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Remediation of contaminated media using a jet pump Part 1: Screening for significant parameters

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Abstract

New legislation is causing a change in the attitudes of industrial processes towards contamination and remediation of contaminated land, encouraging industry to remediate their contaminated sites. One new remediation option is the jet pump scrubber. Parameters that may affect the ability of a jet pump scrubber to remediate contaminated land have not been previously identified. In this study, the effect of five possible parameters of significance to the remediation process, were investigated (i.e. initial contaminant concentration, number of passes, contaminant type, motive pressure and particle size) using a full factorial screening design. For all experiments, washed oven dried silica sand was contaminated with a range of mineral oil contaminants. Samples were analysed using an ultrasonic extraction and spectrophotometric method. Contaminant removal efficiencies of up to 99.1% in the jet pump scrubber were found. Of the 30 possible parameter combinations, 15 parameter/parameter combinations were found to have a statistically significant effect on the remediation process, with the initial contaminant concentration and the number of passes in the jet pump scrubber providing the greatest effect. Therefore, future jet pump scrubber units should be designed such that contaminated media can undergo multiple passes in quick succession.

Keywords: Jet pump; Scrubber; Remediation; Contaminated land; Environmental engineering

1. Introduction

Soil and sediments have been contaminated with industrial waste since the industrial revolution. Current attitudes towards land contamination and remediation have changed, and legislation, such as the Environmental Protection and the Integrated Pollution Prevention and Control Acts, introduced into the U.K. in the 1990s, has played a significant role in encouraging industries to remediate their contaminated land sites. Despite the introduction of new legislation however, there are many contaminated sites that still require remediation [1]. Therefore, there is a real need for a simple and effective remediation process.

This paper will focus on one remediation option called soil washing (or flushing). Soil washing is predominately water and/or solvent-based, and relies on the physical and chemical differences between the contaminants, solid phase, and the wash-water to remove the contaminants from the solid phase into the liquid. Soil washing produces a "dirty" liquid phase which requires further treatment to either destroy or confine the contamination and a "clean" solid phase.

Strazisar and Seselj [2] studied the ability of a soil washing process to remove lead and zinc from contaminated soils in Slovenia. Using a simple attrition scrubber, removal percentages of up to 86% were achieved. Feng et al. [3] attempted to compare the ability of a number of different soil washing processes to remediate samples contaminated with diesel oil. Using a attrition scrubber with vertical mixing rods Feng et al. [3] achieved removal percentages of up to 97%. Bayley and Biggs [4] conducted a number of experiments using a small scale attrition scrubbing unit to remediate sand contaminated with mineral oil and found that efficiencies greater than 95% could be achieved. Bayley and Biggs [4] also investigated the relationship between a number of parameters such as temperature, attrition time, and power on the removal efficiency of the unit and demonstrated that an un-baffled attrition scrubber was very effective at remediation of contaminated sediments. Despite these studies on the efficiency of soil washing as a remediation process, the major bulk of soil washing research has been conducted on the traditional use of soil washing as a size reduction remediation process not as an actual separation of contaminants/media remediation process [5–9].

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A less traditional soil washing process is the jet pump scrubber. A jet pump scrubber has been discussed and promoted widely in literature [1,10–16]. Two of the most informative studies are by Wakefield and Tippetts [16] and Wakefield [11]. The former is a valuable insight into the operation of a jet pump scrubber using actual contaminated media and indicates that the jet pump scrubber may be very efficient at remediation of contaminated land (removal percentages of up to 99.99% are quoted). Wakefield [11] provides a detailed description of a number of jet pump scrubber setups, such as impinging jets and two stage jet pumps, and compares them with more traditional soil washing methods such as barrel washers and paddle type attrition scrubbers. In this case, Wakefield [11] concluded that a two state jet pump scrubber was the most energy efficient scrubbing process. Bayley and Biggs [1] designed, built and commissioned a Contaminated Sediment Remediation Rig (C.S.R.R.), which utilized a jet pump scrubber to remediate contaminated sands. A detailed description of the principles of a jet pump scrubber, for soil washing is also given. Initial results were promising, however a further more vigorous, defined and controlled experimental programme was recommended. Therefore, using the same C.S.R.R. as used by Bayley and Biggs [1] this paper systematically identifies key parameters and any potential interactions between key parameters that may influence the remediation efficiency of a jet pump scrubber for remediation of contaminated media.

2. Key parameters

The current literature on soil washing and the jet pump process was used to identify five key parameters that are considered to have an important effect on the ability of the jet pump to remediate contaminated media. Each of these parameters are discussed in turn, highlighting what previous research has been conducted on these parameters, and why these parameters are considered to be significant.

2.1. Contaminant concentration

A key driver for conducting studies to clean up contaminated media is the level of contamination. When considering the level of contamination it is also important to consider the type of attachment between the contaminant and the media. For example, if there are X sites per particle on which contaminants can attach, then the number of contaminants that can attach to the particle surface is also X. If the number of contaminants is increased by ΔX to $X+\Delta X$, then there are ΔX contaminants that are not directly bonded to the particle surface. These ΔX contaminants are assumed to attach to the X contaminants that are themselves attached directly to the particle surface (Fig. 1). The ΔX contaminants should be easier to remove than the X contaminant, as they are not directly bonded to the surface of the particles. It follows therefore, that as the contamination level increases, there will be a greater amount of contaminant that is not directly bonded to the particle (i.e. an increase in ΔX), for any given particle. Hence, it is hypothesised that a greater total percentage of contaminants will be removed from the media at higher contaminant concentrations, than at lower concentrations, due to the increase in ΔX.

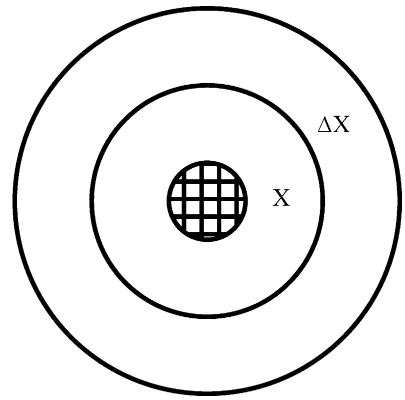

Fig. 1. Two layer surface model of contamination on a solid particle.

2.2. Contaminated media particle size

Feng et al. [3], using a jet reactor, showed that contaminated media with a larger particle size was easier to remediate than media with a smaller particle size. In this case, sand of three different particle sizes, with an average particle size of 0.1, 0.3, and 0.5 mm, were contaminated with 5 wt.% diesel. This observation was due to the greater surface area to mass ratio for the media with a smaller average particle size compared to that of the larger particles. The contaminants attached to the particle surface (i.e. X contaminants described above and Fig. 1) will be harder to remediate, using the scrubbing action of the jet pump, than contaminants not attached to the surface (i.e. ΔX). So it is hypothesised that the media with a smaller average particle size, and hence, larger surface area ratio should be harder to remediate, as more contaminants are tightly sequestered to the particles surface than media with a bigger particulate size and a smaller surface area ratio.

2.3. Contaminant type

The more hydrophobic and the more viscous the contaminant is, the harder it will be to remove from the solid phase into the liquid phase due to the greater required impact energy needed to dislodge the contaminant from the particle. Therefore, hydrocarbons with a lower Relative Molecular Mass (R.M.M.), which are less viscous, should be easer to remove than hydrocarbons with a higher R.M.M. Bayley and Biggs [4] showed that using a paddle type scrubber, there was a considerable difference in the remediation efficiency between silica sands contaminated with mineral oil or bees wax (80.2% and 16.8 % removal efficiencies, respectively). Thorvaldsen and Wakefield [13] also showed that that increasing the carbon chain length of the contaminant reduced the final removal efficiencies in a jet pump scrubber.

2.4. Motive flow pressure

Attrition scrubbing relies on the fact that during an impact involving a particle, there is sufficient energy in the impact to overcome the hydrophobic and Van der Waal/chemical bonding forces that cause contaminants to attach to a particle surface. Therefore, if the impact energy is great enough, then the contaminant can be removed from the particulate surface. It follows, therefore that the greater the amount of energy in the system the greater the likely hood that any single impact will have sufficient energy to successfully remove contaminants from the particle surface.

The energy required for the scrubbing action in a jet pump is supplied by the energy in the motive flow (i.e. the greater the energy in the motive flow the greater the scrubbing action). Therefore increasing the motive flow pressure should increase the rate and overall efficiency of the jet pump scrubber.

Additionally if the pressure in the motive flow is sufficiently high, then cavitation in the combined flow within the mixing chamber of the jet pump can be achieved. Wakefield and Tippetts [16] showed that cavitation could be beneficial to the remediation process by demonstrating that light cavitation improved the overall efficiency of the jet pump scrubber. This increase in contaminant removal efficiency is due to the fact that when cavitation bubbles implode the resulting forces act like shaped explosives. This extremely violent action may also dislodge contaminants from the contaminated media and therefore increase the efficiency of the jet pump scrubber.

2.5. Number of passes through the jet pump

It is hypothesized that an increase in the amount of contaminants removed will be achieved with an increase in the number of passes through the jet pump, since the media has been subjected to additional scrubbing action with each new pass. Preliminary results by Bayley and Biggs [1] showed this to be the case with an increase in contaminant removal with an increase in number of passes through the jet pump.

As stated earlier, the aim of this paper is to describe the effects of the five parameters described above, and their potential interactions, on the jet pump scrubber's ability to remediate contaminated media in the C.S.R.R. In so doing, the operating conditions of a jet pump scrubber for remediation of contaminated media will be optimized.

3. Methods

3.1. Contaminated sediment remediation rig (C.S.R.R.)

Due to the nature of a jet pump, a considerable amount of ancillary equipment is required to run a jet pump scrubber, and therefore a Contaminated Sediment Remediation Rig (C.S.R.R.) was designed. A detailed description of the C.S.R.R. and the commissioning process is given in Bayley and Biggs [1]. A schematic of the C.S.R.R. is also shown in Fig. 2. The C.S.R.R. consists of a motive pump, which is fed by a Motive Pump Feed Tank (M.P.F.T.). The motive pump delivers a motive flow of water at variable pressures (2.5–14 bar, 196–498 rpm) via stainless steel pipe work to the jet pump. The jet pump is fed by a Jet Pump Feed Tank (J.P.F.T.). The J.P.F.T. is situated directly above the jet pump itself and contains the contaminated media and water. The motive feed from the motive pump and the induced feed from the J.P.F.T. combine in the jet pump mixing chamber and form the combined flow, which is pumped into the Receiving Tank (R.T.) that is situated above the J.P.F.T. In the receiving tank the solid and liquid phases can settle and solid samples can be taken via a valve situated at the bottom of the receiving tank. This valve also allows material from the receiving tank to be passed back into the J.P.F.T. Half way up the receiving tank is situated another valve that allows water to be passed back into the M.P.F.T.

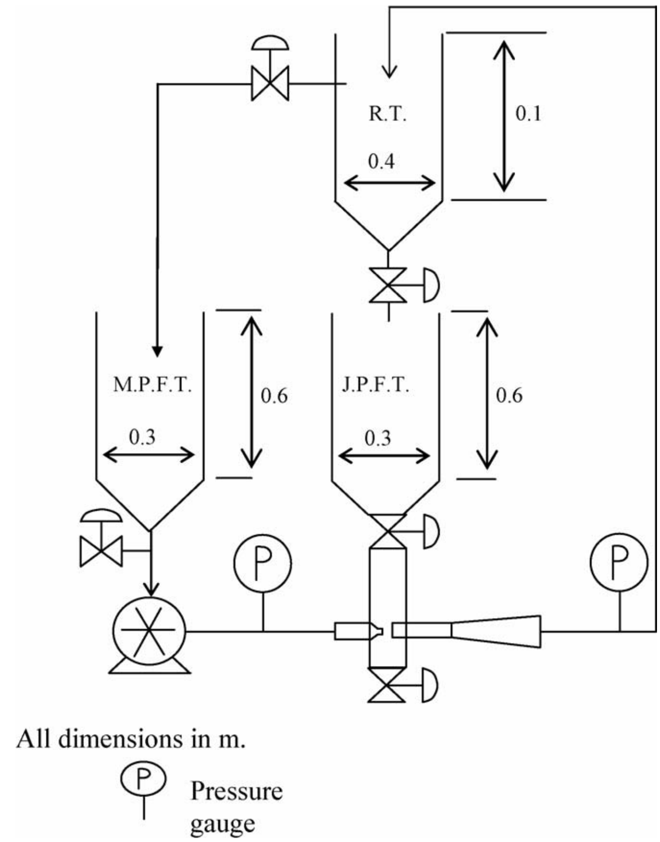

Fig. 2. Representation of the design layout of the C.S.R.R. [1].

3.2. Factorial design

The most effective and efficient method to quantify the effect of several parameters on the efficiency of a jet pump scrubber is to conduct a set of experiments modelled on a full factorial screening design. A full factorial screening design is a standard statistical analysis method, which sets up a number of experiments such that all possible combinations of parameters in question are investigated and compared to each other. A two level factorial design (high and low) provides a screening process to pinpoint the important parameters. The main parameters that have been chosen are:

(i) contaminant concentration,
(ii) number of passes of the media in the jet pump,
(iii) contaminated media particle size,

(iv) contaminant type,
(v) motive flow pressure.

3.2.1. Initial contaminant concentration

To analyse the effect of the initial contaminant concentration on the ability of the jet pump to remediate contaminated media, a high and low level of contamination is required. Thorvaldsen and Wakefield [13], quotes an initial total hydrocarbon contamination level of 99,240 mg/kg. Feng et al. [3] quotes a value of 5 wt.% which equates to 50,000 mg/kg. Due to the limited volumes of mineral oil available, a high level of media contamination of 47,600 mg/kg has been taken rather than 99,240 mg/kg. A low media contamination level of 5000 mg/kg was chosen to provide an order of magnitude difference between the higher and lower concentration levels and therefore should be sufficient to indicate whether the initial contaminant concentration is significant or not.

3.2.2. Contaminated media particle size

To determine the effect of different particle size on the jet pump scrubber efficiency, two types of silica sand were used. The larger silica sand had a particle range of 500–1000 μm (this range contained 97.8% of the entire sample measured) with an average size of 700 μm. The smaller silica sand had a particle size range of 125–355 μm (this range contained 97.7% of the entire sample measured) and an average size of 260 μm.

3.2.3. Contaminant type

Two refined mineral oils called S341 and S379 (Shell U.K. Oil Products Limited) were used as contaminants for all experiments. These mineral oils are de-waxed petroleum based hydrocarbons with a carbon count between C_{20} and C_{50}. Mineral oil type S341 can be considered moderately viscous whereas mineral oil S379 can be considered very viscous. Some of the properties of the mineral oils are outlined in Table 1.

3.2.4. Motive flow pressure

A high motive pressure of 11.3 bar (motive pump setting of 428 rpm) and a low motive pressure of 4.2 bar (motive pump setting of 253 rpm) were chosen to determine the effect of the motive flow pressure on the ability of the jet pump to remediate contaminated media. The high motive pump setting is sufficient to cause cavitation in the mixing chamber, whereas no cavitation occurs at the lower pump setting and hence at these high and low motive pump settings it is possible to analyse the effect of cavitation on the remediation process in the jet pump.

Table 1
Properties of mineral oils

Properties	S341	S379
Kinematic viscosity 20 °C (mm^2/s)	330	2200
Density (kg/m^3)	884	903
Flash point (°C)	240	280

3.2.5. Number of passes through the jet pump

To analyse the effect of the number of passes on the remediation efficiency of the jet pump, a low value of one pass and a high value of 10 passes was chosen.

The number of experiments required is 32, which is based on investigating five parameters at two levels, for example $2^5 = 32$ experiments. To increase the accuracy of the experiments, a full duplicate of the factorial screening design was conducted, thereby increasing the number of experiments to 64. The factorial screening design was produced using Minitab 14© (Minitab Inc.) and the results subsequently analysed in Minitab. For more detailed descriptions of factorial designs see [17] and for mathematical approaches to statistical experimental analysis see [18,19]. The full factorial screening design without replicates is given in Table 2.

3.3. Contamination of sand

As stated in Section 3.2, two types of sand were used, one with an average diameter of 700 μm and the smaller with an average diameter of 260 μm. Both of these sands where supplied by WBB Minerals. The sands were washed and oven dried with less than a 0.28% loss on ignition (data provided by WBB minerals). For each level of contamination, shown in Table 2, 4 kg of sand was weighed (using Swissmade Precisa XB1600C scales) and then either 200 or 20 g of oil was added to give contamination levels of 47,600 and 5000 mg/kg, respectively. The mixture was then mixed by hand for a minimum of 15 min or until the sand and oil resembled a homogenous mixture.

3.4. Experimental procedure

The experimental setup is shown in Table 2, for each experiment, the M.P.F.T. and J.P.F.T. where filled with tap water to a predefined level. The motive pump was then set to the correct setting as shown in Table 2. The contaminated sand was then placed into the J.P.F.T., the valve below the J.P.F.T. was opened and the motive pump switched on. The C.S.R.R. was then run for a defined time such that all the solid matter was pumped into the R.T. The motive pump was switched off and the valve below the J.P.F.T. was closed. The solid matter was then allowed to settle in the R.T. for 1 min and samples could then be taken if required. Some of the water was then returned to the M.P.F.T. and the rest of the solids and water could then be returned to the J.P.F.T. such that the water levels were restored to the original starting levels the system was then ready for another pass.

3.5. Analysis and error

An analysis method has been developed from U.S. E.P.A. [20] and Dong and Stefanou [21] to measure the level of contaminant removed. The method involves removing all the standing water from a sample of contaminated media then mixing 15 g of anhydrous sodium sulphate (analytical grade, Fisher Scientific) to 10 g of sample, to remove any remaining water. An amount

Table 2
Full factorial screening design

Experiment number	No. of passes	Contaminated concentration (mg/kg)	Motive pump setting (rpm)	Particle size (μm)	Viscosity, K (mm^2/s)
1	1	47600	253	260	330
2	10	47600	253	260	330
3	1	47600	428	260	330
4	10	47600	428	260	330
5	1	47600	253	700	330
6	10	47600	253	700	330
7	1	47600	428	700	330
8	10	47600	428	700	330
9	1	47600	253	260	2200
10	10	47600	253	260	2200
11	1	47600	428	260	2200
12	10	47600	428	260	2200
13	1	47600	253	700	2200
14	10	47600	253	700	2200
15	1	47600	428	700	2200
16	10	47600	428	700	2200
17	1	5000	253	260	330
18	10	5000	253	260	330
19	1	5000	428	260	330
20	10	5000	428	260	330
21	1	5000	253	700	330
22	10	5000	253	700	330
23	1	5000	428	700	330
24	10	5000	428	700	330
25	1	5000	253	260	2200
26	10	5000	253	260	2200
27	1	5000	428	260	2200
28	10	5000	428	260	2200
29	1	5000	253	700	2200
30	10	5000	253	700	2200
31	1	5000	428	700	2200
32	10	5000	428	700	2200

of 15 ml of toluene (H.P.L.C. grade, Fisher Scientific) was then added as an extraction solvent.

The sample was then sonicated using a sonication probe with a 1/8 in. horn (Model S-450A, Branson Ultrasonics Corp.) at maximum power for 10 min. The toluene in the sample was then removed using a pipette and passed through filter paper (Whatman GF/A, Fisher Scientific) to remove any particulates.

The extracted liquid was then analysed using a Heλios ε spectrophotometer (Thermo Electron Corp.) at wavelengths of 370 and 380 nm using pure toluene as a blank (HPLC grade, Fisher Scientific). Two wavelengths were used to improve the reading accuracy of the spectrophotometer. The concentration of the sample was then calculated by comparing the result against a set of standards made up with toluene and either S341 or S379 mineral oils at different concentrations. Fig. 3 shows the calibration of absorbance versus concentration for mineral oils S341 and S379.

From analysing the control samples, which included samples with both types of sand and mineral oil, the error for the combined extraction and analysis technique was found to be ±4.7% for S341 and ±4.4% for S379, respectively.

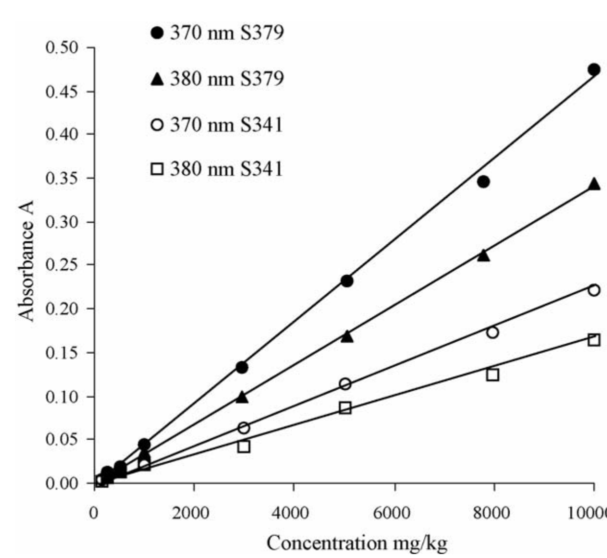

Fig. 3. Absorbance vs. concentration calibration curves for S341 and S379 at 370 and 380 nm wavelengths.

4. Results and discussion

As discussed in Section 2, five key parameters were chosen to investigate the ability of a jet pump scrubber to remediate contaminated media. Table 3 gives the average final contaminant concentration and removal percentages for all the experiments conducted. The lowest removal efficiency was 62.6% (experiment 21) and the highest removal efficiency was 99.1% (experiment 10). Key differences between experiments 21 and 10 are the particle size (experiment 21 used the larger particle size), the type of contaminate (experiment 21 used the less viscous S341), initial contaminant concentration (experiment 21 started with the smaller initial concentration of 5000 mg/kg), and the number of passes (one pass in experiment 21 compared with 10 passes in experiment 10). The only similarity between experimental conditions for experiments 21 and 10 is the motive pump setting at 253 rpm. Superficially, this would suggest that higher remediation efficiency is achieved with more viscous oils, smaller particles size, greater initial contaminant concentration and several passes in the jet pump. This confirms some of the hypotheses presented in Section 2 (e.g. higher initial contaminant concentration, increase number of passes) but contradicts others (e.g. viscosity of the oil and particle size). Crucially, however, the above analysis does not include the potential interaction between the key parameters, which is the main advantage of conducting a factorial design.

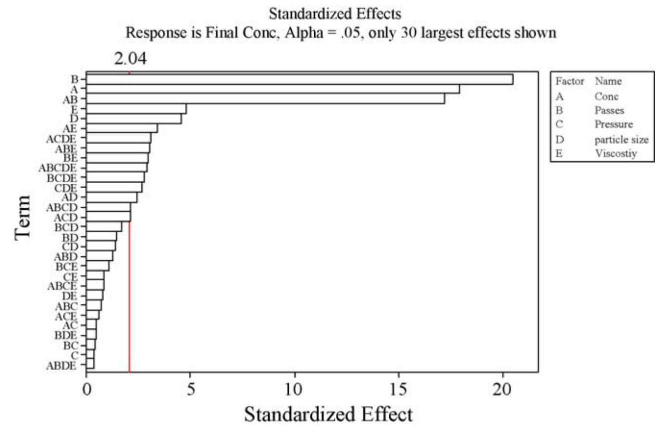

Fig. 4. Significant factors affecting the C.S.R.R.

Table 3
Average final sample contaminant concentrations and removal efficiencies

Experiment number	Initial concentration (mg/kg)	Final concentration (mg/kg)	Removal efficiency (%)
1	47600	9270	80.5
2	47600	515	98.9
3	47600	5875	87.7
4	47600	595	98.8
5	47600	7710	83.8
6	47600	1555	96.7
7	47600	10645	77.6
8	47600	1520	96.8
9	47600	4360	90.8
10	47600	475	99.0
11	47600	5965	87.5
12	47600	420	99.1
13	47600	6705	85.9
14	47600	1000	97.9
15	47600	6930	85.4
16	47600	810	98.3
17	5000	1085	78.3
18	5000	560	88.8
19	5000	1210	75.8
20	5000	685	86.3
21	5000	1870	62.6
22	5000	1145	77.1
23	5000	1430	71.4
24	5000	1075	78.5
25	5000	995	80.1
26	5000	525	89.5
27	5000	1095	78.1
28	5000	570	88.6
29	5000	1370	72.6
30	5000	680	86.4
31	5000	1250	75.0
32	5000	710	85.8

NB: The total error for any sample (extraction/analysis error plus standard deviational error) was a maximum of ±33% but individual errors for groups of samples often were considerably lower than this. The reason for this large error term was due to the fact that there was some deviation between duplicate runs and between the two samples taken from individual passes in some of the experimental runs. These results are being used for the factorial screening analysis and therefore individual values are of less an interest than trends in the data, therefore this error term can be taken into account in the factorial screening analysis. In addition to this using Minitab 14© (Minitab Inc.) the analysis of the residual plots from the experimental data showed that the model used by Minitab to identify significant parameters was accurate.

Fig. 4 depicts the 30 possible combinations of the five parameters that may have an affect on the C.S.R.R. An effect is defined by Montgomery [25] as "the change in response produced by a change in the level of the parameter". In this case, the effect is defined as the difference between the initial and final contaminant concentrations of the samples. The value of any single effect has been calculated using Minitab 14© (Minitab Inc.). The reference line in Fig. 4 is calculated using the $(1 - \alpha/2)$ section of a t-distribution with the degrees of freedom equalling the degrees of freedom for the error term in the factorial design. The α-level is a confidence level for the analysis, which was set to the standard value of 0.05 (which correlates to a 95% confidence level). For further information on factorial design and analysis, see Walpole and Myers [18], Minitab tutorials [19], and Montgomery [25].

Any parameter or combination of parameters greater than the reference line (which has been calculated to be a value of 2.04) can be classified as a significant parameter in the C.S.R.R. The greater the magnitude of the effect, the more significant it is to the system. As can be clearly seen in Fig. 4 the number of passes the media is subjected to (B) and the initial contaminant concentration (A) have the greatest effect on the system. The next greatest effect is the combination of these two parameters. There are 12 other parameters of importance to the system but all of these are considerable less than the first three.

Using a Zeizz, Sterio Discovery V12 microscope camera, Fig. 5 shows solid media before and after remediation through the C.S.R.R. As can clearly be seen there is a considerable differ-

Fig. 5. Sand contaminated to 47,600 mg/kg with S379 and after five passes through the C.S.R.R.

ence between the contaminated and remediated samples. Fig. 5 also shows that for an initial contamination of 47,600 mg/kg, the assumption of the two levels of contamination system as represented in Fig. 1 (i.e. X contaminates attached to the particle and ΔX contaminants attached to the X contaminants), is valid, since there is clearly contaminants that are not directly attached to the surface of the solid particle. Fig. 5 also indicates that all of the ΔX and all the visible X contamination was been removed by

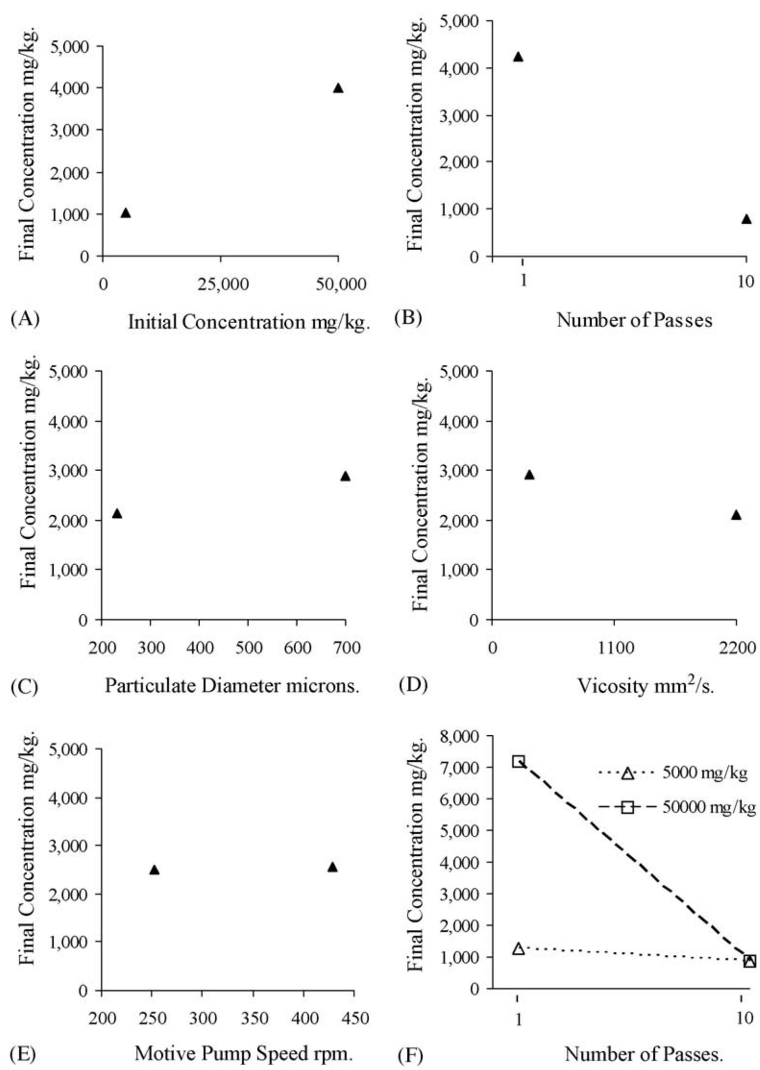

Fig. 6. Relationship between final concentration of contaminated media samples and each of the parameters: (A) initial concentration, (B) number of passes, (C) media particle size, (D) contaminant type, (E) motive power, and (F) combined parameters.

the C.S.R.R. demonstrating that the C.S.R.R. is very effective at remediating contaminated media.

Fig. 6A shows the effect of initial contaminant concentration on the final contaminant concentration. The mean final contaminant concentration was 4055 and 1023 mg/kg for initial contaminant concentrations of 47,600 and 5000 mg/kg, respectively (these final contaminant concentration values represent a combined average of all the experimental runs conducted for one and 10 passes and therefore do not represent the lowest average final contaminant concentration achieved by the C.S.R.R.). These results show that the average removal efficiencies of 91.6% and 79.7% for initial contaminant concentrations of 47,600 and 5000 mg/kg, respectively have been achieved. This result confirms the assumption that higher initial concentrations would yield greater total percentage contaminant removal due to the X and ΔX contamination system.

Fig. 6A clearly shows there is a large difference in final contaminant concentrations between the two initial contaminant concentrations. However, during experiments, recontamination of the media was observed in the C.S.R.R. After each pass, the solid contaminated media was passed back into the water left in the J.P.F.T., and when this took place, the media passed through an oily layer of contaminants that had formed on the top of the J.P.F.T. If there is more contaminant in the system initially (as with the higher contamination level), the amount of contaminants available for recontamination of the media is greater. Therefore, a greater amount of recontamination is expected at the higher initial contamination level. This could lead to a higher final contaminant concentration when compared to media that had a lower initial contaminant concentration as it would have less opportunity for recontamination to occur. This observation can be seen in Fig. 6A, as the media with a lower initial contamination concentration does have a lower final contaminant level suggesting that recontamination is occurring. Therefore, the magnitude of the recontamination must be calculated to prove if the results identified by the factorial design are due to recontamination or due to the fact that the initial contaminant concentration parameter is significant.

To investigate the effect of recontamination further, two additional sets of experiments where conducted with mineral oil S379 and one additional experiment with mineral oil S341. In each case, the initial dry contamination concentration was 50,000 mg/kg and all three experiments were conducted in triplicate to reduced experimental error. All media was subjected to 10 passes through the C.S.R.R. at a motive pump setting of 253 rpm (4.2 bar motive pressure). Two solid samples were taken after 1–5, 7, and 10 passes. For one set of experiments with S379 contamination, after each pass, the water in the J.P.F.T. was removed via a newly added tap on the bottom of the J.P.F.T. and any contaminants attached to the walls of the tank were also removed. Clean water was then added to the J.P.F.T. and the solid media and any water left in the receiving tank were then passed back into the J.P.F.T. This new step in the operation of the C.S.R.R. stopped the described recontamination from occurring. For the other S379 and the S341 experiment, the J.P.F.T. was not cleaned after each pass and recontamination was allowed to occur.

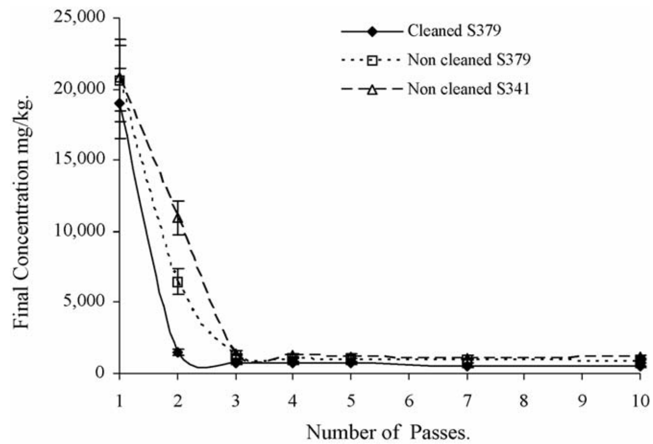

Fig. 7. Final contaminant concentration vs. number of passes for cleaned and non-cleaned S379 and non-cleaned S341.

Fig. 7 shows the effect of cleaning out the J.P.F.T. after each pass (thereby stopping recontamination from occurring in the C.S.R.R.) on the remediation efficiency. The average total error for all three sets of experimental runs was 12.5%, which is considerably lower than that of the factorial screening design, due to the fact the experiments were conducted in triplicate. As Fig. 7 clearly shows, cleaning out the J.P.F.T. has a definite affect on the contaminant concentration.

The first pass is very similar for all three sets of experiments. However, after the first pass, all three sets of experiments deviate. The "cleaned" S379 experiment has a lower contaminant concentration compared to the other two experimental conditions. This indicates that recontamination of the solid media was occurring in the J.P.F.T. as described above and that by cleaning the J.P.F.T. and replacing the water with fresh water after each pass dramatically reduces this recontamination from occurring.

The recontamination for the S341 case was assumed to be greater than that for the S379 case, due to the visual observation that the S341 did not adhere to the J.P.F.T. wall as much as the S379 contamination. Therefore, the S341 contamination produced a thicker layer of oil floating on top of the J.P.F.T. enabling more recontamination to occur as the solid media passed through. When comparing the S379 and the S341 results in Fig. 7, this assumption appears to be valid, as the S341 has a higher contaminant concentration than the S379 suggesting that there is more recontamination occurring in the S341 experiments. However, the difference between the S341 and the S379 experiments for the first pass and after 10 passes is small even when recontamination was taken into account.

Comparing the magnitude between the results in Fig. 6A (a difference of 3023 mg/kg) and the results of the recontamination (a difference of 332 mg/kg between cleaned and non-cleaned S379) then the recontamination can be considered small. Therefore, the initial contaminant concentration parameter is still a valid significant parameter in determining the remediation efficiency of the jet pump scrubber.

Fig. 6B shows the effect that the number of passes has on the final contaminant concentration. The mean final contaminant concentration was 4269 and 809 mg/kg for one and 10 passes, respectively (these final contaminant concentration values represent a combined average of all the experimental runs conducted for the number of passes therefore do not represent the lowest average final contaminant concentration achieved by the C.S.R.R.). As expected, increasing the number of passes in the jet pump increases the amount of contaminants removed and therefore reduces the final contaminant concentration. The large difference between one and 10 passes shows that recirculation of contaminated media is significant and that more than one pass is required to achieve the lowest contamination concentrations. This is also suggested by Wakefield and Tippets [16] for their jet pump system. Fig. 7 also shows the rate of the reduction in contaminant concentration with each additional pass and that after four passes, the level of contamination becomes constant with no further removal of contaminants achieved after this point. Therefore, for the contaminants used, only four passes through the jet pump scrubber are required to reach the lowest contaminant concentration.

Fig. 6C shows the effect of contaminated media particle size on the final concentration level. The mean final concentrations of 2154 and 2923 mg/kg for the media with average particulates sizes of 260 and 700 μm, respectively were calculated (these final contaminant concentration values represent a combined average of all the experimental runs conducted for the particle sizes therefore does not represent the lowest average final contaminant concentration achieved by the C.S.R.R). These values however do not validate the assumption that media with an average larger particulate size should be easer to remediate. One possible reason for the small particle size having a lower final contamination concentration might be due to the number of sand particulates per sample. Media with a smaller average particulate size will have more particles per unit of mass than a media with a larger particulate size (assuming similar densities and spherical particles). Since one of the main methods of remediation in the C.S.R.R. is attrition scrubbing, and since the efficiency of attrition scrubbing is directly related to the number of particles per unit mass then the attrition efficiency should be greater for the small more numerous particles than the larger particulates and this may explain these results.

Comparing the response of Fig. 6C to that of A and B, the conclusion that for the size range used the size of the particles in the contaminated media has only small effect on the remediation process and therefore is a less significant parameter.

Fig. 6D shows the effect of different contaminant types on the final contaminant concentration level. Mean final concentration levels of 2984 and 2093 mg/kg for the mineral oils S341 and S379, respectively, have been calculated (these final contaminant concentration values represent a combined average of all the experimental runs conducted for the two types of contaminants therefore do not represent the lowest average final contaminant concentration achieved by the C.S.R.R.). The more viscous mineral oil S379 had a lower final contaminant concentration than the less viscous mineral oil S341. This is in direct contrast to what was expected (i.e. the more viscous the contaminant the harder to remediate), however as stated above the effect of recontamination was greater for S341 than S379 and therefore a higher final contamination concentration for the S341 samples can be explained. Even when taking the effects of recontamination into account comparing the results shown in Fig. 6D with that of Fig. 6A and B the significance of contaminant viscosity is small, therefore the C.S.R.R. should be able to remediate media with a very wide range of contaminant types.

The effect of the motive pump speed versus the final contaminant concentration is shown in Fig. 6E. Mean final concentration levels of 2510 and 2568 mg/kg for the motive pump settings of 253 and 428 rpm, respectively, have been calculated (these final contaminant concentration values represent a combined average of all the experimental runs conducted for the two motive pressure settings therefore do not represent the lowest average final contaminant concentration achieved by the C.S.R.R.). As Fig. 6E shows there is very little difference between the two motive pump settings, as the lower motive pump setting successfully remediated the contaminated samples just as well the higher motive pump setting, which is direct contrast to the findings of Wakefield [16]. This may be explained by the fact that for the contaminants used, the lower motive pump setting supplied sufficient energy to the scrubbing action in the jet pump to successfully remediate the contaminated media. Therefore increasing the motive pump setting and increasing the energy available to the scrubbing action in the jet pump had very little effect on the final contamination concentration. As with the contaminant type parameter the effect of the motive pump setting is less significant when compared to the effects of initial contaminant concentration and number of passes.

Fig. 6F shows the largest two parameter combination effect, which was given by the combination of initial contaminant concentration and number of passes (AB). At the higher initial contaminant concentration, a mean sample final contaminant concentration of 7241 and 869 mg/kg after one and 10 passes, respectively, was calculated. For the lower initial contaminant concentration, a mean sample contaminant concentration of 1296 and 749 mg/kg after one and 10 passes, respectively, was calculated. (These final contaminant concentration values represent a combined average of all the experimental runs conducted for the two concentrations levels and both levels of the number of passes. Therefore do not represent the lowest average final contaminant concentration achieved by the C.S.R.R.)

This shows that the number of passes has a greater effect when the media has the higher initial contaminant concentration. Even though the effect of number of passes was considerably reduced for the lower initial contamination level, a reduction of nearly 550 mg/kg was still achieved by increasing the number of passes. Due to the fact that the U.K. has no direct guidelines on the required level of remediation for hydrocarbons in soil an "As low as reasonable possible" stance on pollutants should be taken until further legislation is developed by the Environmental Protection Agency. Therefore, even though the significance of the number of passes is reduced at lower initial contaminant concentrations, it is still important, as the lowest possible final contaminant concentrations might be required.

Fig. 4 lists another three, two parameter interactions and seven, three–five parameter interactions that have significant effects on the C.S.R.R. However, they are small in comparison to the effects of number of passes and contaminant type and the combination of these two parameters and therefore can be considered worthy of note but not further discussion until the three largest parameters are more clearly understood.

Five key parameters were investigated in the experimental design based on the current literature. However, there are four other parameters that could affect the ability of a jet pump scrubber to remove contamination, these are:

(i) the temperature at which the scrubbing is conducted,
(ii) the presence of natural organic matter and fine particulates in the solid phase,
(iii) aging of contaminated media,
(iv) the effect of adding a surfactant to the system.

Temperature was not chosen as parameter even though Bayley and Biggs [4], Thorvaldsen and Wakefield [13], and Wakefield and Tippetts [16] state that increasing the temperature increases the efficiency of a scrubbing process, as it is currently not possible to maintain the entire jet pump scrubber and all the ancillary equipment at a constant elevated temperature.

The effect of natural organic matter will vary greatly depending on the type of contaminant and natural organic matter in the system. Fine particulates have an important effect on the remediation efficiency of a soil washing process as described by El-Shoubary and Woodmansee [23]. However, like the natural organic matter parameter the effect of fine particulates will depend on the types of contaminants in the system. Also, the additional presence of natural organic matter and fine particulates would also induce new errors to the extraction and analysis method. Therefore, to accurately define the effect of natural organic matter and fine particulates in the jet pump scrubber would require an exponential increase in the number of experiments and is outside the scope of this paper at the present time but should be considered for future study.

Aging the contaminants has two effects on the contaminated system. Firstly, the contaminants can absorb into any porous structures in the media and thereby become harder to remove by soil washing. However, the media used for contamination was silica sand, which has a very low porosity and therefore this process is unlikely to occur. Secondly, aging of the contaminated media changes the composition of the contaminants and therefore aging of the non-porous media is similar to the contaminant type parameter. For these reasons, the aging of the contaminated media has not been incorporated into these experiments.

Surfactants have been proved to increase the efficiency of attrition scrubbing processes [22–24]. However, the effectiveness of a surfactant in a jet pump scrubber is not necessarily due to the jet pump operating conditions but rather to the type of surfactant used. Therefore, experiments comparing the operation efficiency of a jet pump scrubber with and without surfactants would provide details on the effectiveness of the specific surfactant, rather than a general case on the effectiveness of the operating conditions of the jet pump and therefore is outside the aims and scope of the paper.

5. Conclusion

A full factorial design with five parameters (initial contaminant concentration, number of passes, contaminated media particle size, contaminant type, and motive pump setting) has been designed and completed to investigate the effectiveness of jet pump remediation process. Fifteen parameters and parameter combinations have been identified and quantified as significant to the remediation of contaminated media in the C.S.R.R. Initial concentration, number of passes and the combination of these two parameters had a considerably greater effect on the remediation process in the C.S.R.R. than any of the other fifteen parameters/parameter combinations.

The number of passes had a more significant effect on samples with a higher initial contaminant concentration than samples with a lower initial contaminant concentration. From the factorial design, the optimum parameters for a jet pump scrubber can only be defined if the initial contaminant concentration is known. The jet pump should be run at moderate motive pressures to enhance scrubbing and designed such that the jet pump is run in a multiple pass mode of operation. The jet pump scrubber has shown to be capable of remediating contaminated media very quickly and effectively in addition the factorial design has indicated in which areas future study should be directed.

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