ELSEVIER

Chemical Engineering Journal 118 (2006) 55–62

Chemical Engineering Journal

www.elsevier.com/locate/cej

Remediation of contaminated media using a jet pump Part 2. Remediation dynamics of significant parameters in the jet pump remediation process

R.W. Bayley, C.A. Biggs *

Department of Chemical and Process Engineering, The University of Sheffield, Mappin Street, Sheffield S1 3JD, United Kingdom

Received 14 November 2005; received in revised form 9 January 2006; accepted 24 January 2006

Abstract

The jet pump scrubber is an effective process for the remediation of contaminated sediments. Experiments to investigate the effects of the initial contaminant concentration and number of passes on the efficiency of the jet pump scrubber have been conducted. Additionally, experiments with Alba crude oil and a thin mineral oil were undertaken to identify the effects of extreme contaminants on the remediation efficiency. For all experiments, washed oven dried silica sand was contaminated with either Alba crude or one of three different types of mineral oil. Experiments were conducted with media contaminated at six different concentrations, ranging from 50,000 to 500 mg/kg and subjected to multiple passes through the jet pump scrubber. Samples were analysed using an ultrasonic extraction and spectrophotometric method. Removal percentages of 98 ± 0.1% and 93 ± 0.9% were achieved for mineral oil and Alba crude oil, respectively. Alba crude oil was found to be considerably more difficult to remediate than the mineral oil. A threshold value of 220 ± 25 mg/kg, below which the jet pump scrubber could not remediate, was identified for mineral oil contaminated samples.

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

1. Introduction

Previous work conducted by Thorvaldsen and Wakefield [1], Wakefield and Tippetts [2] and, Bayley and Biggs [3] has demonstrated that the jet pump scrubber can be used to remediate contaminated sediments. However, little is understood about which parameters and operating conditions are likely to influence the ability of a jet pump scrubber to remediate contaminated media, any possible interaction effects between suitable parameters, and also the dynamic response of varying such operating conditions on the remediation process.

Bayley and Biggs [3] set about to identify which parameters had an effect on the remediation efficiency of the jet pump scrubber using a screening factorial design. Five parameters (contaminant concentration, number of passes, contaminated media particle size, contaminant type and, motive flow pressure) where chosen to be evaluated for their effects on the jet pump scrubber. The main conclusions from Bayley and Biggs [3] were:

- There were 15 parameters/parameter combinations that had a significant effect on the jet pump scrubber.
- The initial contaminant concentration, and the number of passes, and the combination of these two parameters were found to have the most statistically significant effect on the remediation process and were the most dominant of all the parameters and parameter combinations investigated.
- Recontamination of the samples due to the design of the Contaminated Sediment Remediation Rig (CSRR) was identified and found to have only a small effect on the final contaminant concentration.
- Further work was required to improve the understanding of the parameters involved in the jet pump scrubber.

Therefore, the jet pump scrubber has been shown to be a suitable remediation process, however, further work is required to clearly describe the effect of operating conditions on the efficiency of the process. The aim of this paper therefore, is to

---

* Corresponding author. Tel.: +44 114 2227510; fax: +44 114 2227501.
E-mail address: c.biggs@sheffield.ac.uk (C.A. Biggs).

1385-8947/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.cej.2006.01.009

investigate the jet pump scrubbing process further and to provide answers to the unknown factors that became apparent from the results obtained by Bayley and Biggs [3]. Specifically, this paper aims to: (i) clearly define the effects of contaminant concentration and number of passes and the combination of these two parameters on the jet pump scrubber; (ii) calculate contaminant removal efficiencies for the jet pump scrubber; (iii) clarify that the contaminant type is a less significant parameter even when extreme contaminants such as crude oil and a very low viscosity mineral oil are used as contaminating agents.

2. Methods

2.1. Jet pump and contaminated sediment remediation rig

A simplified schematic of the jet pump used in all experiments is shown in Fig. 1. The jet pump has been design with a fix geometry with a nozzle to mixer area ratio of 0.16 and an induced flow to motive flow ratio range of 0.51–1.5.

A detailed description of the design and commissioning of the contaminated sediment remediation rig that contains the jet pump scrubber is given by Bayley and Biggs [4]. A schematic of the CSRR is shown in Fig. 2. The CSRR consists of a motive pump, which is fed by a motive pump feed tank (MPFT). The motive pump delivers a motive flow of water at variable pressure (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 (JPFT). The JPFT 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 JPFT combine in the jet pump mixing chamber and form the combined flow, which is pumped into the receiving tank (RT) that is situated above the JPFT. 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 JPFT. Halfway up the receiving tank is situated another valve that allows water to be passed back into the MPFT.

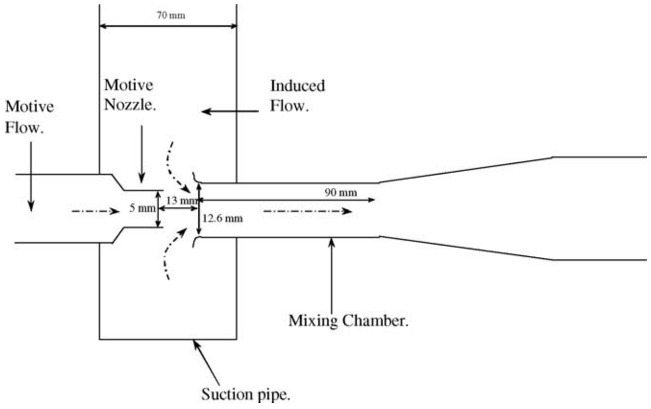

Fig. 1. The jet pump.

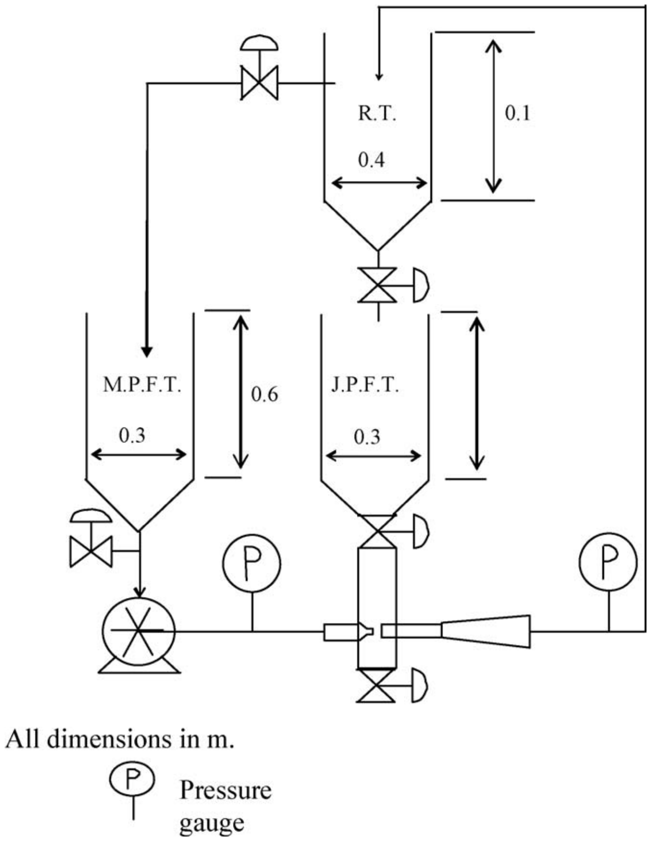

Fig. 2. Representation of the design layout of the CSRR Bayley and Biggs [4].

2.2. Contamination of sand

For each experiment, silica sand was used as the solid media to be contaminated and then remediated. The silica sand had a particle range of 500–1000 μm (this range contained 97.8% of the entire sample measured) with an average particle diameter of 700 μm. The silica sand, supplied by WBB Minerals, was washed, and oven dried, with less than a 0.28% loss on ignition (data provided by WBB minerals). Silica sand was weighed out to the correct mass using Swissmade Precisa XB1600C scales and then the contaminant of choice was added such that the total mass of contaminant and silica sand equalled 4 kg for all experiments. The mixture was then mixed by hand for a minimum of 15 min or until the sand and oil resembled a homogenous mixture.

2.3. Contaminants

Four types of contaminants were used in these experiments, three were refined mineral oils called S33, S341 and S379 (Shell U.K. Oil Products Limited) and the fourth was crude oil provided by ChevronTexaco Corp. The mineral oils are de-waxed petroleum based hydrocarbons with a carbon count between C_{20} and C_{50}. Properties of the mineral oils are outlined in Table 1.

The crude oil is an unrefined Alba crude from the North sea, North platform. All data was collated by Statoil and ChevronTexaco [5,6]. Alba crude has an API of 19.5 and therefore, is classified as a heavy crude oil (API is a method of crude oil

Table 1
Properties of mineral oils

Properties	S33	S341	S379	Alba crude
Density (kg/m^3)	880	884	903	936
Kinematic viscosity 40 °C (mm^2/s)	68.8	99	490	134
Flash point (°C)	>220	240	280	74

classification developed by the American Petroleum Institute). Properties of the Alba crude are given in Table 1 and the composition of the Alba crude is given in Table 2.

2.4. *CSRR experimental procedure*

The CSRR experimental procedures were developed by Bayley and Biggs [4] and perfected in Bayley and Biggs [3]. In each experiment sand and oil of the type required where mixed as described in Section 2.2. MPFT and JPFT where filled with tap water to a predefined level, the motive pump was then set to 253 rpm (4.2 bar motive pressure). The contaminated sand was then placed into the JPFT and the valve below the JPFT was opened and the motive pump switched on. The CSRR was then run for a defined time such that all the solid matter was pumped into the RT. The motive pump was switched off and the valve below the JPFT was closed. The solid matter was then allowed to settle in the RT for 1 min and samples could be taken if required, some of the water was then returned to the MPFT. So that recontamination did not occur the remaining water in the JPFT was then removed via a tap at the bottom of the tank. The JPFT was then cleaned of any visible oil manually and clean fresh water was then added to the JPFT. Finally the solids in the receiving tank and any additional water in the receiving tank were returned to the JPFT. The system was then ready for another pass. For all experiments the average room temperature was a constant 19 ± 0.1 °C, and the average water temperature during experimental runs was measured to be 19 ± 0.1 °C.

2.5. *Number of passes and contaminant concentration experiments*

To clarify the dynamic effect of the number of passes and contaminant concentration and the combination of these two parameters, in the remediation process, a full set of experiments, were conducted. All experiments were conducted in triplicate to reduce experimental errors. Media contaminated with initial dry concentrations of 50,000, 25,000, 10,000, 5000, 1000, and 500 mg/kg were used (total number of experiments equalled 18 runs of 4 kg). All sets of media where subjected to five passes through the CSRR at a motive pump setting of 253 rpm (4.2 bar motive pressure). Two solid samples were taken after every pass for all set of contaminant concentrations. The JPFT was cleaned out after every pass as described in Section 2.4 for all experiments to reduce the risk of contamination as shown in [3].

2.6. *Extreme contaminant experiments*

Two sets of experiments were conducted to analyse the effect of extreme variability in the type of pollutants on the remediation process. In this case, a very thin mineral oil S33 and Alba crude oil were used as the contaminants. For both S33 and Alba crude, 4 kg of sand was contaminated to a dry contaminant concentration of 50,000 mg/kg, and subjected to five passes through the CSRR at a motive pump setting of 253 rpm (4.2 bar motive pressure). Two solid samples where taken after each pass. Both experiments where conducted in triplicate to reduce experimental error. In the case of Alba crude experiments an additional five passes through the CSRR was conducted and samples taken after the 7th and 10th passes. The JPFT was cleaned out after every pass as described in Section 2.4 for all experiments.

Based on the results the Alba crude from the experiment described above, two additional experiments were conducted. Firstly, a re-run of the experiment conducted above but at a motive pump setting of 428 rpm (11.3 bar motive pressure) to see whether contaminant removal could be improved. In addition to this, after 10 passes through the CSRR, the contaminated sand was removed, the CSRR was cleaned, and then the sand was subjected to an additional 10 passes. Samples were taken after the 5th and 10th additional passes (contaminated media was subjected to a total of 20 passes through the CSRR).

Finally, to see the effect of wet media contamination with Alba crude oil, 4 kg of dry media was wetted to saturation and then contaminated with crude to a dry contaminant concentration of 50,000 mg/kg. The contaminated media was subjected to five passes through the CSRR at a motive pump setting of 428 rpm (11.3 bar motive pressure). Two solid samples where taken after each pass, all experiments were conducted in triplicate.

Table 2
Alba crude oil composition [6]

	Whole cut	Light naphtha	Medium naphtha	Heavy naphtha	Kero	Gas oil Atm	Vacuum gas oil		Residuum	
							Light	Heavy	Vacuum	Atm
Temperature, at start (°C)	–	10	80	150	200	260	340	450	570	340
Temperature, at end (°C)	–	80	150	200	260	340	450	570	End	End
Yield of cut (%)	–	0.2	1.0	2.8	6.6	17.5	21.1	21.2	29.6	71.8
Paraffins (vol.%)	–	66.1	33.5	19.4	19.6	12.5	11.3	–	–	–
Naphthenes (vol.%)	–	33.9	58.0	60.9	56.4	50.0	43.4	–	–	–
Aromatic (vol.%)	–	–	8.5	19.7	23.3	28.6	29.1	–	–	–
Thiophenes (vol.%)	–	–	–	0.0	0.7	8.9	16.2	–	–	–
Molecular weight	385	98	120	139	174	218	306	461	781	495

Table 3
Error percentages of extraction and analysis method

Sample	Error (%)
S341	4.7
S379	4.4
S33	5.0
Crude	4.1

2.7. Analysis and error

An analysis method was developed from US EPA [7] and Dong and Stefanou [8] to measure the level of contaminant removed. A detailed description of the experimental procedure is given in Bayley and Biggs [3]. The method involves removing all the water from a weighed sample using anhydrous sodium sulphate (analytical grade, Fisher Scientific) then the addition of a defined amount of extraction solvent (Toluene, HPLC grade Fisher Scientific). The sample is then sonicated at maximum power for 10 min (Model S-450A, Branson Ultrasonics corp.) and the extraction solvent and contaminants are then removed and filtered (Whatman GF/A, Fisher Scientific). The extracted liquid is then analysed using a Heλios ε spectrophotometer at two wavelengths to improve reading accuracy of the spectrophotometer (using pure Toluene as a reference). The sample concentration can then be calculated by comparing the result against a set of standards, of known concentrations of contaminants in Toluene. From analysing control samples, which included samples with both types of mineral oil and crude oil, the error for the combined extraction and analysis technique was calculated for each type of contaminant and are given in Table 3.

3. Results and discussion

3.1. Number of passes and contaminant concentration results

A response curve, showing the dynamics of the remediation process, as represented by the final contaminant concentration, when the number of passes and the initial contaminant concentration is varied, is shown in Fig. 3. Fig. 3 clearly shows that most of the contaminant is removed in the first pass. For the higher initial contaminant concentrations, a second and third pass can also remove large quantities of contamination.

Table 4
Final percentage removals after five passes

Initial conc. (mg/kg)	Percentage removal (%)
50007	98 ± 0.1
25039	98 ± 0.3
10023	98 ± 0.6
5034	95 ± 0.6
1015	82 ± 3.3
557	57 ± 6.5

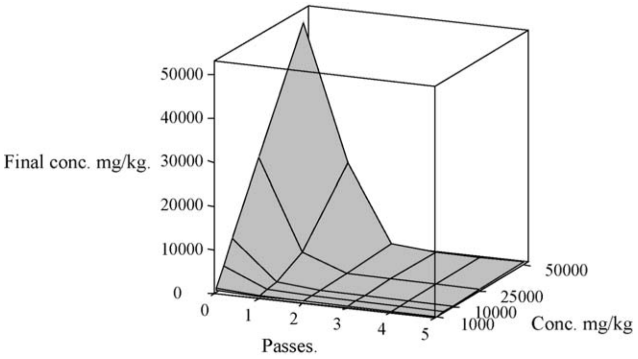

Fig. 3. Response curves for final concentration vs. number of passes for all initial sample concentrations.

Table 4 details the remediation efficiency of the CSRR for all six initial contaminant concentrations after five passes in the jet pump scrubber, as shown in Fig. 3. The highest remediation efficiency achieved was 98.5 ± 0.1% for the highest initial contaminant concentration and the lowest efficiency was 56.5 ± 6.5%, which was for the lowest initial contaminant concentration. Table 4 clearly shows that the remediation efficiency reduces as the initial contaminant concentration decreases. This result supports the findings made by Bayley and Biggs [3], that higher initial contaminant concentration produces better removal efficiencies than lower initial contaminant concentrations.

Fig. 4 shows the percentage removal versus number of passes for different initial contaminant concentrations. For all six sets of experiments, the greatest removal efficiency was achieved during the first pass. For the 50,000, 25,000, 10,000, and 5000 mg/kg experiments, the removal efficiency then reduced after each consecutive pass. For the 1000 and the 5000 mg/kg set of experiments the remediation efficiency is constant after the first pass showing that no further remediation occurs after the first pass.

Initial contaminant concentration batches of 25,000, 10,000 and, 5000 mg/kg have the same removal efficiencies for the first pass after which the 25,000 and 10,000 mg/kg batches match identically, and the 5000 mg/kg batch deviates slightly, becomes constant after the second pass, and gives a lower final removal efficiency.

The 50,000 mg/kg initial contaminant concentration experiment has a lower removal percentage for the first pass compared

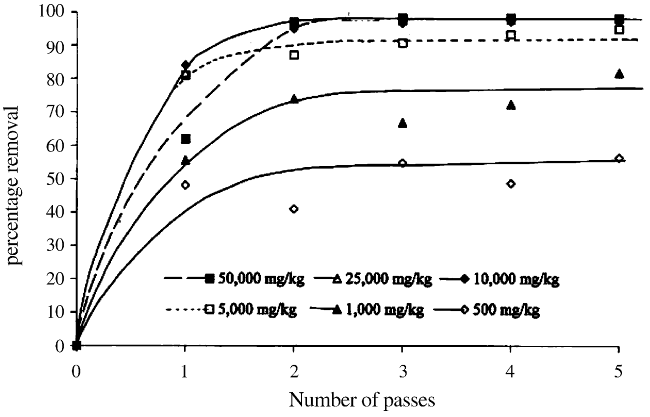

Fig. 4. Percentage removal vs. number of passes for different initial contaminant concentration.

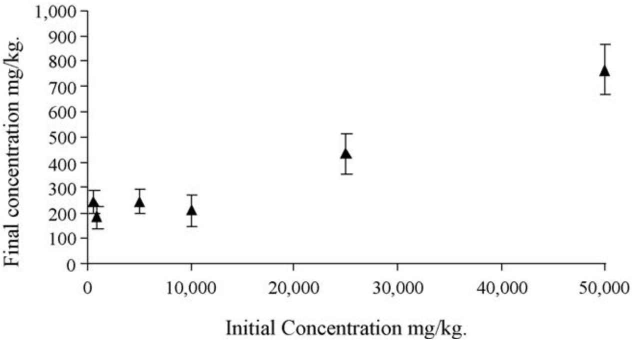

Fig. 5. Average final concentration in mg/kg vs. average initial contaminant concentration in mg/kg.

to that of the 25,000, 10,000 and, 5000 mg/kg sets. This may be due to the fact that there is a large amount of contaminate in the sand and that recontamination in the pipe work in the CSRR is occurring. Hence separation of the contaminants and the solid media in the RT is required before any further remediation can be achieved. This assumption appears to be sound due to the fact that the removal efficiency for the second pass for the 50,000 mg/kg batch is higher than any other second pass removal efficiency. After two passes the 50,000 mg/kg batch nearly matches the 25,000 and 10,000 mg/kg batches and effectively matches after three passes. Both the 1000 and 500 mg/kg batches are radically different from all the other batches with considerably lower final removal efficiencies. As seen in Fig. 3 and Table 4.

Fig. 5 shows the average final concentration in mg/kg versus average initial contaminant concentration in mg/kg. For the 10,000, 5,000, 1000 and, 500 mg/kg initial contaminant concentrations, the final contaminant concentration is very similar averaging at 220 ± 25 mg/kg. This suggests that there is a threshold value at which the jet pump scrubber cannot remediate below.

To identify if further remediation was possible, the media initially contaminated with 10,000 mg/kg was stored after the first five passes, the CSRR was then thoroughly cleaned and the three sand batches were then re-run for another five passes. Two samples where taken after each pass (10 samples per sand batch, 30 samples in total). After the initial five passes the contamination concentration was 209 ± 62 mg/kg. Further reduction in the sample concentration was not found and the average concentration of the 30 samples was 205 ± 26 mg/kg. This shows that there is very little variation between the first additional pass and the last additional pass. Therefore, the addition of five extra passes in a cleaned CSRR has not reduced the final contaminant concentration. Therefore, this provides evidence that there is a threshold contaminant concentration for which the CSRR in its current operation cannot remediate below.

The 50,000 and 25,000 batches have final contaminant concentrations of 763 ± 102 and 433 ± 84 mg/kg, respectively. This is higher than the suggested threshold value and indicates that further remediation may be possible. Hence, three sets of media contaminated to an initial concentration of 50,000 mg/kg with S379 were subjected to an additional five passes through the CSRR. Two samples where taken after the 2nd and 5th additional passes. The final concentration of 763 ± 103 mg/kg after five passes was reduced to 507 ± 68 mg/kg after an additional five passes (total of 10 passes in the CSRR). This final contaminant concentration is still above the threshold value and therefore, further remediation may be possible. However, the rate of removal of contaminants decreased after each additional pass during the experiment, hence to reach the threshold value would require many additional passes.

Since there is a cut off point at which further remediation cannot be conducted, the threshold value will have an increasingly important effect on the removal efficiency as the initial contaminant concentration decreases. If the initial contaminant concentration becomes either the same or very similar to that of the threshold value then the remediation efficiency will be effectively equal to zero as very little contamination is removed.

The threshold value assumption now clearly explains the removal efficiency results, as shown in Table 4. As the initial contaminant concentration decreases and becomes closer to that of the threshold value then the remediation efficiency decreases. Therefore, the initial contaminant concentration is a significant parameter to the operation of the CSRR as it now defines how many passes are required to reach the threshold value.

There are two possible reasons for a threshold value to exist: (i) there is a fine faction of sand in the solid sample that simply cannot be remediated. As all the sand in the experiments was the same then the mass of the fine fraction should be the same for all experiments hence the threshold value is the same for all experiments; (ii) there are a defined number of sites per unit of solid media where contaminants can bond strongly and directly to the particles, and further remediation is not possible, as the attrition process is not able to overcome the bonds. Possibilities for this are:

(1) Organic matter on the sand particles forms bonds with the organic contaminants.
(2) Part of the sand particles and/or some of the contaminants can react together and form very strong bonds.
(3) The sand is not totally non-porous and pores are present in a fraction of the sand particles. Therefore, contaminants can seep into the pores and are beyond the effects of attrition scrubbing.

To identify what might be governing the contaminant threshold limit, six randomly chosen samples were dried and sieved to determine the fraction of small particles in the remediated sand. Harris [9] quotes that for particles below 63 μm in diameter, soil washing has very little effect. For all samples there was effectively no fine fraction, as less than 0.001 g/10 g sample were found to be below 100 μm in size. Therefore, the threshold value cannot be due to an un-washable fine fraction in the samples.

To identify if there was any natural organic matter in the clean media six, 8 g clean media samples where contacted with 1.6 g of water, 15 g of anhydrous sodium sulphate and 12 g of Toluene and extracted for 10 min. These samples where then filtered and measured in a spectrophotometer. The results showed that there was no organic matter in the clean media. Therefore, the threshold value cannot be due to either an un-cleanable fine fraction or natural organic matter in the clean media.

Therefore, the reasons for a threshold limit are either: (i) parts of the sand particles and/or some of the contaminants can react together and form very strong bonds; (ii) the sand is not non-porous and pores are present in a fraction of the sand particles. Therefore, contaminants can seep into the pores and are beyond the effects of attrition scrubbing.

The media is 97% silicon oxide and 2.7% aluminium, iron and potassium oxides (data provided by WBB minerals) which can be considered un-reactive in respect to mineral oils. Therefore, the media must not be completely non-porous and there must be some fraction of sites on the media that can be contaminated which are beyond the range of the scrubbing action and this causes the threshold limit.

3.2. Extreme contaminant results

The results produced by the factorial design in Bayley and Biggs [3] showed that for the contaminant types used the contaminant type was not a significant parameter in the remediation of contaminated media in the CSRR. This result was not expected and further experimentation was deemed necessary. Two new contaminants where chosen, S33 mineral oil and Alba crude oil. The remediation results for the experiments conducted with these two contaminants are given in Figs. 6 and 7.

From Fig. 6, it can be seen that there is very little difference between the S379 and the S33 after three and five passes, even though S33 has a kinematic viscosity of 68.8 mm^2/s at 40 °C compared to that of S379 of 490 mm^2/s, at 40 °C. The final average concentration of each oil after five passes is 746 ± 161 and 763 ± 102 mg/kg for S33 and S379, respectively. The only difference between the two types of contaminant occurs after the first and second passes. S33 has a much greater removal percentage after the first pass compared to that of S379 (91.6 ± 0.28% compared to that of 61.9 ± 0.14% for S33 and S379, respectively). This leads to the conclusion that the S33 mineral oil is easer to remove than the S379 up to a defined contaminant concentration.

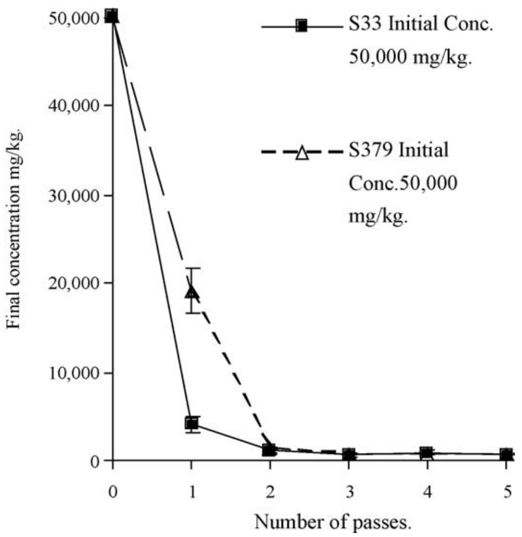

Fig. 6. Mineral oils S379 vs. S33 at a motive pump setting of 253 rpm and an initial concentration of 50,000 mg/kg.

Bayley and Biggs [3] proposed an X and ΔX contamination model, if the X contaminant phase is only attached to the particle surface due to hydrophobic forces and not directly bonded. Then one of the main factors that will determine the strength that the contaminant is attached to the particle surface will be the viscosity. If the viscosity decreases them the contaminant should be easer to remove, this assumption will also be applicable to the bond strength between the X and the ΔX contaminants.

Therefore, if the viscosity is reduced then the X and ΔX contaminants should be easier to remove from the particle surface. This can clearly be seen in Fig. 6 where the less viscous S33 is removed faster than the more viscous S379. However, the removal percentages are effectively the same after the third pass (98.7 ± 0.28% compared to that of 98.4 ± 0.14% for S33 and S379, respectively). Indicating that after most of the contamination has been removed, the contamination concentration reaches a threshold value, and the system becomes independent of the contaminant type and is governed by a new parameter.

Comparison between Alba crude oil, at different motive pump settings and mineral oils can be seen in Fig. 7.

The lowest contaminant concentrations achieved where 7721 ± 1207 mg/kg and 9782 ± 1748 mg/kg for motive pump settings 428 and 253 respectively, for media with an initial crude oil concentration of 50,000 mg/kg. Both of these values were achieved after 10 passes.

These final contaminant concentrations are considerably higher than the values quoted by Wakefield [10], in which simulated oil-spill trials with beach sand were conducted using a jet pump scrubber system. In this case, an initial contaminant concentration of 115,000 mg/kg was reduced to a final contaminant concentration of 70 mg/kg. However, a motive pressure of 17 bar was used, which is considerably higher than the motive pressures used in the CSRR and the beach sand was contaminated with Brent crude/lubricating oil not Alba crude oil, which may explain the difference between the results.

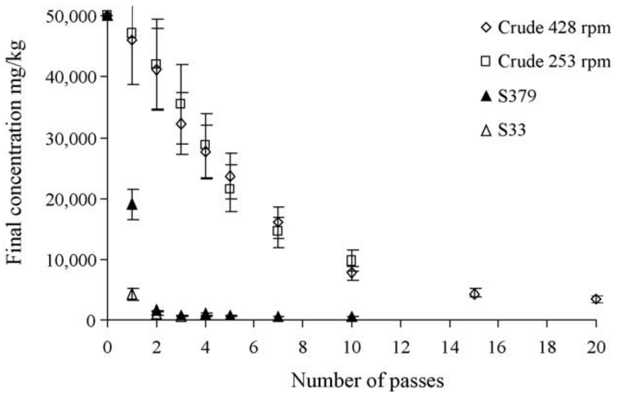

Fig. 7. Crude oil contaminated samples at motive pump settings of 428 and 253 rpm vs. S379 and S33 contaminate samples at a motive pumps setting of 253 rpm.

Fig. 7 also suggests that increasing the motive pressure from setting 253 to setting 428 has little effect on the overall removal of crude oil from the contaminated media as indicated by the factorial design conducted by Bayley and Biggs [3]. However, the higher motive pump pressure does produce a contaminated product that has a slightly lower final contaminant concentration and since the aim is for the lowest possible contaminant concentration possible this could be of useful note. This small increase in contaminant removal would have to be balanced against the extra power requirement needed to determine whether it is beneficial to operate the CSRR at this higher motive pressure setting.

As can clearly be seen in Fig. 7, there is a considerable difference between the crude oil contaminated samples and the S379 and S33 contaminated samples. Both the S379 and S33 contaminated samples have considerably lower contaminant concentrations for all samples taken (removal percentage for S379 was 98 ± 0.1% compared to that of crude oil of 57 ± 6.3% for motive pump setting 253 rpm and initial contaminant concentration of 50,000 mg/kg after five passes). This shows that crude oil is considerably harder to remove than the mineral oil even though the crude oil has a lower viscosity than the S379. This finding, with the addition of the S33 results, indicates that the contaminant type is a significant parameter in the CSRR and that the chosen contaminants in the factorial design by Bayley and Biggs [3] were not sufficiently contrasting to show this. The crude oil result now indicates that the viscosity is not the only factor that defines the bond strength between the contaminants and the particles. During the crude oil experiment the observation that the crude oil was considerably more “sticky” than the S379 and other mineral oils and was harder to remove from the CSRR when cleaning between experimental runs, was found.

The reason for the reduced removal efficiency in the CSRR with crude oil is due to the fact that crude oil has a much more complex make up of hydrocarbons than the mineral oil. Crude oil contains many more branched and carbon rings than mineral oils. Increasing the number of branched and carbon rings in hydrocarbon compounds increases the hydrophobic nature of the oil, and therefore, the oil becomes harder to separate from the contaminated media into the water phase.

Increasing the number of passes from 10 to 20 passes decreased the final contaminant concentration from 7721 ± 1207 mg/kg down to 3487 ± 422 mg/kg (at motive pump setting 428 rpm and an initial contaminant concentration of 50,000 mg/kg) which increased the removal percentage of crude oil from 85 ± 20% to 93 ± 0.9%. This shows that further remediation is possible, but as with the mineral oil contaminated samples, the total mass of crude oil removed per pass decreases as the number of passes increases and an economical balance must be made between the number of passes and the required final contaminant concentration.

The final set of experiments with crude oil contaminated samples was to compare the remediation efficiency of the CSRR when remediating media that had been contaminated dry and media that had been contaminated wet. From an initial contaminant concentration of 50,000 mg/kg after five passes an average removal percentage of 99.9 ± 0.01% (final contaminant concentration of 47 ± 23 mg/kg) was achieved for the wet contaminated media samples. Comparing this value to that of 57 ± 6.3% (21,650 ± 3870 mg/kg) for the dry media contaminated samples under the same CSRR conditions there is a large difference between wet and dry remediation efficiencies. The wet contaminated, final contaminant concentration of 47 ± 23 mg/kg compares well to that quoted by Wakefield [10] of 70 mg/kg. The oil-spill trials conducted by Wakefield [10] used beach sand, which suggests that contaminated media had a high moisture content. This would explain the large difference between the dry contaminated remediation results shown in Fig. 7 and those quoted by Wakefield [10] in the oil-spill trials. This would lead to the conclusion that even though different sands and crude oils were used in each set of experiments, the state that the media is in when contamination occurs is of immense importance to the final remediation concentration.

From visual observations contaminating wet media was extremely difficult as the water on the solid particles appeared to form a barrier between the solid particles and the crude oil, stopping the crude oil from attaching to the solid particles. This effect has also been described by Amro [11]. This effect became apparent when after addition of the contaminated sample to the JPFT a large amount of oil separated from the solid media and floated on top of the water in the tank, this did not occur in the dry contaminated samples. Therefore, wetted samples are considerably harder to contaminate than dry samples and due to this fact are considerably easier to remediate and much lower final contaminant concentrations are possible.

4. Conclusion

Experiments were conducted to determine the effects of the initial contaminant concentration and number of passes on the remediation efficiency of a jet pump scrubber. Experiments with Alba crude oil and a thin mineral oil were undertaken to identify the effects of extreme contaminants. A total remediation efficiency of 98 ± 0.1% after five passes was achieved at high initial contamination concentrations for mineral oil contaminated samples. The total removal efficiency decreased as the initial contamination concentration decreased to a threshold value. In addition, the removal efficiency per pass decreased as the number of passes increased. The number of passes required to reach the maximum total removal efficiency depended on the initial contaminant concentration. A threshold value of 220 ± 25 mg/kg was identified for the CSRR when remediating mineral oil contaminated media.

A total remediation efficiency of 98.6 ± 0.3% after five passes and motive pump setting 253 rpm was achieved for S33 compared to only 57 ± 6.3% for Alba crude oil under the same conditions. This result shown that the type of contamination has a significant effect on the CSRR’s remediation efficiency.

The final contaminant concentration levels also depended greatly on whether the media is wet or dry when contamination occurs. In the case of crude oil contamination, remediation efficiencies of 99.9 ± 0.01% where achieved with wet media contamination, compared to only 57 ± 6.3% under the same conditions for dry media contamination.

Finally, the experiments conducted have shown that the jet pump scrubber can remediate a wide range of contaminants and is flexible and adaptable to remediation of contaminated media. Future work should focus on the effects of temperature, moisture content of the media when contamination occurs, and what effect contact time (time between contamination and remediation) could have on the remediation efficiency.

Acknowledgements

The authors would like to acknowledge the support of The Royal Society-U.K. National Academy of Science and the Engineering and Physical sciences research Council (EPSRC) for this work.

References

[1] G.S. Thorvaldsen, A.W. Wakefield, Hydrotransport 14 (1999) 1–14.
[2] A.W. Wakefield, J.R. Tippetts, in: 11th Inter. Conf. Transp. Sedim. Solid Part, 2002, pp. 233–249.
[3] R.W. Bayley, C.A. Biggs, Remediation of Contaminated Media in a Jet Pump Part 1: Screening for Significant Parameters, Chem. Eng. J., in press.
[4] R.W. Bayley, C.A. Biggs, Trans. IChemE Part B 83 (2005) 381–386.
[5] Statoil Chevron, Research and Technology Company, 1999.
[6] ChevronTexaco Corp., http://www.chevron.com.
[7] U.S. E.P.A Method 3550B, Ultrasonic Extraction, 1996.
[8] M.W. Dong, S. Stefanou, LC-GC 11 (1993) 802–810.
[9] M.R. Harris, Remedial treatment for contaminated land, vol. 7: Ex-situ Remedial Methods for Soils, Sludges and Sediments, 1995, CIRIA.
[10] A.W. Wakefield, Hydrotransport 13 (1996).
[11] M.M. Amro, Chem. Eng. Technol. 27 (2004) 890–894.