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PHYSICAL ABSORPTION OF VOLATILE ORGANIC COMPOUNDS BY SPRAYING EMULSION IN A SPRAY TOWER: EXPERIMENTS AND MODELLING

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ABSTRACT

This study outlines a Volatile Organic Compounds (VOCs) removal spray tower consisting of an empty cylindrical vessel and nozzles spraying an oil/water emulsion into the vessel. Spraying an emulsion into a spray tower absorbs both lipophilic and hydrophilic compounds, facilitates oil transport, improves the interfacial area (oil coats water droplets) and increases the turbulent flow regime enhancing mass transfer. Toluene was chosen as the synthetic lipophilic pollutant. The choice of the organic absorbent, silicone oil (47 V 350 Rhodorsil®), was made by considering several properties: thermal and mechanical stability, non-biodegradable nature, insolubility in water and low value of Henry's constant. Gas-liquid mass transfer and the hydrodynamics of the gas-liquid contactor were thoroughly investigated. It was observed that emulsion spraying allowed the dual absorption of hydro- and lipophilic VOCs (efficiency around 90% for both) and strongly enhanced the liquid mass transfer coefficient. Finally, a model describing the efficiency of the process as a function of time was developed. The predicted values are in good agreement with the experimental results.

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1. INTRODUCTION

Volatile Organic Compounds (VOCs) are defined as any organic component with saturation pressure greater than 10 Pa at ordinary conditions (Council directive 1999/13/EC 1999). This property results in a low boiling point, which causes large numbers of these molecules to evaporate and contribute to climate change, making VOCs the most common pollutants emitted by the chemical process industries, and precursors of ground-level ozone, a major component in the formation of smog.

The presence of VOCs in industrial gaseous effluents, such as wastewater treatment processes, painting and coating processes, petrochemical processes, etc., generates unpleasant odours and is often a source of complaints. Its influence on human health can be critical, especially in industry, where, for example, people who have been exposed to benzene have developed cancer. VOCs can be foul-smelling, carcinogenic, teratogenic or mutagenic (Hueper et al. 1962; Somers 2011; Sram et al. 2007). In addition to irritability of the mucous membranes, skin and eyes, other risks affecting the central nervous system are commonly associated with VOCs. As a consequence of those risks, limit values have been set by the World Health Organization, restricting the concentration of such components to which people can be exposed and, in late 2013, the International Agency for Research on Cancer assessed the carcinogenicity of outdoor air pollution (Loomis et al. 2013). Consequently, rules concerning industrial gas emissions are becoming increasingly strict.

To reduce VOC concentration in air, the first action that needs to be taken is to reduce the production of VOCs at the source by optimizing processes and reducing the use of solvents. Unfortunately those actions are not sufficient or cannot be applied in all chemical processes. In these cases, a specific treatment must be used for the reduction, with the goal of recovering

or eliminating VOCs. Noteworthy among eliminative treatments are thermal processes, with or without a catalyst, and biochemical methods, many of which are still in the research or development phases with new and innovating technologies. The choice of the abatement method depends on the temperature, composition and concentration of VOCs in the pollution; the gas flow rate; and the installation and running costs (Ozturk et al., 2006).

The most common ways of treating VOC pollutants in air by a recovery process are condensation, absorption, adsorption and membrane separation (Khan and Kr. Ghoshal 2000). The technology most widely used for the recovery of VOCs is adsorption, usually with activated carbon, although other adsorbents such as zeolites can be used. This is essentially a batch process since the capacity of the adsorbent is limited. Regeneration of the adsorbent is usually obtained by either heating the adsorbent or stripping with steam (Hester and Harrison 1995).

Further recovery techniques include absorption and condensation. Absorption involves the transfer of a soluble gas molecule to a solvent liquid, such as water or low volatility hydrocarbons. Absorption systems can treat waste gases containing very high concentrations of VOCs (ranges from 500 to 5,000 ppm). Condensation also works well at high VOC concentrations but the technique is most applicable for organic pollutants having reasonably high boiling points relative to ambient conditions.

Classically, absorption is used to remove VOCs from gas streams by bringing the contaminated air into contact with a liquid solvent. Any soluble VOCs transfer to the liquid phase and the air stream is effectively scrubbed. This takes place in an absorber tower designed to provide the gas-liquid contact area necessary to facilitate mass transfer. Using tower packing and trays as well as liquid atomization can provide this contact (Roustan 2003). Packed bed scrubbing uses packing material to improve vapour-liquid contact. Packing can either be randomly dumped

or stacked in the tower. Packing varies widely in size, cost, contact surface area, pressure and material of construction and each packing design has its own advantages (Kherbeche et al. 2013). The packing increases the contact surface area between the phases, and reduces the height needed for the tower (Bhatia et al. 2004). On the other hand, the pressure drop and the energy needs are much greater than in empty spray towers (Le Cloirec, 1998). Water is widely used as an absorbent of hydrophilic VOCs (Biard and Couvert 2013) and oil is used for hydrophobic VOCs. However, two columns are necessary and oil's high viscosity makes the energy expenditure prohibitive for this application (Darracq et al. 2010).

The use of a water/oil emulsion is an alternative that reduces energy requirements and the initial investment in equipment, and it increases the surface area available for gas-liquid exchange and the amount of VOCs that can be treated, as shown by Dumont et al. 2011 in a counter-current packed system.

This study outlines a process based on a traditional spray tower. This innovative tower is a low energy scrubber consisting of an empty cylindrical vessel and nozzles spraying oil/water emulsion into the vessel in order to completely remove both types of VOCs in only one operation. A characterization of the absorption process is proposed in the aim of evaluating the influence of temperature and flow rate on the process efficiency. A model is proposed to describe the absorption processes of hydrophobic VOCs in a spray tower.

1. MATERIAL AND METHODS

The experiments were conducted in a semi-industrial sized spraying tower (3 m height, 0.484 m diameter) with 4 sprayers working between 1 and 1.5 bars. The pilot could operate at a liquid flow rate between 18 and 26 m³/h, with a maximal gas flow ranging from 100 to 350 m³/h. Figure 1.a describes the experimental set-up. The synthetic pollution contained between 20 and 100 ppm of organic carbon. Toluene [C₇H₈] was used to produce it as it is widely present in the

natural environment or in chemical industries (solvents for ink, varnish, glues; pharmaceutical and perfume industry; (Streicher et al. 1981)). Pressurized air was sent to a gas-liquid contactor and passed through the pollutant liquid (toluene) with thermo-control; then the polluted gas was diluted by a Venturi system and sent to the tower. The gas flows at both the inlet and the outlet of the tower were measured by flowmeter propellers (Testo) which also could measure temperature by means of a thermocouple (PT100 Testo). The inlet and outlet flow concentrations were measured by a portable gas-chromatograph (Thermo-FID TG Flame Indicator Detector) from Panametrics. The emulsion prepared with tap water and silicone oil had an oil/water ratio that could vary between 0 and 20%. The mixing was performed in the loop by the volumetric pump and the flow measurement was taken by two rotameters (Fig 1.b), which had ranges from 10 to 50 m³/h (Georges Fisher type 10000/350) and from 1 to 10 m³/h (Georges Fisher type SK30).

Toluene is a very nonpolar and aromatic component (Roustan 2003) so the suitable oil for the emulsion had to have a high molecular mass, like silicone oil. A preliminary selection of oil was made on the basis of physicochemical tests and thermodynamic equilibria. The final choice of silicone oil was based on its low value of Henry's constant together with its mechanical and thermochemical resistance and its reasonable price. It is also convenient to avoid bacteria growth on it. Rhodorsil® fluid silicon oil 47V300 from the Rhodia Company, France was chosen. The physical properties of this oil and toluene are reported in Table 1. An important characteristic is that this silicone oil does not have an organic origin so it contains no naturally absorbed VOCs and, consequently, does not release any VOC pollution.

Table 1. Fluid properties

	Silicone Oil 47v350	Toluene
Supplier	Rhodia	-
Saturation Pressure (mm Hg)	1.33 _{20°C}	3.8 _{25°C}
Boiling Temperature at 1 atm (°C)	-	110.6
Viscosity (mPa.s)	340 _{25°C}	-
Vapour concentration (ppm C) at 20 °C	3.5	-
Vapour concentration (ppm C) at 50 °C	8.6	-
H toluene (Pa.m ³ .mol ⁻¹) at 20 °C	1.83	
Molar Mass (g/mol)	20 000	92.14
Activity Coefficient	0.025	
VLE (ppmv)	-	100
VME (ppmv)	-	150

Henry's constant (m), which is also known as solubility, was determined by the absorption method (Sandler 2006). The pollutant was produced and inserted in a 4-litre glass flask, and a precise volume of the absorbent was injected into the flask at a regulate temperature. After 20 minutes' agitation, equilibrium was reached. A sample of gas was sent to a portable FID and the analyses of the gas gave the exact amount of VOC absorbed by the oil. From the pollutant concentration in the gas (y) and in the liquid phase (x), the constant could be calculated:

$$m = \frac{y}{x} \quad (1)$$

The measurements were performed at several temperatures between 5 and 60°C. As a result, the values of m were related to temperature (T) in a polynomial model described by equation 2:

$$m = 6.35 \cdot 10^{-7} T^2 + 6.63 \cdot 10^{-6} T + 3.75 \cdot 10^{-4}, 5^{\circ}\text{C} < T < 60^{\circ}\text{C} \quad , \quad (2)$$

The interfacial area a_{total} was measured by both a physical and a chemical method. The principle of the chemical method (Andrieu and Claudel 1974) was based on the consumption of solubilized Na₂SO₃ (sulfite) that reacted in water with the oxygen of the air. The physical

method was based on an image processing analysis of high speed camera recordings, as shown in figure 2.a. As an example, for one operating condition, the values for a_{total} (m^2/m^3 of liquid) were $1.37 m^{-1} \pm 15\%$ by the chemical method and $1.46 m^{-1} \pm 20\%$ by the physical method. As the sulphite is only soluble in water, the effective exchange area (a^o) could be defined as the real area occupied by the oil: where α is the overlap rate (figure 2b and 2c). This parameter is defined by the ratio between the surface area covered by oil and the total surface area of the drop. As the global efficiency of the process, for non-soluble compounds in water, is linked to the effective oil exchange area, a first approach is to estimate α from the efficiency with and without oil, as developed in equation 3:

$$\alpha = \frac{E_{water} - E_{emulsion}}{E_{water}} \quad (3)$$

where E is the efficiency of the system (y_e and y_s are the pollutant fraction at the inlet and outlet of the column):

$$E = \frac{y_e - y_s}{y_e} \quad (4)$$

The oil viscosity and density were determined in the laboratory using a capillary viscometer (Haack) and a pycnometer (Roth). A model was developed as a function of temperature T:

$$\mu_{oil}(Pa.s) = 10^{-3}(9.53 \cdot 10^2 - 1.89 \cdot 10^2 \ln(T)) \quad (5)$$

$$\rho_{oil}(Kg/m^3) = 9.7 \cdot 10^2 - 5.31 \cdot 10^{-1}T \quad (6)$$

With $5^\circ C < T < 65^\circ C$

Air viscosity, equation (7), was calculated from several literature correlations. The superficial area of exchange was developed as an adaptation of Murty's correlation exposed in equation (8).

$$\mu_{air}(Pa.s) = 4.2 \cdot 10^{-8}T + 1.74 \cdot 10^{-5} \quad (7)$$

$$d_g = 57 Re^{-0.48} We^{-0.18} S_{spray} 10^{-3} 6.26 10^{-1} \quad (8)$$

Water properties: viscosity, density and surface tension, which also depend on temperature, were modelled by the following polynomials.

$$\mu_{water}(Pa.s) = 5 10^{-7} T^2 - 5 10^{-5} T + 1.8 10^3 \quad (9)$$

$$\rho_{water}\left(\frac{Kg}{m^3}\right) = -5 10^{-3} T^2 + 9.4 10^{-3} T - 10^3 \quad (10)$$

$$\sigma_{water}(N/m) = (-5 10^{-4} T^2 - 1.33 10^{-1} T + 7.56 10^1) 10^{-3} \quad (11)$$

2. MODEL

The purpose of this model is to provide a tool to estimate the efficiency of the absorption column according to time. The model is described for a single VOC for a single absorbent phase working at counter current of gas and liquid with a loop as liquid circulation.

At time $t = 0$ and for $x_e = 0$, the height of a transfer unit in the gas phase, HTU_{OG} , and the number of transfer units, NTU_{OG} , are calculated using to equation (12) (Roustan 2003):

$$Z = HTU_{OG} \cdot NTU_{OG} = \frac{G}{K_G^0 \cdot a^0 \cdot \Omega} \left[\frac{A^*}{A^* - 1} \cdot \ln \left(\frac{A^* - E_G}{A^* \cdot (1 - E_G)} \right) \right] \quad (12)$$

with a^0 and Ω , where A^* is the absorption rate defined by $A^* = \frac{L}{mG}$ with m the Henry constant, L the molar liquid flow rate and G the molar gas flow rate.

The exchange area is calculated by equation (13):

$$a^0 = \frac{6 \cdot L}{d_{drop} \cdot \Omega \cdot U_E} \quad (13)$$

The double film model defines the global transfer resistance (K_G^0) as the consequence of two forces, one from the liquid side (k_L^0) and the other from the gas side (k_G^0). For toluene/silicone 47v350, the transfer resistance is largely localized on the liquid side. This is mainly due to the high viscosity of the oil, which results in poor circulation and therefore a transfer resistance leading to equation (14):

$$\frac{1}{K_G^0} = \frac{m}{k_L^0} \quad (14)$$

From our experiments, an empirical relation giving the mass transfer coefficient k_L as a function of the temperature is proposed:

$$\begin{aligned} \text{If } T \leq 17^\circ C \quad k_L &= 6.24 \cdot 10^{-5} \text{ m/s} \\ \text{If } 60^\circ C > T > 17^\circ C \quad k_L &= 2.4 \cdot 10^{-8} T^2 - 4.0 \cdot 10^{-7} T + 7.010^{-5} \text{ m/s} \end{aligned} \quad (15)$$

As the temperature was constant in all the experiments, the height of transfer unit HTU_{OG} could be considered constant for a transfer resistance localized only in the liquid film side. Once the HTU is determined, it is possible to calculate y_s , x_s and the new value of x_e at each time t with equations using the concept of the number of transfer units. The equation used for determining the number of transfer unit NUT is:

$$NUT_{OG} = \Delta y_{ML} = \frac{(y_e - y_e^*) - (y_s - y_s^*)}{\ln \frac{(y_e - y_e^*)}{(y_s - y_s^*)}} \quad (16)$$

$$\text{with } y_e^* = m \cdot x_s \text{ and } y_s^* = m \cdot x_e$$

Since Z is a constant, based on equation (16), it is possible to obtain the gas molar fraction y_s . Thus the outlet liquid molar fraction x_s is calculated as well as the new value of x_e . It has been observed that to obtain good accuracy on the variation of concentrations, the time step used must be the residence time of the drops in the column (Z/U_g). The flowchart of the calculation procedure is given in figure 3.

3. RESULTS & DISCUSSION

The efficiency is shown as a function of time in Figure 4 for a gas flow ranging from 100 to $350 \text{ m}^3 \cdot \text{h}^{-1}$ and for a 10% emulsion of silicone oil 47v350 in water and air polluted with toluene. According to Fig. 4, regardless of the value of the gas flow rate, the efficiency gradually decreases with time from the maximum value of 90%. This trend is explained by the saturation of the absorbent liquid due to the loop circulation. In addition, increased gas flow induces a decrease in the efficiency at the initial treatment time. More generally, when the gas flow increases or the flow of liquid decreases, the ratio A^* decreases and consequently the efficiency E decreases. A detailed analysis of the influence of the experimental parameters showed that the impact of A^* outweighed that of the other parameters for the conditions studied here. The

model results are also represented in Fig. 4 and describe a decrease in efficiency with an increase in gas flow that is in satisfactory agreement with experiments. However, as gas flow increases, the accuracy decreases. In addition, the error becomes more significant with decreasing efficiency because the analysis noise becomes proportionally higher. These three experiments were performed with the liquid at a controlled temperature of 5°C. The temperature was, therefore, not a source of error. However, the more the flow of gas increased, the more the pollutant concentration decreased. So, for a gas flow rate of 350 m³·h⁻¹, the concentration measurements were less reliable. This also appeared at the end of experiment, when the concentration difference between the inlet and the outlet was low.

The efficiency is shown as a function of time in Figure 5 for different values of the liquid flow rate L (26 m³/h and 18 m³/h). A reduction of about 30% in the liquid flow rate induces a decrease of about 11% with respect to the initial efficiency. According to the theory, a decrease of the liquid flow rate has a negative effect on absorption efficiency, which is confirmed by these experiments. Fig 5 shows that the experiments at a high liquid flow rate were more effective at the beginning of the experiment but then became less effective. Increasing the liquid flow rate increases the exchange surface, so the efficiency improves. However, the solubility also depends on the air concentration: if the liquid flow is slower, the exchange surface is less important, and the efficiency reduction with time is less significant. This explains the crossing of the two curves. Initial efficiency is underestimated by the model for a flow of absorbent liquid of 18 m³·h⁻¹ and is strongly overestimated for times over 5 hours. The model does not give good quantitative results, but it validates the curve trends and especially the crossing point, which is present in both the model and the experimental curves. Another explanation for the discrepancy between theoretical and practical data towards the end of the experiments could

be a temperature increase caused by the pumps: the temperature rise of the liquid would increase the Henry constant and reduce solubility, so the liquid would become saturated faster. Figure 6 shows the results obtained for variable temperature treatments. This figure shows that the initial efficiency increases when the temperature of the absorbing liquid decreases. As the temperature increases, the initial efficiency decreases, the amount that can be absorbed decreases, and the longevity of the treatment decreases. Increasing the temperature has a negative impact on the absorption of toluene in this process. An increase of the temperature implies a more frequent regeneration of the absorbent accompanied by increased running costs. For the range of temperatures studied, it can be observed that the model describes the effect of temperature variation on efficiency well. But it provides better validation of the experiment at 5-7°C than at 17-28°C. Henry's constant could vary little during the experiment and the isothermal model is difficult to apply at these temperatures. Moreover, for an experiment at 47-50°C, humidity can affect measurements of the FID analysers. Also, a high temperature may result in a higher release of oil in the pilot. This release cannot be estimated and it causes a loss of efficiency because the FID analysis is global. In summary, the model worked very well for the study and the errors may have come from the difficulty of controlling the experimental parameters, such as temperature, and inaccuracies in the measurements.

Finally the variation of efficiency with time was observed for several emulsion rates. As the clearance process is based on the absorption of a highly hydrophobic pollutant, the reduction of efficiency when less oil is added to the water was to be expected. Increasing emulsion rate will increase overlap rate (α), so area a° will be larger?. However, it also increases the global liquid viscosity, which makes the drops bigger and reduces a° . The results shown in Figure 7 prove that a high emulsion rate results in a higher initial efficiency. However, the results are not significant: when the emulsion rate is doubled, initial efficiency is improved by only 3 %.

And, in addition to the higher energy expenditure caused by a higher viscosity, the influence on the drop size and overlap rate can have a negative effect in terms of global efficiency.

4. CONCLUSION

The model developed in this study is the result of combining a double film model, the concept of number of transfer units, and experimental results related to the thermodynamics of the absorbent / fluid (silicone oil emulsion torque 47v350/toluene). When the experimental parameters are defined and constant during an experiment and the analytical accuracy is favourable, it is observed that the experimental results and the model give similar trends of efficiency over time. The model of the double film and the concept of the number of transfer units are validated in the case of an emulsion spray. However, the results obtained for some experimental parameters can have an error of the order of 20%. A first example of determination error is the measurement of the rate of recovery. It is not a function of temperature in this model, as it was difficult to estimate its temperature dependence experimentally. A second example of an error of determination is that the droplet diameters are defined as a monodispersion. The determinations of k_L and the equation depending on the temperature were introduced into the model but, as it was difficult to keep temperature constant in this process, the model was not always valid under the operating parameters, which may explain a shift in some cases. The physical properties used in the model are well-described, and the correlations used to describe them are correct. The assumptions made are reliable. Overall, the model works well for studying the absorption of toluene by silicone oil 47v350 in the operating ranges of the study. It would be interesting to vary the type of VOC to assess the effectiveness of the model.

5. NOMENCLATURE

m : Henry's constant in dimensionless form [-];
 x : Fraction molar of the VOC in the gas phase [-];
 y : Fraction molar of the VOC in the liquid phase [-];
 $[VOC]_{eq}$: VOC concentration when in the equilibrium [ppm];
 V_{Mair} : Molar volume of air [L/mol];
 V_{air} : Volume of air in the balloon [L];
 $[COV]_{before\ eq}$: VOC concentration initial before addition of liquid absorbent [ppm];
 $V_{Mliquide}$: Molar volume of the liquid absorbent [L.mol⁻¹];
 V_{liquid} : Volume of liquid added into the balloon [L];
 He : Henry constant [Pa];
 P : Total Pressure [Pa];
 T : Temperature [°C];
 a_{total} : Total superficial area [m².m⁻³];
 α : Overlap rate [-];
 $E_{G,water}$: Efficiency of the spray tower working only with water [-];
 $E_{G,emulsion}$: Efficiency of the spray tower working with water/oil emulsion [-];
 a^o : Effective superficial area [m².m⁻³];
 φ : Molar solute transfer flux [mol.m⁻².s⁻¹];
 $D_{A,G}$: Diffusion coefficient of a solute A in gas phase [m².s⁻¹];
 δ_G : of liquid film [m];
 R : Ideal Gas Constant = 8.314 [J.mol⁻¹.K⁻¹];
 T_K : Temperature [K];
 p_i : Partial pressure on VOC at gas phase at the interface [Pa];
 p : Partial pressure of VOC at gas phase [Pa];
 k_G : Material transfer coefficient at gas film [m.s⁻¹];
 k_L : Material transfer coefficient at liquid film [m.s⁻¹];
 C_G : Solute concentration in gas phase [mol.m⁻³];
 $C_{G,i}$: Solute concentration at the interface of gas phase [mol.m⁻³];
 C_L : Solute concentration in liquid phase [mol.m⁻³];
 $C_{L,i}$: Solute concentration at the interface of liquid phase [mol.m⁻³];
 K_G^o : Global material transfer coefficient [kmol.m².s⁻¹];
 k_G^o : Material transfer coefficient at gas film [kmol.m².s⁻¹];
 k_L^o : Material transfer coefficient at liquid film [kmol.m².s⁻¹];
 $Sh_G = \frac{k_G \cdot d_g}{D_{A,G}}$: Sherwood number at gas phase [-];
 $Sc_G = \frac{\mu_G}{D_{A,G} \cdot \rho_G}$: Schmidt number at gas phase [-];
 $Reg = \frac{U_g \cdot d_g \cdot \rho_G}{\mu_G}$: Reynolds number in the drops;
 d_g : Drop's diameter [m];
 Z : Tower height [m];
 HTU_{OG} : Height of Transfer Unite in gas fluid [-];
 NTU_{OG} : Number of Transfer Unite in gas fluid [-];
 G : Molar Gas flow [mol.s⁻¹];
 L : Molar Liquid flow [mol.s⁻¹];
 Ω : Transversal area of the tower [m²];
 A^* : Absorption rate defined by $A^* = L/m \cdot G$ [-];

E_G : Absorption efficiency calculated by the gas in and out let of the tower [-];

μ : Viscosity [Pa.s];

ρ : Density [kg.m⁻³];

σ : Surface Tension [N.m⁻¹];

U_E : Drops effective velocity [m.s⁻¹];

U_g : Drops terminal velocity [m.s⁻¹];

$We = \frac{U_b \cdot \mu_L}{\sigma_L}$: Weber number for the drops [-];

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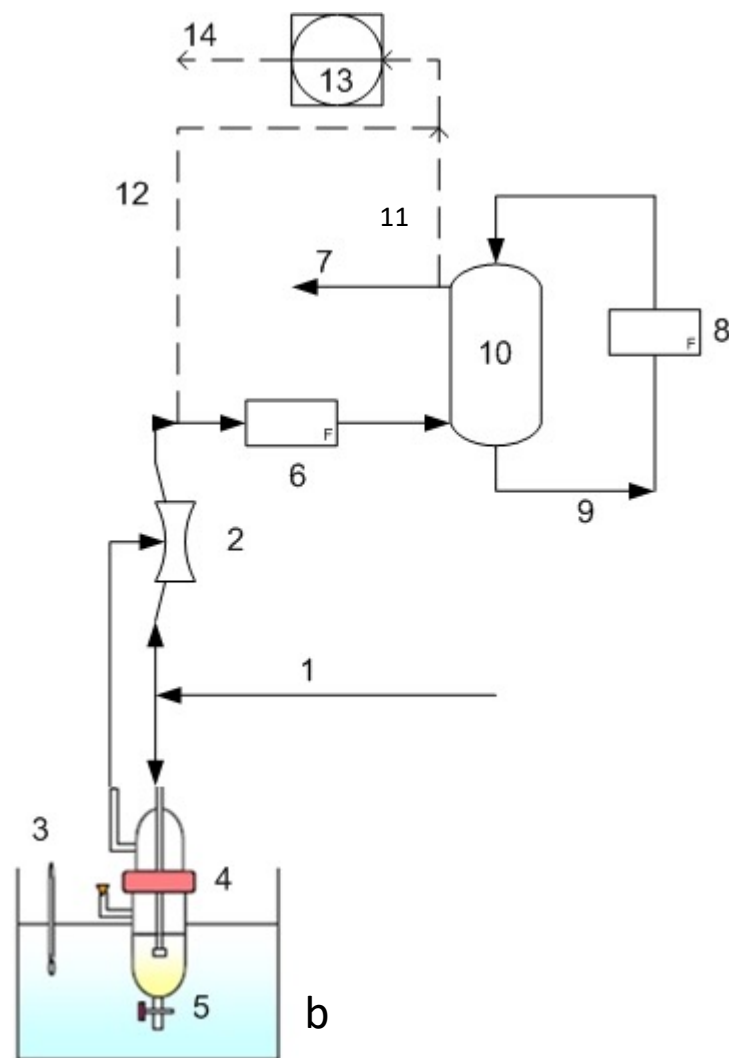
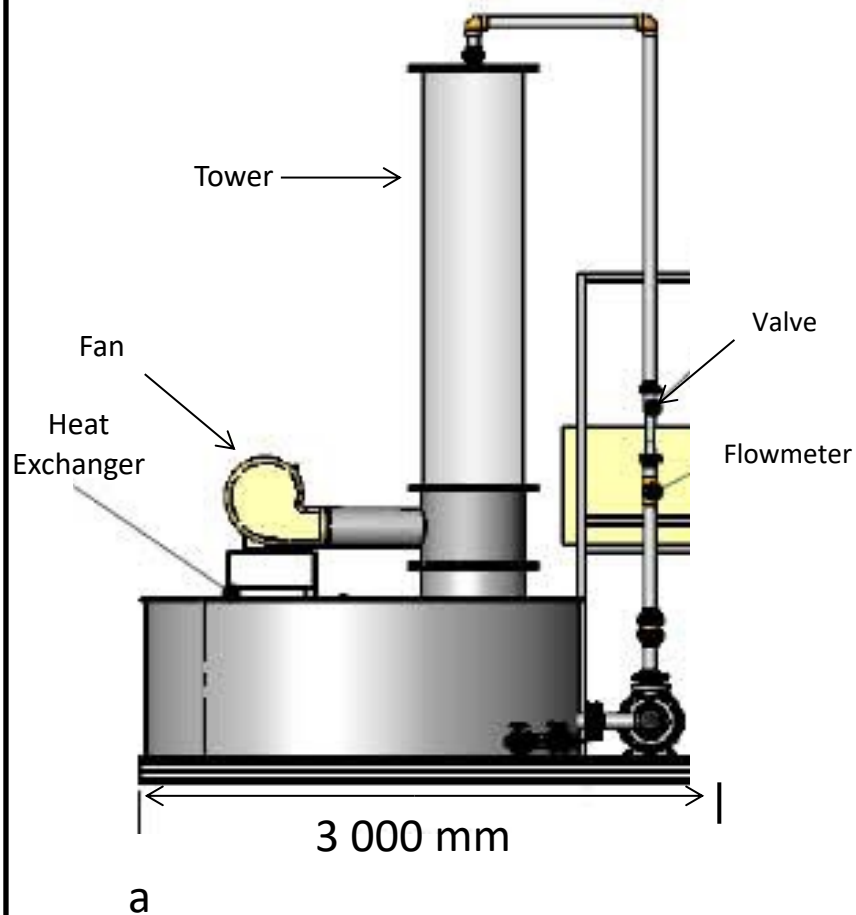
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Figure 1 a. Global pilot experimental set-up. Figure 1 b. 1: Air Inlet; 2: Venturi; 3: Temperature controller; 4: Toluene saturation system; 5: Thermostatic Bath; 6: Gas flowmeter; 7: Air Outlet; 8: Liquid flowmeter; 9: Liquid reinjection; 10: Pulverization Tower ; 11: Gas sample inlet; 12: Gas sample outlet; 13: Chromatography system; 14: Chromatography outlet.



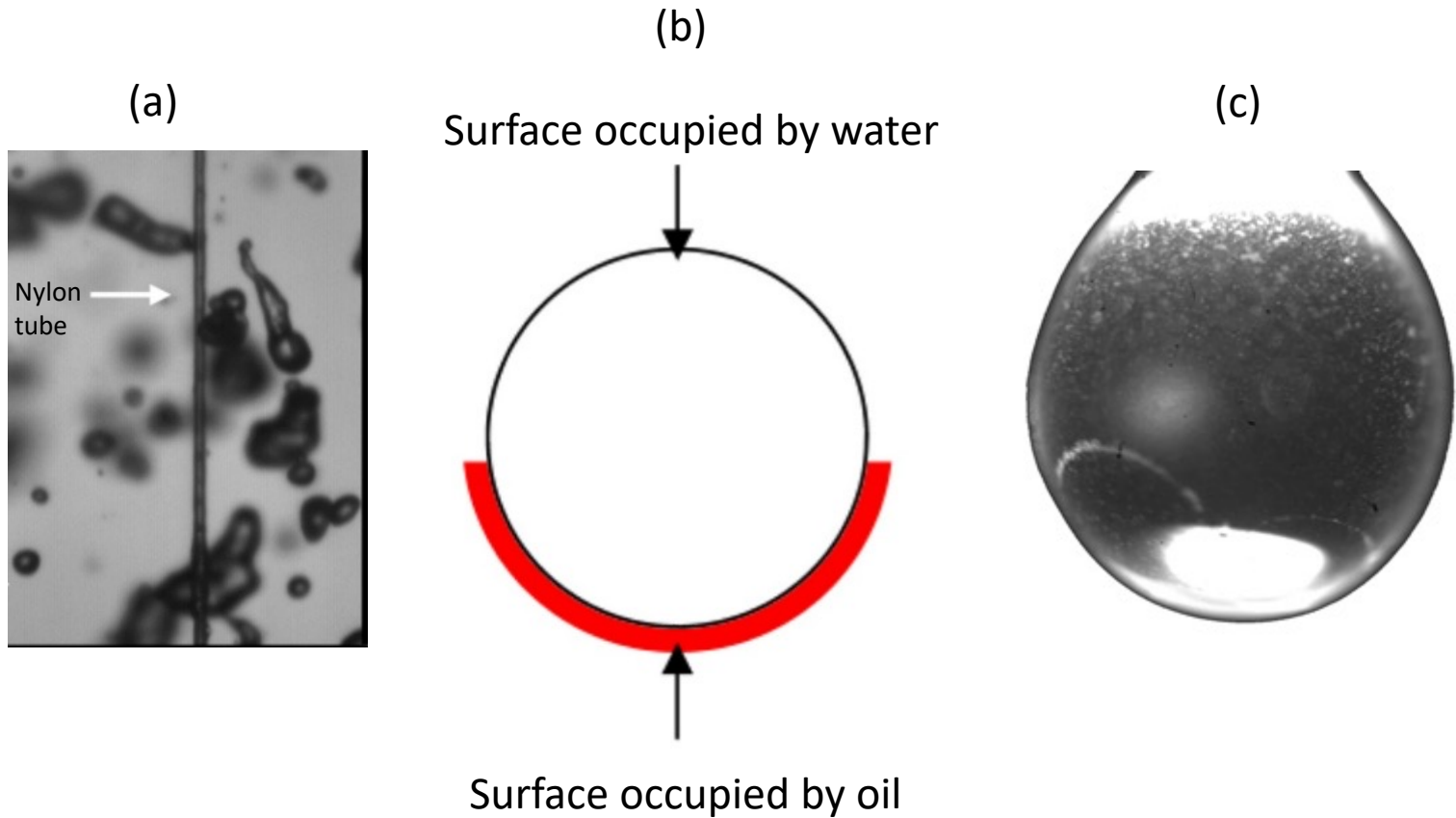
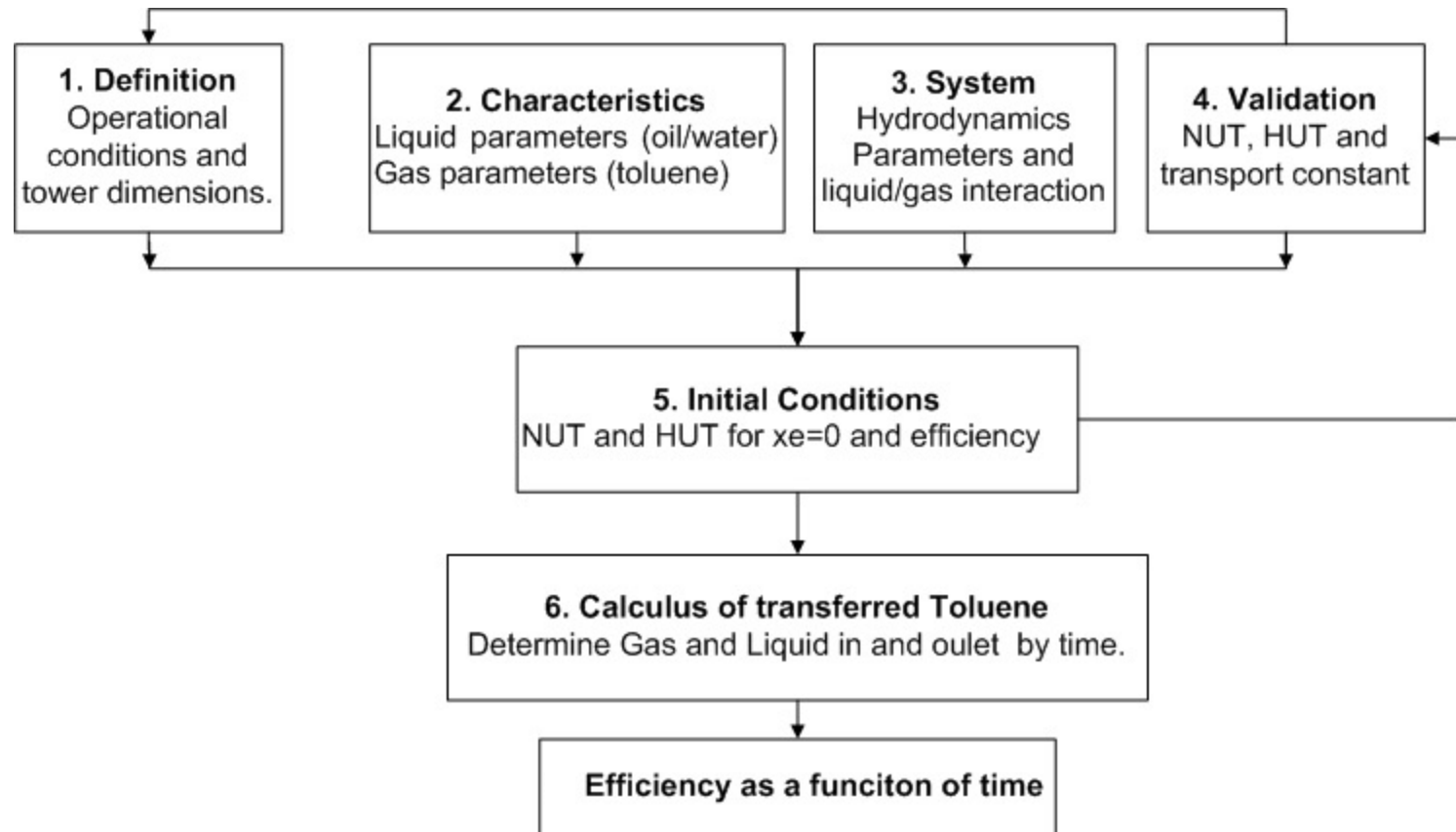


Figure 2 a. An emulsion droplet image (silicon oil/water). Figure 2 b. The scheme proposed to the coerture rate by the oil under the water drop. Figure 2 c. Photography of an emulsion droplet

Figure 3. Model procedure flowchart



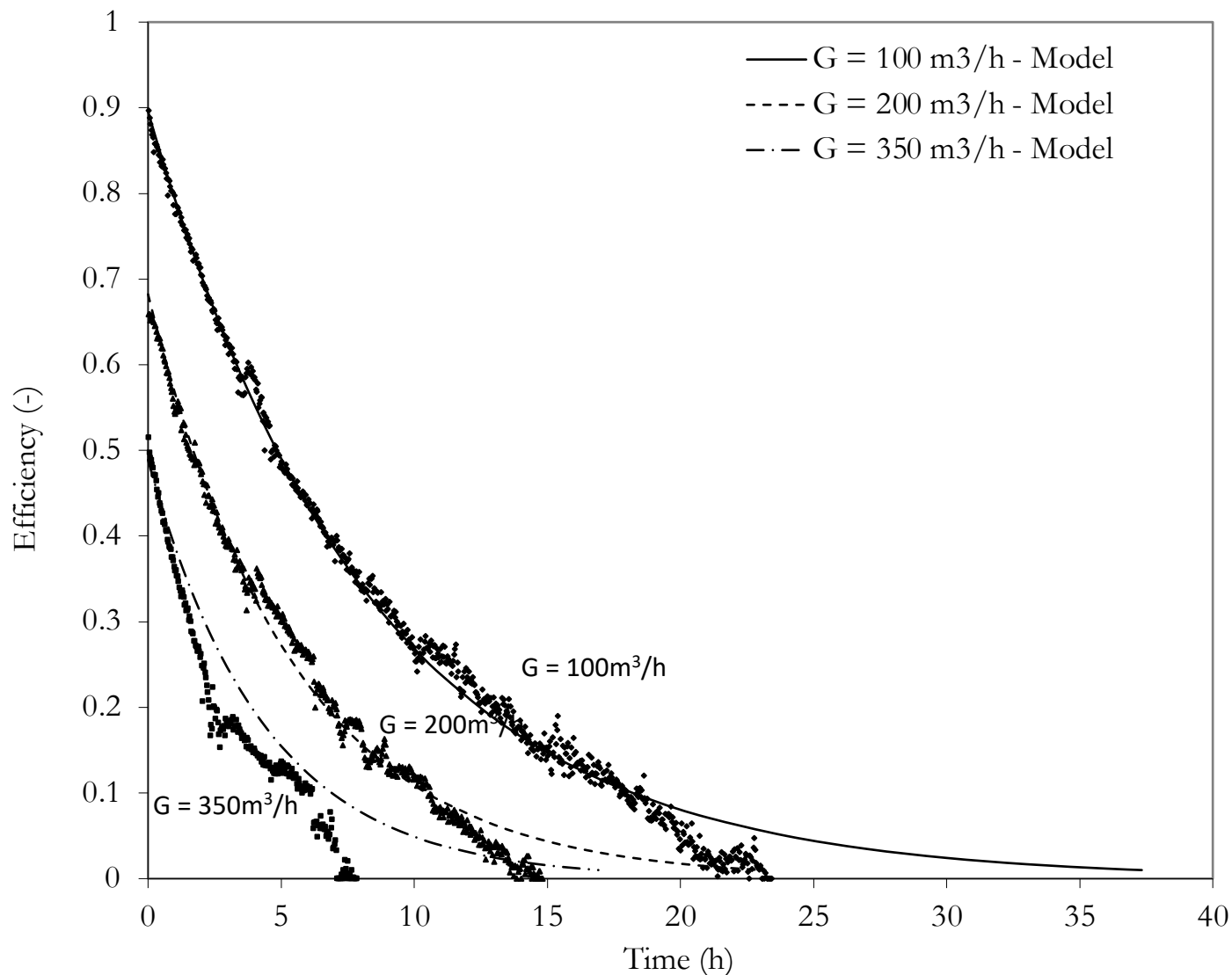


Figure 4. The spray tower efficiency as function of time, experimental and model results, at controlled temperature of 5°C , liquid flow constant equals to $26 \text{ m}^3/\text{h}$, an emulsion ratio of 10% and an initial concentration of [VOC] about 94 ppm. ● $G = 100 \text{ m}^3/\text{h}$ ▲ $G = 200 \text{ m}^3/\text{h}$ ■ $G = 3500 \text{ m}^3/\text{h}$.

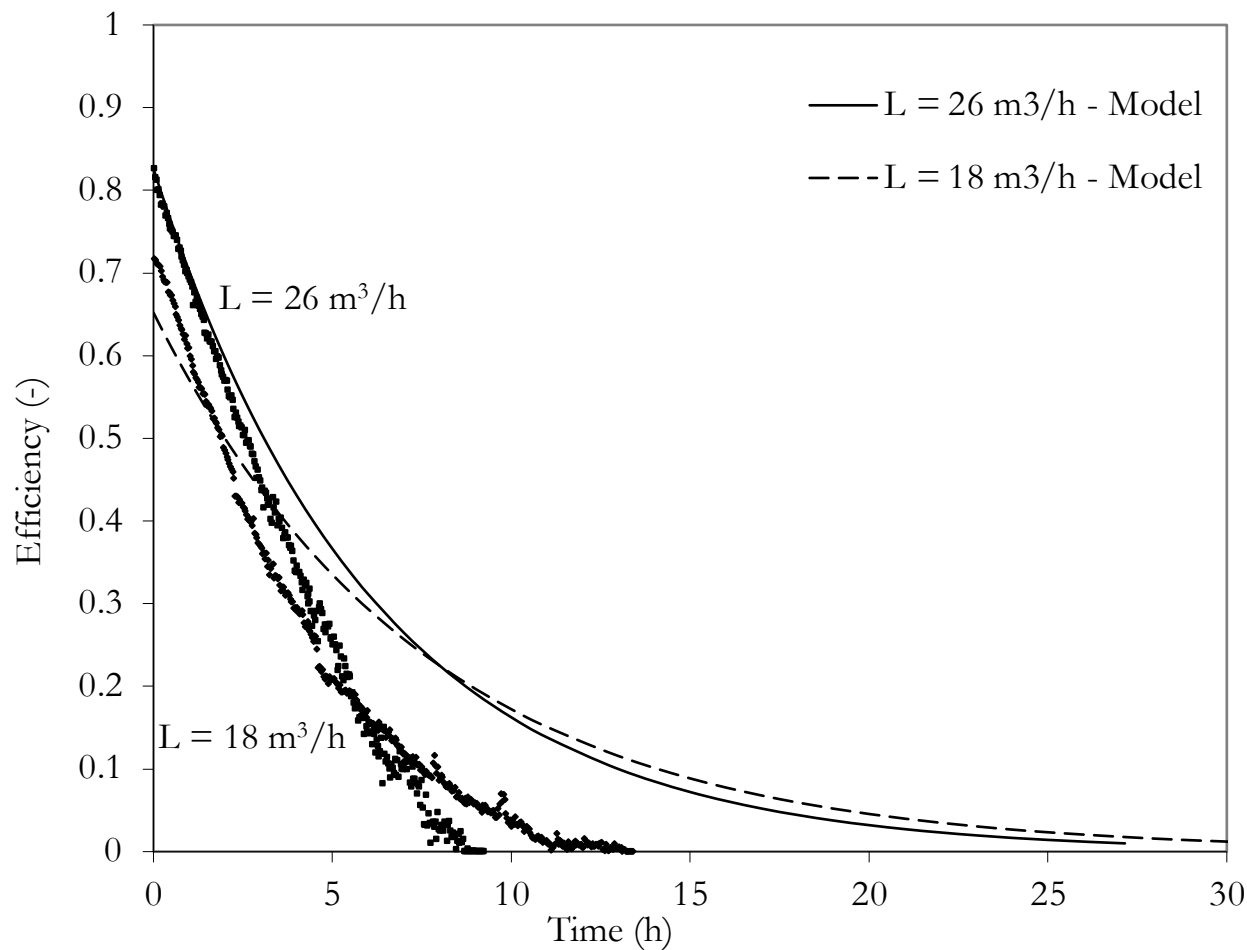


Figure 5. The spray tower efficiency as function of time, experimental and model results, for two different liquid flow with gas flow constant equals to $100 \text{ m}^3/\text{h}$, emulsion ratio of 10% and an initial concentration of [VOC] about 94 ppm. ● $L = 18 \text{ m}^3/\text{h}$ ▲ $L = 26 \text{ m}^3/\text{h}$.

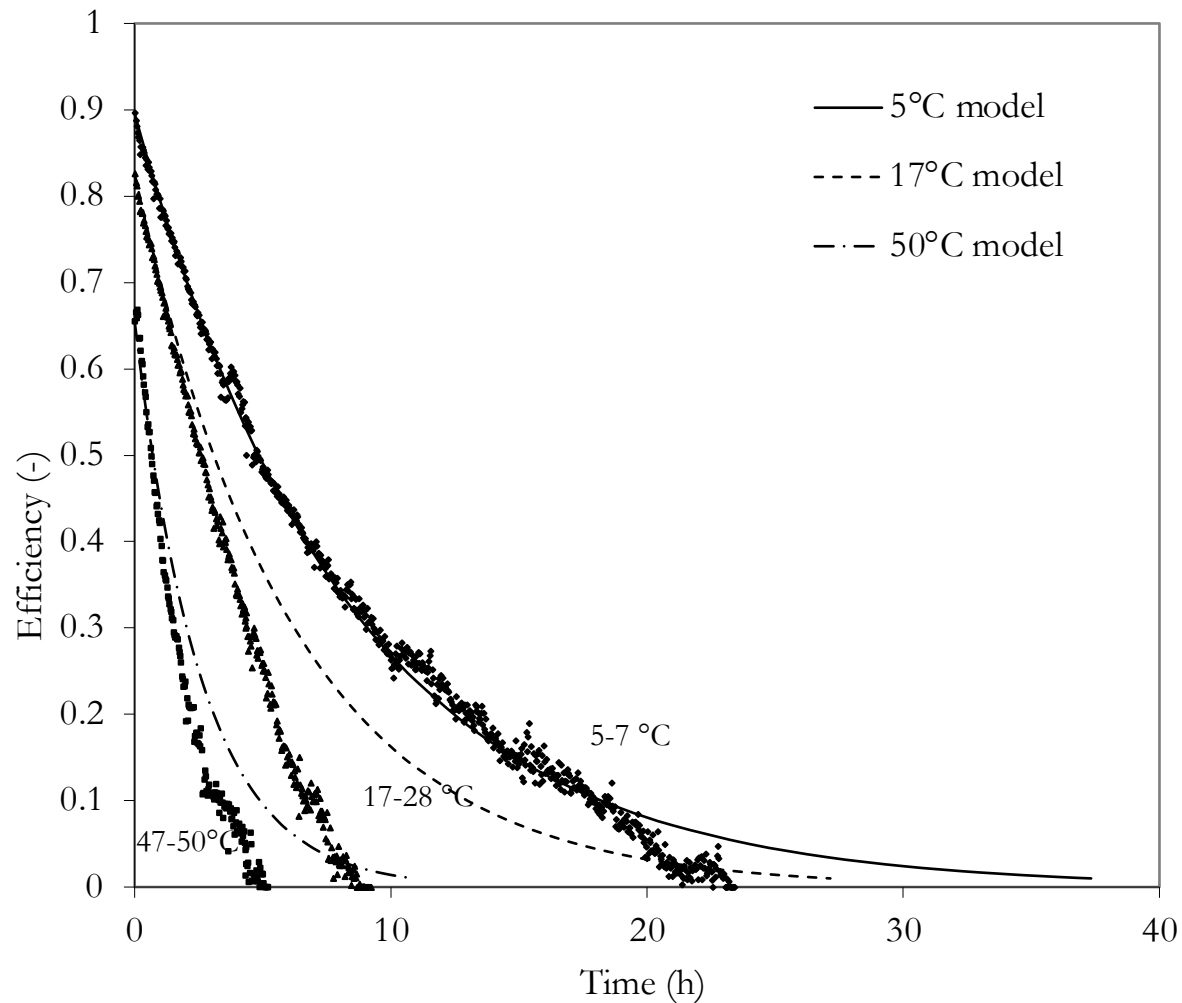


Figure 6. The spray tower efficiency as function of time, experimental and model results, with liquid flow constant equals to 26 m³/h, gas flow also constant equals to 100 m³/h, an emulsion ratio of 10% and an initial concentration of [VOC] about 94 ppm. ● 5-7°C ▲ 17-28°C ■ 47-50°C.

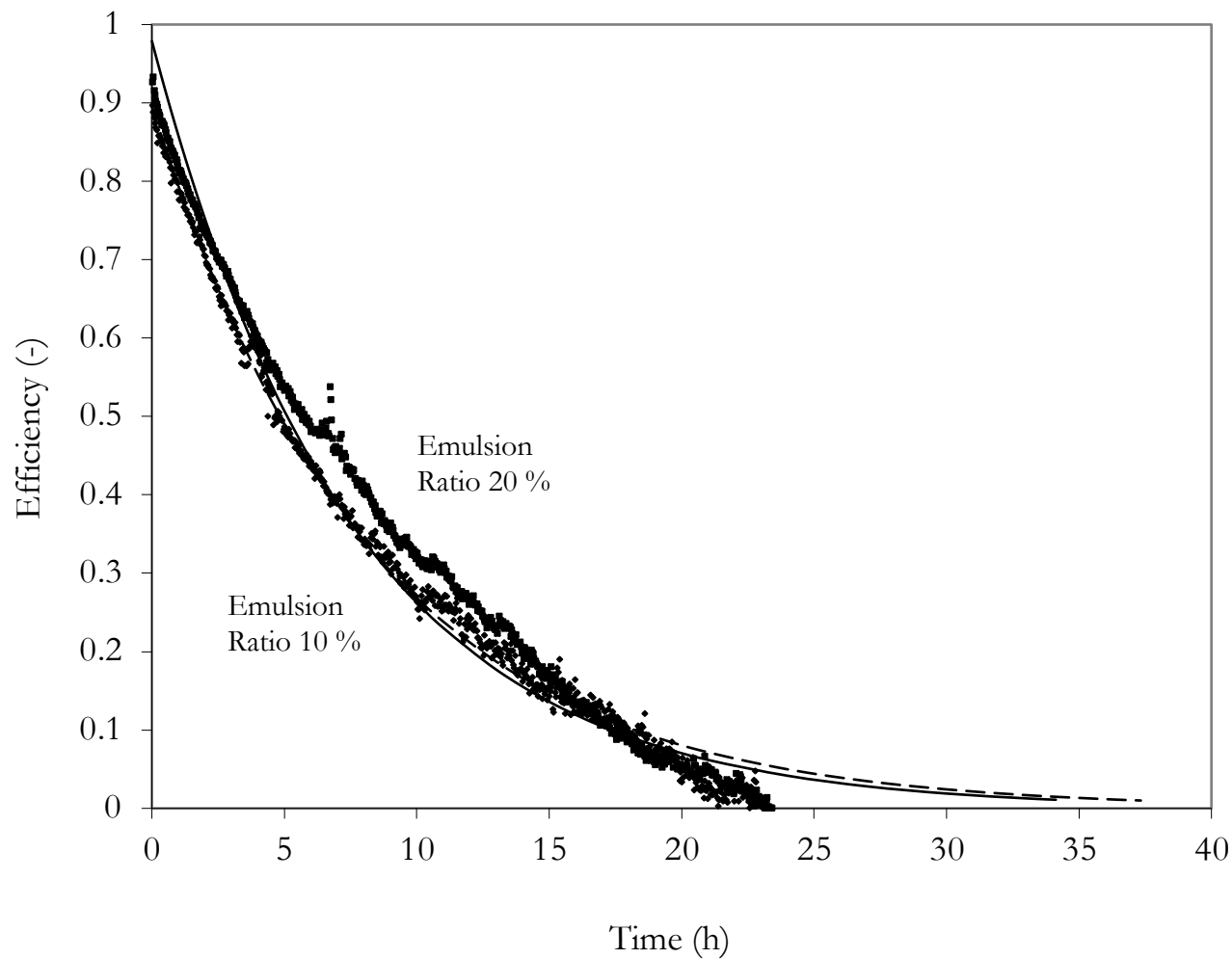


Figure 7. The spray tower efficiency as function of time, experimental and model results, with liquid flow constant equals to 26 m³/h, gas flow also constant equals to 100 m³/h, an two emulsion oil/water ratio for comparison of 10% (●) and 20% (■) with initial concentration of [VOC] about 94 ppm.