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## Study of the Transfer of CO<sub>2</sub>-H<sub>2</sub>O Mass in an Aquarium under the Influence of one Oscillating Railing

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**ABSTRACT:** The mass transfer at the level of an interface gas-liquid is an important phenomenon in numerous industrial and environmental processes. Its speed depends strongly on characteristics of the flow in a very fine region situated directly under the interface. In this study, a controlled turbulence is generated by means of an oscillating railing device and characterized by PIV (Particle Image Velocimetry). Techniques of PLIF (Planar Laser Induced Fluorescence) and PIV are applied in the region close interface to describe the turbulence and the phenomena of mass transfer there. A strong three-dimensional flow and an influence marked with the turbulence on the profiles of field of concentration of the CO<sub>2</sub> and the coefficient of mass transfer are observed.

**KEYWORDS:** Mass transfer, molecular distribution, CO<sub>2</sub> dissolution, KL calculates.

### I. INTRODUCTION

The mass transfer at the level of the interfaces of the oceans and the atmosphere influences the climate, because it controls the abundance in the atmosphere of gases as carbon dioxide, which have much meteorological importance. The diphasic flows are common in numerous industrial applications such as the chemical industry, the energy production and the decontamination (water purification, the CO<sub>2</sub> capture). The example in an airlift for the microalgae culture, before the CO<sub>2</sub> cannot be consumed during the photosynthesis, it must be dissolved in the form of bicarbonate and of dissolved CO<sub>2</sub>. This stage of the gaseous phase transfer towards the liquid phase must be optimized to limit the CO<sub>2</sub> losses in the atmosphere. The performance of these systems depend, thus, partially on the mass transfer between both phases. The prediction of transfer by the codes of calculation is necessary to optimize these installations. But the creation of models reflecting the reality requires a better understanding of the phenomena which govern it as the influence of the form of the interface and the system of the flow.

The objective of this work is to set up a bench test enable to study at the same time the transfer of mass gas-liquid by the techniques of PLIF (field of concentration) and PIV the field of speed in the case of an interface gas settles (liquidates) in the presence of a turbulence in a tank shaken by an oscillating railing.

### II. THEORY OF MASS GAS-LIQUID TRANSFER

The mass transfer between two phases gas-liquid is governed by the molecular distribution in the interface, but the transport by turbulence in the gas or in the liquid can have a not insignificant influence. This mass transfer is controlled by the characteristics of the turbulence in the liquid [1] and also by the characteristics of the deformations

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of the interface under the effect of the moving gas [2]. The establishment of mass transfer models requires then a good fundamental understanding of the physics of these processes. The sources of turbulences can be thus included in three main families (Figure. 1). The turbulence in the gaseous phase as that of the wind over the oceans, the lakes or the rivers. But that in the liquid, created by shearing of a flow in bottom of channel, as it is the case for rivers or agitated tanks. But there is also a turbulence of convective origin, created by the difference of temperature between the free surface and the bottom.

Often, when the speed of the gas is between 3 and 8 m/s it is a turbulence in this phase which is responsible of the transfer of mass. However, for the lower speeds, the turbulence in the liquid phase is dominant [3]. It is the action of this type of turbulence, which is examined, in the current study.

The molecular distribution is the main actor of the mass transfer in the interface gas-liquid, it is given by the Fick law, connecting the flow mass of a solution and the gradient of the concentration of the solution.

$$\underline{j} = -D\underline{\nabla}C \quad (1)$$

Where:

$\underline{j}$  : Flow of mass

$D$ : Coefficient of distribution

$C$ : Concentration in solution

$\underline{\nabla}C$  : Gradient of concentration in solution

Let us consider the equation of total mass transport and let us suppose not insignificant the turbulence, the unidirectional flow of mass (eq.2) is subdivided into term of molecular distribution and transport bound to the turbulence. The latter corresponds to the correlation combining the fluctuations in concentration in CO<sub>2</sub> and in speed of the fluctuations in speed.

$$j = -D \frac{\partial \bar{c}}{\partial z} + \overline{c'w'} \quad (2)$$

The characterization of the mass transfer often results from the coefficient of mass transfer  $K_L$  (eq.3) [1]. This coefficient can be influenced, at the same time, by the degree of interface contamination and by the complex interactions between the molecular distribution and the process of turbulent exchange near the interface.

$$K_L = \frac{J}{\nabla C} = \frac{J}{C_{sat} - C_b} \quad (3)$$

Where:

$k_L$  : Coefficient of transfer

$C_{sat}$  : Concentration of saturation in CO<sub>2</sub>

$C_b$  : Concentration of CO<sub>2</sub> in bottom of tank

In the case of a not contaminated interface, Lewis and Whitman [4] consider that it is possible to decompose this coefficient into two terms:

$$\frac{1}{K_L} = \frac{1}{k_L} + \frac{1}{H_c K_G} \quad (4)$$

Where:

$k_G$  : Coefficient of transfer in the gas

$H_c$  : Henry's constant appropriate to the gas

The coefficient  $k_L$  characterizes the transfer in liquid phase;  $k_G$  characterizes the transfer in gaseous phase. Gases as O<sub>2</sub> and CO<sub>2</sub> have a low solubility in the water, and by consequence, a constant of high Henry ( $H_G$ ). It implies that the term

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$1 / ((Hc. k_G))$  is not important, the resistance in the transfer of the side gas is low. Furthermore, the coefficient of distribution  $D$  of the  $CO_2$ , is around  $0.142 \times 10^{-4} \text{ m}^2/\text{s}$  in air and  $2 \times 10^{-9} \text{ m}^2/\text{s}$  in water. The resistance in the liquid phase thus control the transfer through the interface, the transfer which is also strongly influenced by the hydrodynamic conditions form the liquid side. To understand well the phenomena of transfer. It is classical in this case to concentrate on the turbulence in the liquid below the interface. The transfer evolves according to the distance in the interface. When the superficial tension and the gravity are relatively rather big to prevent a significant deformation of the interface, the superficial tension plays the role of a wall which prevents the whirling structures from getting closer to the interface unless a distance equal to their scale of length. It pulls a decrease of the vertical fluctuating speed at the level of the interface. So, if the whirling structures do not penetrate into the interface gas-liquid, any transport by turbulence disappears, in the immediate boundary of the interface and molecular broadcasting is the only mechanism of transport. If we admit in this case, if in the interface, the fluctuation in the vertical speed is nil ( $w_0 = 0$ ), the coefficient of mass transfer spells.

$$K_L = - \frac{D(\partial \bar{C} / \partial z)_{z=0}}{c_{sat} - c_b} \quad (5)$$

Where  $(\partial \bar{C} / \partial z)_{z=0}$  is the gradient of concentration below the interface, along the vertical direction  $z$ . It is also the tangent in the profile of concentration liquid side as closely as possible to the interface (Figure. 2). By introducing  $\delta_D$  the thickness of the layer of distribution defined by:

$$\delta_D = \frac{c_{sat} - c_b}{(\partial \bar{C} / \partial z)_{z=0}} \quad (6)$$

The coefficient of transfer can spell [4]:

$$K_L = \frac{D}{\delta_D} \quad (7)$$

The purpose of this study is often to arrest the physics of these phenomena which control the process of absorption of  $CO_2$  in an environment dominated by a turbulence generated by cutting in the liquid phase. Then this leads to reconsider the equation (7) to take into account the turbulence. The reserved experience consists in studying the transfer in the interface gas-liquid in a tank shaken by an oscillating railing. The fields of speed and concentrations are simultaneously explored by means of the PIV and the PLIF [5]. To determine the relationship that exist between the hydrodynamics in the liquid phase and the coefficient  $K_L$ .

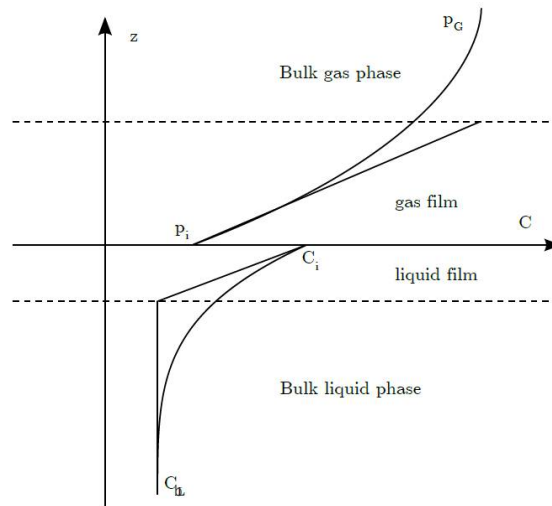


Figure 1: Coat limits to the interface gas-liquid [3]

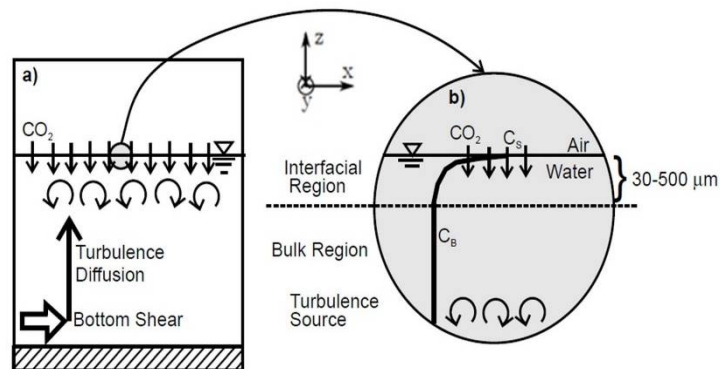


Figure 2: Transfer of mass in the interface gas-liquid (a); Transfer bound to the turbulence (b): Transfer in the interface and the layer limits the liquid side [3]

### III. EXPERIMENTAL DEVICE

#### 1. Turbulence

The bench test is constituted of a tank with internal dimension of  $277 \times 277 \times 550 \text{ mm}^3$ . The tank is composed of Plexiglas to allow the visualization of the flow. The generation of turbulence in the liquid phase is ensured by an oscillating railing of stitch  $M=35 \text{ mm}$  and a thickness of bar  $d=7 \text{ mm}$  what gives a solidity  $\sigma=36\%$  meeting the criteria of Hopfinger and Toly [6]. The interest of this device is the possibility of studying the transfer and the turbulent transport in the presence of a turbulence controlled, in big and small-scale, in an easily explorable flow and an unlimited time of observation.

#### 2. Techniques of laser measuring (PLIF and PIV)

For the PLIF measures, the concentration in  $\text{CO}_2$  is determined from the luminous intensity emitted by the fluorescéine sodium [7]. This fluophore was selected because of its sensibility in the pH, its fluorescence is inhibited when the pH

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decreases, what happened when the CO<sub>2</sub> is dissolved in the water [7]. The tank is filled with demineralized water and  $5 \times 10^{-7} \pm 0, 1 \text{ \% mol / L}$  of fluorescéine sodium. The experimental device uses a source laser Argon, a generator of tablecloth established by a filter pass-band (488 nm) corresponding to the wavelength of excitement of the fluorescein sodium

The acquisition of the high-frequency images PLIF is made through a camera DALSA Falcon 1.4 M HG monochrome connected to a card PCI and piloted by LABVIEW.

But to make the coupled acquisition PIV-PLIF, the shooting is made through a dubber of images combined in an objective 50 mm. This dubber of image LaVision allows projecting a pair of images PLIF-PIV on the sensor of the camera. A first image is obtained after passage through a filter pass-band ( $\lambda = 488 \text{ nm}$ ) to determine the field of speed by PIV. For the second image, a filter pass-top ( $\lambda = 515 \text{ nm}$ ) is used to allow to pass only the fluorescent light for the obtaining of the field of CO<sub>2</sub> concentration by the PLIF technique. The treatments of these images are realized by the software Davis 8.1.

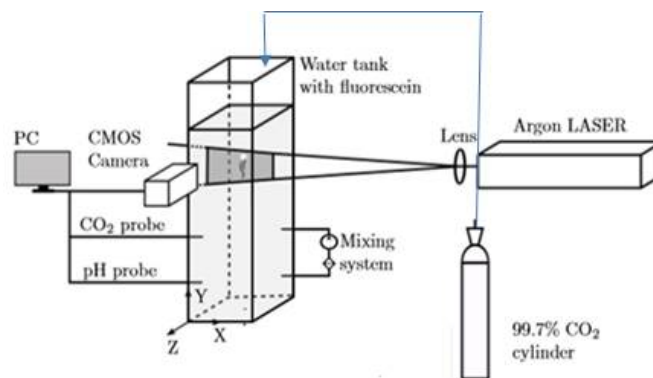


Figure 3: experimental Dispositive

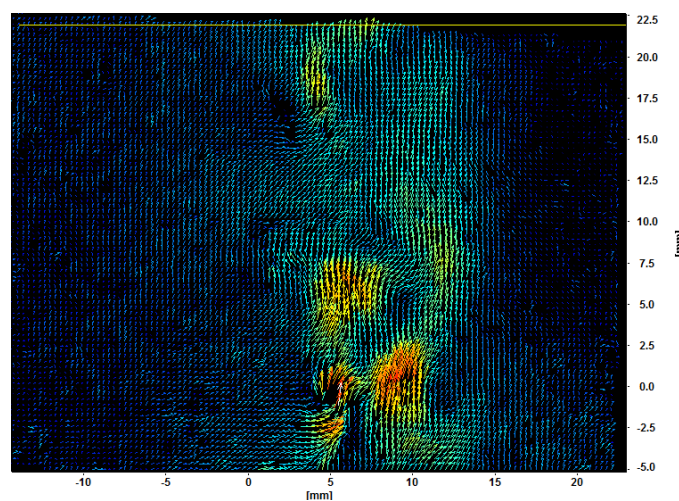


Figure 4: Fields of CO<sub>2</sub> speed

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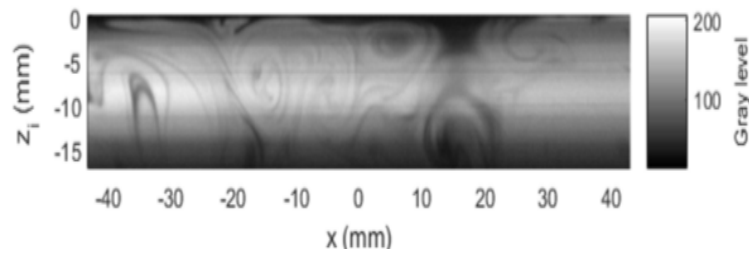


Figure 5: Fields of CO<sub>2</sub> concentration

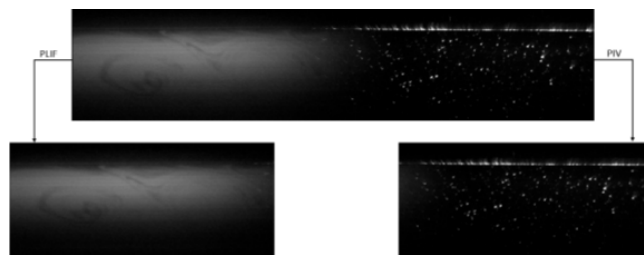


Figure 6: Fields of speed and concentration in coupled CO<sub>2</sub>

## IV. RESULTS AND DISCUSSIONS

For the fields of speed (Figure.4), it was proved that, for a frequency of oscillation given by the railing, the various characteristics been of the turbulence are comparable with those described by [6] and [7]. Two types of structures are observed: the jets and the trails. The jets are directly created by the openings of the railing trained by bars. Trails were formed above and below the railing. The importance of the jets and the trails depends on the geometry of the railing. If the solidity of the railing is important, the jets have an important role in the creation of the turbulence far from the railing. If the solidity of the railing is low and close to 36 %, as the case of the current study, the turbulence is created by the interactions between trails. That's why the intensity of the turbulence at the level of bars is superior to that at the level of openings. So, the jets and the trails return in interaction and the turbulence spreads in the tank. A turbulence without cutting with a very low horizontal variation appears to a sufficient distance of the railing. The vertical distribution of the turbulence can be bound to the characteristics of the railing, exactly to the frequency of oscillation, the amplitude of oscillation, the size of the stitch or the distance enters the center of 2 consecutive bars and the distance the interface gas-water (Figure. 7). Then we can establish the respective relations for the fluctuations in horizontal and vertical speed:

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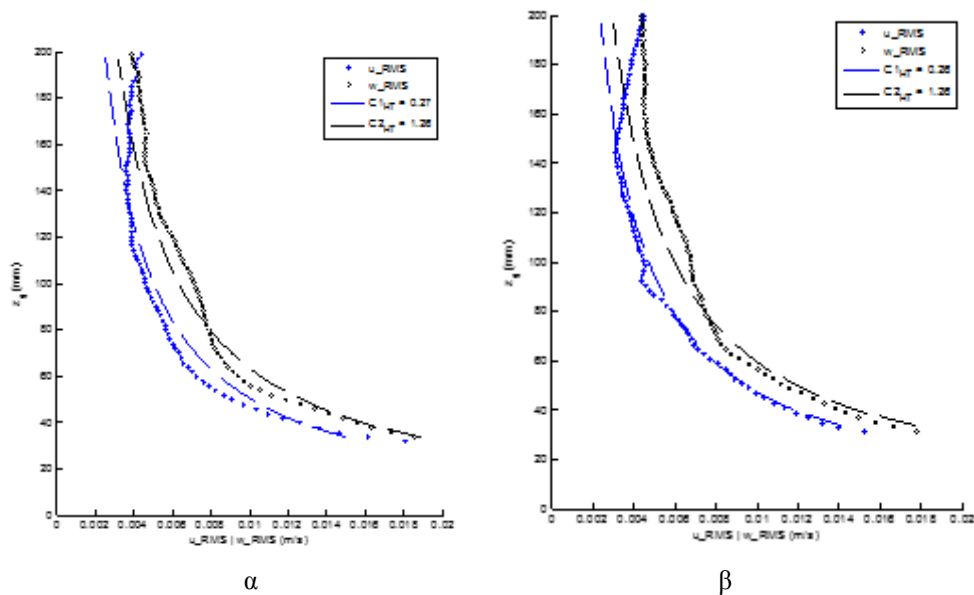


Figure 7: Decrease of the fluctuations in speeds above bars ( $\alpha$ ), of a stitch ( $\beta$ )

$$u'_{HT} = C1_{HT} \cdot f \cdot S^{1.5} \cdot M^{0.5} \cdot z_g^{-1} \quad (8)$$

$$w'_{HT} = C2_{HT} \cdot u'_{HT} \quad (9)$$

In the middle of the tank, the values of  $C1_{HT}$  and  $C2_{HT}$ , according to RMS profile of the fluctuations in speeds averaged (Fig. 7), are comparable to those expressed in [6].

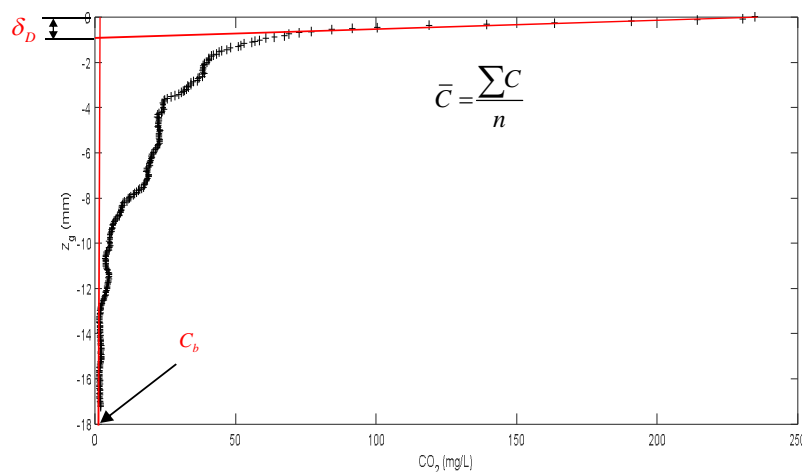


Figure 8: Average Profile of concentration

The field of concentration of  $CO_2$  is shown on the (Figure: 8) and represented in level of grey. The color black corresponds to the regions of concentration raised in  $CO_2$  and the light gray to a low concentration. At the approach of



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the interface, a thin coat corresponds to the limit diffusionnelle coat, which is very fine. Beyond, the concentration in CO<sub>2</sub> quickly decreases, the images are dominated by a clear color corresponding to a low concentration in CO<sub>2</sub> in the region affected permanently by the turbulence generated by the oscillating railing. Indeed, the presence of regions of strong concentration corresponding to the CO<sub>2</sub> pulled towards the bottom by the whirling structures, it is the phenomenon of coat.

These remarks prove that the waste of the turbulence has an effect determining in the transfer of gas through the interface gas-water. The speed in which the CO<sub>2</sub> is transported through the interface where the liquid is in turbulent movement is determined by the thickness reached by the viscous limit layer. Under the action of the turbulence and which speed the turbulent structures replace the liquid loaded in CO<sub>2</sub> near the surface by some liquid with low content in CO<sub>2</sub>. From the immediate fields (fig. 5), fields averaged in time are deducted and an average profile on all the width of the tank was calculated (Fig. 8). The thickness of the limit layer can be deducted according to the equation 6.

$$\delta_D = \frac{C_{sat} - C_b}{\left. \frac{\delta c}{\delta z} \right|_{z=0}} \quad (10)$$

In this study, the saturating concentration not being reached, the thickness of the limit layer can be also defined as the intersection enters the gradient of average concentration the interface and C<sub>b</sub>=2,092 mg. L<sup>-1</sup>, the concentration in bottom of tank measured by a probe pH positioned in bottom of tank (Figure 8). From the data presented on the figure 8, the thickness of the limit layer is  $\delta_D = 0.64$  mm. It was possible to go back then to the coefficient of transfer of mass K<sub>L</sub> from the equation (7):

$$K_L = \frac{D}{\delta_D} = 2,98 * 10^{-6} \text{ m. s}^{-1} \quad (11)$$

### V. CONCLUSION

Through to the implementation of simultaneous measures by PIV and PLIF, it was possible to determine the fields of speed and concentration to the interface gas-liquid under the influence of a turbulence engendered by an oscillating railing. The influence of the parameters such as the frequency and the amplitude of oscillation on the diminution of the turbulence are in accordance with the literature. The field of concentration of CO<sub>2</sub> allows to distinguish two zones, one located close to the interface corresponds to the diffusionnelle coat where the concentration in CO<sub>2</sub> is maximal. The second expecting up to the bottom of the tank, the turbulent structures are at the origin of the training of the CO<sub>2</sub> far from the interface. In addition, other analyses allow to go back to the thickness of the coat of the coat diffusionnelle and in the coefficient of transfer of mass gas-liquid K<sub>L</sub>. A finer analysis should afterward allow to go back up at the end of the turbulent flow it  $c'w'$ .

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