



Recovery comparisons—Hot nitrogen V_5 steam regeneration of toxic dichloromethane from activated carbon beds in oil sands process

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ABSTRACT

The regeneration experiments of dichloromethane from activated carbon bed had been carried out by both hot nitrogen and steam to evaluate the regeneration performance and the operating cost of the regeneration step. Factorial Experimental Design (FED) tool had been implemented to optimize the temperature of nitrogen and the superficial velocity of the nitrogen to achieve maximum regeneration at an optimized operating cost. All the experimental results of adsorption step, hot nitrogen and steam regeneration step had been validated by the simulation model PROSIM. The average error percentage between the simulation and experiment based on the mass of adsorption of dichloromethane was 2.6%. The average error percentages between the simulations and experiments based on the mass of dichloromethane regenerated by nitrogen regeneration and steam regeneration were 3 and 12%, respectively. From the experiments, it had been shown that both the hot nitrogen and steam regeneration had regenerated 84% of dichloromethane. But the choice of hot nitrogen or steam regeneration depends on the regeneration time, operating costs, and purity of dichloromethane regenerated. A thorough investigation had been made about the advantages and limitations of both the hot nitrogen and steam regeneration of dichloromethane.

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1. Introduction

Dichloromethane is widely used as a solvent in bitumen separation to separate high hydrocarbon content from oil sands [1]. After the separation of bitumen, the removal of dichloromethane in gaseous form pollutes the environment and it also causes serious carcinogenic effects on human beings [1,2]. Adsorption experimental simulation studies for dichloromethane had been already made [3–6] but the comparison studies on the types of hot and steam regenerations of dichloromethane had not been established [7]. In the case of cyclohexanone, nitrogen regeneration had higher regeneration efficiencies in comparison with steam regeneration [8]. Nitrogen regeneration had always kept the bed dry and so the adsorption capacities would not be affected once after the regeneration [8]. The occurrence of bed fires was highly unlikely in the case of nitrogen regeneration compared with the steam regeneration [8].

Steam is readily available in industries and also it could be produced relatively at low cost [8]. Steam has regenerated very well the hydrophobic organics like chlorinated solvents and then they are separated by gravity after condensation. Steam had been less preferred to hydrophilic contaminants like alcohols, aldehydes, and ketones [9]. Steam regeneration had been proven to be very effective and economical to regenerate activated carbons and hydrophobic zeolites [9]. The regeneration of organic compounds (P-dichlorobenzene and Methyl Ethyl Ketone) from Ambersorb 563 commercial adsorbent by using steam at 160 °C had been successful for six cycles. It was also reported that there was no significant degradation in the organics of adsorbent [10].

The temperature distribution along the bed in case of steam regeneration was uniform unlike using nitrogen gas for regeneration [11]. Drying is an important step after the steam regeneration, because the moisture left in the bed could dramatically affect the successive adsorption capacity and the operational performances [12]. When the bed was hot right after the regeneration, the ambient air had been passed through the bed and so that drying was faster at the beginning [12]. When the temperature dropped down, the drying could be slow because of the heat exchange between the ambient air and the heat stored in the bed [12]. To overcome this

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Nomenclature

a_p	ratio between the external surface and the volume of the particle (m^{-1})
b_0	parameter of the model (atm^{-1})
b_1	parameter of the model (T^{-1})
C_{p_a}	specific heat capacity of adsorbed phase ($J kg^{-1} K^{-1}$)
C_{p_p}	specific heat capacity of the adsorbent ($J kg^{-1} K^{-1}$)
C_i	VOC concentration in the gas phase ($mol m^{-3}$)
C_{p_g}	specific heat capacity of gas phase ($J kg^{-1} K^{-1}$)
D_L	axial mass dispersion coefficient ($m^2 s^{-1}$)
D_{gl}	global mass transfer coefficient ($m^2 s^{-1}$)
d_c	diameter of the column (m)
D_L	diffusivity ($m^2 s^{-1}$)
D_H	axial heat dispersion coefficient ($J m^{-1} s^{-1}$)
d_p	equivalent particle diameter (m)
e	thickness of the column (m)
H	enthalpy of gas phase ($J kg^{-1}$)
h_w	heat transfer coefficient of wall ($W m^2 K^{-1}$)
h_p	heat transfer coefficient with solid particle ($W m^2 K^{-1}$)
ΔH_i	enthalpy of adsorption/desorption of the compound i ($J mol^{-1}$)
ΔH_{vap}	latent heat of vaporization ($kJ mol^{-1}$)
K_f	external mass transfer coefficient ($m s^{-1}$)
K	global mass transfer coefficient (s^{-1})
PI	VOC ionization potential (eV)
P_i	equilibrium VOC partial pressure (atm)
q_i	adsorbed VOC concentration ($mol kg^{-1}$)
q_i^*	adsorbed VOC concentration at the equilibrium with the gas phase ($mol kg^{-1}$)
q_i^*	VOC adsorbed quantity at the equilibrium ($mol kg^{-1}$)
q_{m0}	parameter of the model ($mol kg^{-1}$)
q_{m1}	parameter of the model (T^{-1})
q_i	VOC concentration in the adsorbed phase ($mol kg^{-1}$)
r_p	particle equivalent radius (m)
r_{mic}	adsorbent average micropore opening (nm)
T	temperature of gas ($^{\circ}C$)
T_p	temperature of solid particle ($^{\circ}C$)
v	superficial velocity ($m s^{-1}$)
V_m	molar VOC volume ($m^3 mol^{-1}$)
v	superficial gas velocity ($m s^{-1}$)
y	VOC molar fraction in the gas
ρ_p	bulk adsorbent density ($kg m^{-3}$)
ρ_g	density of gas phase ($kg m^{-3}$)
ε	bed porosity
λ	thermal conductivity of the material of the column ($W/m/K$) α – VOC polarizability ($10^{-24} cm^3$)
γ	surface tension of the liquid solvent ($mN m^{-1}$)
μ	kinematic viscosity (Pa s)

problem, the adsorption column was heated by a heat exchanger. Once after drying, the bed had been cooled down by circulating water around the column. The heating also reduces the time taken for the regeneration, and so it improves the performance of regeneration [12].

In this study, a Factorial Experimental Design [13] (FED) had been used to change the operating conditions (such as temperature of nitrogen and the superficial velocity of nitrogen) to achieve the maximum regeneration efficiency and optimized operating cost during the nitrogen regeneration cycle. FED had acted as a tool to understand the influence of the operating conditions and also to optimize the best operating conditions for regeneration of

dichloromethane. Finally, the experimental results of adsorption and regeneration were validated by the simulation model which was developed in close co-operation with the company PROSIM. The objectives of this study are (1) to evaluate and compare the performances and the operating costs of hot nitrogen and steam regeneration; (2) to validate the experimental results of adsorption and regeneration by simulation model PROSIM.

2. Theoretical model

The cyclic adsorption–desorption process was simulated by solving the mass and energy balances during each step. The main equations and assumptions which were used are described below:

2.1. Mass balance [3]

$$-D_L \frac{\partial^2 C_i}{\partial z^2} + \frac{\partial(vC_i)}{\partial z} + \frac{\partial C_i}{\partial t} + \frac{1-\varepsilon}{\varepsilon} \rho_p \frac{\partial q_i}{\partial t} = 0 \quad (1)$$

2.2. Linear driving force model (LDF) [3]

The adsorption or desorption kinetics were described according to the linear driving force model:

$$\frac{\partial q_i}{\partial t} = K.(q_i^* - q_i) \quad (2)$$

The effective resistance to the mass transfer between the gas and the solid phases embodies the partial resistance to the mass transfer at the external surface of the particles and the internal mass transfer resistance, expressed as a function of an effective diffusion coefficient D_{gl} [3]:

$$\frac{1}{K} = \frac{\rho_p V_m q_i^*}{K_f a_p y} + \frac{r_p}{5D_{gl} a_p} \quad (3)$$

The external mass transfer coefficient K_f was derived from the correlation from Petrovic and Thodos [20]. The effective diffusion coefficient takes into account the various diffusion mechanisms which control the migration of the organic component to the adsorption sites (porous, Knudsen, and surface diffusion). It is considered as an adjustable parameter. As a first approximation, the global mass transfer resistance data were considered to be unchanged in the desorption step.

2.3. Equilibrium model

The value q_i^* in the linear driving force model (LDF) is computed from the modified Langmuir isotherm model, taking into account the temperature effect on the equilibrium data. The parameters of the modified Langmuir equation were based on the experimental data measured for the dichloromethane – ACV 404 activated carbon system at four different temperatures (20, 40, 60 and 80 °C). For the isotherm experiments, ten glass reactors each of 2.1 l size had been taken. In each reactor, 0.2 g of activated carbon hung on a hook inside the reactor. The concentration of the dichloromethane had been changed in each reactor by adjusting the injected volume of dichloromethane. The range of dichloromethane was from 20 to 400 μ l. Then after the saturation of adsorption of dichloromethane on activated carbon, the concentration in the reactor was measured by using a Gas Chromatography. So the adsorption capacity in each reactor can be calculated from the product of concentration change of dichloromethane and the volume of the reactor which was divided by the mass of the activated carbon. The R-Stat [14] statistical software package was used to check the significance of

Table 1
Langmuir isotherm coefficients results.

Langmuir model coefficients – dichloromethane – ACV404 system			
q_{m0} (mol kg ⁻¹)	q_{m1} (T ⁻¹)	k_1 (T ⁻¹)	k_0 (atm ⁻¹)
3.52	278.86	3086.63	0.004

the computed parameters using an interval of confidence of 95% by Student's *t*-test. The results are summarized in Table 1:

$$q_i^* = \frac{q_{m0} \exp(q_{m1}/T) k_0 \exp(k_1/T) P_i}{1 + k_0 \exp(k_1/T) P_i} \quad (4)$$

2.4. Enthalpy balances [3]

- In the gas phase:

$$-\rho_g D_L \frac{\partial^2 H}{\partial z^2} + \varepsilon \rho_g \frac{\partial H}{\partial t} + \varepsilon \frac{\partial(v \rho_g H)}{\partial z} + 4 \frac{h^w}{d_c} (T - T_w) + (1 - \varepsilon) \frac{6h^p}{d_p} (T - T_p) = 0 \quad (5)$$

- In the solid phase [3]:

$$(\rho_p C_{p_p} + \rho_p C_{p_a}) \frac{\partial T_p}{\partial t} + \frac{6h^p}{d_p} (T_p - T) + \Delta H_i \rho_p \frac{\partial q_i}{\partial t} = 0 \quad (6)$$

The adsorption enthalpy was derived according to the following statistical predictive model [15]:

$$-\Delta H_{ads} = 103.2 + 1.16\alpha + 0.76\Delta H_{vap} - 3.87PI - 0.7\gamma - 26.19r_{mic} \quad (7)$$

As a first approximation, the integral enthalpy of desorption was assumed to be equal to the one computed for the adsorption. The heat transfer terms were included in of the energy balances for both

the solid and the gas phase to represent the heat transfer during the regeneration step.

2.5. Ergun's pressure drop equation [3]

$$\frac{\partial P}{\partial z} + 150 \times 10^{-5} \left(\frac{1 - \varepsilon}{\varepsilon} \right)^2 \frac{\mu}{d_p^2} v + 1.75 \times 10^{-5} \left(\frac{1 - \varepsilon}{\varepsilon} \right) \frac{\rho_g}{d_p} v^2 = 0 \quad (8)$$

The effect of pressure drop on the dynamic behavior of the adsorption and regeneration steps has been considered in the simulation model by Ergun's equation.

3. Experimental

3.1. Characterization of activated carbon

The activated carbon was activated physically. The raw material of the activated carbon is coconut. The physical properties of the activated carbon (CECA – ACV404) such as B.E.T. surface specific area, micropore volume (by Horvath-Kawazoe method), micropore average width (by Density Functional Theory) were measured by nitrogen adsorption isotherm at 77 K (Micromeritics ASAP 2010) [16]; the mesopore and macropore volume, and bulk density were measured by using mercury porosimeter (Micromeritics Autopore IV 9500) [17]. Finally the ratio of oxygen to carbon was measured using an elemental analyzer (ThermoFinnigan Flash EA1112 CHNS-O Analyzer) [18]. The properties resumed in Table 2 were used in simulation models of adsorption and regeneration.

3.2. Experimental setup

Fig. 1 shows the experimental setup which has the thermal swing adsorption and regeneration. It has an adsorption column with the dimension of 0.275 m high × 0.05 m internal diameter. Thermal couples are located at 3 various ports (at 2 cm, 19 cm

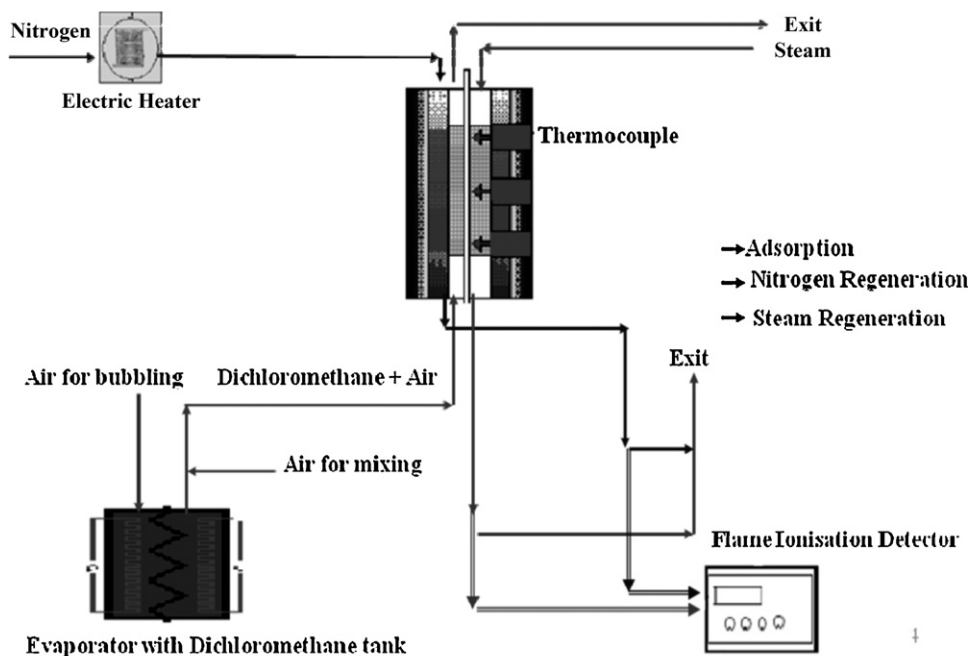


Fig. 1. Experimental setup of dynamic temperature swing adsorption pilot plant.

Table 2
Characteristics of the activated carbon ACV404.

Activated carbon	Micropore size (nm)	Bulk density (mg l^{-1})	Micropore volume ($\text{cm}^3 \text{g}^{-1}$)	BET surface area ($\text{m}^2 \text{g}^{-1}$)	Total volume ($\text{cm}^3 \text{g}^{-1}$)
ACV 404	0.67	0.53	0.54	1256	0.60

and 25 cm from the top of the column) in the column to record the temperature data during adsorption and regeneration cycles. In the event to avoid heat losses, the column was insulated by 2 cm thick glass wool. During the adsorption step, 30 g m^{-3} of dichloromethane was prepared by the VOC generating system (includes the two air streams, one for lifting the vapors of dichloromethane in the reservoir and the other for dilution, and enters the column at temperature = 25.8°C). Once after the adsorption step, there were two modes of regeneration: (1) hot nitrogen; (2) steam regeneration as presented in Fig. 1.

FED has allowed to construct 2×2 design by changing the operating conditions such as temperature of the nitrogen in the range [$130 < T < 170^\circ\text{C}$] and the superficial velocity of the nitrogen in the range [$0.10 < v < 0.17 \text{ m s}^{-1}$]. By doing Analysis of Variance (ANOVA) for the four experiments of regenerations with the statistical analysis software MINITAB, the regeneration efficiency (R_E) and the operating cost (OP_ϵ) are measured as a function of the operating conditions (T , v) by a mechanistic model.

For the steam regeneration, a MAC STM series flow meter had been engaged to measure the volumetric flow rate of hot steam. The pressure of the hot steam at the entrance of the column could be adjusted to 2.7 bars. By adjusting the flow rate to 2.7 bars, the steam flow rate is equivalent to 0.833 g s^{-1} at 140°C and it could be seen in MAC STM series flow meter. Before starting the steam regeneration of dichloromethane, the flow of condensed steam was measured by the presence of activated carbon in the bed. The dichloromethane which was regenerated later will come along with steam (total flow). So the volume of the dichloromethane could be measured from the difference of the volume of total flow and condensed steam. And it had been also cross checked because of the insolubility of dichloromethane with water [20]. This method of measuring dichloromethane has been implemented, because of the measuring troubles caused by the steam, which were condensed along the FID ports on the column and enters the opening of the FID.

4. Results and discussion

4.1. Adsorption step

The dynamic adsorption capacity was calculated by the ratio of mass of dichloromethane adsorbed to the mass of activated carbon in the column. The dynamic adsorption capacity was found to be 35% of the mass of dichloromethane adsorbed. It could also be represented as 4.02 mol kg^{-1} . This dynamic adsorption capacity value could be compared with the equilibrium isotherm adsorption capacity at 20°C to justify that there is not a significant deviation between the dynamic and the static state of adsorption. The value of equilibrium isotherm adsorption capacity was 4.2 mol kg^{-1} and so the error percentage was 4.3%. The breakthrough time was calculated at the point, when the concentration at the exit of the column reaches 10% of the initial concentration (30 g m^{-3}). So it was found to be 80 min. Fig. 2 shows the breakthrough curve of the experimental (Exp) and the simulation (Sim) results. From Fig. 2, it was clear that the simulation model predicts well the experimental points to give the similar breakthrough time and adsorption capacity. But there was dispersion at 90 min between the experimental and simulation points. From this point, the simulation model under predicts the mass transfer coefficient of the gas to the solid compared to the

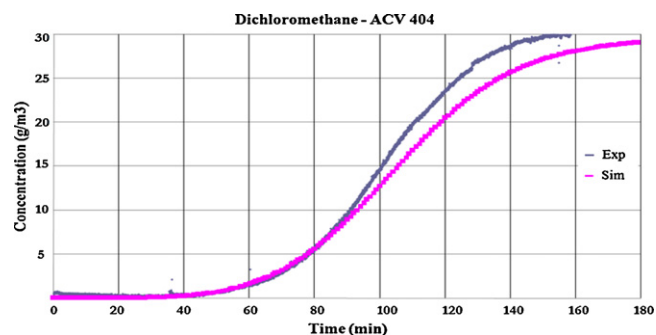


Fig. 2. Breakthrough curve profile of experiment and simulation.

experimental points. Fig. 3 shows an example of the exit temperature profile of the adsorption of dichloromethane on ACV 404. In general there was only a negligible temperature difference of 2°C between the simulation model and the experiment.

4.2. Hot nitrogen regeneration step

Table 3 summarizes all the operating conditions of the hot nitrogen regeneration experiments and the corresponding results such as regeneration efficiency (R_E), operating cost (OP_ϵ). The regeneration efficiency was calculated by the ratio of mass of dichloromethane regenerated to the mass of the dichloromethane adsorbed. The average regeneration rate (ΣR_R) was calculated (see Table 3) to represent as the average speed of regeneration during the cycle of 60 min. The operating cost was calculated on the basis of the nitrogen consumption (0.18 € m^{-3} , Supplier – Air Liquide) and the energy costs for heating nitrogen (60 € Mw h^{-1} , French electricity tariff). The signs (+) and (–) in Table 3 indicates the two ranges of the operating conditions for the FED and they were chosen based on the preliminary experiments. Since it was a 2×2 FED, there had been 4 regeneration experiments (Reg.1, Reg.2, Reg.3, and Reg.4) as shown in Table 3. Regeneration experiment Reg.5 (=) (acts as a central point of the FED) had been performed to check the statistical validity of the mechanistic model obtained by performing ANOVA on the regeneration experiments Reg.1, Reg.2, Reg.3, and Reg.4. Regeneration time was always fixed at 60 min for all cycles. The mechanistic models for evaluating regeneration efficiency (R_E)

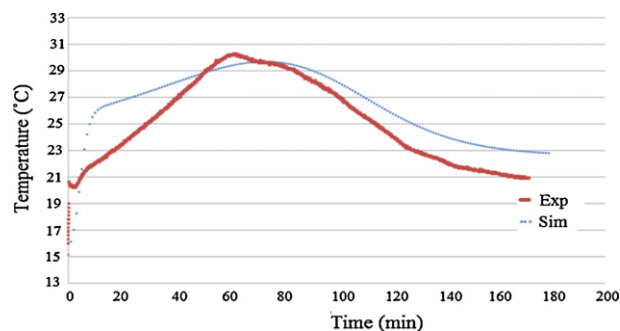


Fig. 3. Temperature profile of experimental and simulation results of adsorption.

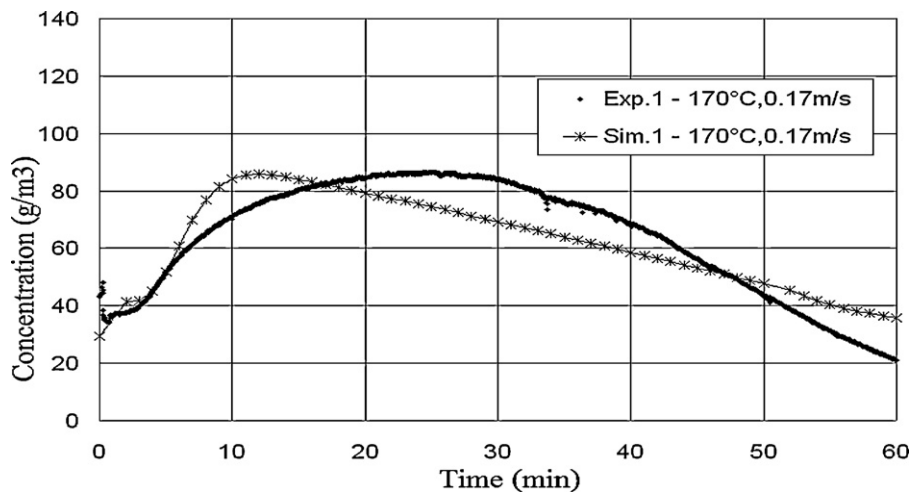


Fig. 4. Regeneration concentration profile of experiment and simulation.

and the operating cost (OP_{ϵ}) obtained by doing an ANOVA with the MINITAB software were as follows:

$$R_E\% = 64.7 + 7.15.T + 11.15.v + 1.8.T.v \quad (9)$$

$$OP_{\epsilon}(\epsilon/\text{kg}) = 3.79 - 0.41.T + 0.11.v - 0.05.T.v \quad (10)$$

From Eq. (9), it could be concluded that the superficial velocity of the nitrogen (v) has influenced more on achieving higher regeneration than the nitrogen temperature (T). The influence could be compared by the coefficient of the corresponding coefficients of the operating conditions (T, v) in Eq. (9). From Eq. (10), it could be concluded that the increase in temperature of nitrogen has decreased the operating cost. This was due to the fact of increasing the temperature had increased the regeneration of dichloromethane and decreased the regeneration time. The decrease in regeneration time has strictly implied less consumption of nitrogen. Regeneration experiment Reg.5 had the operating conditions in the central point of FED ($T = 150^\circ\text{C}$, $v = 0.136\text{ m s}^{-1}$). The experimental results were compared with the mechanistic models and the error percentage of the mass of regeneration is 3.5%. This shows that the mechanistic model was really statistically and realistically consistent with the range of operating conditions chosen. An example of simulation results of regeneration concentration and temperature profile has been shown in Figs. 4 and 5. The average error percent of the mass of dichloromethane regenerated between the simulations and the experiments was 2.7%. It had been noticed in Fig. 4, there has been a delay in the regeneration concentration profile of the experimental in comparison with the simulation results. This was due to the fact of overestimation of the effective mass transfer coefficient of solid to gas (K) in the simulation model. The adjustable effective mass transfer coefficient (K) had been optimized to the best fit of the simulation curve.

There were T1, T2, and T3 thermocouples which have recorded at the 4 ports of the column (at $x = 2, 19$ and 25 cm). The simulation and the experimental readings are marked are 'Exp' and 'Sim',

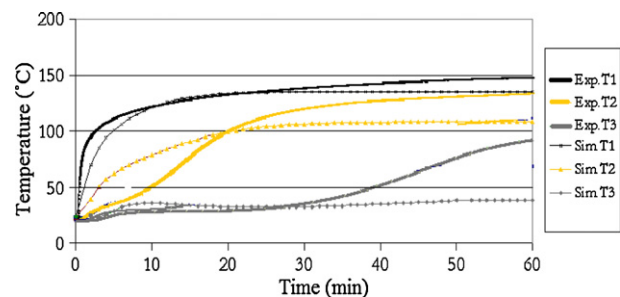


Fig. 5. Nitrogen regeneration temperature profile of Reg.1 at 170°C and 0.17 m s^{-1} .

respectively in the above Fig. 5. In Fig. 5, the rise in temperature profile in the simulation was faster than in the experiment. This explains the delay in the regeneration concentration profile of the experiment in comparison with the simulation.

4.3. Steam regeneration step

For the steam regeneration, the temperatures of steam (T_s) were varied as 140 and 200°C , and the flow rate of the steam (V_s) was kept constant at 0.833 g s^{-1} by adjusting the pressure. The following Table 4 summarizes the operating conditions and the results obtained by the steam regeneration. The operating cost was calculated on the basis of energy required for the steam (2722 kJ/kg of steam, NIST) [19], electricity tariff in France (60€ Mw h^{-1}), cost of drying (drying time = 1 h), and cost of water (used for the production of steam) in France (3€ m^{-3}). The heating cost during drying step had been calculated based on the amount of heat energy spent to eliminate the moisture in the bed by passing hot air.

Figs. 6 and 7 show an example of the steam regeneration concentration and temperature profile, respectively. In Fig. 6, the regeneration profile was obtained by the simulation model. From

Table 3
Regeneration operating conditions and results.

Regeneration experiments	Operating conditions		Regeneration % $R_E\%$	Operating cost $OP_{\epsilon}(\text{€}/\text{kg})$	Avg. reg. rate $\Sigma RR(\text{g min}^{-1})$
	$T(^{\circ}\text{C})$	$V(\text{m/s})$			
Reg.1	170 (+)	0.17 (+)	84.8	3.44	1.30
Reg.2	170 (+)	0.10 (–)	58.9	3.31	0.88
Reg.3	130 (–)	0.17 (+)	66.9	4.35	1.00
Reg.4	130 (–)	0.10 (–)	48.2	4.04	0.72
Reg.5	150 (=)	0.14 (=)	66.5	3.68	0.99

Table 4
Steam regeneration operating conditions and results.

Operating conditions			Regeneration time (min)	Dichloromethane regenerated		OP _e (€ kg ⁻¹)	ΣRR (g min ⁻¹)
Exp	T _s (°C)	V _s (g s ⁻¹)		Experiment%	Simulation%		
Reg.1	140	0.833	16	82.3	72.2	0.85	0.96
Reg.2	200	0.833	14	82.3	72.2	0.87	0.99

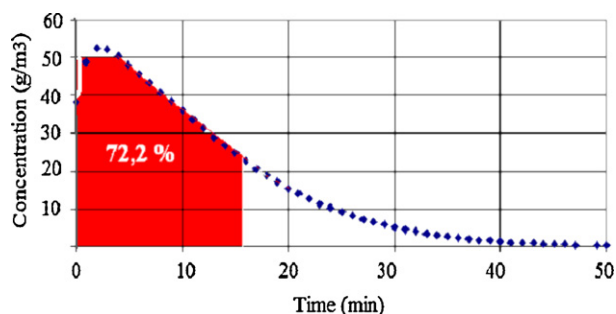


Fig. 6. Steam regeneration concentration profile of Reg.1 at 140 °C and 3 kg h⁻¹.

the results in Table 4, the simulation model had predicted the regenerated dichloromethane less than the experimental results and the error percentage of the mass of dichloromethane regenerated between the simulation and the experiment is 12%. This error could be due to the absence of the effect of enthalpy of latent heat of change of phase from steam to water in the simulation model. This energy would have decreased the error difference between the simulation and experiment.

From the above Fig. 7, the temperature rise during the steam regeneration was uniform along the bed in contrary to the nitrogen regeneration in Fig. 4. From the results in Tables 3 and 4, the nitrogen regeneration had been favorable in terms of achieving slightly higher regeneration efficiency (84.8%) and higher average regeneration rate (1.3 g min⁻¹) compared to the steam regeneration. Also there was no presence of humidity after the nitrogen regeneration, which has kept the successive adsorption cycle retaining 100% adsorption capacity [9]. Since nitrogen is inert, it would regenerate high purity of dichloromethane [9]. Although, nitrogen regeneration was very effective in achieving slightly higher regeneration, but the operating cost was four times higher of the steam regeneration. And also, after the nitrogen regeneration, the step of separation of dichloromethane from nitrogen adds an additional cost. In the case of steam regeneration, it has proved that the regeneration of dichloromethane was effective (82.3%) at a short time (16 min). But the drying step (which includes cooling time of bed) added an additional time of 1 h to retain the bed completely dry, which has decreased the average regeneration rate (0.96 g min⁻¹). The regeneration of the chlorinated derivatives is

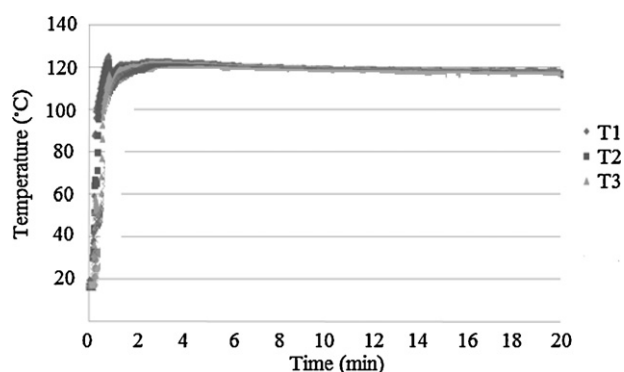


Fig. 7. Steam regeneration temperature profile of Reg.1 at 140 °C and 3 kg h⁻¹.

very efficient with steam at 140 °C and the number of cycles of adsorption and desorption does not influence the adsorption capacity. Since dichloromethane is not soluble in water, it was easy to separate by simple condensation.

5. Conclusion

To summarize, the steam regeneration had been a choice over nitrogen regeneration in the case of dichloromethane because of lower operating cost (0.85€ kg⁻¹); easy choice of separation of dichloromethane of steam by simple condensation; effective regeneration efficiency (82.3%); and also ready availability of the industrial units. The experimental results of adsorption and regeneration had been validated by the simulation model which had featured the optimum design of the process; safety aspects of the process (giving temperature data in the column during adsorption and regeneration step) and also the operating cost of regeneration based on the inputs given to the cost calculation model. The factorial experimental design has proved as an effective tool in understanding the influence of operating conditions of nitrogen regeneration on the regeneration efficiency and the operating cost. The developed simulation model PROSIM had proved to be robust and accurate for different regeneration systems like Vacuum Temperature Swing Adsorption (VTSA) [20]. In this research paper, the TSA regeneration was carried out in the industrial fashion (just using only hot nitrogen or steam regeneration), whereas in the previous work of VTSA, the additional preheating system (hot oil bath) was used [20]. And also the flow rate and the temperature of nitrogen in this research paper are much higher than in the VTSA process [20]. And in the future, new models of mass transfer coefficient models could be developed for further improvement of the simulation results to be even more accurate with the experimental results of the system (TSA) presented in this research paper.

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