Elution Technology of Tubular Vortex Enhanced Diesel-Contaminated Maifan Stone Particles

Kunyu Geng¹, Min Meng¹, Yanliang Ding¹ and Qiang Yang*¹

¹School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai, 200237, China;
*Corresponding author’s e-mail: qyang@ecust.edu.cn

Abstract. In view of the difficulty in repairing petroleum-contaminated soil, a tubular vortex elution device is designed based on previous research findings in this paper. Using the experimental method, the diesel-contaminated maifan stone was taken as the research object, the process of tubular vortex technology to repair the soil was simulated, and the particle motion visualization research was studied. The optimal structure of tubular vortex elution device was determined by adjusting the form and combination of spiral blades. It is found that the optimal structure of the tubular vortex elution device is that the number of spiral blade channels is three, the lead of spiral blade is 12.5 mm, the spiral blades are arranged alternately in different directions, and the number of spiral blades is four. Under the regulation of the vortex in the tube, the particles not only do the spiral revolution, but also do the rotation movement, thereby strengthening the desorption of the pollutants in the particles.

1. Introduction

Petroleum is a complex of saturated hydrocarbons, aromatic hydrocarbons, colloids and asphaltenes. It has the characteristics of complex system, wide coverage, difficult management, long repair period and great harm. During the production and use of petroleum, crude oil and petroleum products will enter the environment and cause pollution. About 8 million tons of oil enters the environment every year through various ways such as running, taking, dripping and leaking, which seriously threatens the safety of soil, groundwater, rivers and oceans. At present, there are many oil-contaminated soil remediation technologies, including soil washing¹-³, chemical oxidation⁴-⁶, electric repair⁷, gas phase extraction⁸,⁹, bio-enhancement¹⁰, and mechanical methods¹¹,¹². Among them, the mechanical method is widely used in the repair of oil-contaminated soils due to its thorough repair and short repair cycle. However, at present, the mechanical method mainly achieves the desorption of pollutants by the method of adding field strength, and has the disadvantage of high energy consumption. Under low energy consumption, it is still to be studied by designing a special mechanical mechanism to regulate the change of the particle's own motion morphology and then to strengthen the elution of soil particles. According to the author's previous research, the spiral movement of soil particles can enhance the desorption of contaminants on the surface and pores. In response to this phenomenon, a tubular vortex elution device was designed to enhance the desorption of contaminants in the particles.

Maifan stone, as a common porous medium, has a large number of micropores, which has a good adsorption effect on the oil phase. In addition, maifan stone particles have large strength and moderate size, which are not easy to be dispersed in the washing solution in the form of small particles, which is conducive to the observation of particle motion form. As one of the important components of petroleum hydrocarbon, diesel is widely used in the experimental study of adsorption/desorption in porous
Therefore, this paper takes diesel-contaminated maifan stone as the research object, simulates the elution of petroleum-contaminated soil by tubular vortex elution device, and visualizes the particle motion morphology through experiments, and finally determines the optimal structure of tubular vortex elution device.

2. Materials and methods

2.1. Materials

The experimental granules were commercially available maifan stone. The experiment used commercially available 0# diesel (Shanghai Tianlian Chemical Technology Co., Ltd, China) as the target pollutant, and the selected diesel had a density of 0.84 g/cm$^3$ and a viscosity of 5.6 cp at 20 °C.

The method for preparing the contaminated maifan stone is to add the maifan stone to the excess diesel and continuously stir to make the surface of the maifan stone and the internal pores fully saturated with the diesel to saturation. After being thoroughly stirred, it is stored under normal temperature and protected from light. During the experiment, the contaminated maifan stone particles were placed on a metal mesh to drain the diesel that could not be absorbed. The initial diesel pollutant concentration in the contaminated maifan stone was measured to be 2%.

2.2. Tubular vortex elution

In the experiment, all the valves were first opened, so that the water phase filled the entire device, and the gas in the device was discharged to prevent the gas from interfering with the experimental results. After the gas is completely discharged, the valve V4 is closed, the valve V5 is opened, and the diesel-contaminated maifan stone particles are added to the plastic tube between the valves V4 and V5. Then, the valve V5 is closed, the valve V4 is opened, and the maifan stone particles enter the tubular vortex elution device (composed of spiral blades, fixed plates and sight glasses) under the transport of the water stream, and finally fall on the metal mesh. The maifan stone particles on the metal mesh were collected, and the residual oil content in the maifan stone particles was measured, and the diesel removal rate was calculated. The structure of the tubular vortex elution device was changed, and the experiment was repeated to evaluate the desorption effect of different structures.

| Serial number | Diameter (mm) | Length (mm) | Direction of rotation | Lead (mm) | Number of channels |
|---------------|--------------|-------------|-----------------------|-----------|-------------------|
| 1             | 25           | 37.5        | Left                  | 37.5      | 1                 |
| 2             | 25           | 37.5        | Left                  | 9.375     | 2                 |
| 3             | 25           | 37.5        | Left                  | 12.5      | 2                 |

Fig. 1. Experimental flow chart. 1. Tank ;2. Screw pump ;3. Mass flow meter ;4. Tubular vortex elution device; 5. High speed camera; 6. Computer; 7. Metal mesh.

The parameters of the spiral blade structure used in the experiment are shown in Table 1. The combination forms of spiral blades are shown in Table 2.
2.3. Data analysis

The residual oil content of maifan stone was determined by infrared spectrophotometry referring to the test method of oil content in water[16]. Firstly, a large amount of water in the maifan stone particles was screened through a metal mesh. Then, the sifted maifan stone with the mass of $M_1$ was added into the volume of $v_1$ carbon tetrachloride (Shanghai Titan Scientific Co., Ltd., China) for ultrasonic extraction, and the extraction time was 10 min. Ultrasonic extraction of carbon tetrachloride was carried out through a sand core funnel containing anhydrous sodium sulfate (Shanghai Titan Scientific Co., Ltd., China) to remove the influence of residual surface moisture and internal moisture of the stone. Carbon tetrachloride passing through anhydrous sodium sulfate was collected and placed in a cuvette, and the oil content was measured by an infrared spectrophotometer to be $m_1$.

The content of residual oil in the maifan stone $K$ can be characterized as:

$$K = \frac{m_1 \times v_1}{M_1}$$  \hspace{1cm} (1)

Where $K$ is in mg/g, $m_1$ is in mg/L, $v_1$ is in L, and $M_1$ is in g.

The removal rate $E$ can be characterized as:

$$E = \frac{K_0 - K}{K_0}$$  \hspace{1cm} (2)

Where $K_0$ is the initial oil content of 20 mg/g. $K$(mg/g) is the content of residual oil in the maifan stone.

3. Results and discussion

3.1. Effect of the number of spiral blade channels on the elution

The lead of the control spiral blade is 37.5 mm, the direction of rotation is left-handed and the number of spiral blades is two. The number of spiral blade channels are changed to 1, 2, 3, 4, 5. The corresponding relationship between the number of spiral blade channels and the diesel removal rate, the number of spiral blade channels and the residual oil content is shown in Fig. 2. As the number of spiral blade channels increases, the elution effect of the particles gradually increases. This finding is attributed to the fact that the washing liquid flows through the spiral blades to generate vortices, and the larger the number of channels, the more the number of vortices at the flow cross section. An increase in the number of channels also increases the fluid flow rate and enhances the strength of the vortex$^{[17]}$. The higher the
vortex intensity is, the faster and more intense the particle motion will be. The vigorously moving particles have a greater centrifugal force, enabling the removal of contaminants therein.

When the number of channels reached five, the elution effect was the best, the diesel removal rate was 89%, and the residual oil content in the pellet was 2.19 mg/g. However, the increase in the number of spiral blade channels will also result in greater energy consumption. Considering the elution effect and energy consumption, the optimal number of spiral blades is determined to be three.

3.2. **Effect of lead of spiral blade on the elution**

The number of control spiral blades is two-channel, the rotation direction is left-handed, the number of spiral blades is two and the lead of the spiral blade is changed to 9.375mm, 12.5mm, 18.75mm, 37.5mm. The corresponding relationship between the lead of the spiral blade and the diesel removal rate, the lead of the spiral blade and the residual oil content is shown in Fig. 3. As the lead of the spiral blade increases, the elution effect of the particles gradually decreases. This finding is attributed to the fact that the smaller the lead of the spiral blade is, the more the number of turns of the particle in the same axial distance. According to previous studies, the more the number of turns of the particles in the spiral motion, the better the desorption effect of the pollutants in the particles.

However, the reduction of the lead will also increase the pressure difference between the inlet and outlet, thereby increasing the energy consumption, and the greater pressure will also affect the safety of the system in which the device is located. When the lead is 12.5 mm, the diesel removal rate in the diesel can reach 91%, which is not much different from the highest removal efficiency. Considering the elution effect and energy consumption, the optimal spiral blade lead is determined to be 12.5 mm.

3.3. **Effect of the arrangement of spiral blades on the elution**

The number of control spiral blades is two-channel, the lead is 37.5mm, and the number of spiral blades is two. The rotation direction of the spiral blades is left-left, left-right, right-left, right-right. The corresponding relationship between the arrangement of spiral blades and diesel removal rate, the arrangement of spiral blades and residual oil content is shown in Fig. 4. It can be seen from the figure that the elution effect of the single-rotating spiral blade combination is lower than that of the different swirling combinations. For a single-rotating combination of spiral blades, the change in the direction of rotation has little effect on the elution, the diesel removal rate is about 84.6%, and the residual oil in the particles is about 3.1 mg/g. For the spiral blades with different combinations of rotation, whether the left-handed leaves are arranged in front or the right-handed blades are arranged in front, the final elution effect is not much different, the diesel removal rate is about 87.5%, and the residual oil in the particles is about 2.5 mg/g. This finding is attributed to the fact that the direction of rotation of the spiral blade can only regulate the direction of motion of the particles, so differently rotated blades will cause the particles to rotate in different directions, but the desorption effect of the contaminants in the particles will not be different. When the direction of rotation changes, the particles and fluid move along the
original motion trajectory for a distance due to inertia. However, due to the different mass, the inertial movement distance of the particles and the fluid is different. When the rotation direction of the particles changes, the fluid will maintain the original rotation motion for a period of time, so the particles will be washed and sheared by the fluid, which will strengthen the removal of pollutants from particles. Therefore, for the pollution particles, the alternate arrangement of different rotating blades has better elution effect.

![Fig. 4. Effect of the arrangement of spiral blades on removal rate and residual oil content.](image1)

![Fig. 5. Effect of the number of spiral blades on removal rate and residual oil content.](image2)

3.4. Effect of the number of spiral blades on the elution
The number of control spiral blades is two-channel, the lead is 37.5mm, the rotation direction is left-handed and the number of spiral blades is changed to 1, 2, 3, 4, 5 respectively. The corresponding relationship between the number of spiral blades and the diesel removal rate, the number of spiral blades and the residual oil content is shown in Fig. 5. It can be seen from the figure that as the number of spiral blades increases, the elution effect of the particles gradually increases, but the growth rate gradually decreases. When the number of spiral blades reaches 4, the spiral blade is continuously increased, but the reinforcing effect is not obvious. The highest diesel removal rate is 91.1%, and the lowest particle residual oil content is 1.78 mg/g. The increase of the number of spiral blades can increase the number of turns of spiral movements and enhance the mass transfer process of the contaminated particles and the washing liquid. Under the action of centrifugal force produced by spiral motion, the desorption of pollutants in the particles was enhanced. On the other hand, the residence time of the particles in the tubular vortex elution device can be increased, thereby enhancing the desorption of the contaminants in the particles.

3.5. Particle motion analysis
The particle motion was observed by high-speed imaging and it was found that the apparent shape of the particles was constantly changing, as shown in Fig. 6. The finding is attributed to the fact that the shape of the experimental particles is non-spherical, and when the particles undergo an autorotation motion, the particles exhibit a varying apparent shape. It is further explained that the vortex generated by the tubular vortex elution device can not only regulate the spiral motion of the particles, but also regulate the rotation of the particles. The rotation of the particles enhances the desorption effect[18], thereby the tubular vortex elution device effectively removes the contaminants in the particles.
4. Conclusions
(1) The number of channels, the lead, the arrangement and the number of spiral blades all affect the removal rate of contaminants in the particles. The optimal structure of the tubular vortex elution device is that the number of spiral blade channels is three, the lead of spiral blade is 12.5 mm, the spiral blades are arranged alternately in different directions, and the number of spiral blades is four.

(2) Under the control of the vortex generated by the spiral blade of the tubular vortex elution device, the contaminated particles not only do the revolutionary spiral motion, but also do the rotation motion, thereby strengthening the desorption of the pollutants in the particles.

Acknowledgements
This research was supported by the National Natural Science Foundation of China (51722806).

References
[1] Gitipour, S., Hedayati, M., Madadian, E. (2015) Soil Washing for Reduction of Aromatic and Aliphatic Contaminants in Soil. Clean soil air water, 43: 1419-1425.
[2] Li, G., Guo, S., Hu, J. (2016) The influence of clay minerals and surfactants on hydrocarbon removal during the washing of petroleum-contaminated soil. Chemical Engineering Journal, 286: 191-197.
[3] Deshpande, S., Shiau, B.J., Wade, D., Sabatini, D.A., Harwell, J.H. (1999) Surfactant selection for enhancing ex situ soil washing. Water Research, 33: 351-360.
[4] Goi, A., Trapido, M., Kulik, N., Palmroth, M.R.T., Tuhkanen, T. (2006) Ozonation and Fenton Treatment for Remediation of Diesel Fuel Contaminated Soil. Ozone: Science and Engineering, Vol.28: 1-24.
[5] Shin, K., Jung, H., Chang, P., Choi, H., Kim, K. (2005) EARTHWORM TOXICITY DURING CHEMICAL OXIDATION OF DIESEL-CONTAMINATED SAND. Environmental Toxicology & Chemistry, Vol.24: 12.
[6] Do, S., Jo, J., Jo, Y., Lee, H., Kong, S. (2009) Application of a peroxymonosulfate/cobalt (PMS/Co(II)) system to treat diesel-contaminated soil. Chemosphere, 77: 1127-1131.
[7] Acar, B., Y., Ozsu, E.E. (1996) Enhance soil bioremediation with electric fields. Chem Tech, Vol.26: 40-44.
[8] Kirtland, B.C., Aelion, C.M. (2000) Petroleum mass removal from low permeability sediment using air sparging/soil vapor extraction: impact of continuous or pulsed operation. Journal Of Contaminant Hydrology, 41: 367-383.
[9] Johnston, C.D., Rayner, J.L., Briegel, D. (2002) Effectiveness of in situ air sparging for removing NAPL gasoline from a sandy aquifer near Perth, Western Australia. Journal Of Contaminant Hydrology, 59: 87-111.
[10] Abed, R.M.M., Al-Kharusi, S., Al-Hinai, M. (2015) Effect of biostimulation, temperature and salinity on respiration activities and bacterial community composition in an oil polluted desert soil. International Biodeterioration & Biodegradation, 98: 43-52.
[11] Feng, D., Lorenzen, L., Aldrich, C., Maré, P.W. (2001) Ex situ diesel contaminated soil washing with mechanical methods. Minerals Engineering, 14: 1093-1100.
[12] Son, Y., Cha, J., Lim, M., Khim, M.A.A.J. (2011) Comparison of Ultrasonic and Conventional Mechanical Soil-Washing Processes for Diesel-Contaminated Sand. Industrial and Engineering Chemistry Research: 2400-2407.

[13] Maceiras, R., Alfonsin, V., Martinez, J., Martinez Vara De Rey, C. (2018) Remediation of Diesel-Contaminated Soil by Ultrasonic Solvent Extraction. International Journal of Environmental Research, 12: 651-659.

[14] Ying, Y., Xiu-hong, S., Song, L., Jing-gang, X. (2014) Aggregation of Diesel Contaminated Soil for Bioremediation. Journal of Northeast Agricultural University (English Edition), 21: 18-24.

[15] Lominchar, M.A., Santos, A., de Miguel, E., Romero, A. (2018) Remediation of aged diesel contaminated soil by alkaline activated persulfate. Science Of The Total Environment, 622-623: 41-48.

[16] Tang, s.l. (2004) determination of petroleum in soil by infrared spectrophotometry. China environmental monitoring: 36-38.

[17] Zhu, jiabin. (2018). Research on optimization of structural parameters of variable-diameter micro-mixer. Master, east China university of science and technology.

[18] Huang, Y., Li, J., Zhang, Y., Wang, H. (2017) High-speed particle rotation for coating oil removal by hydrocyclone. Separation And Purification Technology, 177: 263-271.