The evaluation system of oily drill cuttings treatment technologies based on the fuzzy evaluation method

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Abstract. Oil-based drilling fluids are widely used in oil and gas exploration operations where the drilling process is complex, but there are also a lot of oily drill cuttings that are harmful to the environment. At present, many oily drill cuttings treatment technologies have emerged on the international market, mainly including thermal desorption, solvent extraction, cuttings dryer, incineration, bioremediation and solidification/stabilization, et al. However, there is not yet a technology that can be applied to all treatment conditions. So, an evaluation system is urgently needed to selectively screen treatment technologies according to operating conditions. Therefore, this paper introduces the fuzzy evaluation method, through the comprehensive comparative analysis of main treatment technologies, to determine the evaluation index of the oily drill cuttings treatment. Based on this, a fuzzy evaluation index system is established, and the evaluation process of fuzzy evaluation is expounded. The research results provide a theoretical guidance for choosing the right oily drill cuttings treatment technology for drilling operations.

1. Introduction
With the increasing depth of drilling in oil and gas exploration and the continuous complication of the wellbore structure, the drilling technology puts higher requirements on drilling fluids. Because oil-based drilling fluids have good formation protection capabilities, they are widely used in drilling sites in a variety of complex conditions [1]. However, the use of oil-based drilling fluids during drilling will generate large amounts of oily drill cuttings, as shown in Fig.1. Oily drill cuttings are hazardous wastes, and if handled improperly it will cause great harm to the environment [2].

Currently, there are a wide range of processing technologies for oily drill cuttings, mainly including thermal desorption, solvent extraction, cuttings dryer, incineration, bioremediation and solidification/stabilization [3]. In addition, the treatment scheme of oily drill cuttings is complex, involving many disciplines, and the scope of application is very different. So, it is difficult to evaluate the overall situation by judging the merits of a single treatment technology. Therefore, this paper introduces the fuzzy evaluation method, through the comprehensive comparative analysis of main treatment technologies, to determine the evaluation index of the oily drill cuttings treatment. Based on
this, a fuzzy evaluation index system is established, and the evaluation process of fuzzy evaluation is expounded.

The part “①” represents oil based drilling fluids entering the formation through the inside of the drill string

The part “②” represents breaking the formation with the bit

The part “③” represents oil based drilling fluids carrying oily cuttings back to the ground

**Figure 1. Schematic of oil-based drill cuttings treatment**

2. The main oily drill cuttings treatment technologies

Fig.2 describes the entire process of oily drill cuttings' production and processing, that is "the formation crushed by the bit - a lot of oily drill cuttings produced - the oily drill cuttings carried by oil based drilling fluid to the ground - the primary treatment in the well site - the unhandled waste collected - into the secondary treatment". The main purpose of the primary treatment is to recover expensive oil-based drilling fluids through shaker, hydro cyclone, centrifuges and other solids-control equipment [3]. However, oily drill cuttings after the primary treatment still contain high concentrations of hydrocarbons, which still belongs to the category of hazardous wastes. Therefore, it is necessary to carry out secondary treatment of oily drill cuttings to achieve a harmless treatment of waste [4].

According to whether or not the oil can be recovered, the secondary treatment can be divided into technologies (such as thermal desorption, solvent extraction and cuttings dryer et al.) that can recover the oil and technologies (such as incineration, bioremediation and solidification/stabilization et al.)
that cannot recover the oil. A summary of several major technologies is shown in Table 1. According to Table 1, the biggest advantage of the oil recovery technology is that it can recover expensive base oils. In particular, TCC (Thermal-mechanic Cutting Clean) can not only achieve a solid residue content of less than 1% after treatment, but also the recovered oil can be used as a fuel to burn or a base oil to re-allocate the oil-based drilling fluid. However, the technology that can recover the oil generally has the problems of large investment and high energy consumption. Although the bioremediation technology cannot recover the oil, the use of biodegradation fundamentally realizes the harmless treatment of oily cuttings, and the cost is low. However, bioremediation technology has a huge footprint.

The oily drill cuttings treatment technology is not only various, but also has complicated equipment and process flow, and there is no technology suitable for all treatment situations. Therefore, there is an urgent need for an evaluation system of oily drill cuttings treatment technologies to screen the best technology for specific treatment situations.

3. The establishment of evaluation index system

Establishing a reasonable evaluation index system is the core task of completing the fuzzy evaluation. When constructing the evaluation index system, the following three principles should be considered [6]:

1) Comprehensive and representative, which mean that indicators can reflect the main processing technology and do not overlap with each other;

2) Scientific, which means that indicators can objectively explain the characteristics of processing technology;

3) Operable, which means that the data is easily accessible through observation or measurement, and data sources are reliable and comparable.

Based on the above principles, the typical or easily accessible indicators are selected using the AHP (Analytic Hierarchy Process) to avoid the complication of the model [7]. The evaluation index system of oily drill cuttings treatment techniques is established, including the target layer, factor layer and indicator layer, as shown in Fig.3. The set of first-level factors is B = \{B1, B2, B3\}, and the set of secondary indicators is C = \{C1, C2, C3… Cm\} where m is the number of secondary indicators. Furthermore, the first-level and secondary weights are calculated by the 1-9 scale method [8].

Figure 3. Fuzzy Evaluation index system for cuttings treatment. Revised from OGP, 2003.

The key factor influencing the selection of oily cuttings processing technologies is the environmental factors, and the emission policy is also a basic factor in environmental factors. Emission standards for oily drill cuttings vary from one to another country. For instance, “zero
Table 1. Summary and comparison of main treatment methods

| Method                     | Disposal mechanism                                      | Residue oil content | Cost | Time for treatment | Floor area | Advantages                                                                 | Limitation                                                                 |
|----------------------------|----------------------------------------------------------|---------------------|------|--------------------|------------|-----------------------------------------------------------------------------|----------------------------------------------------------------------------|
| Incineration               | Oxidation or combustion of organic components            | -                   | A    | 5-6 t/h            | Relatively large | Waste reduction and treatment thoroughly                                  | High investment and processing costs and secondary pollution               |
| Indirect thermal desorption| Evaporation and condensation of oil and water            | <1%                 | B-A  | 3-10 t/h           | Relatively large | High efficiency, stability, adaptability, and high oil quality             | High temperature, high energy consumption and large area                   |
| TCC                        | Evaporation and condensation of oil and water            | <1%                 | B    | 6 t/h              | Small       | High efficiency, stability, high oil quality, and less floor space         | High energy consumption and high equipment investment                     |
| Bioremediation             | Biodegradation                                            | <2%                 | C-D  | 10-1200 days       | Very large  | Complete degradation, low processing costs                                 | Long processing cycle and large floor space                               |
| Solidification/             | Solidification, oil/metals stabilized in cuttings matrix | Leaching oil <100   | B    | 1-2 t/h            | Small       | Simple process and low cost                                                | Environmental pollution and cannot recover oil                             |
| stabilizatization          |                                                          | mg/kg               |      |                    |             |                                                                             |                                                                            |
| Cuttings dryer             | Centrifuge forces mud/solids separation                   | 2%–6%               | B-A  | 40 t/h             | Small       | Recover oil and simple equipment                                          | Large energy consumption, noise problem and unable to treat heavy metals  |
| Solvent extraction         | Liquefied HC gases/supercritical solve and remove oil    | <1%                 | B-A  | -                  | Relatively large | High oil quality and recyclable extractants                               | High pressure, high equipment investment and large area                   |

A Cost (US$/m3) A: >200; B: 100–200; C: 50–100; D: <50; -: unknown.
Revised from Ref. [3-5].

Emissions” standards are enforced in the Caspian Sea region of Kazakhstan, while in many regions of Southeast Asia, the oil content of cuttings is regulated to be less than 10% [1]. In addition, environmental factors also include air emissions, power requirements, by-product process and potential environmental stressors, et al.

Secondly, the economics of treatment is the core factor in determining the treatment cost of oily drill cuttings. Although there is an urgent need to deal with oily cuttings in terms of environmental protection, the disposal cost of oily cuttings is high. If the treatment technology is not properly selected, it will seriously increase the burden of business operations. According to the general requirements of the industry, the economics of treatment should consider immediate cost, disposal cost, transportation cost, equipment cost and energy cost, et al.

Finally, evaluation of oily drill cuttings treatment techniques requires full consideration of the operating performance. In general, operating performance is characterized by factors such as safety, human health issues, processing rate, mechanical reliability, space availability, weather conditions and condition of end products, et al.

4. The fuzzy evaluation method of treatment technologies
The fuzzy evaluation method is an evaluation method based on fuzzy mathematics. This method converts qualitative evaluation into quantitative evaluation based on the membership theory of fuzzy mathematics, and thus evaluates the overall evaluation of things or objects subject to multiple factors. The fuzzy evaluation method can comprehensively summarize the opinions of various evaluation subjects and comprehensively reflect the degree of merit of the evaluated objects.
4.1. Determining the evaluation criteria and ranks
The fuzzy evaluation includes three evaluation levels, namely "excellent", "good" and "ordinary", corresponding to the scores "90", "80" and "70" respectively, as shown in Table 2. The criteria of evaluation levels can be determined according to industry regulations, operating procedures, and the advice of engineers and experts.

| Indicators                  | Evaluation levels (scores) | Excellent(90) | Good(80) | Ordinary(70) |
|-----------------------------|-----------------------------|----------------|-----------|---------------|
| Reduction (oil content) in volume of waste/ % | >99% | 98%-99% | 95%-98% |
| Safety                      | Very safe                   | Generally safe | Meet the requirements |

As The "reduction (oil content) in volume of waste" and the "safety" are taken as examples.

4.2. Determining the fuzzy relationship matrix
Based on the evaluation index system and assessing rules, the fuzzy relationship matrix is ascertained as:

\[
F = (f_{ij})_{m \times r} = \begin{pmatrix}
    f_{11} & \cdots & f_{1r} \\
    \vdots & \ddots & \vdots \\
    f_{m1} & \cdots & f_{mr}
\end{pmatrix}
\]

(1)

Where, \( f_{ij} \) represents the fuzzy membership of the itch index belonging to the jet rank.

Based on the established evaluation index system, the factors that affect the treatment technology of oily drill cuttings include qualitative and quantitative indicators.

For qualitative factors, The AHP-Delphi method [9] is used to obtain the weight values of indices and the scores are graded according to Table 3. Then the ranking of each factor is normalized according to the number of experts, result of which is the membership of the different criteria corresponding to the sub-indices [10].

| Rank   | Percentage interval | Median |
|--------|---------------------|--------|
| Excellent | 100-90             | 95     |
| Good    | 90-80               | 85     |
| Ordinary | 80-70               | 75     |

For the quantitative factors, because of its physical significance, the original data need to be normalized, and then according to the following formulas to calculate the index membership [11].

\[
f_{ik}(x) = \begin{cases}
    1 & x \geq v_{ik} \\
    \frac{x - v_{i(k+1)}}{v_{ik} - v_{i(k+1)}} & v_{i(k+1)} \leq x \leq v_{ik} \\
    0 & x \leq v_{i(k+1)}
\end{cases} \quad k = 1
\]

(2)
4.3. Calculating comprehensive evaluation grade

As shown in Eq. (5), the fuzzy membership of comprehensive evaluation classes can be calculated by multiplying weight vector and fuzzy relationship matrix.

\[
E = W \otimes F = (w_1, w_2, \cdots, w_m) \begin{pmatrix} f_{11} & \cdots & f_{1r} \\ \vdots & \ddots & \vdots \\ f_{m1} & \cdots & f_{mr} \end{pmatrix}
\]

\[
= (E_1, E_2, \cdots, E_r)
\]

Where, \(w_i\) is the weight of the MTh index; \(Err\) is the fuzzy membership of treatment technology belonging to the rah rank.

Fuzzy evaluation rank is determined by the maximum membership degree, in order to distinguish between the advantages and disadvantages of the same membership in the product, the evaluation vector can be multiplied by the median of the three ranks in Table 3, and get the evaluation result \(Z\) of the percentage system.

\[
Z = E \otimes B = (E_1, E_2, \cdots, E_r) (B_1, B_2, \cdots, B_r)
\]

Where, \(B\) is the median and \(r\) is the rank.

When \(70 < Z \leq 80\), the treatment technology is "ordinary"; when \(80 < Z \leq 90\), it belongs to "good"; when \(Z > 90\), it belongs to "excellent". The assessing results have been validated by the data provided by suppliers and users.

5. Discussion and conclusions

Compared with the oily drill cuttings treatment technologies, under the influence of a series of factors such as complicated policies and costs, for the moment, there is no method applicable to all oily drill cuttings treatment situations, and the technology most suitable for this treatment must be selected through evaluation methods. Thus, the evaluation system proposed in this paper is a good way to solve this problem.

Based on the proposed evaluation system and fuzzy evaluation method, aiming at different treatment situations such as the oil and gas exploration in land, offshore or shale gas development, reasonable increasing or decreasing of indicators in the evaluation system, inviting relevant experts to
score and fuzzy evaluation calculations, and the most suitable treatment technology for the situation will be gotten. The research results provide a theoretical guidance for choosing the right oily drill cuttings treatment technology for drilling operations.

Acknowledgments

This work reported in this paper has been funded by the Technology Special Project of China (Grant No.: 2016ZX05040-006)

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