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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 $\mathrm{m\,h^{-1}}$ and liquid velocities ranging from 10 to 150 $\mathrm{m\,h^{-1}}$, while air superficial velocities in biofilters and biotrickling filters usually range from 60 to about 1000 $\mathrm{m\,h^{-1}}$ occasionally up to 6000 $\mathrm{m\,h^{-1}}$, (Gabriel and Deshusses, 2003), while the liquid superficial velocity in biotrickling filters rarely exceeds 10 $\mathrm{m\,h^{-1}}$. 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:

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

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

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.

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

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

$$k_G a_t = C_1 U_G^{i_1}, \quad (4)$$

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.

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

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

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

$$k_G a_w = C_2 U_G^{i_2}, \quad (7)$$

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:

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

Eq. (8) was rearranged to

$$k_L a_w = C_3 U_L^{i_3}, \quad (9)$$

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