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Economic Evaluation of Soil Remediation Using Supercritical Fluid

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ABSTRACT: Supercritical fluid extraction (SCFE) is a soil remediation technology. At present, only a few companies are using from this method, all of which are technical based on conventional methods of extraction such as soilex solvent extraction. Because of the hard enforcement of environmental conservation law, using green technology seems imperative. This paper endeavors to carry out the feasibility studies of supercritical fluid extraction units for such as purpose. It also analyzes the cost and benefit of these processes in industrial scale and presents an economical approach for this purpose. If compared to other remediation processes, the supercritical CO_2 extraction (whit CO_2 recycling) shows relevant economical advantages.

Key words: supercritical fluid, feasibility study, operating cost, naphthalene, contaminants

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INTRODUCTION

Among the organic contaminants, oil and coal refineries are responsible for several cases of soil contamination with Polycyclic Aromatic Hydrocarbons (PAHs).The PAHs are a family of compounds formed by two or more aromatic rings of carbon atoms linked together. Among the PAHs, naphthalene is the simplest molecule, formed by two rings only. Studies from many authors (Andersson, *et al*., 2001; Canet, *et al*., 2001; Khodadoust, *et al*., 2000) refer to contamination by PAHs at former gas work plant areas with concentration values ranging from tens or hundreds of ppm up to 3.0×10^6 ppm at a site near Bedford (Khodadoust, *et al*., 2000).

There are many techniques available for soil decontamination, all of them having some advantages and disadvantages (Castelo-Grande and Barbosa, 2003).

Supercritical fluid extraction (SCFE) is a technique that presents some important and unique advantages over the other decontamination processes, among which we stand out the low impact in the structure of soil and on the environment. In the 1970's, due to the energy crisis, the interest in supercritical extraction has increased a tendency that continues until nowadays, mainly due to environmental concerns. SCFs are particularly good solvents because their capacity for dissolving substances is close to that of the liquids, but their viscosity and diffusion coefficient are close to the gases, thus improving the transport and mass transfer characteristics of these fluids. Furthermore, since the surface tension of SCFs is equal to zero, these fluids are particularly suitable for the extraction of substances from solid matrices, such as soil. Another advantage in the use of SCFs is the possibility of changing their dissolving power by changing the pressure and/or temperature of the fluid, thus allowing the fractional extraction and separation of solutes, and the complete recovery of the solvent by simple pressure adjustments. Of all the SCFs that have been studied, carbon dioxide

(CO_2) is the most commonly used because of its low critical temperature (T_C= 304.2 K) and pressure (P_C= 7.39 MP_a) (Castelo-Grand and Barbosa, 2003), non-toxicity, availability and low cost. Pressure above its critical point (Medina, *et al.*, 1998) is used as the extracting solvent (Tavlarides, *et al.*, 2000). SCFs are particularly good solvents because their capacity for dissolving substances is close to that of the liquids, but their viscosity and diffusion coefficients are close to those of the gases, this improve the transport and mass transfer characteristics of these fluid. The supercritical extraction with CO_2 has been successfully applied to the removal of a variety of contaminants from soils, even the most persistent to treat, such as PBCs and PAHs.

MATERIALS & METHODS

The naphthalene used in this study has a purity of 99%. The soil type was determined by sieving it by mean of sieves with different mashes. The composition of the soil used for the contamination-decontamination process has the following characteristics:

- Fine sand (0.06-0.25 mm), %55
- Medium sand (0.25-0.5 mm), %20
- Coarse sand (0.5-2 mm), %25

Acetone was used for soil spiking, because the solvent has to solve the naphthalene easily. Toluene was used for naphthalene collection.

SCFE units typically consist of at least two extractors, a series of separators for separating extracts from solvent a reservoir to receive the recycled CO_2, a heater to maintain operating temperature, stainless steel extraction cell whit a volume of 2 liter, and a compressing piston pump. The apparatus used to carry out our experimental study is schematically shown in Fig.1. This apparatus can operate under pressure up to 45 MPa, and temperatures ranging from 278 to 373^0 K.

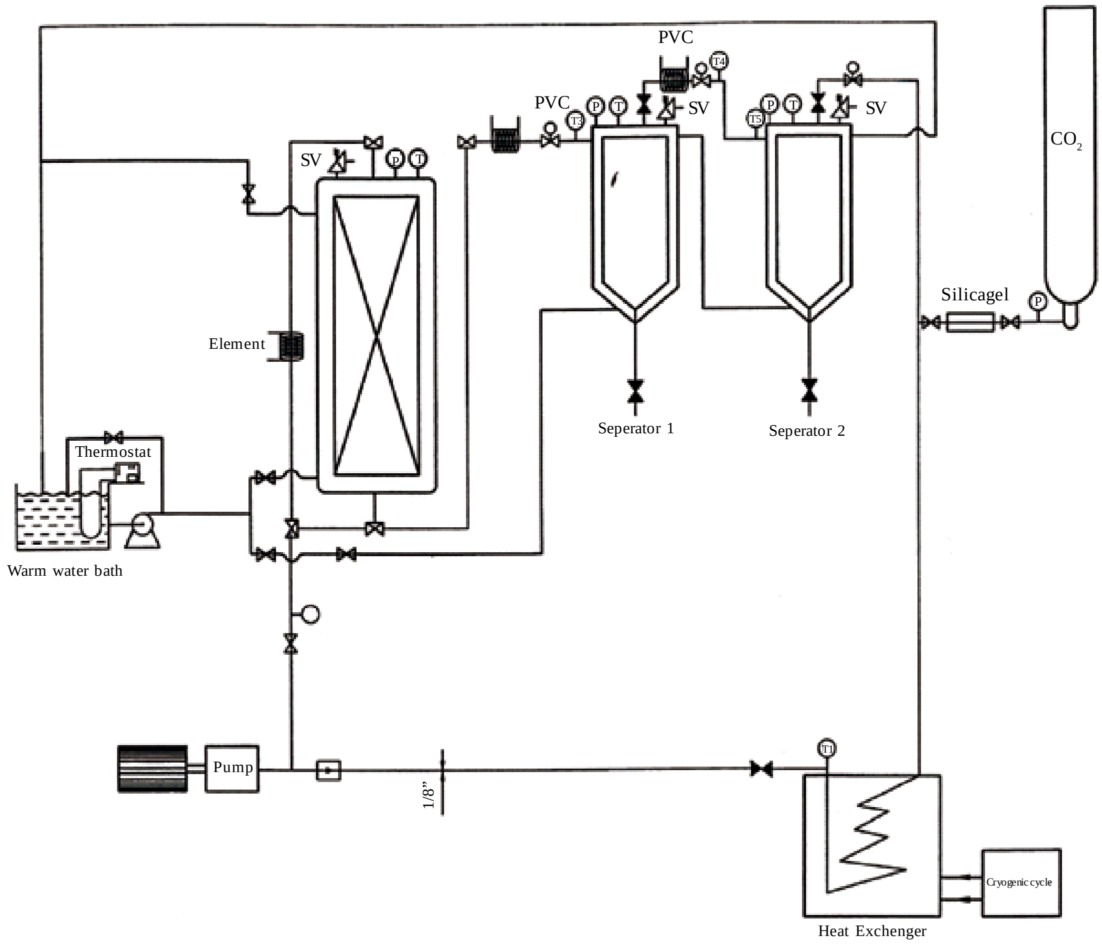

Fig. 1. Supercritical fluid extraction pilot plant scheme

In a SCFE unit, the cost consists of two groups; first, direct or variable costs, which depends directly on production rate and includes the cost of purchasing and preparing the raw material, labor, CO_2 supply, utility, and transportation. Second is the fixed cost that consists of depreciation, plant overhead, administrative cost, tax, and insurance.

Most chemical process industries (CPI) facilities are automated to some degree, many in fact, requires little or no operator attention. Nevertheless, at least some personnel are needed during each shift to monitor the control instrumentation and make periodic process- area walk- through, and perform other routine tasks. The following straightforward equation can be used to estimate the process operating labor cost (C_L) in dollars per year:

C_L= (L) (H/8) (P_L)

Where:

L= operating labor hours per shift

H= process annual operating hours

P_L= operating labor rate, in dollars per hours

The cost of maintaining process equipment varies considerably according to the equipment type, age and condition, the geographical location, and the severity of service. As with the operating labor requirements, the best sources of maintenance cost data are facility databases. In the ideal situation, a well designed and previously installed computerized Maintenance Management System (CMMS) has consistently, accurately and thoroughly accounted for the hours worked by each maintenance employee; it similarly has accounted for the maintenance materials costs, as well as the cost of maintenance contracts (Singer, 2002).

In many situations, however, the engineer charged with making a direct operating cost estimate does not have a CMMS to draw upon. In these cases, he or she must either predict the amount of maintenance labor and the materials the facility will require, or estimate the total maintenance cost as a percentage of the facility's total capital investment (TCI),

C_M= (M) TCI

Where:

M= 0.01 to 0.025, typically (Vatavuk, 2005)

The total raw materials cost (“C_{RMi}) is simply the sum of the individual raw materials:

“ $C_{RMi=}$ “ $Q_{RMi}P_{RMi}$

Where:

Q_{RMi}= quantity of Raw Material i required (units/ year)

P_{RMi}= price of Raw Material i ($/ unit).

Every process consumes electricity and one or more other kinds of utilities. Motors, heaters, instrumentation and other equipment require electricity. In general, the cost of each utility (C_{Ui}) is the product of its annual consumption (Q_U, units/ year) and its price (P_U, $/ unit):

C_{Ui}= Q_{Ui} P_{Ui}

The total utilities cost is the sum of the individual utility expenditures.

The operating supplies are 15% of maintenance cost.

Fixed cost is independent of production quantity. Total fixed cost is about 14% of total original investment.

RESULTS & DISCUSSIONS

The cost related to soil decontamination by supercritical CO_2 extraction can be divided into fixed costs and variable costs. The variable costs are direct function of the operating conditions, while the fixed costs mainly relate to the investment for the extraction time. In general, such costs vary, as any of the parameters is modified, within the range allowed by the extraction plant design. The design parameters for a supercritical extraction (SCFE) plant, suitable for recovery of soil with an initial concentration up to 6000 ppm, are summarized in Table 1.

Table 1. Design parameters for supercritical CO_2 extraction plant

Parameter	Measure Unit	Value
Treated Medium		Contaminated Soil
Textural Analysis of Soil		Sand
Contaminated		Naphthalene
Bed Density	Kg/m^3	1400
CO_2 Density	Kg/m^3	750
Extraction Temperature	C^0	31-40
Extraction Pressure	MPa	7.5-15
Extraction Time	min	50
Operating Time		16 h/day, 300 day/y

Table 2. Operating cost for a supercritical extraction plant

Item Description	Remarks	Cost ($/m^3)
CO_2 Supply	0.3 $/Kg	650 (max)
Operating Labor (L)	1 per shift, 2 $/h	1.7
Direct Supervision (S)	2$/h	1.7
Maintenance (M)	4% of total equipment cost	2.01
Operating Supplies	15% of maintenance	0.3
Transfer of Soil into Vessel	Extraction and Transportation	35
Utilities	1 $/h	0.85
Total Operating Costs		691.56

Table 3. Fixed costs for supercritical extraction process

	Remarks	Cost ($/m^3)
Plant Overhead	%60 of (L+S+M)	3.01
Administrative Cost	%15 of (L+S+M)	0.75
Depreciation	Equipment costs over 15 years	17.6
Total Fixed Costs		21.36

Table 2. Summarize the operating cost for supercritical extraction plant based on the design parameters of Table 1.

The fixed costs refer to the capital costs for the extraction plant construction, plus the administrative costs and other costs not directly dependent from the operating conditions.

Cost calculations for the extraction vessel and the pump are base on the data (Peters and Timmerhaus, 2003). The total fixed costs (Table 3) obtained by calculating the equipment depreciation over 15 years, plus the administrative costs and the plant overhead (heating, light, rent, etc). The equipment depreciation calculated on the hypothesis of 16 h/day, 300 day/year plant operation (Montero, *et al.*, 1996).

The total cost for naphthalene soil remediation, with an initial contaminant concentration of 6000 ppm, is equal to:
Total cost =Variable costs + Fixed costs = 691.56 + 21.36 = 712.92 $/m^3.

The CO_2 supply cost, equal to 650 $/m^3, represents 94% of the total cost.

Table 4. Comparison of the soil remediation costs of different methods

Remediation Process	Cost ($/m^3)
Supercritical Fluid Extraction (with CO_2 recycling)	139
Supercritical Fluid Extraction (without CO_2 recycling)	713(max)
Supercritical Water Oxidation	250-733
Bio-clean	191-370
Acurex Solvent Wash	196-569
KPGE	211-378
Vitrification	255-548
Chemical Waste Landfill	260-490
O.H.M Methanol Extraction	400-514
Soilex Solvent Extraction	856-913
Incineration	1713-1826

The introduction of a CO_2 recycling step would largely reduce this cost. For instance, if 90% of the CO_2used is recovered (for instance by adsorption of the impurities on active carbon) and recycled, the CO_2 supply cost would be reduced to 65 $/m^3.

The introduction of recycling step requires suitable equipment in the extraction plant, which would increase the fixed costs. The total cost calculation would therefore is modified as follows:

Total Cost (with CO_2 recycling) = 106.56 + 32.04 = 138.6 $/m^3

If compared to other remediation processes (Table 4), the supercritical CO_2 extraction shows relevant economical advantages.

CONCLUSION

The results obtained indicate the supercritical CO_2 extraction as an adequate and cost effective method for naphthalene removal from contaminated soils. In particular, remediation costs as low as 139 $/m^3 make the process very competitive compared to more traditional methods, such as land filling, solvent extraction or biological remediation. The CO_2 supply cost represents 91% of the total cost. The introduction of a CO_2 recycling step would largely reduce this cost.

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