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Determination of mass transfer coefficients for packing materials used in biofilters and biotrickling filters for air pollution control—2: Development of mass transfer coefficients correlations

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Abstract

Correlations that allow determination of gas film mass transfer coefficients ($k_G a_t$, $k_G a_w$) and liquid film mass transfer coefficients ($k_L a_w$) for packing materials used in biofilters and biotrickling filters for air pollution control are presented. Lava rock, polyurethane foam cubes (PUF), Pall rings, porous ceramic beads, porous ceramic Raschig rings, and various compost–woodchips mixtures were used as packing materials. The functionality of gas and liquid velocity on mass transfer coefficients ($k_G a_t$, $k_G a_w$, $k_L a_w$) obtained experimentally (see Part 1 of this paper) was correlated using modified Onda-type equations. The correlation equations helped to better understand the sensitivity of gas and liquid velocities on mass transfer, and the effects of packing wetting. Each packing had a different functionality with gas and liquid velocity and different wetting property, hence different correlation equations were needed for the different packing materials. Most of the fitted data fell within ±20% of the experimental values.

Keywords: Mass transfer; Absorption; Packed-column; Biotrickling filter; Biofilter; Onda correlation; Environmental engineering

1. Introduction

Several correlations have been used to predict gas and liquid mass transfer coefficients in chemical engineering process. For example Sherwood and Holloway (1940) considered only resistance in the liquid film, while the Shulman model (Shulman et al., 1955) and the Onda model (Onda et al., 1968) included both gas and liquid films resistances. Onda's correlations are known for their good fit with experimental data (Roberts et al., 1985) and have been recommended by many chemical engineering handbooks (Perry et al., 1984). However, Onda's correlations were developed from only a few plastic packing materials with limited sizes, which restricted their applicability to a few packings and limited their accuracy to about ±20% (Onda et al., 1968). Thus, several attempts were made to modify and evaluate Onda's correlations in order to expand their applicability, although these efforts focused on plastic packings of different shapes (Djebbar and Narbaitz, 1998; Dvorak et al., 1996). The applicability of such correlations for the determination of mass transfer coefficients in biofilters and biotrickling filters used for air pollution control is uncertain because of the greatly different packing materials and operating conditions. In general, wet scrubbers operate at superficial gas velocities ranging from about 1000 to 10, 000 $m\,h^{-1}$ and liquid velocities ranging from 10 to 150 $m\,h^{-1}$, while air superficial velocities in biofilters and biotrickling filters usually range from 60 to about 1000 $m\,h^{-1}$ occasionally up to 6000 $m\,h^{-1}$, (Gabriel and Deshusses, 2003), while the liquid superficial velocity in biotrickling filters rarely exceeds 10 $m\,h^{-1}$. In Part 1 of this paper, mass transfer coefficients for packings used in biofilters and biotrickling filters were determined experimentally (Kim and Deshusses, 2007). The experimental mass transfer coefficients were markedly different than those predicted by Onda's correlations because Onda's correlations were developed for much higher gas and liquid velocities. Thus, the objective of this study was to propose mass transfer correlation equations to predict the mass transfer coefficients for packings commonly

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used in biofilters and biotrickling filters used for air pollution control.

2. Correlation equation for mass transfer coefficients

Onda's original correlations read as follows:

$$\frac{k_G RT}{a_t D_G} = 5.23\left(\frac{G}{a_t \mu_G}\right)^{0.7}\left(\frac{\mu_G}{\rho_G D_G}\right)^{1/3}(a_t D_p)^{-2.0}, \tag{1}$$

$$k_L\left(\frac{\rho_L}{\mu_L g}\right)^{1/3} = 0.0051\left(\frac{L}{a_w \mu_L}\right)^{2/3}\left(\frac{\mu_L}{\rho_L D_L}\right)^{-0.5}(a_t D_p)^{0.4}. \tag{2}$$

These two equations were used as a starting point to correlate experimental results of gas film mass transfer in biofilters ($k_G a_t$), gas film ($k_G a_w$) and liquid film ($k_L a_w$) mass transfer coefficients in biotrickling filters.

2.1. Correlation equation for gas film mass transfer coefficient ($k_G a_t$) for biofilter packings

In a biofilter, in the absence of free liquid phase, only the mass transfer from the gas phase to the interphase is considered and Eq. (1) was modified as follows: the Reynolds number in Eq. (1) was expressed, and the 5.23 constant and the 0.7 exponent were replaced by C and i_1, respectively, as these are expected to be specific to biofilter packing materials and biofiltration conditions.

$$k_G a_t = C\left(\frac{\rho_G D_p}{\mu_G}\right)^{i_1}\left(\frac{\mu_G}{\rho_G D_G}\right)^{1/3} D_p^{-2.0} D_G U_G^{i_1}. \tag{3}$$

Further, Eq. (3) was rearranged as follows:

$$k_G a_t = C_1 U_G^{i_1}, \tag{4}$$

where

$$C_1 = C\left(\frac{\rho_G D_p}{\mu_G}\right)^{i_1}\left(\frac{\mu_G}{\rho_G D_G}\right)^{1/3} D_p^{-2.0} D_G.$$

All the variables and constants except the gas velocity U_G on the right-hand side of Eq. (3) were included in the constant, C_1. Thus, C_1 depends on the properties of the gas and operating temperature which are usually constant for biofiltration conditions, and on the structure of the packing material, which varies from one packing to the other, but remains constant for experiments with the same packing material.

2.2. Correlation equation for gas film mass transfer coefficient ($k_G a_w$) for biotrickling filter packings

Eq. (1) was multiplied by the wetted area (a_w) and the wetting ratio $\eta = a_w/a_t$ was expressed after Eq. (1) was rearranged.

$$k_G a_w = C\eta\left(\frac{\rho_G U_G D_p}{\mu_G}\right)^{i_2}\left(\frac{\mu_G}{\rho_G D_G}\right)^{1/3}(a_t D_p)^{-2.0}(a_t D_G)a_t. \tag{5}$$

Next, the total surface area (a_t) cancelled out and the equation was rearranged.

$$k_G a_w = C\eta\left(\frac{\rho_G D_p}{\mu_G}\right)^{i_2}\left(\frac{\mu_G}{\rho_G D_G}\right)^{1/3} D_p^{-2.0} D_G U_G^{i_2}, \tag{6}$$

$$k_G a_w = C_2 U_G^{i_2}, \tag{7}$$

where

$$C_2 = C\eta\left(\frac{\rho_G D_p}{\mu_G}\right)^{i_2}\left(\frac{\mu_G}{\rho_G D_G}\right)^{1/3} D_p^{-2.0} D_G.$$

Thus, $k_G a_w$ (Eq. (7)) depended on two parameters: a constant C_2 and i_2 the power index of the superficial gas velocity. C_2 consists of three main groups: the first which depends on the gas properties, the second which is a function of the nominal size of the packing, and the third group which depends on the wetting ratio. Group one was not changed in the mass transfer experiments since air was used and the temperature was kept constant. Group two was not changed for a given packing material. Only group three, the wetting ratio, changed during experiment with various liquid and gas velocities. Thus wetting ratio was the only variable determining C_2 during the experiment where other variables remained constant.

2.3. Correlation equation for liquid film mass transfer coefficient ($k_L a_w$) for biotrickling filter packings

Similarly, Eq. (2) was multiplied by the wetted area (a_w) and the wetting ratio was expressed:

$$k_L a_w = C\eta^{1/3}\left(\frac{\rho_L D_p}{\mu_L}\right)^{i_3}\left(\frac{\mu_L}{\rho_L D_L}\right)^{-0.5} \times D_p^{0.4}\left(\frac{\rho_L}{\mu_L g}\right)^{-1/3} a_t^{7/5} U_L^{i_3}. \tag{8}$$

Eq. (8) was rearranged to

$$k_L a_w = C_3 U_L^{i_3}, \tag{9}$$

where

$$C_3 = C\eta^{1/3}\left(\frac{\rho_L D_p}{\mu_L}\right)^{i_3}\left(\frac{\mu_L}{\rho_L D_L}\right)^{-0.5} D_p^{0.4}\left(\frac{\rho_L}{\mu_L g}\right)^{-1/3} a_t^{7/5}.$$

Eqs. (7) and (9) are somewhat similar in that they consist of three groups. A major difference is that Eq. (9) depends on the liquid property and the total surface area of the packing material. In mass transfer experiments designed to obtain $k_L a_w$ for a given packing, it is only the wetting ratio which changed with the operating conditions; all other parameters remained constant in C_3.

2.4. Mass transfer coefficients data

Gas and liquid film mass transfer coefficients obtained with lava rock, polyurethane foam cubes (PUF), Pall rings, porous ceramic beads, porous ceramic Raschig rings, and various compost–woodchips mixtures were correlated with the above equations. Detailed materials and methods as well as a detailed discussion of the values of these mass transfer coefficients can be found in Part 1 of this paper (Kim and Deshusses, 2007). In short, CO_2 in air was absorbed in caustic water (for biotrickling filter packings) or caustic impregnated packing (for biofilters) to determine k_Ga_w and k_Ga_t, respectively, while absorption of oxygen from air in deaerated trickling water was used to determine k_La_w in biotrickling filters. The gas and liquid superficial velocities were chosen to broadly cover the range of possible conditions in biofilters and biotrickling filters used for air pollution control.

3. Results and Discussion

3.1. Correlation for k_Ga_t in biofilter packings

In order to obtain the parameters C_1 and i_1 specific to each biofilter packing, Eq. (4) was linearized as follows:

$$\log k_Ga_t = \log C_1 + i_1 \log U_G. \quad (10)$$

The results from the linear regressions of Eq. (10) on mass transfer data of compost mixtures and lava rocks are plotted in Fig. 1 and summarized in Table 1. A good correlation coefficient was obtained in all cases, indicating that Eq. (4) had a suitable form for describing k_Ga_t in biofilters. As the fraction of compost in the packing increased, the value of i_1 decreased, while the y-intercept, i.e., $\log C_1$, increased. Mixtures with low compost volume ratios were more sensitive to the gas velocity than mixtures with high compost ratio. This can be explained by considering the porosity resulting from the addition of woodchips into the packing. Woodchips are larger in size than compost and their presence results in larger air channels inside the compost mixture (Cardenas-Gonzalez et al., 1999). Convective mass transfer from the gas to the packing was strongly influenced by the air velocity in these flow channels, an observation consistent with pressure drop data presented in Part 1 of this paper. The only variable not related to gas property in C_1 was the nominal size of the packing D_p, which depended on the volume ratio of compost and woodchips. The higher the compost ratio, the smaller the nominal size of packing. According to the definition of C_1 (Eq. (4)), C_1 is inversely proportional to D_p as long as i_1 does not exceed 2.0, which was the case. Lava rock had higher i_1 and lower C_1 than compost based packings. This is consistent with the fact that lava rock is more porous than compost, hence that it was more sensitive to gas velocity, and to the fact that its nominal size is larger than compost. Overall, Eq. (4) and the i_1 and C_1 parameters listed in Table 1 provide the basis for the estimation of k_Ga_t in a wide range of biofilter packing materials.

3.2. Correlation for k_Ga_w in biotrickling filter packings

In order to determine the parameters for the gas film mass transfer coefficients in biotrickling filters, Eq. (7) was linearized

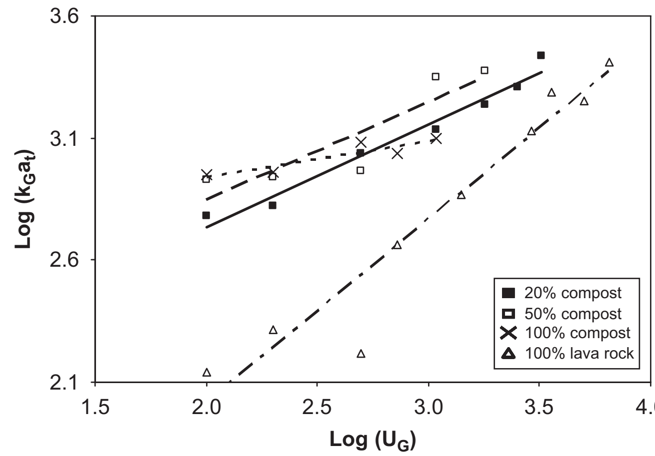

Fig. 1. Linear regression for k_Ga_t in the compost-woodchips mixtures and lava rock.

Table 1
Linear regression of k_Ga_t in biofilter packings using Eq. (10)

Packing material	Linear regression of Eq. (10)		
	i_1	$\log C_1$	R^2
Compost 20%	0.42	1.90	0.97
Compost 50%	0.40	2.05	0.81
Compost 100%	0.15	2.65	0.84
Lava rock	0.75	0.52	0.93

as follows:

$$\log k_Ga_w = \log C_2 + i_2 \log U_G. \quad (11)$$

The results from the regression of Eq. (11) for the five biotrickling filter packing materials are summarized in Table 2. Besides a few exceptions, a good correlation of the data was obtained with Eq. (11). The coefficient i_2 in Eq. (11) represents the functionality of the superficial gas velocity on the mass transfer coefficient, k_Ga_w. Thus comparison of i_2 values between the different packings is warranted. For this, i_2 values at a constant liquid velocity of $6.3\,\mathrm{m\,h^{-1}}$ were chosen. This was the most appropriate liquid velocity because some packing materials had low R^2 at low or high liquid velocities. Lava rock, PU foam and Pall rings had comparable i_2 ranging from 0.24 to 0.29 (average 0.27), but the porous ceramic beads had a 37% higher i_2 while the porous rings had a 37% lower i_2 than the average of i_2 from lava rock, PU foam, and Pall rings. Similarly to the results obtained for the biofilter packings, these results illustrate that i_2 depends on the packing material size and shape. For each packing material, i_2 decreased with increasing the liquid velocity except in two cases: lava rock at $0.1\,\mathrm{m\,h^{-1}}$ which was not linear at all, and the Pall rings at $10\,\mathrm{m\,h^{-1}}$ which exhibited a large i_2 value. As the liquid velocity increased, the wetting area increased until the entire surface area of the packing material was covered by liquid. Thus, at a trickling rate of $0.1\,\mathrm{m\,h^{-1}}$, only a very limited area of packing material was wetted which resulted in low k_Ga_w. On the other hand, at very

Table 2
Linear regression of $k_G a_w$ in biotrickling filter packings using Eq. (11)

Packing material	Linear regression of Eq. (11)			
	Liquid velocity ($m\,h^{-1}$)	i_2	$\log C_2$	R^2
Lava rock	0.1	0.02	2.83	0.03
	6.3	0.24	2.81	0.83
	10	0.14	3.06	0.53
	Average	0.13	2.90	
PUF	0.1	0.31	1.19	0.83
	6.3	0.29	1.93	0.97
	10	0.07	2.75	0.28
	Average	0.22	1.96	
Pall ring	0.1	0.55	0.83	0.97
	6.3	0.28	2.24	0.87
	10	0.37	1.86	0.94
	Average	0.40	1.64	
Porous ceramic beads	0.1	0.46	2.03	0.96
	6.3	0.37	2.72	0.95
	10	0.35	2.78	0.87
	Average	0.39	2.51	
Porous ceramic rings	0.1	0.58	1.47	0.97
	6.3	0.17	2.88	0.97
	10	0.09	3.08	0.33
	Average	0.28	2.48	

high liquid velocity, the large liquid holdup reduced the contact area for mass transfer and reduced the sensitivity to gas velocity.

As shown in Eq. (7), C_2 depended on the wetting ratio, the nominal size of the packing material and the power index, i_2. If nominal size of packing material and power index were fixed, the effect of liquid on wetting could be studied. Thus C_2 values were compared for given packing materials and in order to avoid the influence of i_2, a fixed liquid velocity of $6.3\,m\,h^{-1}$ was used for comparison purpose. The y-intercept ($\log C_2$) represented the wetting ratio. The results are shown in Table 3. With the exception of the porous ceramic rings all the packing materials had increasing C_2 when liquid velocity increased. This indicates that wetting increased as the liquid velocity increased. There was a large increase of the wetting when the liquid velocity increased from $0.1\,m\,h^{-1}$ to $6.3\,m\,h^{-1}$, which proves that wetting is only partial at low liquid velocity as identified by others (Treybal, 1980). A contributing factor may be the difficulty to ensure homogenous liquid distribution at the lowest trickling rates. Once the packing was well wetted, increasing the liquid velocity to over $6.3\,m\,h^{-1}$ did not improve wetting much. However, C_2 for porous ceramic rings did not change at all, most likely because the porous ceramic rings had a high degree of wetting even at the lowest liquid velocity (Kim and Deshusses, 2007). In contrast, experiments conducted with porous ceramic beads made from same material showed that wetting was increasing with increasing liquid velocities at the lower watering rates. Therefore these results suggest that wetting depends not only on the material properties but also on the packing structure.

Table 3
Effect of liquid velocity in linear regression using Eq. (11)

Packing material	Liquid velocity ($m\,h^{-1}$)	i_2	$\log C_2$	% Difference of $\log C_2$[a]
Lava rock	0.1	0.24	2.14	0
	6.3	0.24	2.81	31
	10	0.24	2.75	28
PUF	0.1	0.29	1.27	0
	6.3	0.29	1.93	52
	10	0.29	2.00	57
Pall ring	0.1	0.28	1.82	0
	6.3	0.28	2.24	23
	10	0.28	2.16	18
Porous ceramic beads	0.1	0.37	2.31	0
	6.3	0.37	2.72	18
	10	0.37	2.74	19
Porous ceramic rings	0.1	0.17	2.88	0
	6.3	0.17	2.88	0
	10	0.17	2.85	−1

[a] % Difference=[(log C_2 at liquid velocity−log C_2 at $0.1\,m\,h^{-1}$)/ log C_2 at $0.1\,m\,h^{-1}$] × 100%.

Table 4
Linear regression of $k_L a_w$ in biotrickling filter packings using Eq. (12)

Packing material	Linear regression of Eq. (12)			
	Gas velocity ($m\,h^{-1}$)	i_3	$\log C_3$	R^2
Lava rock	100	0.84	1.23	0.99
	720	0.86	1.29	1.00
	2520	0.84	1.36	0.99
	Average	0.85	1.29	
PUF	100	0.82	0.52	0.98
	720	0.90	0.53	0.99
	4700	0.87	0.56	0.99
	Average	0.86	0.54	
Pall ring	100	0.84	0.63	0.99
	720	0.83	0.67	0.99
	4700	0.82	0.76	0.99
	Average	0.83	0.69	
Porous ceramic beads	100	0.94	1.44	0.99
	400	0.94	1.45	0.98
	720	0.95	1.41	0.97
	Average	0.94	1.43	
Porous ceramic rings	100	0.59	0.99	0.86
	720	0.82	1.34	0.95
	2520	1.03	1.17	0.99
	Average	0.81	1.17	

3.3. Correlation for $k_L a_w$ in biotrickling filter packings

Similar to Eqs. (4) and (7), Eq. (9) was linearized:

$$\log k_L a_w = \log C_3 + i_3 \log U_L. \qquad (12)$$

Results from the regression of Eq. (12) on experimental $k_L a_w$ data for the five biotrickling filter packing materials are summarized in Table 4. Very good correlation coefficients were

Table 5
Universal parameters for mass transfer coefficients (k_Ga_t, k_Ga_w, k_La_w) in biofilters and biotrickling filters (Eqs. (10), (11), (12))

Packing material	i_1	$\log C_1$	i_2[b]	$\log C_2$[c]	i_3	$\log C_3$
Compost mixture[a]	0.32	2.20	–	–	–	–
Lava rock	0.75	0.52	0.19	2.94	0.85	1.29
PU foam	–	–	0.18	2.34	0.86	0.54
Pall ring	–	–	0.33	2.05	0.83	0.69
Porous ceramic beads	–	–	0.36	2.75	0.94	1.43
Porous ceramic rings[d]	–	–	0.13	2.98	0.59	0.99
Porous ceramic rings[e]	–	–	–	–	0.93	1.26

[a]The volume ratio of compost mixture ranged from 20% to 100%.
[b]Average of i_2 at liquid velocity of 6.3 and $10\,\mathrm{m\,h^{-1}}$.
[c]Average of $\log C_2$ at liquid velocity of 6.3 and $10\,\mathrm{m\,h^{-1}}$.
[d]Correlation equation for porous ceramic rings in k_La_w was separated to two equations. This equation was for low gas velocity.
[e]Correlation equation for porous ceramic rings in k_La_w above $720\,\mathrm{m\,h^{-1}}$ gas velocity.

obtained, indicating that Eq. (9) was suitable for the determination of k_La_w in biotrickling filter packings. In general, the value of i_3 was relatively constant and close to 1. This indicates that the effect of the liquid velocity was independent of the gas velocity, as discussed in Part 1 of this paper. It also indicates that k_La_w increased linearly with the liquid velocity. The values of C_3 listed in Table 4 differ from one packing to the other, as expected from the formulation of C_3, but do not vary greatly for a given packing. A detailed examination of Eq. (9) reveals that most terms in C_3 are constant, except for the low functionality with the wetting ratio. Thus, Eq. (9) was very suited to describe liquid film mass transfer coefficients in biotrickling filter packings.

3.4. Universal correlation equation for each packing material

In an effort to obtain single equations to correlate all mass transfer coefficients (k_Ga_t, k_Ga_w, k_La_w) obtained in this study, the parameters for a given packing were averaged. Doing so removes the effect of some factors such as nominal packing size, or wetting ratio, but greatly simplifies the applicability of the proposed mass transfer correlations. The results are presented in Table 5 for k_Ga_t in biofilters, k_Ga_w in biotrickling filters and k_La_w in biotrickling filters.

The effect on lumping several correlations was lower than initially thought. For example, the average variation of the logarithm of k_Ga_t was between $\pm 1\%$ and $\pm 3\%$, and between $\pm 1\%$ and $\pm 7\%$ for k_La_w. In the case of ceramic porous rings, a single correlation could not fit all the k_La_w data, because of the marked effect of gas velocity. Thus, two correlation equations were proposed depending on gas velocity.

A summary of the observed and fitted values of k_Ga_w and k_La_w using the universal correlations is presented in Figs. 2 and 3. The figures show that a good fit was obtained using the various correlations with a vast majority of the fitted data falling within $\pm 20\%$ of the experimental value. This is the same uncertainty reported for the original Onda's correlations, and could be expected here from the heterogeneity of the packings and large range of operating conditions covered by the correlations.

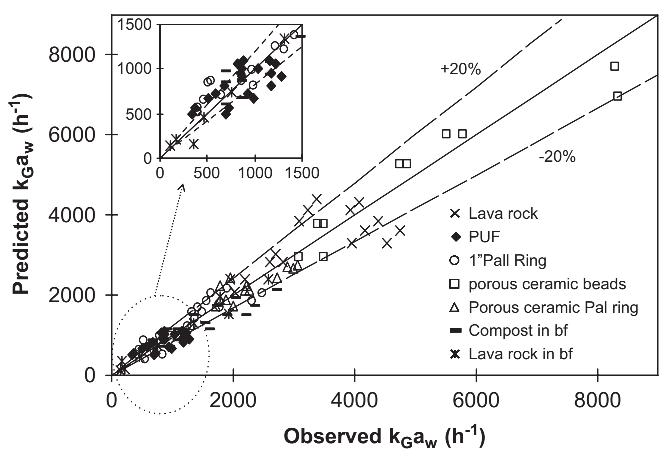

Fig. 2. Comparison of correlation results and experimental data for gas film mass transfer coefficient (k_Ga_w in biotrickling filter, k_Ga_t in biofilter).

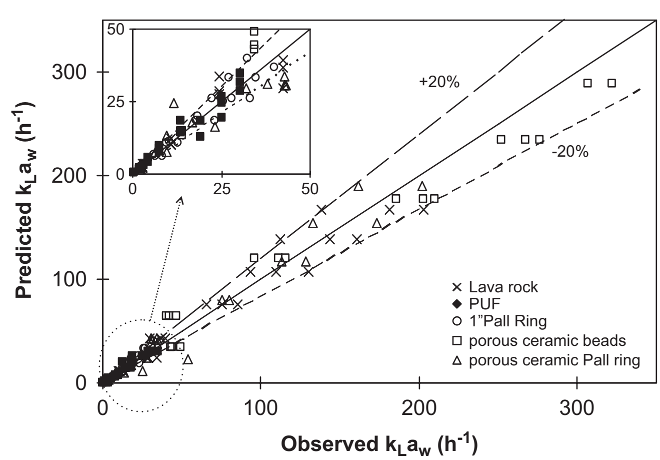

Fig. 3. Comparison of correlation results and experimental data for liquid film mass transfer coefficient (k_La_w).

Lastly, the mass transfer coefficients obtained experimentally and using Onda's correlations and those proposed herein are compared for Pall rings at two different conditions in Table 6. The mass transfer coefficients of other packings could

Table 6
Comparison of k_Ga_w and k_La_w for Pall rings determined by Onda's model, the current correlations, and determined experimentally

Gas	Liquid	Onda's equation			Calculation by present model		Experimental result	
$m\,h^{-1}$	$m\,h^{-1}$	Wetting	k_Ga_w (h^{-1})	k_La_w (h^{-1})	k_Ga_w (h^{-1})	k_La_w (h^{-1})	k_Ga_w (h^{-1})	k_La_w (h^{-1})
3000	6.3	0.28	4760	502	1580	23	1500	25
5000	6.3	0.28	6790	502	1870	23	2300	25

not be compared similarly because key parameters (e.g., nominal diameter of the packing) are not known. Examination of the data in Table 6 reveals that Onda's correlations overestimate k_Ga_w by a factor of about 3, and k_La_w by a factor of about 20. This discrepancy validates the needs for the mass transfer correlations proposed in this paper.

4. Conclusions

Correlation equations for the determination of gas and liquid film mass transfer coefficients for packings and conditions specific for biofilter and biotrickling filter used for air pollution control were developed based on Onda et al. (1968) mass transfer correlations and fitting of experimental results. The correlations allowed obtaining the functionality of k_Ga_t, k_Ga_w, and k_La_w with the gas and liquid velocities. Because of the variety of packings that was used, each packing material had different correlation; however, the correlations adequately fitted experimental data. It is likely that such correlations will find application in modeling and design of biofilters and biotrickling filters used for air pollution control.

Notation

a_t	total specific surface area, $m^2\,m^{-3}$
a_w	wetted specific surface area, $m^2\,m^{-3}$
C	constant in Onda correlation equation
C_1	constant in correlation equation for k_Ga_t in biofilter
C_2	constant in correlation equation for k_Ga_w in biotrickling filter
C_3	constant in correlation equation for k_La_w in biotrickling filter
D_G	diffusivity in gas phase, $m^2\,h^{-1}$
D_L	diffusivity in liquid phase, $m^2\,h^{-1}$
D_p	nominal size of packing material, m
g	gravitational constant, $m\,h^{-2}$
G	superficial mass velocity of gas, $kg\,m^{-2}\,h^{-1}$
i_1	power index of Reynolds number for k_Ga_t in biofilter
i_2	power index of Reynolds number for k_Ga_w in biotrickling filter
i_3	power index of Reynolds number for k_La_w in biotrickling filter
k_G	gas film mass transfer coefficient in Onda correlation, $kmol\,m^{-2}\,h^{-1}\,atm^{-1}$
k_Ga_t	gas film mass transfer coefficient in biofilter, h^{-1}
k_Ga_w	gas film mass transfer coefficient in biotrickling filter, h^{-1}
k_L	liquid film mass transfer coefficient, $m\,h^{-1}$
k_La_w	liquid film mass transfer coefficient in biotrickling filter, h^{-1}
L	superficial mass velocity of liquid, $kg\,m^{-2}\,h^{-1}$
R	gas constant, $m^3\,atm^{-1}\,mol^{-1}\,K^{-1}$
T	absolute temperature, K
U_G	superficial gas velocity, $m\,h^{-1}$
U_L	superficial liquid velocity, $m\,h^{-1}$

Greek letters

η	wetting ratio, $a_wa_t^{-1}$
μ_G	viscosity of gas phase, $kg\,m^{-1}\,h^{-1}$
μ_L	viscosity of liquid phase, $kg\,m^{-1}\,h^{-1}$
ρ_G	density of gas phase, $kg\,m^{-3}$
ρ_L	density of liquid phase, $kg\,m^{-3}$

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