Measurement 117 (2018) 125–132

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

A concentration measurement model of suspended solids in oilfield reinjection water based on underwater scattering

Ling Ma[a], Fajie Duan[a,*], Gencai Song[b], Lei Zhao[b]

[a] State Key Lab of Precision Measuring Technology and Instruments, Tianjin University, Tianjin 300072, China
[b] Dongxin Oil Production Plant, Shengli Oilfield, Dongying 257000, China

ARTICLE INFO

Keywords:
Oilfield reinjection water
Suspended solid
Underwater scattering
Mie scattering theory
Lambert-Beer law
Concentration measurement

ABSTRACT

There are many particles such as suspended solids (SS) and oil particles in oilfield reinjection water, of which the concentrations have important effect on the property of reinjection water. To measure the concentration of SS accurately, an underwater scattering model is proposed in the paper. The light extinction effect resulting from oil particles, SS and water was discussed based on Lambert-Beer Law. According to the Mie scattering theory, the integral calculation for a single particle within the scattering angle was accomplished, and the relationship between the SS concentration and the intensity of 90° scattered light was worked out. The influences of the diaphragm spot, the light beam position and the concentration of oil particles to the measurement model were analyzed. An underwater scattering measuring system corresponding to this model was established to measure the concentration of SS in solution samples that simulated the oilfield reinjection water. The regression analysis results show that the correlation coefficient of the model and the actual experimental results is 0.998, and the root-mean-square error is 0.0775 V, which proved the feasibility of the SS underwater scattering model.

1. Introduction

The constituents in oilfield reinjection water are complex, including SS, oil particles, various microorganisms, and algae. The concentration of oil particles and the concentration of SS are the two main detection indexes that commonly represent the quality of oilfield reinjection water [1,2]. The high content of these two substances can be destructive to the longevity of water injection system, and threat the quality of underground water. The reliable measurement of their concentrations is necessary to guarantee efficient development of water-drive oil extraction.

Many researches of SS concentration measurement have been done on ocean water or turbid estuarine water [3,4], but few of them are on oilfield reinjection water. Phytoplankton in natural water is an essential factor that influences optic measurement because of its color and its absorption effect of light. But in reinjection water, not much microorganisms exist as in natural water. There are mainly metal-ions (bring in color), mineral compound particles, and oil particles. The measurement of oil concentration can be realized via ultra-violet fluorescence method, which is very accurate and independent of other particles [5–8]. But the measurement of SS concentration in oilfield reinjection water is greatly affected by several types of optical effects such as the light attenuation and the scattering [9,10].

Optical measurement has several advantages, such as continuous on-line monitoring and no need for reagent preparation. It fits the situation where reinjection water flows in pipe with high speed [11]. The traditional optical methods of measuring SS concentration include transmission method and scattering method. When a parallel light beam passes through the solution, there is an attenuation of light intensity due to the existence of particles. Transmission method utilizes the relationship between the intensity of transmitting light and the SS concentration in sample solution to obtain the latter. This method can be carried out online, but the measurement sensitivity is relatively low, especially when the SS concentration is low [12].

Based on Mie scattering theory, the incident light can be scattered to all directions by suspended particles (both oil and SS). At a fixed direction, the intensity of scattered light is related to the SS concentration. In this way scattering method is effective for SS concentration measurement. Compared to transmission method, scattering method has higher sensitivity and better ability to measure trace constituents. The light scattering can occur either on the surface of the liquid or underwater. Therefore, the scattering method is divided into surface scattering method and underwater scattering method. The former utilizes the light scattered by the suspended particles in a thin layer near the liquid surface. It can avoid the light extinction effect of the liquid itself [13], but is only applicable in high concentration measurement.

* Corresponding author.
E-mail address: fjduan@tju.edu.cn (F. Duan).

https://doi.org/10.1016/j.measurement.2017.11.061
Received 4 April 2017; Received in revised form 2 October 2017; Accepted 30 November 2017
Available online 01 December 2017
0263-2241/

The latter has a wider measurement range, and facilitates device embedding. It is suitable for on-line measuring application, but the light intensity attenuation needs to be considered when light travels underwater [14]. Literature [15,16] proposed a light backscattering method for soot particle concentration measurement by analyzing the backscattering light intensity. So, the intensity of scattered light is a useful parameter in the evaluation of particle concentration measurement.

Usually the relationship between the intensity of scattered light and the SS concentration is expressed as

$$I_S = Kf(NL) \tag{1}$$

where IS is the intensity of scattered light, K is a constant, L is the optical path length, and N is the concentration of SS. When the function f is simplified and approximated to a linear form, which is in most cases applied, it is very convenient to use under low concentration condition with a small measuring range. But it brings in error, especially when it is applied to a wide range measurement. Therefore, a model with the least approximation is needed to explain the specific relationship. The model works as an instruction to help determine whether the relationship can be approximated to linear form. And when approximation is not advisable, the model provides an accurate SS concentration calculating function.

Considering the minute size, uniform distribution and stable composition of SS in oilfield reinjection water, the SS concentration can be obtained by turbidity measurement method prescribed as 90° scattering detection in international standard ISO7027, with a light source of 860 nm wavelength [17–19]. In this paper, a theoretical model is proposed for SS concentration measurement based on underwater scattering method. This model calculates the intensity of scattered light in the most direct way and uses the least approximation. With it the relationship between SS concentration and scattered light intensity is well explained, and the accuracy of calculated result is guaranteed.

The concentration measurement of SS was implemented in the sample solution that had a similar property with oilfield reinjection water. The oil concentration of this sample solution was known. The influences of scattering angle and diaphragm size on the intensity of scattered light were analyzed, the light extinction effect of contents in sample solution was considered, and the relationship between SS concentration and 90° scattered light intensity was figured out. After the scattering model was established, its measuring range and sensitivity and other effecting parameters were discussed in detail, with simulations carried out as well. Based on the measurement model, a scattering experimental system was set up, and reliable experiment results were obtained. The regression analysis results of the model and the experimental data verified the feasibility of this underwater scattering measurement model for SS in oilfield reinjection water.

The model was proposed based on the need of SS concentration measurement in oilfield reinjection water, of which the constituents are mainly oil particles and SS. The validation experiment was also implemented in sample solution that simulated the oilfield reinjection water. In addition, the model is available for all situations where minute mineral SS exist, if some of the parameters are properly modified.

2. Measurement principle

When light beam penetrates through the sample solution, there are two reasons causing the light intensity attenuation – the absorption of all substances and the scattering of particles. Because of the stretching vibration among methyl (–CH_3), methylene (–CH_2) and aromatic hydrocarbon (Ar-H) of oil molecules, the oil particles absorb infrared light to compensate the vibrational consumption. Compared to absorbed light, the light scattered by oil particles is much less. However, The SS particles in reinjection water are non-dissipative medium. Unlike oil particles, there is a stronger scattering action to the incident light for SS particles, while the absorptive action is so weak that can be ignored.

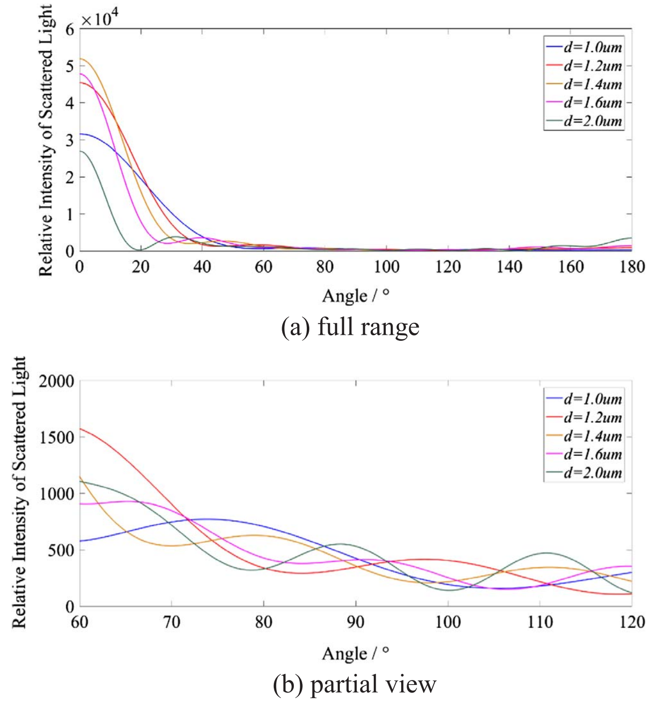

Fig. 1. The intensity of scattered light changes with scattering angle.

Based on the 90° scattering turbidity measurement method prescribed in international standard ISO7027, a SS particle concentration measuring model was proposed in this paper. Particles of different size have diverse intensity characters of scattered light, but they are the closest only at the direction of 90°. Fig. 1(a) shows how intensity of scattered light changes with scattering angle, and Fig. 1 (b) is the partial enlarged view of Fig. 1 (a) from 60°to 120°. It is obvious that the differences among several curves are the minimum at 90°.

Fig. 2 shows the principle diagram of underwater scattering measurement for SS concentration. A parallel unpolarized incident light beam is utilized to illuminate the sample solution, and a photodiode is fixed at 90° direction to detect the scattered light. When the light beam penetrates through the sample solution, some of the light is absorbed by particles, some is scattered, and the left can pass through the solution. Both oil particles and SS influence the light transmission and scattering, but the intensity of scattered light mainly depends on the concentration of SS.

SS and oil particles are the major constituents in oilfield reinjection water. The distribution of oil particle size in oilfield reinjection water is within 1–10 μm [20], and that of SS particle size is around 1–2.2 μm [20,21]. The distribution is uniform and fixed. Based on the Lambert-Beer law, when light penetrates through a medium with a stable

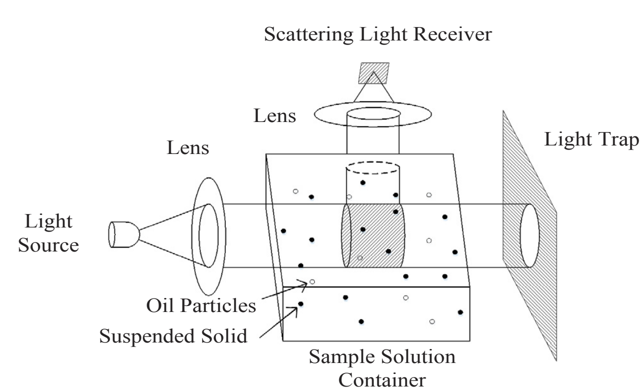

Fig. 2. The principle of SS concentration measurement.