Influence of relative air/water flow velocity on oxygen mass transfer in gravity sewers

Lucie Carrera, Fanny Springer, Gislain Lipeme-Kouyi and Pierre Buffiere

ABSTRACT
Problems related to hydrogen sulfide may be serious for both network stakeholders and the public in terms of health, sustainability of the sewer structure and urban comfort. H2S emission models are generally theoretical and simplified in terms of environmental conditions. Although air transport characteristics in sewers must play a role in the fate of hydrogen sulfide, only a limited number of studies have investigated this issue. The aim of this study was to better understand H2S liquid to gas transfer by highlighting the link between the mass transfer coefficient and the turbulence in the air flow and the water flow. For experimental safety reasons, O2 was taken as a model compound. The oxygen mass transfer coefficients were obtained using a mass balance in plug flow. The mass transfer coefficient was not impacted by the range of the interface air-flow velocity values tested (0.55–2.28 m·s⁻¹) or the water velocity values (0.06–0.55 m·s⁻¹). Using the ratio between $k_{L,i}$ to $k_{L,H_2S}$, the H2S mass transfer behavior in a gravity pipe in the same hydraulic conditions can be predicted.

Key words | air velocity, hydraulics, hydrogen sulfide, mass transfer coefficient, reaeration

NOTATION

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<tr>
<td>a</td>
<td>specific surface</td>
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<tr>
<td>C(z)</td>
<td>oxygen concentration</td>
<td>mol/m³</td>
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<tr>
<td>C₀</td>
<td>equilibrium concentration</td>
<td>mol/m³</td>
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<td>d</td>
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<tr>
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<td>compound i diffusivity coefficient</td>
<td>m²/s</td>
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<tr>
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<td>hydraulic diameter</td>
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<tr>
<td>E_z</td>
<td>axial dispersion coefficient</td>
<td>m²/s</td>
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<tr>
<td>Fr</td>
<td>Froude number</td>
<td>-</td>
</tr>
<tr>
<td>g</td>
<td>standard gravity</td>
<td>m/s²</td>
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<td>h</td>
<td>water height in the canalization</td>
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<td>k_{L,i}</td>
<td>compound i mass transfer coefficient</td>
<td>m/h</td>
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<tr>
<td>u</td>
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<tr>
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<td>axial distance along the canalization</td>
<td>m</td>
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<tr>
<td>δ</td>
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<td>°</td>
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<tr>
<td>μ</td>
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<tr>
<td>ρ</td>
<td>density</td>
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<tr>
<td>σ²</td>
<td>variance of the distribution</td>
<td>s²</td>
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INTRODUCTION

The appearance of gaseous hydrogen sulfide (H2S) causes multiple problems in sewer networks. The most serious issues are the corrosion of metal and concrete in the canalization, the toxicity of the gas and the odor nuisance. Hydrogen sulfide is produced in anaerobic conditions in the liquid phase, but its impact is only effective after transfer into the gas phase. It is thus important to know the influence of different flow conditions on the liquid to gas mass transfer. Because of safety issues, the liquid/gas transfer of H2S cannot be easily studied in laboratory experiments. However, there are similarities between the gas transfer of oxygen and that of hydrogen sulfide (Jensen & Hvitved-Jacobsen 1991). The mass transfer ratio $k_{L,i,H_2S}/k_{L,O_2}$ can therefore be deduced from the diffusivity ratio $D_{H_2S}/D_{O_2}$. 

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(Liss & Slater 1974; Hvitved-Jacobsen 2002), according to Equation (1).

\[
\frac{k_{L H_2S}}{k_{L O_2}} = \left( \frac{D_{H_2S}}{D_{O_2}} \right)^n
\]

In this expression, \( n \) is not well defined from a theoretical point of view. Experimentally, \( n \) is about 1 in a sewer with a laminar flow and close to 0.5 under turbulent flow conditions. The diffusion coefficient ratio is assumed to be between 0.72 and 0.89, with a mean arithmetic value of 0.87 (Hvitved-Jacobsen 2002; Yongsiri et al. 2003).

Similarly to many dissolved gases, the mechanism of \( H_2S \) transfer is assumed to be controlled by the mass transfer in the liquid film. In gravity pipes, the diffusion layer in the liquid film depends on the turbulence intensity. It is therefore impacted by the pipe slope and the wall characteristics (Lahav et al. 2004, 2006a).

Lahav et al. (2006b) also evidenced the influence of turbulent conditions, expressed with the velocity gradients, on the \( O_2 \) mass transfer phenomenon in gravity sewers and completely mixed tanks.

In open channel flows, a high slope (>1%) and high velocity conditions result in a high volume/area ratio exposed to the atmosphere and in a decrease of the interface thickness, enhancing the transfer process. At low water velocity (\( u < 0.8 \text{ m s}^{-1} \)), the residence time is higher. The turbulence is also low, so thicker biofilms may grow. Sulfur production and concentration in the liquid phase are therefore enhanced, whereas the liquid-gas transfer is restricted (Santry 1965).

The concentration of \( H_2S \) in the gas phase has an impact on the emission rate via the saturation concentration \( C_{i,L}^a \), influenced by the movement of the air phase along the sewer (Yongsiri et al. 2003). Smith & Watts (1994) showed an increase in odor emissions as wind velocity increased in a tunnel system where an emission source of cattle waste was placed. With insufficient ventilation, \( H_2S \) (density 1.18) will accumulate in the vicinity of the liquid-gas interface and limit the transfer flux. For simplification purposes, the impact of the gas phase concentration on the transfer is often neglected. The aeraulic conditions govern the gradient concentration and the turbulence phenomena at the liquid-gas interface.

The results reported in the literature on this topic are contradictory. Argo et al. (1999) noted that the \( k_L \) appeared to be independent of the wind velocity in a velocity range between 0.1 and 0.5 m/s, while Schmidt & Bicudo (2002) considered that the \( H_2S \) concentration was dependent on the wind speed ranging from 0.14 to 2.1 m/s. Using the WATER9 model for the \( k_L \) calculation, Santos et al. (2012) showed that the volatilization of hydrogen sulfide was approximately constant at low speed, i.e. when the friction velocity is lower than 0.3 m s\(^{-1}\), from investigations on quiescent liquid surfaces under laboratory conditions in a wide range of air velocity values [0.5–4.5 m/s]. In the three above-mentioned studies, experiments were respectively performed in a convective emission chamber (Argo et al. 1999) and in wind tunnels (Schmidt & Bicudo 2002; Santos et al. 2012) in which \( H_2S \) emission rates from a tank simulating the area source were measured. In these experimental devices, the emission rates did not result from a continuous liquid flow, as is mostly the case in sewer networks. Therefore, interactions between hydraulic and aeraulic flow conditions were not examined.

The main aim of the present work was to study the effect of air turbulence on the oxygen liquid/gas coefficient in an experimental system reproducing a common real-scale geometry in sewer pipes. The experimental device was designed so as to investigate the interactions between aeraulic conditions, hydraulic conditions and mass transfer: the influence of the air velocity on the liquid flow and the oxygen mass transfer coefficient was studied. Investigations were performed in an experimental gravity pipe under controlled hydrodynamic and aeraulic conditions in a wide range of air wind velocities [0.55–2.28 m s\(^{-1}\)], and typical values of liquid flow velocity [0.06–0.55 m s\(^{-1}\)] likely to trigger \( H_2S \) production and emission in gravity pipes. From the values of the oxygen mass transfer coefficient, \( H_2S \) mass transfer coefficient values were deduced.

**MATERIALS AND METHODS**

**Experimental setup**

Experiments were carried out in a 10 m long PVC sewer pipe with an internal diameter of 0.2 m (Figure 1). The sewer slope was fixed on a rig with an adjustable incline at 0.3%. The water was pumped from a continuously mixed 2,000 L water tank into the pipe. The pumping flow rate was adjusted by a frequency controller (Mitsubishi E500). A flow meter (Rosemount 8732 E) measured the water velocity between the pump and the pipe entry. A second pump was set up (MAPRO CL 12/21G) to control inlet air flow. In the pipe, the oxygen concentration was measured continuously by oxygen probes at four points. The measuring device (Mettler Toledo easySense O\(_2\) 21 Oxygen Sensor) was installed in the bottom of the pipe.
Ten small windows were opened on the pipe surface, in order to measure the air velocity with a hot wire anemometer in the gas phase.

**Experimental procedure**

**Hydrodynamic conditions**

The water flow velocities ranged from 0.06 to 0.55 m/s, corresponding to Reynolds numbers from 6,641 to 35,146. These hydrodynamic conditions have been shown to promote H₂S formation in sewer pipes (Santry 1965).

The controlled and monitored initial parameters were the water flow rate and the initial dissolved oxygen concentration in the tank. In open surface gravity pipes, flow characterization consists of: (i) checking the steady flow pattern; (ii) determining the flow conditions (velocity, hydraulic diameter, etc.); (iii) evaluating the turbulence level (different flow patterns may appear in the liquid phase such as turbulent or laminar, subcritical or supercritical flow); (iv) studying the flow (plug flow or an axial dispersion flow).

Turbulence was characterized via Reynolds and Froude numbers:

\[
Re = \frac{\rho U_{\text{water}} d_m}{\mu} \quad (2)
\]

\[
Fr = \frac{U_{\text{water}}}{\sqrt{gd_m}}. \quad (3)
\]

In the literature, Re < 2,000 corresponds to a laminar flow, 2,000 < Re < 4,000 to a transient flow and Re > 4,000 to a turbulent flow.

Concerning the Froude number, if Fr < 1, the flow is subcritical, i.e. the mean velocity of the flow is smaller than the speed of the surface waves. Physically, a ripple of a wave could move downstream as well as upstream. For Fr > 1, the flow is supercritical.

Under any flow condition, in a cylindrical pipe, the specific surface \(a\) and the hydraulic diameter \(d_m\) can be determined via the pipe diameter (d) and the \(\delta\) angle with the expression (Equations (4) and (5)):

\[
d_m = 4 \times \frac{1}{0.2\delta} \times \frac{d^2(\delta - \sin \delta \cos \delta)}{4} \quad (4)
\]

\[
a = \frac{d \sin \delta}{100 \times S} \quad (5)
\]
Table 1 gives the hydrodynamic conditions tested in the present study.

The flow pattern can be determined with the Peclet number, defined as the ratio of the convective transport to the dispersion transport flux (Equation (6)):

$$Pe = \frac{l_{4u_{\text{water}}}}{D}$$  \hspace{1cm} (6)

The Pe number enables the importance of axial dispersion (backmixing) to be evaluated, assuming that:

- $Pe \to \infty$, then $D \to 0$: for an ideal plug flow, the Peclet number is close to infinity and the diffusivity coefficient is close to zero. More generally, a plug flow is assumed when $Pe > 100$.

- $Pe \to 0$, then $D \to \infty$: when the Peclet number is low, a dispersion transport regime is considered.

To calculate the Peclet number of the liquid flow in the experimental pipe, the residence time distribution was characterized by analyzing the response function after a tracer impulse was injected at the pipe inlet. A sodium chloride solution (325 g/L, CAS number 7647-14-5 ROTH) was used as a tracer, and its concentration was detected with a conductimeter. Typically, a plug flow system would release all tracer molecules within the same short period of time and the peak would be very distinct and thin. According to the Danckwerts conditions, for a boundless reactor with injection in the inlet, the Peclet number can be calculated from Equation (7), where $\sigma$ is the dimensionless variance of the dispersion response function.

$$\frac{8}{Pe^2} + \frac{2}{Pe} + \sigma^2 = 0$$  \hspace{1cm} (7)

All measurements were made at least in triplicate.

Air flow characteristics

The inlet interface air velocity ranged from 0.55 to 2.28 m/s, the maximum circulation likely to occur in sewer pipes. In the experimental device, the air circulation was co-current with the water flow.

After checking the steady flow regime, the air velocities were measured with a hot wire anemometer (Thermoanemometer V100, Kimo, France) in order to draw the air flow profiles. The experimental uncertainty of the anemometer was $\pm 0.05$ m/s for air velocities less than 3.0 m/s.

The air velocity was controlled at the pipe inlet. The air flow injection was characterized by determining the mean air flow velocity on the pipe height along the pipe length and drawing the air profile at the pipe inlet. The air profiles were rebuilt at the pipe outlet, i.e. 7 m after the pipe inlet, and compared with the measurements at the pipe inlet. To ensure that a fully developed flow was measured, the first measurement spot was beyond the developing length of the liquid flow.

In a cross-section, the velocity profiles were mapped with a ten-point measurement every centimeter from the interface up to the highest point in the pipe.

Reaeration procedure

The measurement of the $O_2$ mass transfer coefficient was based on the conventional re-oxygenation method (ASCE 2003; Capela et al. 2004). The experimental procedure consisted of depleting the $O_2$ content in the tank by adding an adequate amount of sulfite ($Na_2SO_3$, CAS 7757-83-7) and 1 mg/L of Cobalt ($CoSO_4$, CAS 10026-24-1), i.e. the amount of sulfite needed to decrease the oxygen concentration by about 0.06 mg/L. The initial concentration was not null so as to avoid an excess of sulfites. Steady-state was reached after a few minutes (Figure 2, left picture). Averaged steady-state values of oxygen concentrations were used to calculate the mass transfer coefficient according to the method described in the previous section (Figure 2). The saturated oxygen concentration $C^*$ was taken from the Winkler table.

Oxygen-depleted water was then pumped into the pipe. The in-depth dissolved oxygen was measured every second at four locations along the pipe.

Air velocities (0.55; 2.28 m/s) were experimented at four water velocities (0.06; 0.14; 0.20 and 0.55 m/s).

All $k_{L}$ measurements were made at least in triplicate.
Data interpretation and oxygen transfer coefficient calculation

The oxygen transfer coefficient was determined according to the two film theory (Liss & Slater 1974). In plug flow conditions, the mass balance equation for oxygen can be written as:

$$\frac{\partial C}{\partial t} + u \frac{\partial C(z)}{\partial z} + k_{L,a}(C(z) - C^*) = 0$$  \hspace{1cm} (8)

The mass balance equation for oxygen in a horizontal open-channel flow can be written as Equation (9), in which radial dispersion is neglected:

$$\frac{\partial C(z)}{\partial t} + u \frac{\partial C(z)}{\partial z} - E_Z \frac{\partial^2 C(z)}{\partial z^2} + k_{L,a}(C(z) - C^*) = 0$$  \hspace{1cm} (9)

where $C(z)$ is the oxygen concentration, $u$ the liquid velocity and $E_Z$ the axial dispersion coefficient (m$^2$s$^{-1}$), $z$ being the horizontal coordinate. Axial dispersion can be advantageously represented by the dimensionless Peclet number for dispersion (Equation (10)):

$$Pe = \frac{u \times L}{E_Z}$$  \hspace{1cm} (10)

In this equation, $L$ is the total length of the pipe (in our case, it was considered as the distance from the water inlet to the last oxygen probe). If the steady-state is reached for oxygen concentration all through the pipe, Equation (3) can be integrated as:

$$\frac{C(z)}{C^*} = \left(\frac{C(z=0)}{C^*}\right) \times \exp\left[\frac{Pe - \sqrt{Pe^2 + 4Pe(k_{L,a}u)/L}}{2} \times z\right]$$  \hspace{1cm} (11)

This expression was then used to plot $\ln((C(z) - C^*)/(C(z=0) - C^*))$ as a function of the distance $z$. A linear relation was obtained, and the slope $SL$ of the straight line was used to find the value of the mass transfer coefficient $k_{L,a}$:

$$k_{L,a} = u \left(\frac{SL^2 \times L}{Pe} - SL\right) = u \left(\frac{SL^2 \times E_Z}{Pe} - SL\right)$$  \hspace{1cm} (12)

Since the Peclet number (or the axial dispersion coefficient) was required to calculate the $k_{L,a}$, axial dispersion was obtained from tracer tests. In practice however, the experiments were performed at high Peclet numbers, which means that the pipe behaved as a plug-flow system. The integration of Equation (3) in plug-flow at steady-state leads to Equation (13):

$$C(z) - C^* = (C(z=0) - C^*) \times \exp\left(-\frac{k_{L,a}u}{u} \times \frac{z}{L}\right)$$  \hspace{1cm} (13)

In this case, the logarithmic plot used was more straightforward and the mass transfer coefficient was obtained as:

$$k_{L,a} = -SL \cdot u$$  \hspace{1cm} (14)
The saturated oxygen concentration \( C^* \) was taken from the Winkler table. The \( k_{La} \) measurements were corrected for a temperature of 20 °C, according to Equation (15) (Jensen 1995).

\[
k_{La}(20°C) = k_{La}(T) \cdot 1.047^{(T-20)}
\] (15)

RESULTS AND DISCUSSION

Hydrodynamic conditions

First, the Peclet number was calculated using the residence time distribution and plotted versus the liquid flow rate (Figure 3). It is logically expected that a decreasing liquid velocity will increase the residence time as well. Therefore, for slow water velocities, the response function is wider and more diffuse than for fast water velocities. The limit for the validation of the plug flow hypothesis is usually set by \( Pe = 100 \). Figure 2 shows that, with a slope of 0.5%, most Peclet values are found underneath this limit (57% of all tested velocities). For a water velocity of 0.59 m/s, the Peclet number is 115 and for a water velocity of 0.55 m/s, the Peclet number was calculated as 105. Considering the experimental uncertainty, the plug flow was ascertained for all hydraulic conditions between 0 and 0.55 m/s.

The highest liquid velocity fulfilling the plug flow conditions in the experimental device was selected: 0.55 m/s. With this hydraulic flow, the Reynolds number was 35,146, characterizing a turbulent flow and the Froude number was 0.70, showing a subcritical flow.

Air velocity effect on oxygen transfer coefficient

On eight measurement locations, the air profile was reconstituted. The inlet profile at \( z = 0 \) m was systematically compared to the outlet one at \( z = 7 \) m, and the data analysis showed that the shape of the air profile did not change significantly, with a variation of less than 15% measured (results not shown).

At the pipe outlet (\( z = 7 \) m), the air profile for a given mean inlet air velocity between 0.55 and 2.28 m/s was investigated. Figure 4 presents the air profiles from various inlet air velocities. First, the comparison between the inlet air mean velocity and the outlet air mean velocity calculated from the experimental measurement did not exhibit a significant variation (below 15%), confirming the permanent air flow. Secondly, Figure 3 shows that with an increasing air velocity the shape of the air profile becomes parabolic.

This might indicate that the air velocity is lower near the water surface (2 cm above the liquid/gas surface) and the pipe walls (10 cm above the liquid/gas surface), due to the boundary layers.

Figure 5 plots the oxygen mass transfer coefficient versus the relative velocity, i.e. the difference between the interfacial air and liquid velocities. The measured values

![Figure 3 | Peclet number for the tested velocities.](https://iwaponline.com/wst/article-pdf/75/7/1529/453588/wst075071529.pdf)
show a considerable scatter, ranging between 0.22 and 0.25 m/h for a respective relative velocity of 0 and 1.2 m/s.

In this work, the experimental characteristic depicts a slight increase in the oxygen transfer coefficient with the relative velocity increase (Figure 5). Although this increase is noticeable, it is within experimental error. In light of these results, it can be considered that the O₂ transfer coefficient is not significantly influenced by the air flow.

Furthermore, these values are in the same order of magnitude, but about 5 times higher than the values mentioned in the literature for winds between 1 and 3 m/s, though literature results also show a considerable scatter (Garbe et al. 2007). This discrepancy could be due to outdoor site measurements, where interface flow patterns may significantly differ for a given mean wind speed.

Yongsiri et al. (2004) found that \( k_{L,H_2S} \) was proportional to the \( k_{L,O_2} \) and was independent of the turbulence. Consequently, the trend displayed in Figure 5 would be the same for the \( H_2S \) mass transfer rate in the same hydraulic and aeraulic conditions.

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**Figure 4** | Air profiles for water velocity of 0.55 m/s.

**Figure 5** | Oxygen transfer coefficient as a function of the relative velocity (\( \nu_{water} = 0.55 \) m/s).
As a result, the aeraulic conditions are negligible for future models representing $k_L$ in the range of air velocities (0.55; 2.28) m/s, for a fully developed and turbulent flow with a water velocity of 0.55 m/s.

Nevertheless, the influence of the air velocity on the concentration gradient in the air phase remains effective, and the air renewal engendered by the flow turbulence is still an influencing factor for the transfer rate enhancement. Therefore, modeling the air phase to predict the liquid-gas mass transfer rate remains relevant.

Otherwise, for aeraulic flow velocities higher than 2.58 m/s, the approach using surface renewal should be envisaged (Garbe et al. 2007).

**Extended hydrodynamic conditions**

The hydraulic conditions tested were extended so as to extrapolate the results to other liquid flow characteristics (below 0.55 m/s, considering the intended application of this work). Figure 6 shows air profiles at the pipe inlet (dashed lines) superimposed on the air profiles at the pipe outlet (solid lines), measured with a constant water velocity ranging from 0.06 to 0.55 m/s, corresponding to Reynolds numbers from 6,641 to 35,146. These hydrodynamic conditions were shown to promote H$_2$S formation (Santry 1996). The inlet interface air velocity was 0.55 to 2.28 m/s.

Many tested inlet air velocities are depicted in Figure 6. As previously detailed, the air velocity profiles were plotted versus the height in the pipe atmosphere.

Figure 6 evidences the boundary zones at the pipe walls, where the air velocity decreases rapidly 2 cm before the pipe wall (10 cm above the liquid-gas interface). These boundary effects cause an unsteady velocity shape near the pipe walls, for the highest air velocities tested. Boundary effects are also observable at the interface, where a slight entrainment effect of the air flow by the liquid flow can be noticed for low inlet air velocities.

Figure 6 also shows that the comparison of the air velocity profile measured at the pipe outlet with the air velocity profile at the pipe inlet exhibits a variation of $-6\%$ to $+12\%$ for the local velocities. Consequently, for the water velocities experimented here (0.06 to 0.55 m/s), the air profiles are not significantly affected by the liquid flow rate.

Nevertheless, this observation must be qualified, since a sharp difference was noticed between the face inlet velocity value and the measured value at the pipe inlet. This discrepancy, which grows with the inlet air velocity and becomes significant in the hydraulic condition of a 0.55 m/s flow rate, may be due either to boundary pipe wall effects or to an immediate influence of the liquid flow rate on the air flow: at the liquid velocity of 0.55 m/s, the liquid flow rate hinders the air velocity by up to 25%. This speed decrease may be induced by the shear stress exerted by the liquid phase, keeping in mind that the difference between the phase densities is significant. Since the shear stress increases when the liquid superficial velocity increases, this trend would be enhanced at higher liquid velocities (Pan et al. 2015).

Figure 5 shows that the mean $kLO_2$ value for the water velocity of 0.55 m/s exhibited the highest variation for a relative velocity of 1.2 m/s, even though it was within experimental error. From these conclusions, it is suspected that there is a threshold value of relative velocity beyond which the mass transfer coefficient is significantly affected by interface phenomena. Indeed, for a given water rate, the entrainment and pressure-drop increase with air mass rate (Wicks & Duckler 1959), thereby increasing the interface turbulent phenomena intensity. By increasing the gas flow rate, the
thickness of the liquid boundary layer decreases, enhancing the mass transfer flux (Lioumbas et al. 2005).

To conclude, the comparison between the inlet and the outlet air velocities showed a variation ranging from –6 to +12% of the inlet air velocity versus the water flow velocity. The influence of the highest water flow velocity experimented (0.55 m/s) is in this range of values and was shown to cause no significant impact on the $k_L$ measured values (Figure 5). It can therefore be assumed that for all the lower water velocities investigated, the liquid-gas mass transfer coefficient would be unchanged. Consequently, the previous conclusions (3.2) are extended to the experimental range of values (0.06; 0.55) m/s for the water flow velocity, equivalent to Reynolds numbers (6,641; 35,146).

CONCLUSIONS

The aim of this work was to measure the gas-liquid oxygen mass transfer coefficient ($k_L$) in a free surface gravity pipe under different air and water flow conditions, in the conditions of a fully developed, turbulent and subcritical liquid flow. By studying the residence time distribution in the pipe, plug flow was confirmed and applied to calculate the oxygen transfer coefficient. The oxygen transfer coefficient varied between 0.216 and 0.247 m/h, which is equivalent to 0.186 and 0.213 m/h for the H2S transfer coefficient with the interfacial relative velocity. This leads to the conclusion of the same effect on the H2S transfer coefficient with the air velocity is hindered and at the liquid-gas interface, inlet velocity (0.55; 2.28) m/s, the air profiles were shown not to be affected significantly by the liquid flow rate, except in the boundary layer zones. At the pipe walls, the air velocity is hindered and at the liquid-gas interface, from a threshold value of relative velocity, the liquid flow may have an influence on the air flow rate.

The influence of the highest water flow rate experimented (0.55 m/s) on the air profile was found to be equivalent to other flow rates tested. An increase in the air flow velocity for a given water flow rate of 0.55 m/s was shown not to cause any significant impact on the $k_L$ values. It can therefore be assumed that for all the lower water velocities investigated, the liquid-gas mass transfer coefficient would be unchanged.

More generally, with a view to modeling the complex processes related to H2S emission in sewer networks, provided that the interface aeraulic and hydraulic velocities are within (0.55; 2.28) m/s and (0.06; 0.55) m/s respectively, the effect of aeraulic conditions on the $k_L$ modeling may be reasonably neglected in this range of hydraulic conditions.

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REFERENCES


Lahav, O., Sagiv, A. & Friedler, E. 2006a A different approach for predicting $H_2S(g)$ emission rates in gravity sewers. Water Research 40 (2), 259–266.


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