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► **To cite this version:**

Pierre-François Biard, Annabelle Couvert, Christophe Renner, Jean-Pierre Levasseur. WET SCRUBBING INTENSIFICATION APPLIED TO HYDROGEN SULPHIDE REMOVAL IN WASTE WATER TREATMENT PLANT. Canadian Journal of Chemical Engineering, 2010, 88, pp.682-687. 10.1002/cjce.20310 . hal-00904248

HAL Id: hal-00904248

<https://hal.science/hal-00904248>

Submitted on 14 Nov 2013

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1 **WET SCRUBBING INTENSIFICATION APPLIED TO HYDROGEN**
2 **SULPHIDE REMOVAL IN WASTE WATER TREATMENT PLANT**

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16 **Abstract**

17 Hydrogen sulphide removal in a Waste Water Treatment Plant at semi-industrial scale
18 in a compact wet scrubber has been investigated. The gas residence time in the scrubber was
19 reduced to 30 ms using a NaOCl caustic scrubbing solution. The contactor is composed of a
20 wire mesh packing structure where liquid and gas flow co-currently at high velocity (> 12
21 m.s^{-1}). H_2S removal percentages higher than 95% could be achieved whereas a moderate
22 pressure drop was measured (< 4000 Pa). Both the hydrodynamic and chemical conditions
23 can influence the efficiency of the process. Correlations were developed to predict both the
24 pressure drop and the H_2S removal efficiency at given operating conditions.

25

26 **Résumé**

27 Le traitement du sulfure d'hydrogène dans un laveur de gaz compact a été étudié à
28 l'échelle semi-industrielle en station d'épuration. Le temps de contact dans le laveur est réduit
29 à une trentaine de ms en utilisant une solution d'hypochlorite de sodium à pH basique. Le
30 contacteur se compose d'une structure tissée métallique dans laquelle le gaz et le liquide
31 circulent à co-courant et grande vitesse (> 12 m.s^{-1}). Un abattement de l' H_2S de plus de 95%
32 peut être obtenu avec une perte de charge modérée (< 4000 Pa). A la fois les conditions
33 chimiques et hydrodynamiques influencent les performances de traitement. Des corrélations
34 ont été développées pour prédire la perte de charge mais aussi l'abattement dans des
35 conditions opératoires données.

36

37 **Keywords:** Absorption, chemical scrubbing, compact scrubber, hydrogen sulphide,
38 odour control.

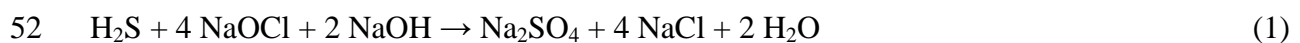
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40 INTRODUCTION

41

42 Hydrogen sulphide is the major compound involved in odour emissions from WWTPs
43 (Gostelow, 2001). The strategy applied in WWTPs to reduce odour emissions consists to
44 ventilate the odorous stages (pre-treatment, biological aeration, sludge treatment, etc) and to
45 bring the collected air into a single odour control unit in which different processes can be
46 implemented (Busca and Chiara, 2003). The most common process used is the packed towers,
47 in which pollutants are removed by chemical scrubbing (Bonnin, 1991 ; Chen et al., 2001).
48 Chemical scrubbing involves pollutant mass transfer in an aqueous phase and subsequent
49 reactions with acidic, basic or oxidant reagent(s). Most of the time, H₂S is oxidised by sodium
50 hypochlorite (NaClO) in an alkaline solution (pH ≥ 9):

51



53

54 H₂S consumption in the liquid phase allows to maintain a driving force in order to
55 achieve mass transfer. Moreover, when the reaction kinetics is fast compared to the mass
56 transfer kinetics, mass transfer enhancement is involved.

57 Chemical scrubbing in packed towers has revealed high investment and operating
58 costs (Couvert et al., 2008). Indeed, it implies the construction of high and large wet
59 scrubbers. Moreover, long and expensive pipes and powerful fans are necessary to bring the
60 waste air to the odour control unit. An alternative leading to the reduction of investment and
61 operating costs could consist in treating odorous gas near each emission source in compact
62 scrubbers in which the fluid residence time is significantly shorter. Process intensification,
63 through mass transfer and superficial velocity enhancement inside the contactor, allows to
64 decrease the reactor size and the fluid residence time.

65 The key element of the new Aquilair PlusTM process is a patented high voidage
66 contactor specially adapted to compact wet scrubbing (Sanchez et al., 2007a ; Biard et al.,
67 2009a). This down flow co-current contactor consists of a wire mesh packing structure where
68 gas flows at high velocity ($U_{SG} > 12 \text{ m}\cdot\text{s}^{-1}$). The liquid, swept along by the gas, collides with
69 the wire mesh and is dispersed into fine droplets. At the laboratory scale, high mass transfer
70 rate has been demonstrated for a moderate pressure drop (Sanchez et al., 2007b). The gas
71 residence time could be reduced to less than 50 ms instead of about 1 or 2 seconds in packed
72 towers to treat H_2S (Sanchez et al., 2007c). At the laboratory scale, an increase of the
73 superficial gas velocity (U_{SG}) and in a minor extent of the superficial liquid velocity (U_{SL}) led
74 to better interfacial area (a^0) and gas and liquid mass transfer coefficients (k_{GA}^0 and k_{LA}^0) due
75 to a higher energy loss (Sanchez et al., 2007b ; Biard et al., 2009b).

76 The aim of this study was to test the potentialities of the process at the semi-industrial
77 scale (designed to treat gas flow rates Q_G ranging between 1500 and 2000 $\text{m}^3\cdot\text{h}^{-1}$) with a real
78 gaseous effluent extracted from a WWTP. Scale-up difficulty is due to wall effects reduction
79 at larger contactor sizes, which can induce both lower liquid dispersion and mass transfer rate.
80 Between the laboratory and the semi-industrial scales, the spatial disposition of the wire
81 meshes was modified to provide higher tortuosity. Both the pressure drop (ΔP) and the H_2S
82 removal percentage were determined versus several parameters. The influence of the
83 superficial gas velocity (U_{SG}), the superficial liquid velocity (U_{SL}), the pH, the sodium
84 hypochlorite concentration of the scrubbing liquid ($[\text{ClO}^-]$) and the H_2S inlet concentration
85 ($[\text{H}_2\text{S}]_{G,i}$) was characterised. A model was developed in order to predict H_2S removal
86 efficiency and pressure drop in the scrubber.

87

88

89 MATERIALS AND METHODS

90

91 The contactor is composed of a wire mesh structure of 200 mm diameter (void fraction
92 $\approx 99.0\%$). The initial height (H_r) of the packing was 600 mm but after the first experiments,
93 the packing was compressed to 500 mm. The polluted air was pumped from the extraction
94 pipe of the WWTP with a fan (AEIB) (Figure 1). By opening a valve placed before the fan, it
95 was possible to dilute polluted air with clean air to modify the inlet H_2S concentration
96 ($[H_2S]_{G,i}$ in ppmv: Part Per Million by Volume). The gas flow rate Q_G was measured and
97 controlled by means of a Pitot Tube (Deltabar S PMD 70 from Endress Hauser) and a
98 frequency variator (Allen Bradley). The liquid injection upstream the contactor was insured
99 by a spray nozzle SpiralJet (Spraying System). A 400 L tank allowing to store the scrubbing
100 liquid and to separate the gas-liquid mixture was placed downstream the contactor. A droplet
101 separator was placed downstream the tank before emission in atmosphere (Horus
102 Environnement). The storage tank was filled with ground water previously softened. Reagents
103 (NaOCl and NaOH provided by Brenntag) were pumped from 1000 L tanks to the storage
104 tank by two metering pumps Gamma L (Prominent). The scrubbing liquid was recirculated to
105 the top of the contactor by a centrifugal pump (MDFL from Iwaki) and the liquid flow rate
106 was controlled by an electromagnetic flowmeter (Promag 10 P from Endress Hauser).

107 A bypass located after the recirculation pump allowed the measurement of the pH,
108 Redox, temperature and conductivity of the scrubbing liquid by specific probes (Endress
109 Hauser). The pH and the hypochlorite concentration of the scrubbing liquid, clean water
110 supply and drain were regulated respectively by the pH, the Redox and the conductivity
111 measurements. Pressure measurements upstream and downstream the contactor involved two
112 pressure sensors Cerabar S PMC 71 (Endress Hauser). The H_2S concentration was
113 continuously measured upstream ($[H_2S]_{G,i}$) and downstream ($[H_2S]_{G,o}$) the contactor by

114 means of two electrochemical sensors Polytron (Dräger). The H₂S removal efficiency was
115 defined as:

116

$$117 \quad \text{Eff} = \frac{[\text{H}_2\text{S}]_{\text{G,i}} - [\text{H}_2\text{S}]_{\text{G,o}}}{[\text{H}_2\text{S}]_{\text{G,i}}} = 1 - \frac{[\text{H}_2\text{S}]_{\text{G,o}}}{[\text{H}_2\text{S}]_{\text{G,i}}} \quad (2)$$

118

119 **Results and discussion**

120

121 **Influence of the hydrodynamic conditions on the pressure drop and the H₂S removal**

122

123 Through the transparent PVC pipe contactor, a strong dispersion of the liquid into
124 small droplets was observed for U_{SG} higher than 13-14 m.s⁻¹. The ratio L/G, which represents
125 the ratio of the recirculated liquid mass flow rate and the treated gas mass flow rate, is
126 generally close to 3 when H₂S is treated in packed columns (Bonnin, 1991). The pressure
127 drop ΔP was measured for 600 < Q_G < 2800 m³.h⁻¹ and 3500 < Q_L < 8000 L.h⁻¹ (L/G from 1.1
128 to 11.2). It could be observed that ΔP strongly increased with U_{SG}, since the gas is the
129 continuous phase, and with a minor extent with U_{SL} (Figure 2). This energy loss is partly
130 transferred to the liquid to achieve a better liquid dispersion and mixing. As a consequence,
131 when U_{SG} increases, mass transfer rate increases, leading to an improvement of the H₂S
132 removal efficiency (Figure 3). Hence, a compromise must be realised for the selection of U_{SG}
133 in order to limit the pressure drop to ensure the process economic viability. The pressure drop
134 per reactor height unit (ΔP/H_r) could be well correlated to the gas and liquid superficial
135 velocities U_{SG} and U_{SL}:

136

137
$$\frac{\Delta P}{H_r} (\text{Pa.m}^{-1}) = 285.7 \times U_{SG}^{1.68} \times U_{SL}^{0.47} = 11.9 \times U_{SG}^{2.15} \times \left(\frac{L}{G}\right)^{0.47} \quad (3)$$

138

139 The determination coefficient (R^2) between the experimental and the predicted
140 pressure drops is 99.94 %. However, this equation is valid only for this packing geometry and
141 diameter and should not be used for scale-up.

142 Otherwise, Figure 4 demonstrates that an increase of U_{SL} (proportional to L/G) at a
143 given gas flow rate induces a significant better H_2S removal. This evolution could be
144 attributed to a better hydrodynamic behaviour. Indeed, Sanchez et al. (2007a) demonstrated at
145 the laboratory scale that $k_L a^0$ increases with the liquid velocity (or flow rate). Moreover, L/G
146 increasing implies that more liquid flows in the contactor (the liquid hold-up increases),
147 which allows to limit the pH and hypochlorite concentration decrease due to the oxidation
148 reaction. However, increasing the liquid flow rate generates a higher pressure drop and
149 consumes more electrical power for the recirculation, which leads to a more expensive
150 operation.

151

152 **Influence of the chemical conditions on the H_2S removal**

153

154 Chemical conditions can notably influence the H_2S removal. Now, no significant
155 variation of the H_2S removal was observed when the pH varied between 9.5 and 11 (not
156 presented here). However, for a pH close to 9.5, the formation of a yellow precipitate of
157 colloidal sulphur was observed whereas for a pH close to 11, the formation of a white
158 precipitate of carbonates could be noticed (due to the reaction between NaOH and CO_2
159 present in atmospheric air). Then, all the results presented in this paper were performed with a
160 pH ranging between 10 and 10.5 (low and high pH thresholds of the regulation). Figure 4
161 demonstrates a positive influence of the sodium hypochlorite concentration on the H_2S

162 removal. When the hypochlorite concentration increases, the oxidation kinetics improvement
 163 favours H₂S oxidation in the liquid film which enhances the removal efficiency. This result is
 164 particularly interesting considering that it is a low cost operating solution comparing to an
 165 increasing of U_{SG} and U_{SL}. Several experiments were carried out for U_{SG} = 14.1 m.s⁻¹, U_{SL} =
 166 0.093 m.s⁻¹, 10 < pH < 10.5 and [ClO⁻] ≈ 3 g.L⁻¹, but with [H₂S]_{G,i} varying from 6 to 80 ppmv.
 167 The H₂S removal was not significantly different and close to 96 %. The H₂S removal is
 168 consequently independent of the inlet concentration. However, one has to keep in mind that
 169 working with high inlet concentration favours hydroxide anion and hypochlorite
 170 consumptions in the scrubber. Consequently, the amount of H₂S treated must be lower than
 171 twice the amount of hydroxide anion and 4 times the amount of hypochlorite in the scrubbing
 172 liquid at the inlet. With a classical H₂S inlet concentration in WWTP of 5-6 ppmv, it is
 173 therefore possible to reach an H₂S outlet concentration ranging between 0.1 and 0.2 ppmv,
 174 which is close to the values that deodorisation unit designers guaranty (Verguet et al., 2008).

175

176 **H₂S removal modelling**

177

178 Assuming a plug flow of the gas phase, in an elementary contactor height (dz in m),
 179 the H₂S transferred flow (dN in mol.s⁻¹) can be expressed as:

180

$$181 \quad dN = k_L a^0 E ([H_2S]_L^* - [H_2S]_L) S_{col} dz = K_L a^0 \left(\frac{[H_2S]_G}{H_{H_2S}} - [H_2S]_L \right) S_{col} dz \quad (4)$$

182

183 k_L and K_L are respectively the local and overall liquid mass transfer coefficients (m.s⁻¹)
 184 ¹, a^0 is the volumetric interfacial area (m².m⁻³), S_{col} the contactor section (m²), $[H_2S]_L^*$ the
 185 H₂S concentration in the liquid phase at the gas-liquid interface (mol.m⁻³) and $[H_2S]_L$ the H₂S

186 concentration in the bulk of the liquid ($\text{mol}\cdot\text{m}^{-3}$). $H'_{\text{H}_2\text{S}}$ is the Henry's law constant in water of
 187 H_2S at 293 K ($= 0,363 \text{ mol L}^{-1} / \text{mol L}^{-1}$). E is the enhancement factor, equal to the rate of H_2S
 188 transferred when the reaction occurs divided by the rate of H_2S transferred when no reaction
 189 occurs ($E \geq 1$). K_L is linked to k_L and k_G (the local liquid and gas mass transfer coefficients)
 190 and E by:

191

$$192 \quad \frac{1}{K_L} = \frac{1}{Ek_L} + \frac{1}{H'_{\text{H}_2\text{S}}k_G} \quad (5)$$

193

194 Oxidation of H_2S by hypochlorite at basic pH is fast and happens in the liquid film at
 195 the vicinity of the gas-liquid interface (Danckwerts, 1970). It means that H_2S is completely
 196 consumed in the liquid film by the oxidation reaction, leading to $E \gg 1$ and $[\text{H}_2\text{S}]_L \approx 0$. In
 197 this case, the first ratio of the right-hand terms of the Equation (5) may become negligible
 198 (instantaneous surface reaction) showing that all the resistance for mass transfer can be
 199 located in the gas film. However, the results demonstrated that the removal efficiency
 200 increased with the hypochlorite concentration, i.e. with the reaction kinetics, which clearly
 201 shows that a part of the resistance for mass transfer is still located in the liquid film and can
 202 not be neglected. Consequently, E must be estimated and depends on two dimensionless
 203 numbers: the Hatta number for a 2nd order kinetics (Ha) and the enhancement factor for an
 204 infinitely fast reaction (E_i) (Danckwerts, 1970):

205

$$206 \quad E = \text{Ha} = \frac{\sqrt{D_{\text{H}_2\text{S},w} [\text{ClO}^-] k_{\text{ox}}}}{k_L} \quad \text{and} \quad E_i = \frac{D_{\text{ClO}^-,w} [\text{ClO}^-]}{D_{\text{H}_2\text{S},w} [\text{H}_2\text{S}]_L^*} \quad (6)$$

207

208 k_{ox} is the apparent kinetics constant ($L.mol^{-1}.s^{-1}$) of the oxidation reaction and $D_{H_2S,w}$
 209 and $D_{ClO^-,w}$ are respectively the diffusion coefficients of H_2S ($1.6 \cdot 10^{-6} m^2.s^{-1}$) and ClO^- (1.3
 210 $10^{-6} m^2.s^{-1}$) in water. The Hatta number represents the maximum pollutant conversion in the
 211 liquid film compared with its maximum transport through the film.

212 According to usual hypochlorite concentrations in the scrubbing liquid ($> 0.1 g.L^{-1}$),
 213 hypochlorite is in great excess comparing to hydrogen sulphide at the gas-liquid interface. In
 214 this case, the kinetics is pseudo-first order and the enhancement factor E is equal to Ha
 215 considering that this last number is large (see Table 1) but significantly lower E_i (which is in
 216 the range 4 000-92 000 at the scrubber inlet, depending on $[ClO^-]$ and $[H_2S]_{G,i}$).

217 The amount of hydrogen sulphide treated in the scrubber is negligible comparing to
 218 the amount of hypochlorite at the inlet. The hypochlorite concentration, and by the way the
 219 Hatta number, are consequently constant in the scrubber, assuming that k_{ox} does not depend in
 220 a great extent of the pH which should decrease due to the hydroxide anion consumption.
 221 Therefore:

222

$$223 \quad \frac{1}{K_L} = \frac{1}{k_L \sqrt{D_{H_2S,w} [ClO^-] k_{ox}}} + \frac{1}{H'_{H_2S} k_G} = \frac{1}{\sqrt{D_{H_2S,w} [ClO^-] k_{ox}}} + \frac{1}{H'_{H_2S} k_G} \quad (7)$$

224

225 According to the Equation (7), the Equation (4) can be rewritten:

226

$$227 \quad dN = \frac{a^0}{\frac{1}{\sqrt{D_{H_2S,w} [ClO^-] k_{ox}}} + \frac{1}{H'_{H_2S} k_G}} \frac{[H_2S]_G}{H'_{H_2S}} S_{col} dz \quad (8)$$

228

229 By integration considering the height of the scrubber (H_r), an analytical equation of the
 230 overall flow of H_2S transferred is deduced:

$$231 \quad N = \frac{a^0}{\frac{H_{H_2S}}{\sqrt{D_{H_2S,w} [ClO^-] k_{ox}}} + \frac{1}{k_G}} \frac{[H_2S]_{G,i} - [H_2S]_{G,o}}{\ln([H_2S]_{G,i} / [H_2S]_{G,o})} S_{col} H_r \quad (9)$$

232
 233 The gas phase mass balance between the inlet and the outlet leads after rearrangement
 234 to the equation (10):

$$235 \quad \text{Eff} = 1 - \frac{[H_2S]_{G,o}}{[H_2S]_{G,i}} = 1 - \exp \left(- \frac{a^0}{\frac{H_{H_2S}}{\sqrt{D_{H_2S,w} [ClO^-] k_{ox}}} + \frac{1}{k_G}} \frac{H_r}{U_{SG}} \right) \quad (10)$$

236
 237 This equation shows that the removal efficiency depends on the liquid dispersed state
 238 (through a^0), the turbulences in the gas phase (through k_G) and the oxidation kinetics (through
 239 the product of $[ClO^-]$ and k_{ox}). Moreover, the efficiency is not influenced by the absorption
 240 rate and the inlet H_2S concentration while hypochlorite and hydroxide anions are in excess. At
 241 the laboratory scale (Sanchez et al., 2007b), and considering that the surface tension, density
 242 and viscosity of the scrubbing liquid are constant in the scrubber, hydrodynamic study
 243 demonstrated that a^0 is a power law function of the superficial velocities: $a^0 = A \cdot U_{SG}^\alpha \cdot U_{SL}^\beta$
 244 with A , α and β three constants. Then, the Equation (10) can be rewritten:

$$245 \quad \text{Eff} = 1 - \exp \left(- \frac{A \cdot U_{SG}^{\alpha-1} \cdot U_{SL}^\beta}{\frac{H_{H_2S}}{\sqrt{D_{H_2S,eau} [ClO^-] k_{ox}}} + \frac{1}{k_G}} H_r \right) \quad (11)$$

246

247 k_G should be influenced by U_{SG} . However, this variation can be neglected assuming
 248 that U_{SG} has been slightly modified (from 14.1 to 18.6 $m.s^{-1}$). Therefore, k_G can be considered
 249 as a constant. In the equation (11), A , α , β , k_G and k_{ox} are unknown. Due to the high H_2S
 250 oxidation kinetics, k_{ox} should be in the range $10^6 - 5 \times 10^8 L.mol^{-1}.s^{-1}$. Consequently, A , α , β
 251 and k_G have been determined (Table 1) for different values of k_{ox} in this range by numerical
 252 fitting by the least square method trying to minimise the residual:

253

$$254 \quad \text{Residual} = \frac{1}{M} \sum_{i=1}^M \left(\frac{\text{Eff}_{\text{exp}} - \text{Eff}_{\text{mod}}}{\text{Eff}_{\text{mod}}} \right)^2 \text{ with } M = 18 \text{ the number of experimental data} \quad (12)$$

255

256 The model correlates with a good agreement the experimental results whatever the
 257 value of k_{ox} selected with an average error lower than 1 % (Table 1). It demonstrates that
 258 assuming k_G as a constant is not aberrant. When the selected value of k_{ox} decreases, a^0
 259 increases to compensate the lower enhancement by chemical reaction. At the laboratory scale,
 260 for similar superficial velocities, the average interfacial area and gas side mass transfer
 261 coefficient were respectively in the range of 1500-2000 $m^2.m^{-3}$ and 0.1-0.2 $m.s^{-1}$. These
 262 values would be reached at the semi-industrial scale for a k_{ox} equal to $6 \times 10^6 L.mol^{-1} s^{-1}$.
 263 However, this value should be considered with care since the scale difference between the
 264 laboratory and this study (and consequently the difference of Reynolds Number) may lead to
 265 significant variations of the ranges of a^0 and k_G .

266

267 **Pressure drop and removal efficiency simulations**

268

269 Using Equations (3) and (11), simulations of the pressure drop and the removal
 270 efficiency for different operating conditions can be achieved. In order to limit the operating

271 cost of the process, a low value of U_{SG} (but sufficient to insure a strong liquid dispersion \Rightarrow
272 $U_{SG} > 13 \text{ m.s}^{-1}$) must be selected. Consequently, two simulations have been realised at 13.3
273 and 14.1 m.s^{-1} (respectively 1500 and $1600 \text{ m}^3.\text{h}^{-1}$) using $k_{ox} = 6 \times 10^6 \text{ L.mol}^{-1}.\text{s}^{-1}$ (Figure 5).
274 The choice of the quintet A, a, b, k_G and k_{ox} does not influence the results of the simulation.
275 Simulations confirm that the removal efficiency increases significantly with the hypochlorite
276 concentration when lower than 3 g.L^{-1} . Moreover, the removal efficiency increases strongly
277 with the L/G ratio until 5. Using a hypochlorite concentration and a L/G ratio higher than 3
278 g.L^{-1} and 5 is not necessary whatever the gas superficial velocity. Using such operating
279 conditions, the removal efficiency reaches 95 % for a moderate pressure drop which remains
280 lower than 3500-4000 Pa (maximal pressure drop to insure the process economic viability).

281

282 **CONCLUSION**

283

284 A new compact chemical scrubber was implemented in a WWTP. Results showed that
285 both hydrodynamic and chemical conditions significantly influence the H_2S removal. A
286 model was developed to predict the pressure drop and the H_2S removal at any given operating
287 condition. An interesting economic compromise was deduced for a moderate gas velocity and
288 a high hypochlorite concentration. The new packing has not been optimised yet and some
289 improvement of the structure would certainly offer a lower pressure drop for a similar mass
290 transfer rate. To insure a high level of deodorisation, two scrubbers in series could be
291 implemented but the increasing of the pressure drop must be taken into account.

292

293 **NOMENCLATURE**

294	[A]	concentration of the compound A
295	A, α and β	coefficients determined by numerical resolution
296	a^0	interfacial area related to the volume of the contactor ($\text{m}^2 \cdot \text{m}^{-3}$)
297	$D_{\text{H}_2\text{S},\text{w}}$	diffusion coefficient of H_2S in water ($\text{m}^2 \cdot \text{s}^{-1}$)
298	dz	infinitesimal height of contact (m)
299	E	enhancement factor
300	E_i	enhancement factor for an infinitely fast reaction
301	Eff	H_2S removal efficiency (%)
302	Ha	Hatta number
303	$H'_{\text{H}_2\text{S}}$	H_2S Henry's constant in water
304	H_r	height of the contactor (m)
305	k_G (K_G)	(overall) gas phase mass transfer coefficient ($\text{m} \cdot \text{s}^{-1}$)
306	k_L (K_L)	(overall) liquid phase mass transfer coefficient ($\text{m} \cdot \text{s}^{-1}$)
307	k_{Ga}^0 (K_{Ga}^0)	(overall) gas phase volumetric mass transfer coefficient (s^{-1})
308	k_{La}^0 (K_{La}^0)	(overall) liquid phase volumetric mass transfer coefficient (s^{-1})
309	k_{ox}	kinetics constant of H_2S oxidation by hypochlorite at basic pH ($\text{L} \cdot \text{mol}^{-1} \cdot \text{s}^{-1}$)
310	L/G	ratio of liquid and gas mass flow rates
311	N (dN)	(infinitesimal) flow of H_2S transferred ($\text{mol} \cdot \text{s}^{-1}$)
312	Q_G (Q_L)	gas (liquid) volume flow rates ($\text{m}^3 \cdot \text{h}^{-1}$ or $\text{m}^3 \cdot \text{s}^{-1}$)
313	S_{col}	section of the contactor (m^2)
314	U_{SG} (U_{SL})	gas (liquid) superficial velocity ($\text{m} \cdot \text{s}^{-1}$)
315	WWTP	Waste Water Treatment Plant
316		
317		

318 Greek letters

319 ΔP pressure drop (Pa)

320 Indices

321 i inlet

322 G gas

323 L liquid

324 o outlet

325 * interface

326

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364 **Figure captions**

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366 Figure 1. Set-up scheme.

367 Figure 2. Pressure drop inside the scrubber versus U_{SG} for different U_{SL} ($Q_L = 3.5, 5.0, 6.5$

368 and $8.0 \text{ m}^3 \cdot \text{h}^{-1}$).

369 Figure 3. H_2S removal and pressure drop versus U_{SG} ($L/G = 3.5$; $40 < [\text{H}_2\text{S}]_{G,i} < 50$ ppmv ;

370 $[\text{ClO}^-] \approx 1.5 \text{ g} \cdot \text{L}^{-1}$; $10 < \text{pH} < 10.5$).

371 Figure 4. H_2S removal and pressure drop versus L/G ($U_{SG} = 15 \text{ m} \cdot \text{s}^{-1}$; $40 < [\text{H}_2\text{S}]_{G,i} < 50$ ppmv

372 ; $10 < \text{pH} < 10.5$).

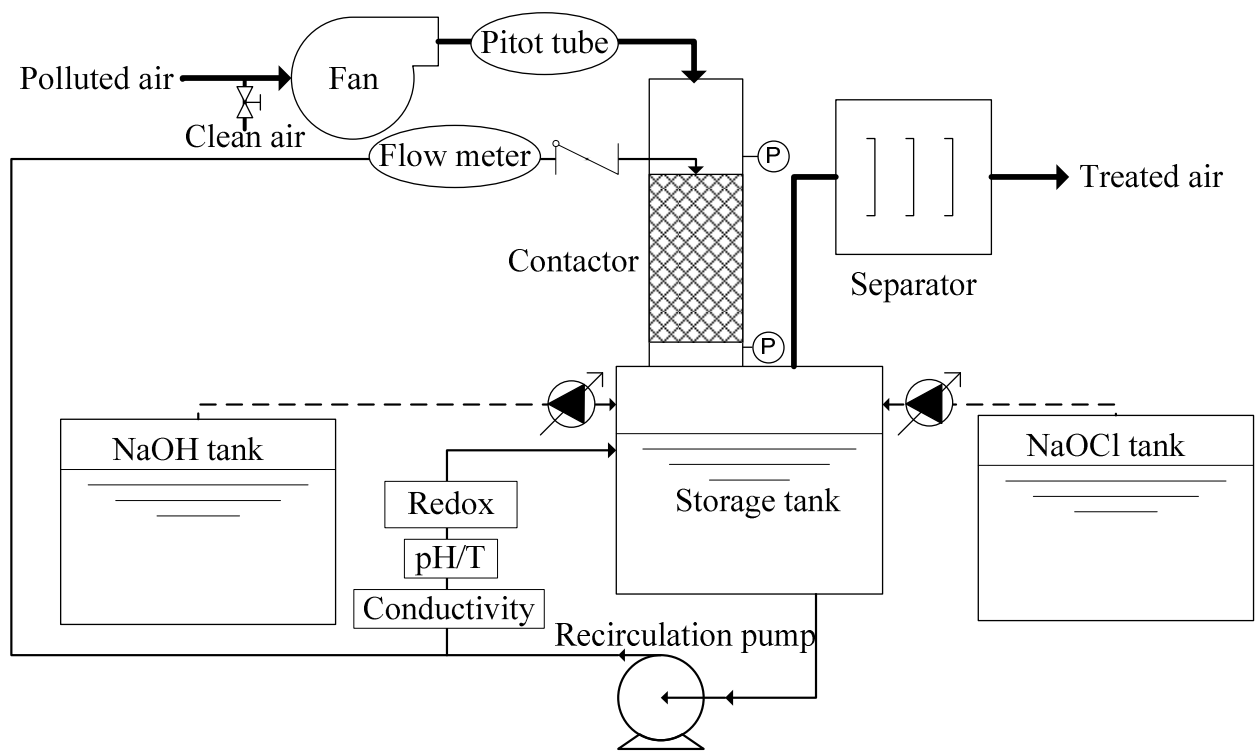
373 Figure 5. Simulation of H_2S removal and pressure drop for two gas superficial velocities (U_{SG}

374 = $13.3 \text{ m} \cdot \text{s}^{-1}$ ($Q_G = 1500 \text{ m}^3 \cdot \text{h}^{-1}$) and $14.1 \text{ m} \cdot \text{s}^{-1}$ ($Q_G = 1600 \text{ m}^3 \cdot \text{h}^{-1}$)) for $2 \leq L/G \leq 6$ and $1 \leq$

375 $[\text{ClO}^-] \leq 4 \text{ g} \cdot \text{L}^{-1}$.

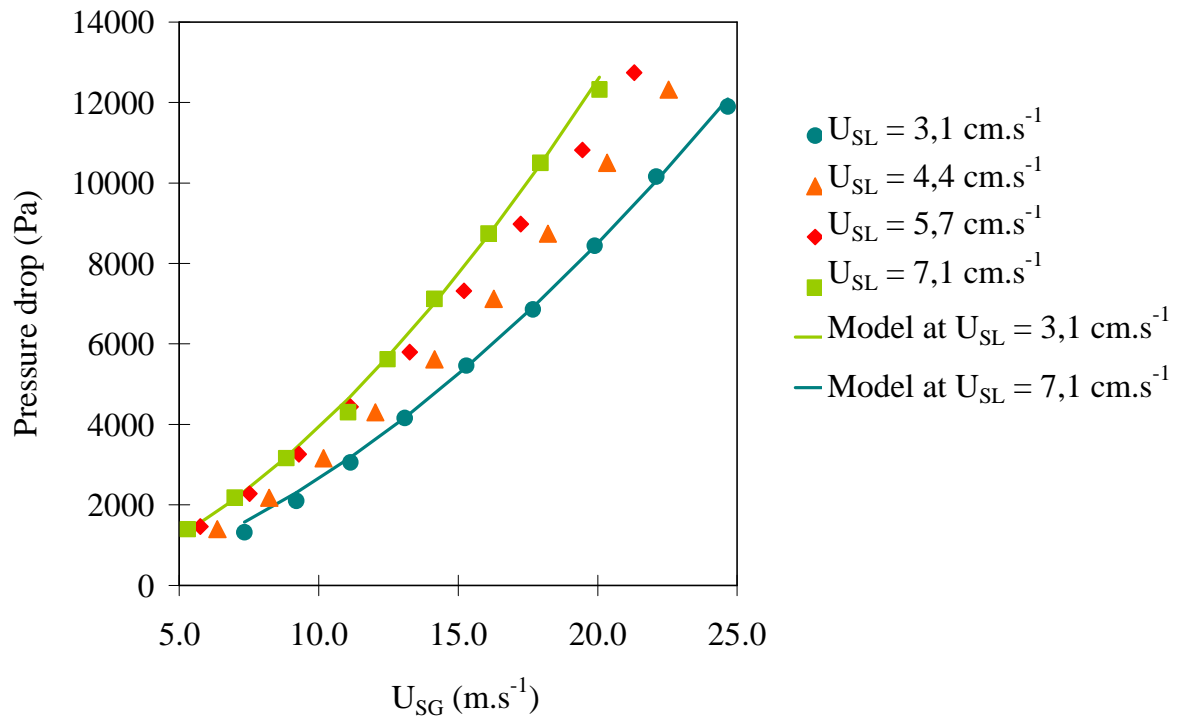
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Figure 1

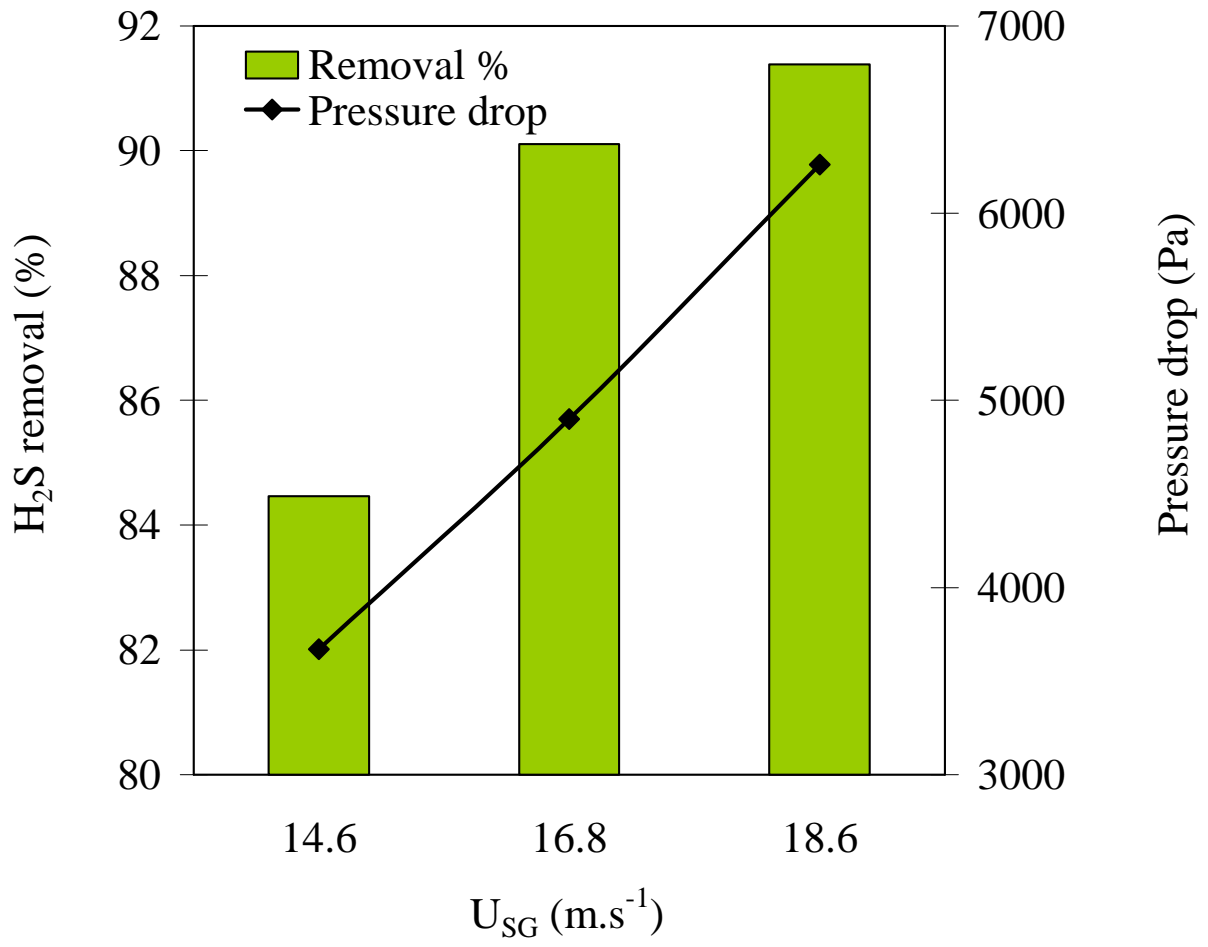


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Figure 2



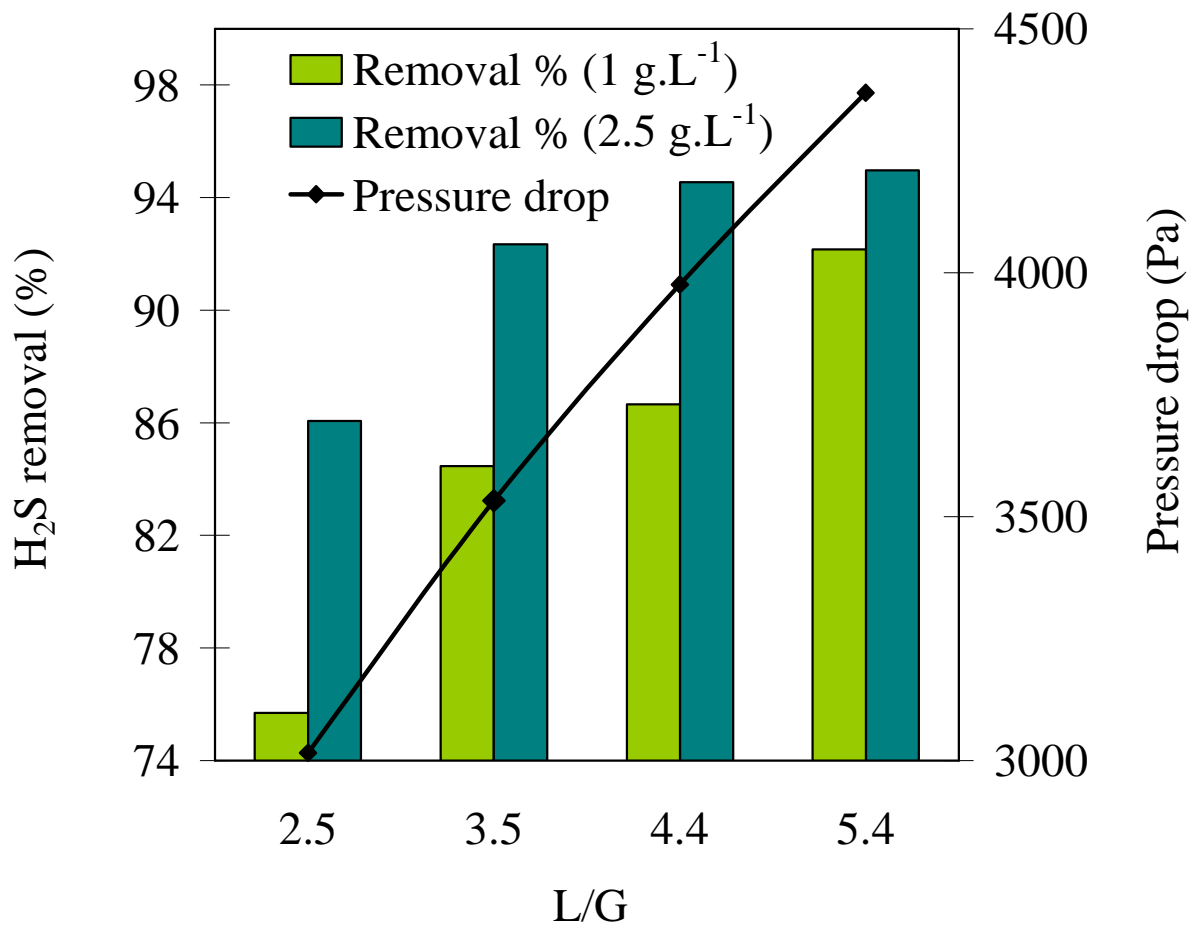
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Figure 3

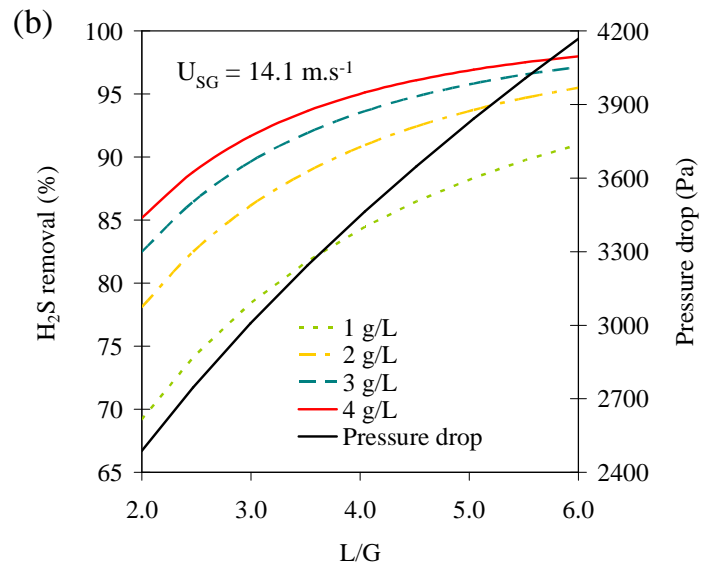
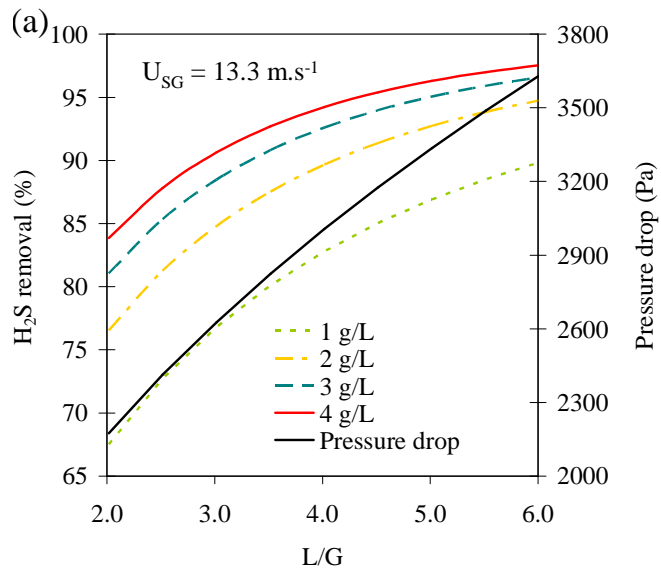


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Figure 4



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Figure 5

394 Table 1. Hatta range values (considering $k_L = 10^{-4} \text{ m.s}^{-1}$) and results of the numerical fitting
 395 for several values of k_{ox} .

396

$k_{ox} (\text{L.mol}^{-1}.\text{s}^{-1})$	1.0×10^6	6.0×10^6	1.0×10^7	1.0×10^8	5.0×10^8
Hatta range	80-116	195-285	250-370	790-1 160	1 770-2 600
A	205.06	146.98	118.43	47.67	25.85
α	1.61	1.45	1.44	1.37	1.21
β	0.59	0.61	0.61	0.62	0.64
$k_G (\text{m.s}^{-1})$	0.14	0.24	0.31	0.85	2.07
a^0 average ($\text{m}^2.\text{m}^{-3}$)	3 636	1 575	1 225	398	135
$k_G a^0$ average (s^{-1})	510	378	380	338	277
R^2 (%)	97.44	97.97	97.99	98.06	97.94
Average error (%)	0.83	0.72	0.71	0.67	0.68

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