OATAO is an open access repository that collects the work of Toulouse researchers and makes it freely available over the web where possible.

This is an author’s version published in: http://oatao.univ-toulouse.fr/24104

Official URL: https://doi.org/10.1021/acs.jchemed.8b00898

To cite this version:

Any correspondence concerning this service should be sent to the repository administrator: tech-oatao@listes-diff.inp-toulouse.fr
Using the “Red Bottle” Experiment for the Visualization and the Fast Characterization of Gas–Liquid Mass Transfer

Nicolas Dietrich,* Kritchart Wongwailikhit,† Mei Mei,‡ Feishi Xu,† Francisco Felis,∥ Abderrahmane Kherbeche,§ Gilles Hébrard,† and Karine Loubière∥

†Laboratoire d’Ingénierie des Systèmes Biologiques et des Procédés LISBP, CNRS, INRA INSA, Université de Toulouse, Toulouse 31077, France
‡Department of Environmental Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand
§International Center for Applied Mechanics, State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi’an Jiaotong University, Xi’an 710049, People’s Republic of China
∥Laboratoire de Génie Chimique LGC, Université de Toulouse, CNRS, INPT, UPS, Toulouse 31077, France

Supporting Information

ABSTRACT: This paper presents a demonstration of the visualization and the characterization of gas–liquid mass transfer in a small bubbly column. The aim is to show how simple experiments can be used to directly quantify mass transfer without the need of sophisticated probes or complex titrations. The method here proposed is based on the “red bottle” reaction, i.e., the reversible oxidation by oxygen of dihydroresorufin to red resorufin. This reaction produces a distinctive red color, and in the specific condition identified, the time required to turn from colorless to red solution can be directly correlated with the inverse of the volumetric mass transfer coefficient $k_L a$ (s$^{-1}$). Therefore, this reaction can be used to estimate the mass flux of oxygen transferred from the gas phase (bubbles) to the liquid phase and to study how this flux is affected by geometrical and operating parameters of bubbly flows. The lab work described is thus very convenient for education purposes. This is the first visual demonstration allowing mass transfer to be quantified with good precision, opening up a wide range of applications.


INTRODUCTION

The “blue bottle” experiment, in which a transparent liquid turns blue when shaken and becomes colorless when left at rest, is a very popular reaction for both demonstration purposes and practical work in educational activities. It requires three chemicals: glucose, sodium hydroxide, and methylene blue (dye) in water. The origins of this experiment are not well-known. The first references to reactions between sugar and this dye (synthesized by Heinrich Caro in 1876) date back to the 1920s. The name “Blue Bottle Experiment” was first popularized by Campbell in 1963 who demonstrated the occurrence of a 4-step reaction scheme between glucose, dissolved air (oxygen), and dye, and proposed a global equation of the reaction of glucose and air with the dye, regenerated in the reaction system, as a catalyst. Many variations and modifications of the pioneer experiment have been put forward. Researchers proposed the use of other sugars and dyes to achieve different reaction rates and colors or a “green” version based on the use of vitamin and avoiding the use of sodium hydroxide. Some of these systems can be implemented to display other colors, like the “red bottle” experiment, sometimes called the “Vanishing Valentine”, involving resazurin, or a sequence of three colors yellow/red/green called the “multicolored bottle” using indigo carmine. These reactions have been used as an interesting activity on reaction mechanism identification. Recently, alternative compositions have been proposed by adding benzoin in the liquid phase in order to catalyze the reaction, and

DOI: 10.1021/acs.jchemed.8b00898
suggested other molecules as the dye: safranin (red), phenanthrenequinone (orange), erioaglaucine (light blue), and tetrazolium chloride (red). This reaction has been largely used as a demonstration, but recently, some authors have used it as an accurate tool to characterize the mass transfer at the gas–liquid interface in chemical engineering systems. The first works devoted to mass transfer around bubbles flowing in a millimetric channel have been reported in refs 15−19. Later, the mass transfer was studied in a thin gap cell and in a bubbly column. Thanks to a specific calibration procedure and by considering a simple mass balance in the liquid phase, the oxygen flux transferred and the gas–liquid mass transfer coefficients could be quantified in different types of systems. However, all these studies have required expensive high-speed or high-resolution image acquisition systems and specific, heavy image processing that are quite impossible to implement in a chemistry lab for students. Recently, a simple demonstration has been proposed to illustrate the gas–liquid mass transfer in a stirred tank at different scales; for that, they have used the “blue bottle” reaction to visualize the rate of mass transfer and how this rate was affected by the size of the vessel, the air flow rate, and the rotational speed. The time required to obtain a steady color change could be analyzed and discussed in relation with the classical gas–liquid mass transfer correlations in order to illustrate the effects of the operating conditions. These authors did not note that this time could also be directly linked to the overall gas–liquid mass transfer coefficient, and that a direct and simple calculation would be possible if the “red bottle” experiment was used instead of the “blue bottle” thanks to its faster kinetic properties.

The objective of the present paper is to propose a demonstration that enables the gas–liquid mass transfer to be visualized and, with the observation of the color change from colorless to red, the overall gas–liquid mass transfer coefficient to be determined. For illustrative purposes, this is applied in a small bubble column where bubbles are generated by sparging.

**PRINCIPLE**

This method is performed with the reaction system involving resazurin with sodium hydroxide and glucose in a small bubbly reactor (250 mL). In bubbly reactors, aeration provides a perfect mixing to the liquid phase (i.e., the concentration is uniform in the liquid phase); then, on the basis of an oxygen mass balance in the liquid phase, one can write

$$\varphi_{O_2} = \frac{dC_{m,O_2}}{dt} = E_k \cdot \frac{dC_{m,O_2}}{dt}$$

with \(\varphi_{O_2}\) being the mass flux of oxygen transferred per unit of volume in g/s/m³, \(C_{m,O_2}\) the mass concentration of oxygen in g/m³, \(E_k\) the volumetric gas–liquid mass transfer coefficient in s⁻¹, \(E\) the enhancement factor, and \(C_{m,O_2}\) the oxygen saturation concentration in g/m³.

In this study, a chemical reaction involving resazurin with sodium hydroxide and glucose in a small bubbly reactor (250 mL) has been considered. This reaction is fast (typically few milliseconds): the concentration of oxygen, \(C_{m,O_2}\) remains always null (\(C_{m,O_2} = 0\)) as it is instantly consumed by the dye (dihydrosorubin). Some authors have also demonstrated that the enhancement factor, \(E\), is equal to 1 in the classical bubble column condition (namely, when liquid-side mass transfer coefficients \(k_L\) are about \(10^{-4}\) m/s, see the Supporting Information). As shown in eq 2, 2 mol of dye react with 1 mol of oxygen:

$$O_2 + 2\text{dihydrosorubin (colorless)} \rightarrow 2\text{resorufin (pink/red)} + 2H_2O$$

As a consequence, and because no oxygen is present in the liquid at the beginning, one can write

$$\frac{dC_{O_2}}{dt} = \frac{1}{2} \frac{dC_{\text{colored dye}}}{dt}$$

(3)

Here, \(C_{O_2}\), \(C_{\text{colored dye}}\) and \(C_{\text{colored dye}}\) are, respectively, the molar concentrations in oxygen, dihydrosorubin (colorless), and resorufin (colored) in mol/m³. By coupling eqs 1 and 3, the following equation is obtained:

$$\frac{1}{2} \cdot \frac{dC_{\text{colored dye}}}{dt} = k_{\text{L}} \cdot \frac{C_{m,O_2}^*}{M_{O_2}}$$

(4)

With integration of eq 4 from \(t = 0\) to time \(t\), the following equation is deduced:

$$k_{\text{L}} \cdot \frac{C_{m,O_2}^*}{M_{O_2}} = \frac{1}{2} \cdot \frac{dC_{\text{colored dye}}}{dt}$$

(5)

with \(M\) being the molar mass (either of oxygen or dye) in g/mol and \(C_{m,O_2}^*\) the dye concentration in g/m³. When all the colorless reactant (dihydrosorubin) is consumed (complete conversion), the solution reaches its maximum color intensity, corresponding to a concentration where the red dye (resorufin) is equal to the initial concentration of the colorless dye (dihydrosorubin), namely, \(C_{m,O_2}^* = C_{m,O_2}^\text{initial}\). In such conditions, it becomes possible to calculate the volumetric gas–liquid mass transfer coefficient directly from the knowledge of the initial concentration of dye and the measured aeration time, as illustrated in eq 5. To make the calculation easier, the initial concentration of the dye could fulfill the following condition:

$$C_{m,O_2} = \frac{2M_{dye}}{M_{O_2}} \cdot C_{m,O_2}^*$$

(6)

With \(M_{dye} = 229.19\) g/mol, \(M_{O_2} = 32\) g/mol, and \(C_{m,O_2}^* = 8.15\) mg/L, this concentration then corresponds to \(C_{m,O_2} = 116.7\) mg/L or \(C_{m,O_2} = 0.51\) mmol/L. In this specific condition, the calculation of the volumetric gas–liquid mass transfer is equal to the inverse of the coloration time as

$$k_{\text{L}} = \frac{1}{t_{\text{coloration}}}$$

(7)

It can be noted that this concentration is only recommended for an easy and direct calculation of the mass transfer coefficient (eq 7); the concentration of the dye can indeed be increased in order to make the experiment longer, thus increasing the precision of the measurement. The concentration can also be reduced in order to reduce the cost of the experiments.

It is interesting to observe that this experiment is very close to the sulfate static method classically used for the measurement of the mass transfer coefficient. In the latter method, for a given aeration time, the sodium sulfite (Na₂SO₃) reacts with the oxygen transferred into the liquid phase by the bubbles generated. The concentration of the remaining sulfite is determined by the iodometric method (oxidation of sulfate...
by iodine, and titration of excess iodine by sodium thiosulfate). As the initial oxygen concentration is kept at zero (nitrogen flushing), \( k_{a1} \) is then calculated from a very similar mass balance linking the aeration time to the amount of sulfite reacted:

\[
k_{a1} = \frac{C_{\text{Na}_2\text{SO}_3} \cdot M_{\text{O}_2}}{2C_{\text{O}_2} \cdot M_{\text{Na}_2\text{SO}_3} \cdot t_{\text{aeration}}} - \frac{1}{2}
\]

As a consequence, this technique with the “red bottle” proposed in this paper can be seen as a visualization extension of the classical titration with sulfite.

It is also important to keep in mind that, at present, the technique can be applied only with resazurin. Indeed, the knowledge of additional data (kinetic constant and order, diffusion coefficients in basic solution of oxygen and dye) is needed to validate that the chemical regime is still fast with respect to the mass transfer process. This has been demonstrated for the resazurin system\(^ {17} \) but not yet for the “blue bottle” experiment and other systems. If this condition is not reached (\( t_{\text{transfer}} = 1/k_{a1} \gg t_{\text{reaction}} \)), the enhancement factor \( E \) can become higher than 1, meaning that the methods cannot be used as previously described and further calculations are needed.

### MATERIAL

Experiments were carried out in a glass bubble column (0.045 m in diameter, 0.40 m high, 0.23 m height of liquid), submerged in a water bath regulated in temperature (Figure 1). The air sparger was a multiple orifice plate with two orifice sizes, 0.5 and 0.8 mm, having an interval of 1 cm between adjacent orifices. The gas was provided from a pressurized gas network in the laboratory. The gas superficial velocity (flow rate over the column section) was set to 0.6 cm/s, corresponding to a flow rate of 0.6 L/min. The column was filled with 250 mL of the colorimetric solution. The concentration of the dye was chosen at 116.7 mg/L in order to use the simple eq 7. In the presence of sodium hydroxide (20 g/L), and glucose (20 g/L), the resazurin (blue) was first reduced to resorufin (pink/red), which was then reduced to dihydroresorufin (colorless) as shown by eq 2. The presence of glucose and sodium hydroxide in a larger amount than the dye made it possible for this reaction to be reversible (the resorufin being transformed back into dihydroresorufin), with slow kinetics (a few minutes). However, this reversibility remains limited by the initial amount of glucose, which tends to oxidize after several hours.

For demonstrative purposes, the volumetric overall mass transfer coefficients \( (k_{a1}) \) associated with the train of bubbles generated were also measured using the dynamic method\(^ {30} \) involving oxygen probes (Ox 50, Unisense, Denmark) and also using a high-speed monochromatic camera (Vision Research, Miro-M110, USA) as depicted in Figure 1. These elements are not required when proposing this demonstration to students; they are used here only to validate the technique.

### DEMONSTRATION

The procedure consists of filling the vessel with the “red bottle” solution of potassium hydroxide, glucose, and resazurin (at the concentrations reported previously) and by sparging it with nitrogen gas until the pink/red color disappears. Then, nitrogen is replaced by air, at the desired flow rate, making the pink/red color reappear. The time where the color level remains unchanged can be measured with a stopwatch.

A typical sequence is represented in Figure 2. As the reaction is reversible, if the air is stopped, the solution becomes colorless again, and the experiment can be run another time (this operation could also be performed with a nitrogen flush). Thus, the student can experiment with many operating conditions in a short time. The authors recommend nevertheless operating the experiment less than 3 h after making up the dye solution in order to minimize the glucose oxidation reaction. Sequential runs under different conditions can demonstrate the effect of orifice size on the mass transfer, and the effect of adding a packing system in the column (Figure 3b).

### HAZARDS

Sodium hydroxide and its solutions are corrosive. Protective gloves and a laboratory coat should be worn together with safety eyewear. Dissolution of solid sodium hydroxide in water is a highly exothermic reaction, and a large amount of liberated heat can pose a threat to safety through the possibility of splashing. Personal protective equipment such as a dust mask, eyeshields, and gloves should be used for the manipulation of the resazurin dyes.

### RESULTS AND DISCUSSION

In order to validate the technique, the images shown in Figure 2 were analyzed by implementing image processing software (Matlab, Mathworks, USA). The averaged gray level of the

---

**Figure 1.** Experimental setup.

**Figure 2.** Evolution of the color in the column as a function of the time. The superficial velocity of gas is 0.6 cm/s, and the orifice diameter is 0.5 mm. The solution is getting more red as a function of the time. These photographs are used to measure the gray light intensity over time.
concentration in the vessel is null. At this criterion, the precision of the measurement was estimated to reach 95% of the gray level value decrease. With eq 5, the precision was calculated as 2% of difference. This could be explained by the occurrence of bubble breakup on the packing grid, leading to a decrease in bubble size and an increase in interfacial area \( a \) (the ratio between the total bubble surface and the liquid volume, in \( m^{-1} \)). Finally, the increase of the orifice size strongly decreases the mass transfer coefficient (25% of difference), which can be explained by the formation of bigger bubbles. These types of experiments, in different operating conditions, represent an interesting base to discuss with students regarding what parameters control the gas–liquid mass transfer phenomena and how the latter can be improved.

### DEMONSTRATION WITH STUDENTS

The same set of experiments has been displayed to each member of a volunteer panel of 35 students and professors at the University of Toulouse. These sequences corresponded to the experiment performed in the device at two different orifice sizes, with and without packing. The panel was asked the simple question: "What is the time corresponding to the final change of color of the liquid?" The results obtained were averaged, and the mass transfer coefficient corresponding to the panel as a whole has been added to Table 1. The difference between the three techniques was very small (less than 3%), but it can be observed that the panel always underestimated the mass transfer, and so overestimated the aeration time needed to reach the steady red color. This phenomenon could be explained by the persistence of vision occurring when an observer watched the bubble column for a long time. However, the overestimation was small enough to allow the experiment to be run with only the eyes of the students, without sophisticated and expensive cameras or probes. Finally, this activity is a striking example of how a well-known chemical reaction could help in the quantification of the chemical engineering operation of gas–liquid mass transfer.

---

**Figure 3.** (a) Evolution of the averaged gray level of the liquid in the bubble column as a function of time. The superficial velocity of gas is 0.6 cm/s, and the orifice diameter is 0.5 mm. (b) A typical sequence for the experiments with a grid solid packing system. The superficial velocity of gas is 0.6 cm/s, and the orifice diameter is 0.5 mm

<table>
<thead>
<tr>
<th>Operating Condition</th>
<th>Orifice Size</th>
<th>Solids</th>
<th>Panel ( k_{(a)} (s^{-1}) )</th>
<th>Image Processing ( k_{(a)} (s^{-1}) )</th>
<th>Probe Technique ( k_{(a)} (s^{-1}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6 L/min (0.6 cm/s)</td>
<td>0.5 mm</td>
<td>No solids</td>
<td>0.0134 ± 0.003</td>
<td>0.0142 ± 0.005</td>
<td>0.0135 ± 0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Packing</td>
<td>0.0132 ± 0.003</td>
<td>0.0136 ± 0.005</td>
<td>0.0135 ± 0.001</td>
</tr>
<tr>
<td>0.8 mm</td>
<td>No solids</td>
<td>0.0975 ± 0.003</td>
<td>0.0100 ± 0.005</td>
<td>0.0102 ± 0.001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Packing</td>
<td>0.0110 ± 0.003</td>
<td>0.0117 ± 0.005</td>
<td>0.0122 ± 0.001</td>
<td></td>
</tr>
</tbody>
</table>

---

Figure 3. (a) Evolution of the averaged gray level of the liquid in the bubble column as a function of time. The superficial velocity of gas is 0.6 cm/s, and the orifice diameter is 0.5 mm. (b) A typical sequence for the experiments with a grid solid packing system. The superficial velocity of gas is 0.6 cm/s, and the orifice diameter is 0.5 mm.
CONCLUSION

In this paper, an experimental setup and specific procedure have been proposed to adapt the well-known “red bottle” reaction so as to visualize and quantify chemical engineering principles related to mass transfer phenomena. The main advantages are the low cost of the materials and the ease of use. Contrary to classical techniques, it requires no oxygen probes, no titration, and no calibration procedure. The experiment is as simple as a colorimetric titration method. The new calculation method proposed, based on the measurement of the aeration time, requires only a stopwatch, and thanks to the reversible properties of the reaction, multiple runs of the visualization can be performed in succession. This new demonstration offers thus a striking, colorful visualization of the effects of various operating parameters (i.e., oriﬁce size, gas ﬂow rate, and packing) on mass transfer, but a number of other conditions can easily be compared, such as the effect of vessel size or of the sparger design. The demonstration can also be combined with a simple acquisition video with the objective to dissociate the effect of the interfacial area, $a$ (linked to the bubble size and gas hold-up), and the mass transfer coeﬃcient, $k_{L}$. This experiment also constitutes a good introduction to discuss the competition between mass transfer and reaction. A further opportunity, not developed in this work, would be to perform comparisons of the recent adaptations of the blue bottle reaction system to “environment-friendly systems”, reducing the hazardous conditions or systems catalyzed.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.8b00898.

Extensive discussion and detailed experimental methods (PDF, DOC)

AUTHOR INFORMATION

Corresponding Author

*E-mail: nicolas.dietrich@insa-toulouse.fr.

ORCID

Nicolas Dietrich: 0000-0001-6169-3101

Abderrahane Kherbeche: 0000-0003-4698-145X

Notes

The authors declare no competing financial interest.

REFERENCES

(1) Lane, J. H.; Eynon, L. Estimation of Sugar in Urine by Means of Fehling’s Solution with Methylene Blue as Internal Indicator. Analyst 1924, 49 (581), 366–371.


COLORIMETRIC SOLUTION COMPOSITION:
- 117 mg/L of resazurin sodium salt (CAS Number 62758-13-8),
- 20 g/L of glucose (CAS Number 50-99-7),
- 20 g/L of sodium hydroxide (CAS Number 1310-73-2). This could be replaced by potassium hydroxide,
- Water.

All experiments were made with Sigma-Aldrich products (www.sigmaaldrich.com).

HAZARDS
Sodium hydroxide and its solutions are corrosive. Protective gloves and a laboratory coat should be worn, together with protective eyewear. The dissolution of solid sodium hydroxide in water is a highly exothermic reaction (a reaction where a large amount of heat is liberated), posing a threat to safety through the possibility of splashing.

NOTE FOR THE INSTRUCTORS:
- The purity of resazurin must be checked before the solution is prepared. The purity is around 80% according to the supplier.
- The device must be made of glass in order to resist to the attack by sodium hydroxide solution.
- Special attention must be paid to the salt dissolution.
- The glucose must be added to the sodium hydroxide solution only when the solution is at ambient temperature. The dye must be added last. We recommend using nitrogen to mix the solution compounds without adding oxygen.
- The colorimetric solution could be made by the students. This would help them understand the principle of the reactions from the blue color of the dye, to pink then colorless.
- The visualization of mass transfer must take place less than 3 hours after the making of the dye solution in order to minimize glucose oxidation. The authors do not recommend keeping the solution for more than a day, as it turns dark yellow 24 hours after the mixing of the compounds.
- To reduce the cost or the experimental time, the concentration of the dye can be decreased, but the authors do not recommend decreasing the dye concentration to a value resulting in an experimentation time shorter than 30 seconds. The concentration of the resazurin can be increased in order to extend the experiment time if the transfer time of the equipment is too short. Some other gas-liquid contactors can be used in order to change the coloration time (see below).
- The concentration of glucose and sodium hydroxide can also be changed in order to increase or decrease the back reaction (red color to pink) and allow a larger number of experiments to be done in series. Nevertheless, the authors do not recommend using concentrations higher than 40 g/l of glucose as the the viscosity and fluid properties need to be kept close to those of water to maintain the validity of the equations.
IMPACT OF THE GAS-LIQUID CONTACTOR ON THE MASS TRANSFER COEFFICIENT

The activity described in this paper is performed with a simple bubble column. Other gas-liquid contactors could be used in order to illustrate other chemical engineering unit operations or to change the coloration time (increasing \( k_{L,a} \) allows indeed a strong reduction of the dye concentration with an acceptable experiment time). These contactors are used to realize the mass and heat transfer between a gas phase and a liquid phase and can be used in separation processes (e.g. distillation, absorption) or as gas–liquid reactors or to achieve both purposes within the same device (e.g. reactive distillation) such as: falling-film column, packed column, bubble column, spray tower or gas–liquid agitated vessel.

Some important factors to take into account to choose the typology of gas–liquid contactor more suitable for a particular application are the liquid hold-up and the surface area of the gas–liquid interface. In particular heat and mass transfer rates are increased with equipment possessing high gas–liquid interface surface areas. Liquid hold-up is also an important factor for the economy of the process, because for low values of liquid hold-up a bigger equipment is needed to have the same heat and mass transfer rates. For this reason, gas–liquid contactors with low liquid-hold-up (e.g. falling-film column) are in general not used at industrial scale\(^1,2\).

<table>
<thead>
<tr>
<th>Contactor</th>
<th>Dispersed phase</th>
<th>Interfacial area ((\text{m}^2/\text{m}^3))</th>
<th>Dispersed phase hold-up (-)</th>
<th>Mass transfer coefficient (k_L) ((\text{m/s}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bubble column(^1)</td>
<td>gas</td>
<td>50-400</td>
<td>1-30</td>
<td>1-5 (\times10^{-4})</td>
</tr>
<tr>
<td>Stirred tank(^1)</td>
<td>gas</td>
<td>50-300</td>
<td>1-20</td>
<td>2-5 (\times10^{-4})</td>
</tr>
<tr>
<td>Fixed bed(^1)</td>
<td>gas</td>
<td>50-300</td>
<td>1-10</td>
<td>1-4 (\times10^{-4})</td>
</tr>
<tr>
<td>Static mixer(^1)</td>
<td>gas</td>
<td>100-1000</td>
<td>1-20</td>
<td>5-20 (\times10^{-4})</td>
</tr>
<tr>
<td>Packed column(^1)</td>
<td>liquid</td>
<td>50-300</td>
<td>4-15</td>
<td>0.5-4 (\times10^{-4})</td>
</tr>
<tr>
<td>Spray column(^1)</td>
<td>liquid</td>
<td>10-100</td>
<td>1-10</td>
<td>1-4 (\times10^{-4})</td>
</tr>
<tr>
<td>Venturi(^1)</td>
<td>liquid</td>
<td>20-300</td>
<td>1-10</td>
<td>3-7 (\times10^{-4})</td>
</tr>
<tr>
<td>Milli and micro reactor(^3)</td>
<td>gas and liquid</td>
<td>1000-5000</td>
<td>1-30</td>
<td>0.5-2 (\times10^{-3})</td>
</tr>
</tbody>
</table>

Table 1. Main characteristic of mass transfer properties of gas-liquid contactors

More references for students and instructors:

IMPACT OF THE ORRIFICE SIZE ON THE BUBBLE DIAMETER

The first studies on bubble formation were published by Tate (1864) and Bashforth & Adams (1883). A review on the subject can be given to the student for illustrating the effect of hydrodynamic with:


Some visualization of bubble formation can be found in the paper of:


The equalization of the pushing force and the capillary force at the orifice leads to the well-known relation:

\[
\left( \frac{d_b}{d_0} \right)^3 = \frac{6}{E_o} \tag{1}
\]

With \(E_o\) the Eötvös number at the orifice \(= \frac{gd^2}{\Delta \rho \sigma}\), also called the Bond number \((Bo)\), a dimensionless number measuring the importance of gravitational forces compared to surface tension forces and used to characterize the shape of bubbles or drops moving in a surrounding fluid.

This expression totally neglects the pinch effect at the neck of the bubble and the expression of the bubble diameter \(d_b\) provided by the equation (1) is considered as a maximum that can lead to an overvaluation of the volume of the bubble. Nevertheless, it is a simple tool to illustrate and validate the effect of the bubble size with the orifice size. For more precise measurements, the most complex model, presented in Kulkarni & Joshi (2005) can be used:

\[
\frac{d_b}{d_0} = \left( \frac{5,0}{Bo_0^{0.08}} + 9,261 \frac{Fr_0^{0.36}}{Ga_0^{0.39}} + 2,147 Fr_0^{0.51} \right)^{1/3}
\]

The use of a simple camera could also make possible the measurement of the bubble size and then to dissociate the effect on the interfacial area \(a\) and the mass transfer coefficient \(k_L\) from the measure \(k_La\) coefficient.