The height of the transfer global units HTU_{OV} is determined through the expression:

$$HTU_{OV} = HTU_V + \lambda NTU_L \tag{23}$$

$$HTU_V = \frac{u_V}{\beta_V a_{Ph}}$$

$$NTU_L = \frac{u_L}{\beta_V a_{Ph}}$$

The quality λ is given by

$$\lambda = m\frac{V}{L} \tag{24}$$

where m is the ratio of the slope of the equilibrium line to the operation line, and $\frac{L}{V}$ is known as the removed factor. The absorption factor is the inverse of λ.

If the gas is highly soluble in the liquid, Henry's constant is small. In this case the liquid-side resistance is negligible. If the gas is relatively insoluble (large Henry's constant), the gas-side resistance becomes negligible in comparison with the liquid-side resistance. The relative magnitude of the individual resistance evidently depends on gas solubility. This explains the common statements that "the liquid side resistance is controlling" in the absorption of a relatively insoluble gas, and the "gas-side resistance is controlling" when a relatively soluble gas is absorbed (or stripped) [13].

Use of the ININ packing

Table 1 shows the geometric characteristics of the ININ structured packing.

Table 1. Geometric characteristic of the ININ structured packing [14].

Packing	ININ	Units
Material	Stainless Steel	
α	35	
n_t	36	
B	0.0165	m
S	0.012	m
θ	45	°
ρ_p	317.1	kg/m^3
ε	0.9633	
a_g	418	m^2/m^3

3. RESULTS

Figure 1 describes the theorical and experimental behaviour of the liquid hold up and the HTU_{OV} for the SO_2-air/water system at 304.16K and pressure of 69.864 kPa. A column of 2.52 m of packed bed height and 0.252m diameter was used. The SO_2 fraction mol of the gas feeding was 0.0012035.

Tables 2, 3 and 4 show adjustment parameters at loading, flooding points and mass transfer behavior between those regimens.

Figure 1 shows the experimental data and liquid holdup and overall height of a mass transfer unit predicted values. The average deviation between the measured values of liquid hold-up to the predicted values is 5 times higher than the experimental data.

At 70% of the flooding point, it was obtained 3.33 meters as an overall height of a mass transfer unit. Increasing such percentage up to 90%, decreases the HTU_{OV} to 0.98m, thus achieving lower heights in the stripping of SO_2.

Table 2. Loading Regimen Adjustment Parameters Obtained.

$u_V = m/s$	$u_L = m/s$	C_S	n_S
1.014285673	0.0234777	20	-0.723
	0.0221484	18.2	-0.723
	0.0183244	16.8	-0.723
	0.0159110	16	-0.723
	0.0136070	14.7	-0.723
	0.0103570	9.4	-0.326
	0.0073521	8.7	-0.326

Table 3. Flooding Regimen Adjustment Parameters Obtained.

$u_V = m/s$	$u_L = m/s$	C_{Fl}	n_{Fl}
1.014285673	0.0234777	15	-0.708
	0.0221484	13.5	-0.708
	0.0183244	12.5	-0.708
	0.0159110	11.7	-0.708
	0.0136070	10.7	-0.708
	0.0103570	9	-0.194
	0.0073521	8.5	-0.194

Table 4. Mass Transfer Adjustment Parameters Obtained.

$u_V = m/s$	$u_L = m/s$	C_L	C_V
1.014285673	0.0234777	1.963	1.02
	0.0221484		
	0.0183244		
	0.0159110		
	0.0136070		
	0.0103570		
	0.0073521		

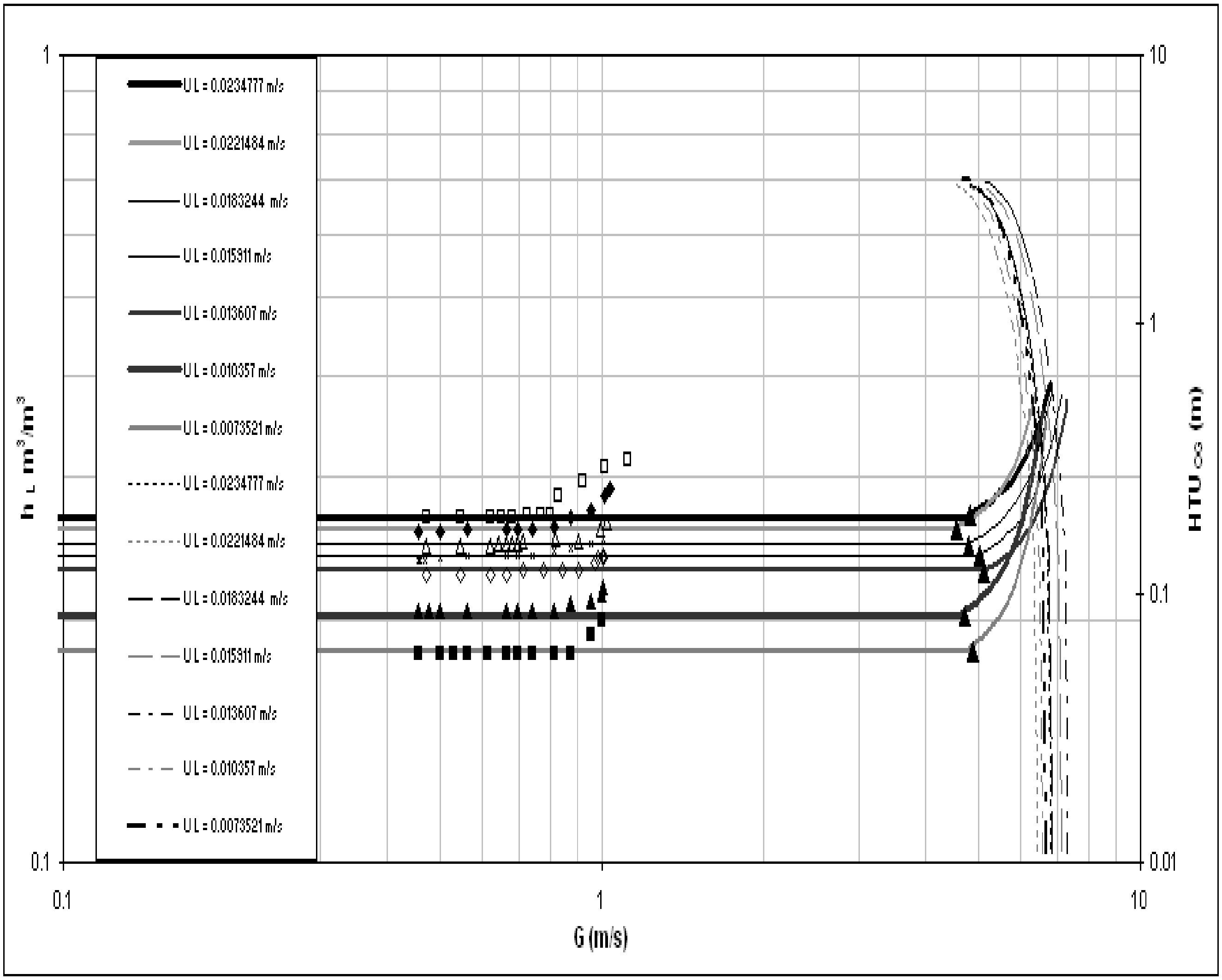

Figure 1. Liquid hold up and mass transfer unit height, versus the gas velocity.

4. CONCLUSIONS

The fluid dynamics and mass transfer description takes 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.

The average deviation between the measured and predicted values is 3 times increased from experimental data.

Considering the results presented in this work, we recommend the ININ packing for SO_2 recovery both it is necessary to increase experimental data.

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