

Comparative Scale-Up and Cost Estimation of a Biological Tricking Filter and a Three-Phase Airlift Bioreactor for the Removal of Methylene Chloride from Polluted Air

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ABSTRACT

Laboratory scale biological trickling filters and three-phase airlift bioreactors have been studied for the elimination of methylene chloride (or dichloromethane) vapors from waste air, and the results used herein for the design of small industrial-scale reactors. The conditions chosen for scale-up were an air flow rate of $100 \text{ m}^3 \text{ h}^{-1}$, a methylene chloride inlet concentration of 2 g m^{-3} , and a target removal of 99.5%. The scale-up procedure, design, and cost analysis are discussed. The full-scale biotrickling filter appears to be the most cost-effective reactor, with global costs of about \$62 per $1,000 \text{ m}^3$ treated. Treatment in the airlift reactor was estimated to be twice as expensive and catalytic oxidation 5 times as expensive. Biological waste air treatment offers economical alternatives to conventional techniques for waste air treatment.

INTRODUCTION

Biological treatment of contaminated air is a new and promising technique that utilizes mixed microbial

populations to degrade gaseous chemicals. Gaseous pollutants or vapors are sorbed into an aqueous phase prior to biodegradation. Biological treatment techniques offer cost-effective treatment for large air streams containing low pollutant concentrations. These techniques excel in two main domains: removal of odoriferous compounds,¹⁻³ and elimination of volatile organic chemicals, primarily solvents, from waste air.³⁻⁹ Inorganic wastes may also be efficiently removed.¹⁰⁻¹² Recently, biological waste air treatment was also considered for waste air generated by soil vapor extraction.¹³ Biological waste air treatment is an environmentally friendly technique that represents a major development towards reducing industrial atmospheric pollution.

Reactors for biological waste air treatment are distinguished by their operational mode, the existence of a free liquid phase, and their continuous phase reaction media (gas or liquid).

Biofilters are reactors in which a humid, polluted air stream is passed through a porous packed bed on which pollutant-degrading microbial cultures are naturally immobilized. Biofilters present a tremendous potential for air treatment. They have been implemented at full-scale and have proven cost-effective operation,^{3,14-16} but are generally not appropriate for continuous treatment of high concentrations of acid-producing pollutants, such as chlorinated solvents.

Bioscrubbers are reactors where a pollutant-containing waste air stream is contacted with a scrubbing solution. Here, either simultaneous or subsequent biodegradation of absorbed pollutants occurs as a result of the actions by growing microbes. Because of the continuous supply of fresh scrubbing solution, bioscrubbers generate small

IMPLICATIONS

Biological waste air treatment is a promising development in environmental protection. Unlike biofilters, which have been applied to a number of large-scale applications, no full-scale biotrickling filter or airlift reactor has been constructed yet for waste air treatment. This is particularly unfortunate because these reactors have shown remarkable performance at the bench scale. In this paper we detail the scaling-up of both a biotrickling filter and an airlift reactor based on three years' operation at the bench scale. The scale-up procedure, treatment costs, and design presented here provide a general framework for the choice of cost-effective alternatives to conventional treatment techniques.

amounts of wastewater that can be easily treated. Bioscrubbers offer promise for the elimination of such acid-producing pollutants as chlorinated VOCs, including dichloromethane (DCM or methylene chloride), trichloroethylene (TCE), and perchloroethylene (PCE),¹⁷⁻²⁰ or such inorganics as H₂S.^{10,12} Bioscrubbers have yet to be implemented for industrial use, primarily due to higher costs and complexity, and clogging by biomass growth.^{21,22} Among the various types of bioscrubbers, biotrickling filters and three-phase airlift reactors are the most promising equipment.^{7,20,23} Airlift reactors are extensively used for wastewater treatment, and have recently been shown highly effective for waste air treatment.^{20,25} Although more complex and more expensive than biofilters, bioscrubbers have proven superior in eliminating acid-producing pollutants, such as chlorinated VOCs. One reason for this is that in bioscrubbers, pH control and removal of metabolites are easier to achieve because of the existence of a free liquid phase. Also, nutrients are continuously supplied and, in the presence of net biomass growth, higher pollutant degradation rates are obtained. Unlike biofilters, which have been applied to a number of large-scale applications,^{14,16} biotrickling filters or airlift reactors have been rarely scaled-up for industrial waste air treatment. This is particularly regrettable because these reactors have shown remarkable performance at the bench scale.^{18,20,24} In this paper, we describe the scale-up of a biotrickling filter and three-phase airlift reactor for treatment of dichloromethane-contaminated air. The design is based on three years of highly effective operation of bench-scale units. Cost estimation is provided and compared to conventional treatment techniques. The reactor designs described herein are versatile and apply equally to the treatment of other pollutant vapors.

SCALE-UP OF THE BIOREACTORS

The conditions considered for the full-scale biotrickling filter are described in Table 1. These conditions are representative of a small, but concentrated, industrial exhaust air flow rate.

Table 1. Conditions for scale-up.

Waste air flow rate ^a :	100 m ³ h ⁻¹
Pollutant:	CH ₂ Cl ₂ (methylene chloride or dichloromethane)
Pollutant inlet concentration:	2 g m ⁻³ (~530 ppmv)
Removal targeted:	99.5%
Outlet DCM concentration:	<0.01 g m ⁻³

^a Higher air flow rates (e.g., 300 m³ h⁻¹) and lower DCM inlet concentrations could be treated with similar removal percentages.

Scale-Up Common to Both Reactors

Biodegradation of 99.5% of 200 g DCM h⁻¹ corresponds to 2.34 mol h⁻¹ and results in the generation of 4.69 mol h⁻¹ of HCl. This means 187 g h⁻¹ of NaOH pellets to maintain the pH constant or, if a 30% solution (8.7·10³ mol m⁻³) is used, a flow of 0.54·10⁻³ m³ h⁻¹. A corresponding tank volume of 0.79 m³ is necessary if the solution is prepared every two months. The composition of the scrubbing solution was not optimized at the bench scale, but was designed so that the process culture will not be limited by mineral salts. To calculate salt consumption costs, the amounts used at the bench scale were multiplied by the scale-up factor, with the following results: ammonium sulfate, 23.0 g h⁻¹; potassium dihydrogen phosphate, 9.2 g h⁻¹; magnesium sulfate heptahydrate, 8.4 g h⁻¹; and calcium nitrate tetrahydrate, 3.4 g h⁻¹.

The combination in an aqueous solution of the phosphate anions with the magnesium and calcium cations may precipitate owing to their low solubility. It is therefore an advantage to store and provide those minerals in a solid form. Since 1 kg of salt in powder form occupies about 1 L, a tank to contain the total amount needed for two months should have a volume of 65 L. This type of storage also has the advantage of avoiding the formation of algae in the tank. Different authors report the use of additional trace elements in the scrubbing solution.^{20,21,25} The amounts, however, are about 1,000 times smaller than the above-mentioned salts and are neglected in this discussion.

The variables that need to be controlled are pH, conductivity, and temperature. It may also be useful to monitor dissolved oxygen to avoid oxygen limitation. The pH control allows the degradation rate to be calculated²⁰ and can therefore be used to control the addition of the salt needed by the biomass. The conductivity measurement should be used for the control of the liquid residence time with a fresh water flow to avoid an inhibition by the chloride concentration.^{20,21,25} The temperature is kept at 30 °C with a steam flow. The energy balances are established with the values listed in Table 2. In both cases, the reactors are supposed to be thermally perfectly insulated.

For energy balances, the air flow entering the reactors is assumed to be at ambient temperature and dry, but the calculation can easily be modified for hot and/or humid air streams. The reaction heat is negligible and is

Table 2. Values for the establishment of the energy balances.²⁶

Heat capacity of dry air:	1.3·10 ³ J kg ⁻¹ ·K ⁻¹
Heat capacity of water:	4.18·10 ³ J kg ⁻¹ ·K ⁻¹
Water vaporization energy (30 °C):	2.28·10 ⁶ J kg ⁻¹
Steam condensation energy (3 bar):	2.16·10 ⁶ J kg ⁻¹

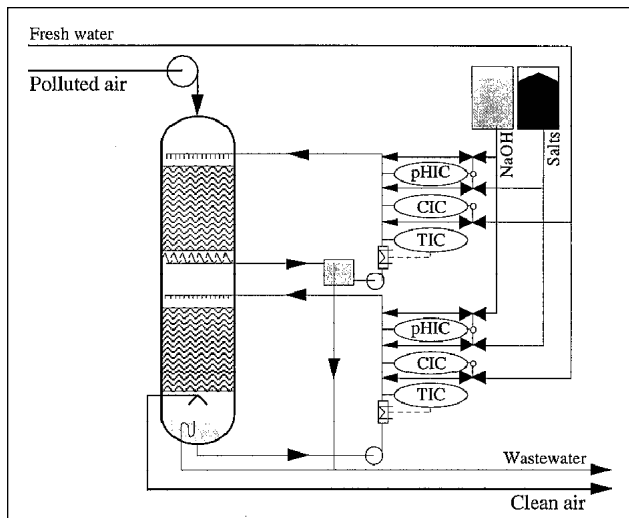


Figure 1. Schematic of a full-scale-up trickling filter for the conditions listed in Table 1.

omitted in the following calculations. The air can be considered to be saturated with water vapor at the outlet; thus, heat is needed to compensate the vaporization energy. The absolute humidity saturation of air at 30 °C is 0.028 kg m⁻³. Thus, 1.77 kW are needed to provide the heat of vaporization to saturate the dry air flow.

Scale-Up of the Biotrickling Filter

The scale-up of the biotrickling filter is based on the standard experimental operating conditions of the bench-scale reactor.²⁰ The column diameter is calculated by assuming the same empty-tube superficial gas velocity (160 m h⁻¹). The packing (Sulzer Mellapak 350Y) is the same as studied at the bench scale. It is a stainless steel structured packing that provides a large surface for gas/liquid absorption and for biofilm formation, and a high void volume so that clogging problems caused by biomass growth can be significantly reduced.²⁰ In the full-scale reactor, it is divided into two sections to ensure proper pH control and homogeneous wetting. With only one large section, liquid channeling could not be excluded. Also, the two-section design allows one section to be cleaned while the other is still removing DCM. In doing so, major impact on the environment during maintenance can be prevented because 92% of the DCM is removed in the first section and the remaining 7.5% in the second section. A relaxation modeling approach²⁰ showed that two sections of 2.4 m height are necessary to achieve 99.5% removal under the conditions considered. It should be noted that under these conditions, the DCM is essentially biodegraded and that the amount of DCM leaving with the liquid purge is virtually zero. For the conditions chosen, the diameter of the biotrickling filter equals 0.89 m (cross-section area of 0.625 m²). The total of 3 m³ packing volume provides about 1,050 m² of surface area for biofilm formation.

Gas flows downward co-currently with the liquid through the packing. As verified experimentally, the trickling filter does not produce any significant pressure drop over extended operating time, and therefore no special compressor is required.

The liquid circulates in two loops, wetting the two sections of the packing. On the basis of the performance obtained at different liquid velocities,²⁰ 11 m h⁻¹ is appropriate and implies a liquid flow of 6.88 m³ h⁻¹ in each loop. For the choice of the recirculation pump, the head pressure in the recycling loop should not exceed 0.5 bar. The dynamic liquid hold-up has been evaluated at 0.09 m³ of liquid per m³ of reactor,²⁰ or 0.14 m³ for each section. In the upper loop, a small tank (0.05 m³) retains water for the different controls (see Figure 1), whereas in the lower loop, the bottom of the column is used for this purpose. A total volume of approximately 0.2 m³ of liquid is obtained for each loop. For an average hydraulic residence time of 3 h, the two loops need a total fresh water flow of 0.13 m³ h⁻¹.

The energy needed to maintain the system at constant temperature can be approximated as follows. Because dry air has a heat capacity of 1,300 J kg⁻¹·K⁻¹, 0.4 kW are needed to raise its temperature of 20°C to 30 °C, and 1.8 kW are needed to heat the fresh water flow. Obviously, if the residence time of the liquid is increased, this energy need decreases. The total heat energy needed by the reactor is therefore the sum of the water heating, the air heating, and the compensation of the evaporation. The result is 4.0 kW, which can be brought to the reactor through the heat exchangers in the two liquid loops. A schematic of the industrial scale trickling filter is shown in Figure 1.

Scale-Up of the Three-Phase Airlift Bioreactor

Scaling-up a three-phase airlift reactor is a difficult task, as preferential liquid flows might lead to a partial fluidization of the carrier on which the process culture is immobilized. The scale-up calculations are based on the work of Heijnen et al.,²⁷ who reported the successful operation of a 17 m high three-phase airlift reactor for wastewater treatment, containing sand as a biomass carrier. The downcomer flow was obtained with a draft tube of 3.1 m, and the total diameter was 4.5 m. The corresponding downcomer/riser cross-sectional area ratio therefore was 111%. This is a reasonable value for high velocities in the riser, as reported by Weiland.²⁸

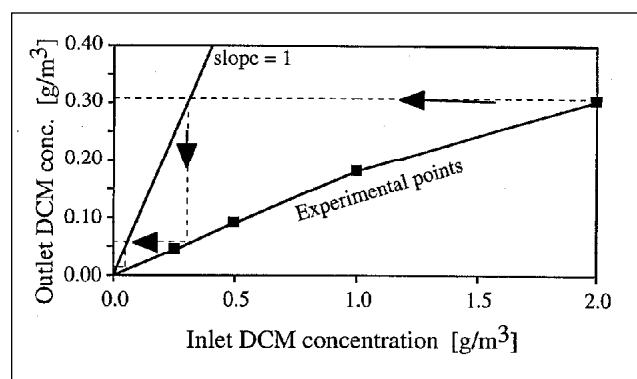
As for the biotrickling filter, the reactor diameter is calculated with the similarity in gas velocity between the bench and the full-scale airlift. For a gas velocity of 183 m h⁻¹ (empty basis), the diameter of the riser must have a cross-sectional area of 0.546 m²; thus, a diameter of 0.83 m. To be comparable to the proportions of the reactor described by Heijnen et al.,²⁷ the downcomer must

Table 3. Currency rates in May 1995 for 1 US\$. Inflation based on Chemical Engineering Plant Cost Index.³⁰

Currency Rates		1988-1994 Inflation Indexes			
1.205	Swiss Franc:	1988:	342.5	1992:	358.2
1.45	German Mark:	1990:	357.6	1993:	359.2
1.62	Dutch Guilder:	1991:	361.3	1994:	368.1

have a cross-sectional area of 0.606 m², and the diameter of the outer tube becomes 1.2 m. Since our prototype airlift reactor was found to be controlled by this gas-liquid transfer of DCM up to a gaseous concentration of about 15 g m⁻³, the reactor height corresponds to the length for which the required gas-liquid transfer is achieved. The full-scale reactor is designed with a larger downcomer area than the prototype to ensure optimum fluidization of the biocatalyst and should equal, if not surpass, the performance of the prototype. However, the process will still be controlled by gas-liquid transfer. A mathematical model assuming the airlift reactor to be similar to a bubble column did not allow the removal of DCM to be predicted with sufficient confidence for the present scale-up.²⁰ Therefore, a graphical method based on experimental results obtained with the bench-scale airlift was used to predict the reactor height needed. As illustrated in Figure 2, for an inlet gaseous concentration of 2 g m⁻³, the outlet concentration of methylene chloride for the bench-scale reactor was 0.30 g m⁻³. A stagewise construction shows that three reactor heights are sufficient to reduce the DCM concentration to the required 0.010 g m⁻³. Because the liquid height in the bench-scale reactor was 0.83 m, the total height for the full-scale plant should be 2.5 m. Owing to the difficulty of the gas sparging in the base, 0.5 m is added to ensure proper gas distribution.

The final height obtained for the riser is 3 m, which corresponds to a total riser volume of 1.6 m³, with a gas hold-up of

**Figure 2.** Experimental results of DCM removal in the airlift reactor and stagewise construction to determine the height needed to reach an outlet concentration of DCM of 0.01 g m⁻³ for an inlet concentration of 2 g m⁻³. Gas velocity (empty basis) is 183 m h⁻¹.

0.13 m³ (8%), and an outer ring volume of 1.8 m³. The total reactor volume obtained is 3.4 m³. As for the prototype, sand (density 2.6·10³ kg m⁻³) is used as a carrier for biomass. The proportions are kept the same (195·kg m⁻³) so that the sand mass is 660 kg. The total volume of liquid found by difference is 3 m³.

The waste air must be pumped into the reactor. The pressure required is about 0.5 bar: 0.3 bar for the water column and about 0.2 bar for the sparger specially designed to avoid back-flowing. The turbulence of the airlift reactor was shown to produce important amounts of foam, possibly because of macro-molecules released by biomass damaged by the shear forces. Anti-foam was shown to increase gas bubble size and is therefore not appropriate. The foam can be destroyed with a rotating disk or with a high-pressure jet. This second option was successful for the reactor described by Heijnen et al.²⁷ Foam destruction should be reached with a liquid jet of 0.1 m³ h⁻¹ at 10 bar.

Regarding energy balances, the reactor must be kept at 30 °C. The flow of energy has to take into account the heat produced by the compression of the air flow. The reversible and adiabatic compression of air (bi-atomic molecules) from atmospheric pressure to 0.5 barg was approximated as follows:²⁹

$$T_2 = T_1 \frac{P_2}{P_1}^{0.286} \quad (1)$$

where T is the temperature in K, and P is the pressure. For a pressure increase of 0.5 bar and an initial temperature of 20 °C, the final temperature is 56 °C. This can kill locally the biocatalyst and diminish the gas-liquid mass transfer. Consequently, a heat exchanger is designed, using the fresh water flow to decrease the polluted air stream

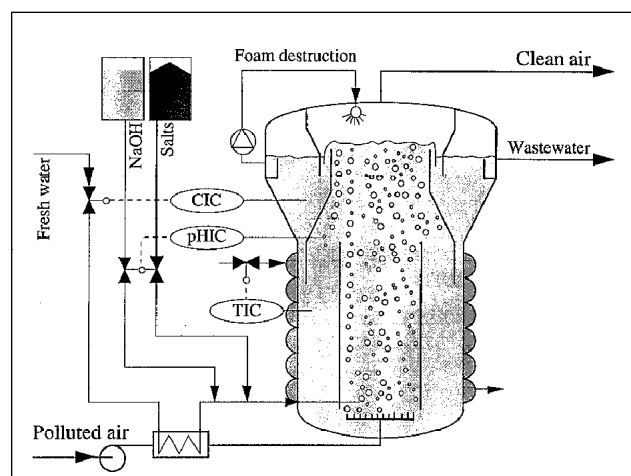
**Figure 3.** Schematic of a full-scale airlift reactor for the conditions listed in Table 1.

Table 4. Variable costs for a Swiss chemical industry in January 1995.³¹

Tap water:	2.73 \$ m ⁻³
Cooling water:	0.40 \$ m ⁻³
Waste water (industrial):	2.02 \$ m ⁻³
Electricity:	0.10 \$ kWh ⁻¹
Steam at 3 bar:	0.026 \$ kg ⁻¹
Personnel:	60 \$ h ⁻¹

temperature to 30 °C. The water flow needed to keep the hydraulic residence time at 3 h is 1 m³ h⁻¹. The exchange of 1.2 kW between the air and the water will raise the temperature of the water stream about 1 °C. Assuming the water supply is at 18 °C, an additional energy flow of 13 kW is needed to reach the required temperature of 30 °C. The total heat energy needed by the reactor in this case is the sum of the water heating and the compensation of the evaporation. It amounts to 14 kW, and can be brought to the reactor through a coil around the reactor body.

A schematic of the design of the industrial scale three-phase airlift reactor considered here is shown in Figure 3.

INVESTMENT AND TREATMENT COST ESTIMATION

Since cost estimations are based on different currencies, all costs were converted to US\$, with the following rates and inflation values reported in Table 3.

Only the main variables and fixed costs for both reactors are estimated. Table 4 indicates the variable costs; Table 5, the costs of the mineral salts. It should be mentioned that the costs reported in these tables can differ as much as 1 order of magnitude, depending on local rates, with significant consequences for the treatment costs. The values in Tables 4 and 5 are probably at the high end.

The cost estimations of pumps, heat exchanger, and power requirement were achieved with ASPEN (Version 8.5-6, 1990), Aspen Technology Inc., Massachusetts, USA). The tank prices were obtained from Walas,³² except for the small tank containing the mineral salts, which was taken from the 1995 Semadeni catalogue (Semadeni AG, Bern, Switzerland).

In the following section describing the total costs specific to the bioreactors, the variable costs are reported in US\$ per year. A year consists of 8,760 hours (100% operation).

Biological Trickling Filter

Costs for the biotrickling filter are summarized in Table 6. The cost listed in Table 6 is for an installation working on a continuous basis for 10 years. The investment per hour of operation is therefore \$2.10 h⁻¹. Added to the operating cost of \$4.11 h⁻¹, one obtains a total cost of \$6.21 h⁻¹. For a flow of 100 m³ h⁻¹ containing 2 g m⁻³, the cost for a removal of 99.5% in a trickling filter is \$62 per 1,000 m³.

Table 5. Costs of the mineral salts (technical grade) in a Swiss chemical industry in January 1995.³¹

Sodium hydroxide	0.95	\$ kg ⁻¹
Ammonium sulfate	8.5	\$ kg ⁻¹
Potassium dihydrogen phosphate	14	\$ kg ⁻¹
Magnesium sulfate heptahydrate	7.0	\$ kg ⁻¹
Calcium nitrate tetrahydrate	10	\$ kg ⁻¹

Airlift Bioreactor

Costs for the airlift reactor are summarized in Table 7. The cost listed in Table 7 is for an installation working on a continuous basis for 10 years. The investment per hour of operation is therefore \$3.16 h⁻¹. Added to the operating cost of \$9.10 h⁻¹, one obtains a general cost of \$12.3 h⁻¹. For a flow of 100 m³ h⁻¹ containing 2 g m⁻³, the cost for a removal of 99.5% in a three-phase airlift reactor is \$123 per 1,000 m³.

Economical Considerations

The two estimations determined the following treatment

Table 6. Total cost calculation for the biotrickling filter. The costs of the column and the packing were a personal communication by Sulzer AG, Switzerland.

Description of the cost	Investment	Operating cost
	[US\$]	[US\$ year ⁻¹]
Column (stainless steel)	72,000	
Packing Sulzer Mellapak 350Y	16,200	
Blower for the air flow	5,500	
Electricity (250 W)		220
2 pumps for the water circulation flow	2,500	
Electricity (330 W, twice)		580
Tank in the upper loop (stainless steel)	1,200	
Chemicals		
Tank for the base	2,800	
NaOH consumption		1,560
Tank for the mineral nutrients	100	
Mineral consumption		3,650
2 heat exchangers (stainless steel)	15,600	
Steam flow (4,000 W)		1,520
Subtotal of the basic investment	115,900	
Secondary cost		
Controls (12% of the basic investment)	13,900	
Pipes (20% of the basic investment)	23,100	
Insulation (7% of the basic investment)	8,100	
Building (20% of the basic investment)	23,100	
Tap water (0.13 m ³ h ⁻¹)		3,110
Waste water (0.13 m ³ h ⁻¹)		2,300
Personnel (4 days per month or 384 h year ⁻¹)		23,040
Totals	184,100	35,980

costs for 1,000 m³ of waste air: biotrickling filter—\$62 per 1,000 m³, and airlift reactor—\$123 per 1,000 m³.

According to these calculations, the biotrickling filter appears to be about 50% cheaper than the airlift reactor. The comparison of the obtained costs with previously published values must be considered with care as chemical and energy costs may vary greatly with local rates. Also, the reactor size and the outlet gas concentration considered are generally different. Diks²¹ reported a cost of \$4 per 1,000 m³ for a trickling filter operating with 10,000 m³ h⁻¹ of air and 85% removal of the 1 g m⁻³ inlet DCM concentration. For a trickling filter similar to the one reported in our study, a predicted cost of \$8 per 1,000 m³ can be calculated from Jackman and Powell.³³ A detailed design and requests for bids, as well as estimation of operating cost with local rates, would be necessary for an accurate figure of the overall treatment cost. Besides differences due to calculation methods, the above examples illustrate that specific costs significantly increase for smaller reactors, high inlet concentrations, and high removal percentages. Thus, cost effectiveness of biological waste air treatment becomes more interesting with large air streams.

As seen in Tables 6 and 7, tap and waste water expenses represent a large fraction (20 to 50%) of the operating costs. Even if these numbers will most likely vary according to local rates (as much as 10 times lower than listed in Table 4), particular attention should be given to optimize the water flow rate. For the airlift, the tap water flow can be reduced by decreasing the volume of the reactor by choosing a smaller downcomer/riser section ratio. In both reactors, water can be saved by increasing the hydraulic residence time until an inhibitory salt concentration is reached.

The \$62 and \$123 for the treatment of 1,000 m³ of polluted air in the trickling filter and the airlift reactor, respectively, can be compared to the expenses associated with conventional treatment. Costs were obtained from a Swiss chemical industry using thermal combustion to treat 50 m³ h⁻¹ of waste gas containing over 300 g m⁻³ of chlorinated solvents. The advantage of thermal combustion is the almost total freedom it allows with respect to the inlet concentration and the composition of the flow treated (e.g., mixtures of pollutants). The investment for the oven was about \$440,000; with other investments, a total of \$750,000 was obtained. Operating costs were \$72,000 per year. For 10 years' operation, the specific costs were \$335 per 1,000 m³ of air. This demonstrates that biological treatment is about 3 to 5 times cheaper than thermal oxidation.

CONCLUSIONS

The results of bench-scale three-phase airlift and biotrickling filter reactors have been used to conceptually design full-

Table 7. Total cost calculation for the airlift reactor. The secondary costs were estimated from Diks.²¹

Description of the cost	Investment [US\$]	Operating cost [US\$ year ⁻¹]
Airlift with coil for the heating	150,000	
Heat exchanger for the air flow (stainless steel)	4,500	
Pressure pump for the air flow	15,400	
Electricity (3,000 W)		2,630
Pressure pump for the foam destruction	1,500	
Electricity (200 W)		180
Chemicals		
Tank for the base	2,800	
NaOH consumption		1,560
Tank for the mineral nutrients	100	
Mineral consumption		3,650
Total steam flow (14,000 W)		5,480
Subtotal of the basic investment	174,300	
Secondary cost		
Controls (12% of the basic investment)	20,900	
Pipes (20% of the basic investment)	34,900	
Insulation (7% of the basic investment)	12,200	
Building (20% of the basic investment)	34,900	
Tap water (1 m ³ h ⁻¹)		23,910
Waste water (1 m ³ h ⁻¹)		19,270
Personnel (4 days per month or 384 h year ⁻¹)		23,040
Totals	277,200	79,720

scale reactors for the treatment of polluted air containing DCM vapors. The conditions chosen for scale-up were an air flow rate of 100 m³ h⁻¹, a methylene chloride inlet concentration of 2 g m⁻³, and a target removal of 99.5%. A rapid cost estimation demonstrates that the biotrickling filter is more cost effective than the airlift reactor. Also, the amount of base knowledge on both reactors tends to favor the choice of the trickling filter over the three-phase airlift reactor, as packed columns have been scaled-up for many years in the chemical and petroleum industry. The three-phase airlift reactor is a rather recent development, but presents very interesting characteristics as far as reaction rate and long-term operation stability are concerned. Finally, the comparison for the treatment economics in thermal and in biological reactors clearly demonstrates the cost effectiveness of biological techniques and should promote the construction of both full-scale airlift reactors and biotrickling filters for waste air treatment.

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