Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28427

261 (2022) 94–106
June

Filtration model and its application progress in oilfield produced water treatment

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Received 12 October 2021; Accepted 24 March 2022

ABSTRACT

The classic filtration model is based on inorganic particles and filter media and was designed for urban wastewater treatment without considering the characteristics and particle size distribution of oil-field produced water; thus, this model cannot accurately predict the filtration process of oily water from oil fields. The parameter design of the filter bed depends on experience, which separates the connection with filtration models. Based on these shortcomings, this study investigates the effects of various parameters on filtration efficiency and filtration rating using the Yao-Tien filtration model and simulations. The dominant mechanism and its transformation law of the oil-field filter are discussed, and the role of straining in the fine filter cannot be ignored. The role of the wettability of organic media in oil-field filters is emphasized, and the corresponding empirical parameters should be introduced into the correction model.

Keywords: Filtration models; Oilfield; Filtration rating; Straining; Wettability

1. Introduction

The reinjection of oilfield produced water after treatment can reduce wastewater discharge and form a virtuous circle of production and reinjection, which is important socially and economically [1]. However, the application of polymer flooding technology enhances the stability of produced water and increases treatment difficulty [2]. If the treatment of wastewater from polymer flooding (WPF) fails to meet standards, it will lead to problems such as reservoir plugging and reduced recovery, affecting the production and operation of oil fields [3]. Therefore, improving the treatment efficiency of WPFs is a bottleneck to oil field production and has attracted much attention. Deep-bed filtration is important in treating WPFs as a refining treatment in oilfields and directly affects the quality of oilfield reinjection water [4]. Deep-bed filtration has a long history in the field of urban water treatment and plays a key role in oilfield water treatment, depending on the application and development of the filtration model. The filtration model describes the effect of filter bed parameters on filtration performance and can predict the filtration process. Currently, the most accurate deep-bed filtration models include the phenomenological model and the trajectory model, which form the theoretical basis for investigating the filtration process.

The phenomenological model is an empirical model that is derived from experimental data with a set of partial differential equations based on the mass balance equation and empirical rate expression, which describes the variation in the particle deposition rate with filtration time and depth in filter media [Eq. (1) [5]. Most modified forms of this model consider how to correct the filtration coefficient (λ), as shown in Eq. (1) [5,6]. The phenomenological model describes the entire filtration process, including the overall dynamic filtration behaviour, using empirical

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parameters without physical explanations. The mechanism of particle transportation and attachment is not clearly described, and the interactions of forces between suspended particles and porous media are not considered (Fig. 1) [7,8]:

$$\frac{\partial c}{\partial L} = -\lambda c \quad (1)$$

The trajectory model is a mechanism model with a motion equation to describe the path of particles through pores to evaluate whether particles can be removed. O'Melia and ASCE [10] applied trajectory theory to the filtration of colloidal particles in wastewater for the first time. Happel and Brenner [11] proposed an external flow model of an isolated single sphere model and Reddi and Bonala considered the unit combination of uniform capillary channels as porous media. The trajectory model is suitable for clean filter beds and ignores the real pore structure of filter media; this model cannot accurately explain the efficiency change caused by the ripening stage or blocked by particles [13]. Later, other scholars proposed a modified model to consider the influence of sediments. Putnam and Burns [14] simulated a single sedimentary particle and its hindrance to further deposition using the spherical model. Burganos et al. [15] found that the shrinkage tube model could describe the geometric structure of pore space more accurately than the capillary model. In recent years, a combination of the network model and numerical simulation technology has been widely used, which promotes the development of deep bed filtration. However, these new models do not consider the characteristics of oily wastewater [16–18].

After years of development, a systematic theory and model of deep-bed filtration has been established but only describes the removal of inorganic suspended solids in urban water treatment and does not consider the influence of oil, polymers or surfactants. Oilfield-produced water may not follow the previous filtration equation of a single pollutant. Sediments composed of oil particle aggregates have unique physical characteristics. Suspended particles attached to oil beads will produce discrete aggregates (Fig. 2); thus, the applicability of oil removal efficiency to WPFs must be investigated in more detail. In the treatment of oilfield water, the oil content of the reinjection water and the concentration of suspended particles must meet certain standards, and the particle size distribution in the effluent must meet corresponding standards. The particle size distribution of effluent is an important control standard of oilfield reinjection water. With the increasing difficulty of oil production in low permeability oilfields, stricter treatment requirements are being instituted. Although the classical filtration model includes the parameters of particle size, it does not consider the particle size distribution of effluent and only considers the removal rate. Related research in oilfield wastewater treatment is also limited to exploring the rule of particle size distribution through experiments, which is not related to the filtration model. Existing research on the effect of the surface properties of filter media on the filtration model ignores the effect of the wettability and surface energy between organic filter media and inorganic filter media on oil removal efficiency. The design of filter parameters typically follows engineering experience and is separated from the filtration model. Filtration technology in oilfields has been developing continuously, but the corresponding filtration model was not been improved recently. The traditional filtration model must be developed while considering the characteristics of oilfield wastewater. The filtration model suitable for oilfield water treatment should be established based on the traditional model as soon as possible.

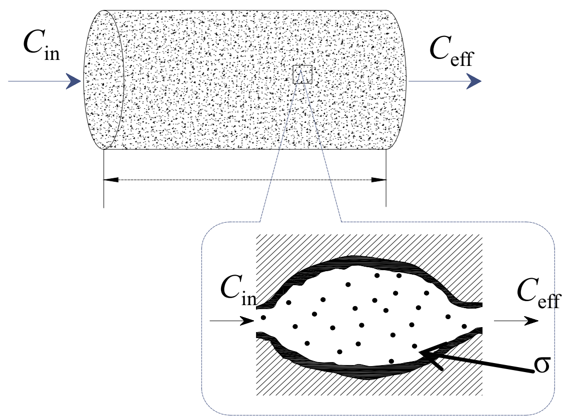

Fig. 1. Schematic diagram of a phenomenological model of the particle deposition process of a filter bed [9].

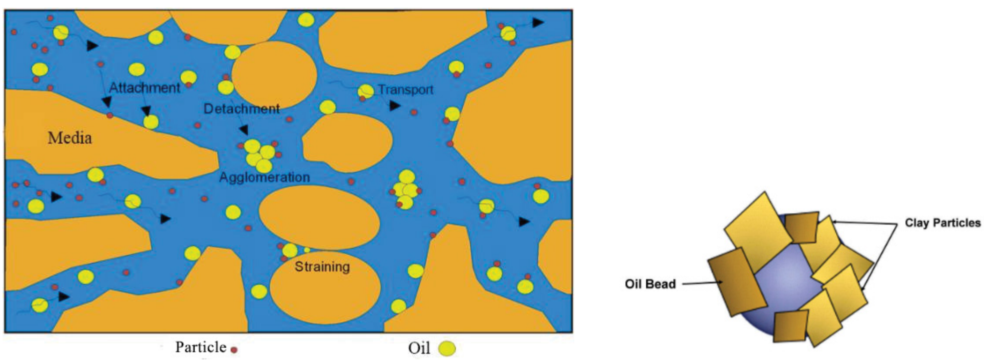

Fig. 2. Schematic diagram of the filtration process of oily water in a filter bed [19].

2. Model and calculation method

2.1. Filtration efficiency model

Yao et al. [20] proposed the transport efficiency (η) of single collector under trajectory theory and approximated η_0 as the sum of the efficiencies of diffusion (η_D), interception (η_I) and sedimentation (η_G) [20], as shown in Eq. (2) and Fig. 3:

$$\eta_0 = \eta_D + \eta_I + \eta_G = 0.095\left(\frac{KT}{\mu d_p u d_c}\right)^{\frac{2}{3}} + \frac{3}{2}\left(\frac{d_p}{d_c}\right)^2 + \frac{\left(\rho_p - \rho\right) g d_p^2}{18\mu u} \quad (2)$$

It is unreasonable to assume that η of each mechanism is so large that the sum will exceed 100%. Therefore, although Yao's model [22] can describe the filtration process accurately, some deficiencies remain. Tien and Payatakes [23] proposed using the particle escape probability to calculate η, as shown in Eq. (3). When η of any mechanism is equal to 100%, Eq. (2) is no longer applicable, and when the transport efficiency of all mechanisms is far less than 100%, the higher-order product term can be ignored:

$$\begin{aligned} &\eta_0 = 1 - \left(1 - K_1\left(d_p d_c u\right)^{-\frac{2}{3}}\right)\left(1 - K_2\left(\frac{d_p}{d_c}\right)^2\right)\left(1 - K_3\frac{d_p^2}{u}\right) \\ &K_1 = 4A_s^{1/3}\left(\frac{3\pi\mu}{k_B T}\right)^{-\frac{2}{3}}, K_2 = \frac{3}{2}A_s(1-\varepsilon_0)^{2/3}, K_3 = \frac{\left(\rho_p - \rho\right)g}{18\mu} \end{aligned} \quad (3)$$

Based on the aggregation of particles on a single collector and considering the mass balance of the unit bed, the relationship between the filtration coefficient (λ), as defined in Eq. (1), of phenomenological models and the η of the trajectory model was established, as shown in Eq. (4) [23]:

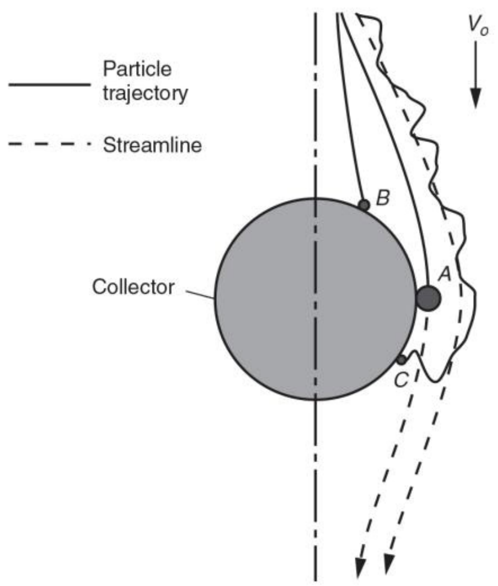

Fig. 3. Particle transport mechanisms in fundamental filtration theory: (a) interception, (b) sedimentation, and (c) diffusion [21].

$$\lambda_0 = \frac{-3\left(1-\varepsilon\right)\eta_0}{2d_c} \quad (4)$$

The filtration efficiency (E) is obtained by integrating the height of the filter bed:

$$E = 1 - \frac{c_{\text{eff}}}{c} = 1 - e^{\frac{-3(1-\varepsilon_0)}{2}\frac{L}{d_c}\eta_0} \quad (5)$$

2.2. Filtration rating model

The filtration rating is an important parameter for characterizing membrane performance. Membrane filtration refers to the maximum allowed particle size or membrane pore size. In deep-bed filtration, no accurate filtration rating theory or definition exists. If the filtration rating of the deep-bed filter refers to the pore size between filter materials, all the particles larger than this pore size will be removed from the surface layer, which is unrelated to the deeper filter layers. This process does not conform to the design concept that deep-bed filtration primarily depends on transport and adhesion. In this study, a new definition of the filtration rating of a deep-bed filter is proposed: the particle size with removal rate approaches 100% after the n-layer unit bed element (UBE), as shown in Fig. 4 [23]. When the filter media are arranged in the closest tetrahedron, according to the geometric relationship, the relationship between the number of UBE and L/d_c is:

$$n = \frac{2\sqrt{3}}{3}\frac{L}{d_c} \quad (6)$$

Eqs. (3) and (5) show the functional relationship between the parameters and the single-layer transport efficiency (η) and the filtration efficiency (E) of the filter bed under the coupling mechanism, including the influent particle size (d_p). The filtration rating is obtained by solving d_p after setting the removal rate (E) in Eq. In engineering, when the filter bed is considered to be dominated by a certain transport mechanism or only a single transport mechanism is considered, the transport efficiency η in Eq. (3) can be simplified from three terms to one. If E = 100%, the filtration rating has nothing to

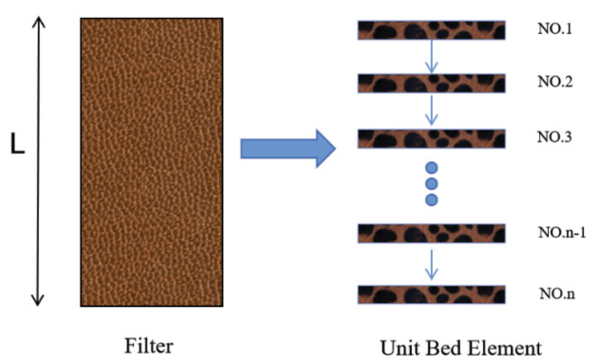

Fig. 4. Schematic diagram of unit bed element (UBE).

do with the number of filter beds. Therefore, we solve d_p from Eq. (5) with E = 99% as the filtration rating.

2.3. Calculation method

Based on Eqs. (3) and (5), the relationship between filtration rates (u), media size (d_c), particle size (d_p), filter bed height (L) and filtration efficiency (E) is investigated. Relevant parameters change within the appropriate range of filter bed parameters, and other parameters are set according to typical filters. In this study, ε_0 = 0.40, T = 300 K, ρ_p–ρ = 50 kg/m^3, d_p = 1 μm, d_c = 0.5 mm, and u = 10 m/h. The result is obtained by calculating the equation in Excel.

3. Results and discussion

3.1. Effect of filter bed structure on filtration efficiency

In this section, based on the Yao-Tien filtration model [Eqs. (3) and (5)] with a coupling mechanism, the law of filter bed parameters on filtration efficiency is clarified by calculations and simulations, which provide theoretical guidance for parameter design.

3.1.1. Effect of suspended particle size on filtration efficiency

The effect of particle size on η is not monotonic, and there is a most unfavourable particle size, as shown in Fig. 5. Yao et al. [20] predicted the lowest removal efficiency with a particle size of 1–2 μm, which has been verified experimentally. However, the applicability of this most unfavourable particle size to oilfield filter beds must be described in detail.

3.1.2. Effect of filtration rate on filtration efficiency

The filtration rate of the oilfield filter is typically approximately 5~15 m/h. As shown in Fig. 6, at 2~6 m/h, the filtration rate has a stronger effect on the transport efficiency. When the filtration rate is greater than 6 m/h, the transport efficiency changes slowly, which can provide a theoretical basis for improving the filtration rate of oilfield filter beds; however, the problem of detachment must be solved.

The results shown in Fig. 6 do not consider detachment; particles will be detached from the surface of the filter material under hydraulic action. Mints thinks that the deposition rate of particles is constant; adhesion and detachment occur simultaneously during filtration; and the amount of detachment is directly proportional to the specific deposition amount (σ) [24]. Moran reduced the influent concentration at the end of a long filtration experiment, but some previously deposited particles were still separated, which showed that hydraulic shear stress can lead to particle detachment [25]. When particles are firmly attached to filter media, gravity, adhesion and fluid shear force reach equilibrium [26], the adhesion model determines whether particles remain attached by calculating the conservation of momentum. If the momentum exerted by gravity is greater than that exerted by fluid, the particles will adhere to the filter material [27]. When the chemical conditions of particles and water are determined, the forces other than the shear force of water flow are determined; thus, the filtration rate is the key parameter to control the filtration efficiency. Bergendahl and Grasso [28] developed a mathematical model of particle shedding from the balance of shear force and adhesion moment. Bradford et al. [29] developed a detachment model in the form of torque. However, none of these models described particle adhesion and detachment quantitatively [30]. Therefore, the filtration rate is the key parameter to control the filtration efficiency.

3.1.3. Effect of L/d_c on filtration efficiency

As shown in Fig. 7, when the media size is 0.1 to 0.5 mm, the effect on the transport efficiency is large, but when the media size is more than 0.5 mm, the effect begins to weaken. The size of the filter media affects the number of UBEs. Increasing the height of the filter layer can increase the chance of the filter contacting the particle and balance the effect of increasing the size of the filter media. Regardless of adopting the mode of fine media with a high bed layer

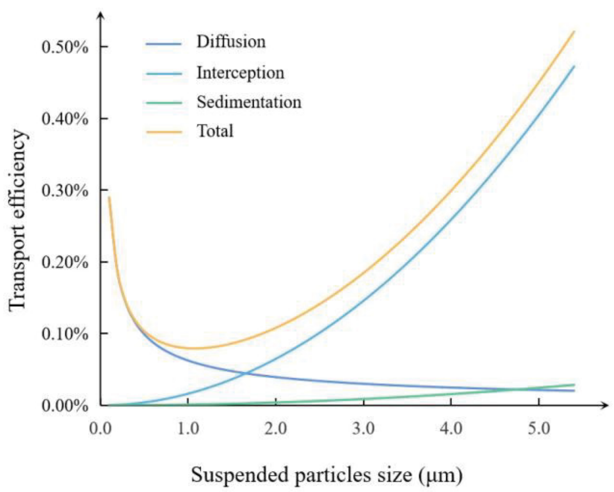

Fig. 5. Effect of suspended particle size on transport efficiency.

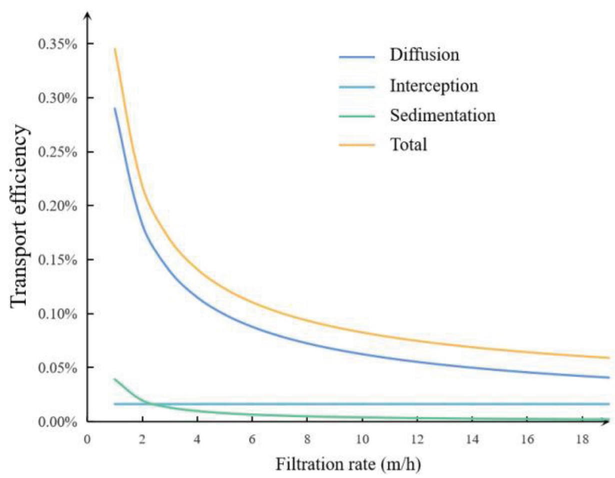

Fig. 6. Effect of filtration rate on transport efficiency.

or course media with a low bed layer, the filter bed can obtain a good filtration effect, but different design modes affect construction and operation cost.

The role of L/d_c in filter beds was first proposed by Kawamura, who suggested that the recommended value should not be less than 1,000 when designing filter beds. Eq. (7) establishes the relationship between L/d^n and filtration efficiency by deriving Eqs. (3) and (5). The model shows that there is a functional relationship between filtration efficiency and L/d^n under the coupling mechanism. It is not accurate to predict filtration efficiency with L/d^2 or L/d, which has certain limitations. Even if the filter beds have the same L/d_c, if the combination forms of L and d_c are different, the filtration efficiency will be different:

$$E \approx 1 - e^{\frac{-3(1-\varepsilon_0)}{2}\left[K_2 d_p^2 \cdot \frac{L}{d_c^3} + K_1 \left(d_p u\right)^{-\frac{2}{3}} \cdot \frac{L}{d_c^{\frac{5}{3}}} + K_3 \frac{d_p^2}{u} \cdot \frac{L}{d_c}\right]} \tag{7}$$

The simulation calculation was performed by Eq. (7), and the results are shown in Fig. 8. The model calculates the filtration efficiency and the relationship between the filter media size and L/d_c, and shows that when the filtration efficiency reaches more than 90%, the media size should be less than 0.4 mm, and L/d_c should be greater than 3,000. The filtration efficiency model is an exponential function; thus, with increasing L/d_c, the increase in the removal efficiency slows. Therefore, it is theoretically feasible to adopt the design mode of low height and fine filter material in oil field filter beds.

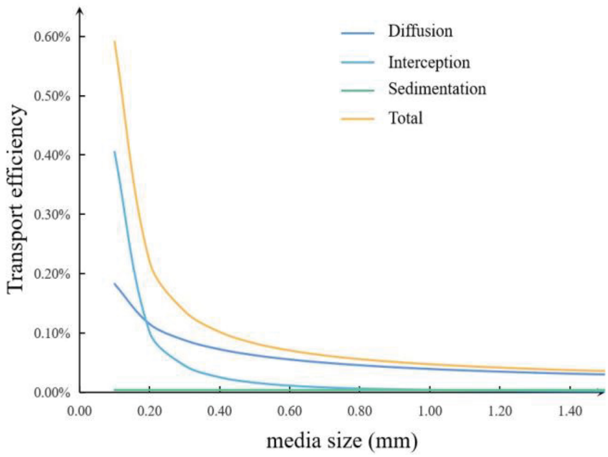

Fig. 7. Effect of filter media size on transport efficiency.

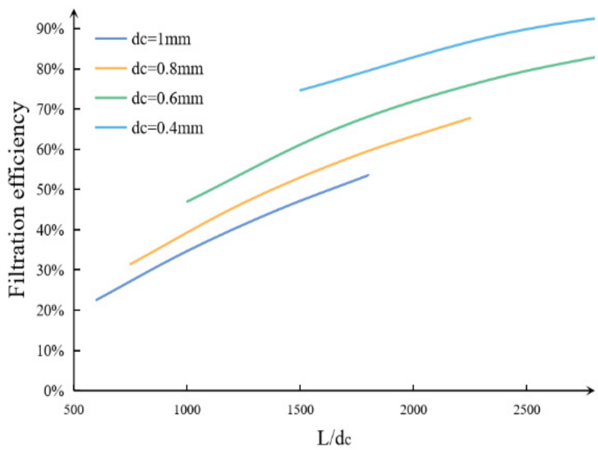

Fig. 8. Effect of L/d_c on filtration efficiency.

3.2. Effect of filter bed structure on filtration rating

In this section, based on the Yao-Tien trajectory model, the effect of parameters on filtration rating is characterized by calculations and simulations, and the law of parameters on filtration rating is discussed, providing theoretical guidance for the parameter design of the filter.

3.2.1. Analysis of filtration rating of sedimentation

The model shows that the form of L/d_c has no effect on the filtration rate of sedimentation, while the absolute value of L/d_c and the filtration rate have an effect on sedimentation. Fig. 9 shows that from the perspective of the sedimentation mechanism, the filtration rate should be less than 2 m/h, and L/d_c should be greater than 2,000 to reduce the filtration rating to less than 5 µm.

3.2.2. Analysis of filtration rating of interception

The effect of the size of the filter media on the interception filtration rating has two important characteristics: (i) the effect on the transport efficiency (η) of UBE and (ii) the effect on the number of UBEs. Fig. 10 shows that, from the perspective of the interception mechanism, the size of the filter media should be less than 0.2 mm, and L/d_c should be greater than 2,000 to reduce the filtration rating to less than 2 µm.

3.2.3. Analysis of the filtration rating of diffusion

The filtration rate of diffusion with typical oilfield filter bed parameters is only a few nanometres, and there are few nanoparticles in the effluent, which is of no practical significance for guiding oilfield filter selection. Therefore, we investigate an extreme particle size with complete failure of diffusion. E_n = 1% (Fig. 11), which is defined as the filtration failure rating of diffusion. When the particle size is greater than the filtration failure rating of diffusion, this mechanism will fail to remove the particle. The failure filtration rating is also applied to sedimentation and interception, and controls the particle size distribution of the effluent.

3.3. Effect of straining and deposited particles on the filtration model

3.3.1. Analysis of the dominant filtration mechanism of the oilfield filter

Previous studies did not emphasize which mechanism is dominant in real filter beds. When the deep-bed filtration

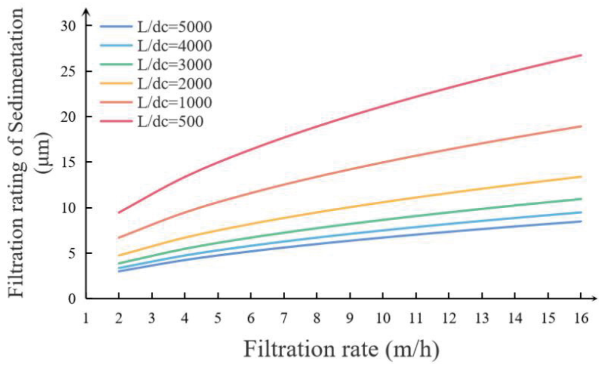

Fig. 9. Prediction of sedimentation filtration rating.

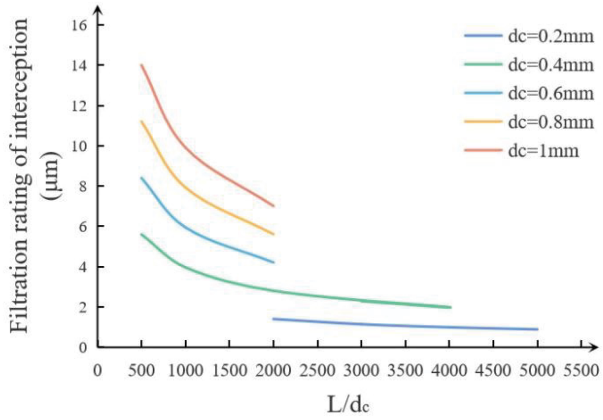

Fig. 10. Prediction of interception filtration rating.

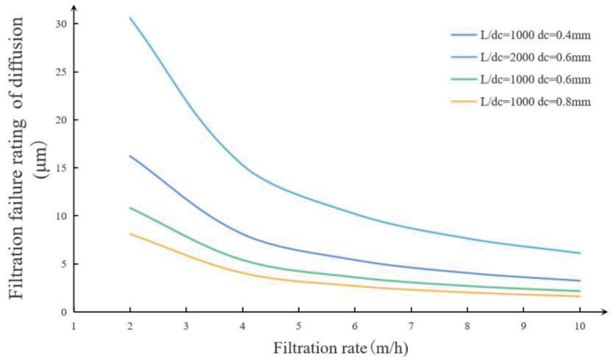

Fig. 11. Prediction of diffusion filtration failure rating.

model is applied to the oil field filter, the functions of the three primary mechanisms should be reconsidered. When the role of a certain transport mechanism is negligible, the filtration model can be simplified. Then, the filtration efficiency and filtration rating can be improved according to the dominant mechanism. The diffusion mechanism plays a role in nanoparticles [31]. Currently, the produced water of the oilfield enters the filter after the coagulation and sedimentation tank. The particle size generally ranges from 1 to 100 μm, the distribution is average, and the number of nanoparticles is small. Although the temperature of oilfield water is higher than that of urban wastewater, it has little effect on diffusion. Fig. 5 shows that diffusion is not the primary transport mechanism of the oil field filter. The density of suspended particles is marginally higher than that of water, but emulsified oil is marginally lower than that of water. Assuming that the density difference between oil and suspended particles is the same as that of water, the current model has the same result, ignoring the relative movement of fluid and particles. In addition, the theory of the advection sedimentation tank is roughly used without considering the geometric shape between filter materials; thus, the theoretical model of the sedimentation mechanism must still be improved. During oilfield production, emulsifiers, corrosion inhibitors, fungicides, particularly polyacrylamides and other organic substances are typically used. The existence of polymer molecules in WPF increases the viscosity, which limits the effect of sedimentation [32,33].

This study proposes a method to judge the dominant transport mechanism: when the transport efficiency (η) of one mechanism is 10 times greater than that of the other mechanisms, this mechanism is considered dominant. When η of one mechanism is smaller than 1/10 of that of the other mechanisms, this mechanism is considered negligible. Fig. 12 shows the dominant areas of sedimentation and interception. The ratio of the two mechanisms has nothing to do with the particle size but only with the structure of the filter bed: the smaller the filter media size is, the greater the filtration rate and the more important the interception. The filtration rate of the oilfield is approximately 5~15 m/h, and the filter media is generally smaller than 1 mm; thus, the contribution of the two mechanisms can be considered to be coupled or that interception is dominant.

3.3.2. Analysis of the effect of straining on the fine granular filter

The mechanisms of granular filtration are similar to two of the mechanisms used to characterize membrane filtration. Fig. 13 shows that granular media can exhibit the mechanisms of cake filtration due to straining and pore filling [34]. From the microscopic perspective, small particles can enter the pores of the membrane and adhere under the action of surface forces. From the macroscopic perspective, when the size of the filter media in a granular filter is small, straining and cake filtration gradually become the dominant mechanisms [21]. (a) Complete pore blocking, (b) intermediate pore blocking, (c) cake filtration, and (d) standard pore blocking.

There are some differences between the definitions of straining in membrane filtration and granular filtration, which must be clarified. As shown in Fig. 14, straining in a granular filter means that the streamlines of particles just pass through the pore throats between the two filter materials [35]. Mechanical filtering in a granular filter means that when the particle size ratio is relatively large, particles cannot pass through pores and are directly intercepted by the surface layer. Interception means that the streamline of particles just passes through the surface of a single filter material and is adhered. The three mechanisms depend entirely on the particle size ratio (d_p/d_c) and all belong to the generalized

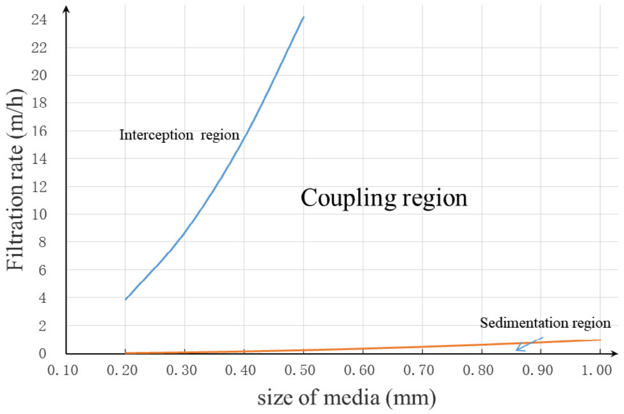

Fig. 12. Dominant of sedimentation and interception.

interception. The difference lies in the single-sphere model and multi-sphere model.

Membrane filtration is primarily used for advanced treatment after conventional granular filtering [37,38]. WPF aggravates membrane fouling and blockage and hinders backwashing. Although many improvements and studies have been made, membrane filtration cannot replace granular filters in oil fields. According to traditional deep-bed filtration theory, mechanical filtering should be avoided as much as possible to allow the full capacity of the deeper bed layer to be used effectively. The idea of membrane filtration is similar to a dynamic membrane in filtration and a conventional granular filter in backwashing [39–41]. As the particle size of the filter media decreases, the role of the particle size ratio d_p/d_c and the role of interception become increasingly important. When the particle size of filter media is relatively fine, straining and mechanical filtering will become the dominant filtration mechanisms, replacing the three basic transport mechanisms [42].

3.3.3. Analysis of the effect of filter bed ripening on the filtration model

The Yao-Tien trajectory model was developed for a clean filter bed without considering the effect of deposited particles. In the engineering of oil field filters, surfactants are known to lead to pore narrowing and reduced water passage [43]. The effect of deposition on pore diameter

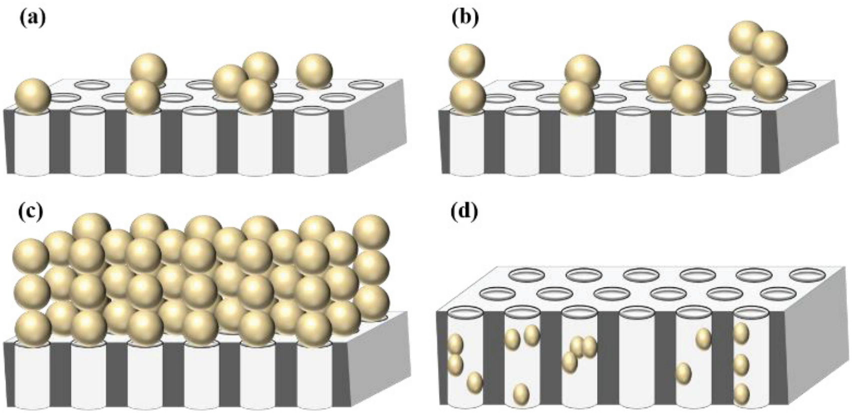

Fig. 13. Schematic representation of Hermia's fouling mechanisms [34].

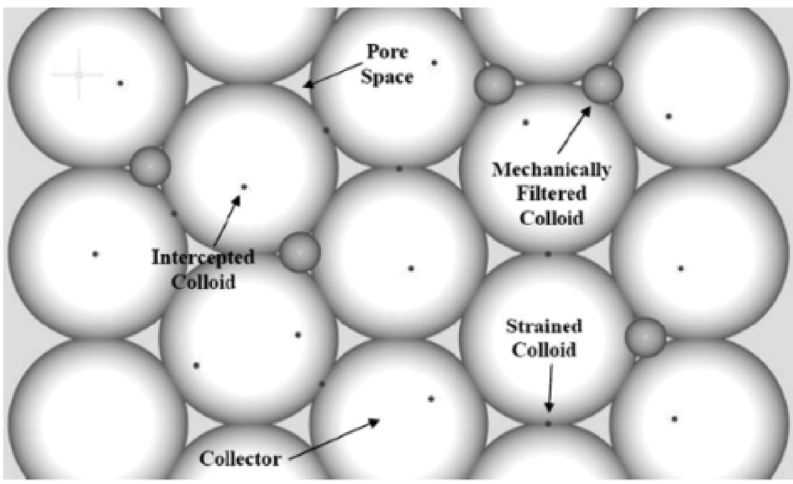

Fig. 14. Porous media collectors showing mechanically filtered, strained and intercepted colloid [36].

cannot be ignored, which has different degrees of effect on sedimentation, interception and diffusion, but the most important effect is straining.

The performance of filter bed ripening is based on the increase in the specific deposition amount (σ), which decreases the porosity (ε) of the filter bed. Straining is the mechanism that is primarily affected by filter bed ripening, which can be explained with the phenomenological model and capillary model. A phenomenological model can be used to describe the relationship between the specific deposition amount (σ) and operation time (t) and influent concentration (c):

$$\frac{d\sigma}{dt} = \lambda v c \tag{8}$$

Tien and Payatakes [23] described the relationship between the porosity (ε) and specific deposition amount (σ) of the filter bed:

$$\varepsilon = \varepsilon_0 - \frac{\sigma}{1-\varepsilon_d} \tag{9}$$

The capillary model developed by Jing et al. [44] considers the ripening stage of the filter and established the relationship between pore diameter (d_0) and porosity (ε):

$$d_0 = \frac{2\varepsilon}{3\varphi\left(1-\varepsilon\right)} d_c \tag{10}$$

Eqs. (8)–(10) provide the basis for explaining the ripening of the filter and provided theoretical guidance for the design of the influent concentration and operation time.

3.4. Effect of the surface properties of the filter media on the correction filtration model by experiment

3.4.1. Definition of adhesion efficiency

The transport efficiency (η) ignores the effects of detachment and surface force between the filter media and particles. The adhesion efficiency (α) solves this problem using the correction of transport efficiency (η) or filtration coefficient (λ) as defined in Eq. (1) to predict the filtration efficiency (E) of the real filter. Adhesion efficiency (α) is a semiempirical term obtained by fitting experimental data, and the empirical terms are summarized in Table 1. The undetermined coefficient of the equation is obtained by fitting the experimental results. α_1 represents the effect of particle detachment (α_1 = the number of particles washed away by water from the surface of media divided by the number of particles that contact the filter media). α_2 represents the effect of the surface force between the filter media and particles (α_2 = the number of particles actually transported to the filter material under the surface force divided by the number of particles predicted by the model without considering the surface force). In the experiment, it is difficult to distinguish α_1 and α_2; thus, α_1 and α_2 are combined into a single α as a correction of transport efficiency to represent the difference between experimental data and model prediction, where α is the real filter bed filtration coefficient divided by the model prediction filtration coefficient:

$$\alpha = \frac{\lambda_e}{\lambda_m} = \frac{\eta_e}{\eta_m} = f\left(N_1, N_2, \cdots\right) \tag{11}$$

3.4.2. Effect of van der Waals forces on the correction filtration model

The Yao model does not consider the influence of microscopic force between particles and collectors (Eq.12). Rajagopalan and Chi [46] used a spherical cell model to explain the attraction between the media and particles caused by van der Waals forces, and explained the deviation caused by viscous resistance [Eq. (13)]. Tufenkji and Elimelech [47] integrated van der Waals forces into the primary transport mechanism more fully [Eq. (14)]. These models are semiempirical expressions that are related to the numerical simulation results (Fig. 15). Suspended particles are affected by the microscopic force of filter media, which has an effect on the transport trajectories of the three basic transport mechanisms. The R-T model and T-E model show that the effect of van der Waals forces

Table 1
Common dimensionless parameters [45]

Parameters	Notation	Definition
$N_1 = N_{\mathrm{Re}}$	Reynolds number	$v\rho d_g/\mu$
$N_2 = N_R$	Interception parameter	d_p/d_g
$N_3 = N_{\mathrm{Pe}}$	Peclet number	$d_g v/D_{\mathrm{BM}}$
$N_4 = N_{\mathrm{LO}}$	London number	$4H/9\pi\mu d_p^2 v$
$N_5 = N_G$	Gravitational number	$\Delta\rho d_p^2 g/18\mu v$
$N_6 = N_{\mathrm{Fr}}$	Froude number	$v^2/g d_g$
$N_7 = 1/\pi\ N_{\mathrm{trd}}$	Retardation parameter	d_p/λ_w
$N_8 = N_{E1}$	First electrokinetic parameter	$e_f e_0(\zeta_p^2 + \zeta_g^2)/3\pi\mu v d_p$
$N_9 = N_{E2}$	Second electrokinetic parameter	$2\zeta_p\zeta_g/(\zeta_p^2 + \zeta_g^2)$
$N_{10} = N_{E3}$	Third electrokinetic parameter	$N_A I d_g^3$
$N_{11} = N_{\mathrm{DL}}$	Double-layer force parameter	κd_p

on transport efficiency cannot be compared with the contribution of the three fundamental transport mechanisms; thus, van der Waals forces cannot be considered an independent fundamental mechanism:

$$\eta_{\text{Yao}} = 3/2N_R^2 + N_G + 4N_{\text{Pe}}^{-2/3} \tag{12}$$

$$\eta_{\text{R-T}} = A_s N_R^{15/8}\left(4/3N_{\text{LO}}\right)^{1/8} + 0.00338A_s N_R^{-0.4}N_G^{1.2} + 4A_s^{1/3}N_{\text{Pe}}^{-2/3} \tag{13}$$

$$\eta_{\text{T-E}} = 0.55A_s N_R^{1.675}N_{\text{LO}}^{1/8} + 0.22N_R^{-0.24}N_G^{1.11}N_{\text{LO}}^{0.053} + 2.4A_s^{1/3}N_R^{-0.081}N_{\text{LO}}^{0.052}N_{\text{Pe}}^{-0.715} \tag{14}$$

3.4.3. Effect of electrostatic force on the correction filtration model

There are many inorganic salts containing Ca^{2+}, Fe^{3+}, Mg^{2+}, etc. in oilfield wastewater. The added coagulant changes the ionic strength and the surface potential between the filter media and particle [48]. Research has shown that the surface potentials of filter media and particles affect the transport and adhesion of oil and solid particles, which can be explained by the DLVO model [49,50]. O'Melia and ASCE [10] found that the electrostatic repulsion between the filter media and suspended particles made the prediction of the classical filtration model deviate. Elimelech [51] also found that the adhesion efficiency was related to the maximum electrostatic repulsion between the particles and the filter media. Raveendran and Amirtharajah [52] found that detachment is inversely proportional to ionic strength and directly proportional to pH. Chase successfully predicted the filtration efficiency according to the change in the surface potential of the filter media and found that the surface potential affects the adhesion efficiency [53]. Kim et al. [54] studied the dependence of filter bed ripening on surface charge and showed that the importance of zeta potential

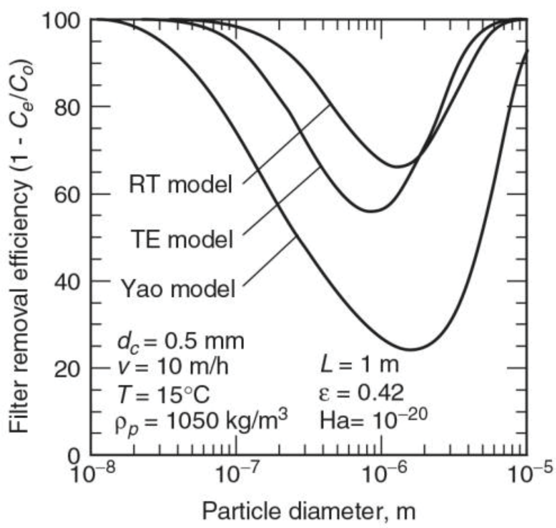

Fig. 15. Comparison of predictions by each model for removal efficiency [21].

decreases with time. Yang and Chang [55] found that the absolute value of the zeta potential of zeolite and magnetite is larger, followed by walnut shell and quartz sand, while anthracite and manganese sand are smaller. Li and Johnson [56] studied the filtration coefficient (λ) of several filter materials and reported the importance of zeta potential and surface charge density during filtration. Bai and Tien [45] thought that electrostatic force had an effect on all transport mechanisms and showed experimentally that α had the best correlation with the four dimensionless parameters $N_{E1}N_{\text{DL}}N_{E2}N_{\text{LO}}$ [Eq. (15)]. The new correlation equation described the experimental results well, but he also thought that the adhesion efficiency model proposed had limitations. Chang [57] believes that the influence of electrostatic force should be considered independent of the basic transport mechanism [Eq. (16)]:

$$\alpha_{\text{B-T}} = \prod_{i=1}^{x} N_i^n = 2.527\times10^{-3}N_{\text{LO}}^{0.7031}N_{E1}^{-0.3121}N_{E2}^{3.511}N_{\text{DL}}^{1.352} \tag{15}$$

$$\alpha_{\text{C-C}} = 0.024N_{\text{DL}}^{0.969}N_{E1}^{-0.423}N_{E2}^{2.880}N_{\text{LO}}^{1.5} + 3.176A_S^{1/3}N_R^{-0.081}N_{\text{Pe}}^{-0.715}N_{\text{LO}}^{2.687} + 0.222A_S^{1/3}N_R^{3.041}N_{\text{Pe}}^{-0.514}N_{\text{LO}}^{0.125} + N_R^{-0.24}N_G^{-1.11}N_{\text{LO}} \tag{16}$$

3.4.4. Effect of wettability of media on correction filtration model

In oil field filtration, the removal rate of oil by organic filter media is generally higher than that by inorganic filter material. This phenomenon can be attributed to the wettability of filter media for oil and water (Fig. 16). Yang and Chang [55] found that the lipophilic nature of walnut shells was prominent, followed by the hydrophilic nature of anthracite, manganese sand, zeolite and quartz sand and the hydrophilic and lipophilic nature of magnetite, which established a functional relationship with the surface energy of filter media. Liu et al. [58] conducted a modification study on the surface of a natural walnut shell by introducing hydrophilic sulfonic acid groups so that the surface property was changed from lipophilic to hydrophobic, and the oil removal rate of the modified filter material steadily improved.

Table 1 shows that the surface energy or wettability of filter media was not considered to be the parameter of adhesion efficiency in a previous study. In the oilfield filter bed, the effect of capillary force cannot be ignored (Table 2). The primary difference between organic filter media and inorganic filter media is not the van der Waals force and surface electrostatic force but the difference in the binding ability to water or oil. Thus, new parameters must be introduced to describe the adhesion efficiency to adapt to the oilfield filter. Wettability is a characterization of the binding ability of solid materials to the liquid phase and is related to the surface energy and polarity [60]. The surface energy has an effect on the contact angle of filter media with oil and water. Surface roughness is also an important factor that affects the dynamic wetting behaviour. Wang showed that roughness magnifies the wettability of liquid and can

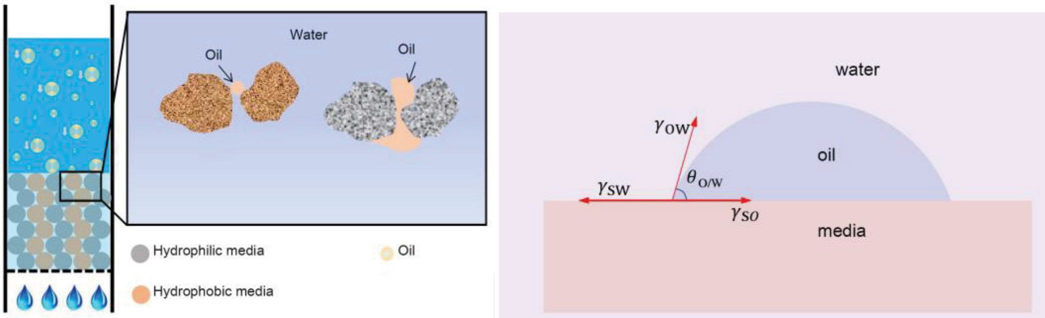

Fig. 16. Effect of the wettability of filter media on oil droplets [59].

Table 2
Scope of microforce

Microscopic force	Scope of action	Considered conditions
van der Waals force	Far greater than 0.1 µm and can reach several microns	Microscale conditions
Electrostatic force	Reach 10 µm, and the action is strongest when the distance is less than 0.1 µm	Electrolyte solution
Capillary force	Scale up to 100 µm	Two-phase flow

construct roughness on the solid surface of filter material to achieve a hydrophilic and oleophobic or lipophilic hydrophobic surface [61].

4. Prospective of related experiments

The discussion in this paper is based on the analysis of the Yao-Tien classic deep-bed filtration model. Although this model has been shown to predict the filtration process accurately after many studies, it is necessary to develop empirical equations based on experimental data. The detailed derivation process of the formula of the transport mechanism of the Yao-Tien model is based on the mathematical method to analyse the trajectory of fluid and particles, which has been strictly proven, but some simplifications have been made in the derivation process. For example, the entire filter bed is simplified into layers of UBE, the interception mechanism simplifies UBE into a single ball outflow model, the sedimentation mechanism simplifies UBE into a rectangular sedimentation tank, and the real structure of the filter bed is tortuous and complex, which will create discrepancies between the model and reality. As described in Section 3.4, current research on the model is based on the classic Yao-Tien model, and the empirical equation is directly introduced. We suggest that the true pore structure of the filter bed can be considered by strict mathematical methods in the derivation process, and the Yao-Tien model can be fundamentally modified by a nonempirical model, which is the way to essentially solve the model deviation. It is difficult to study the transport efficiency of single-layer UBE by the traditional laboratory filtration experiment method. First, we must design and build a clever microlaboratory device to simulate single-layer UBE. The removal rate will be low, making it difficult to draw an effective conclusion. The filtration rating theory proposed in this paper provides a new idea for verifying the single-layer transport efficiency or the Yao-Tien model, and can be verified whether the particle size of single-layer UBE with 100% removal rate or zero removal rate fits the model. In addition, with the development of CFD application, it is another way to use simulation software, such as Fluent, for reference to study the transport efficiency of UBE with different filtration mechanisms through discrete phase model (DPM) and discrete element method (DEM) [62].

A theory of the dominant transport mechanism of the filter bed is proposed in this paper. The sedimentation mechanism and interception mechanism play a major role in the oil field filter bed. Because sedimentation does not interact with the particle size of the filter media, and interception does not interact with the filtration speed, we can determine which mechanism plays a dominant role in a certain parameter range by investigating the filter efficiency of the filter bed after changing the particle size or the filtration rate. When changing the conditions, it is necessary to strictly prove that the detachment of particles remains unchanged, which requires pre-experiments, and a high-speed camera observation method can be considered. The theory of filtration rating proposed in this paper provides a new experimental idea. It can be proven that the degree of detachment has nothing to do with the size of the suspended particles. The change in the extreme point of the particle size distribution of the effluent after changing the parameters can be investigated to judge the dominant mechanism of the filter bed without considering the influence of detachment.

When the filter bed is dominated by the interception mechanism, particularly the fine filter bed of the oil field with a filter material size near 0.1 mm, the role of the straining gradually becomes prominent. Accordingly, the influence of the aging of the filter bed on the pore structure must be emphasized. Through a set of filter columns or pilot-scale experiments, the change curve of the filtration efficiency of the filter bed in a complete filtration cycle is investigated. The earlier method is used to learn from phenomenological model and establish the empirical formula of specific deposition and filtration coefficient [Eq. (8)] when the influent concentration and operation time are known. Another method is to use the trajectory model [Eqs. (9) and (10)] for reference to establish a functional relationship between specific deposition and pore diameter to characterize the influence of filter bed aging on the filter model.

The high oil removal efficiency of organic walnut shell filter material is likely due to the effect of surface energy and wettability. Referring to the experimental method of introducing surface potential parameters into the filtration model, the lipophilic-hydrophilic ratio (LHR) of a dimensionless parameter is a suitable parameter that characterizes the wettability and surface energy of materials. By modifying the LHR of media for filtration experiments, the fitting empirical equation with LHR parameters is developed using the calculation software.

5. Conclusion

The design of filter bed parameters should be closely considered with a filtration model. The classical trajectory model established by Yao-Tien includes an equation that relates various design parameters and filtration efficiency. The most unfavourable particle size, the inflection point of filter material particle size and the filtration rate provides a theoretical basis for the design of filter bed parameters. The theory of filtration rating is proposed in this paper to characterize the particle size distribution of the effluent from the oil field filter bed. There are corresponding dominant filtration mechanisms and transformation rules in fine filter beds in oil fields, and the role of straining and mechanical filtering cannot be ignored. The polarity and wettability of filter media play an important role in oil removal by filter beds in oil fields. Relevant empirical parameters should be introduced into the correction equation to fit the experimental equation of oilfield water treatment. The traditional filtration model must be developed in combination with the characteristics of oilfield wastewater, and a filtration model suitable for oilfield water treatment should be established based on the traditional model as soon as possible.

Funding

This study was financially supported by the National Natural Science Foundation of China (No. 5207040321), the Natural Science Foundation of Heilongjiang Province (No. B2015012), the PetroChina Innovation Foundation (No. 2016D-5007-0604), the Application Research and Development Program of Heilongjiang Province (No. GC13C305), and the Graduate Education Innovation Project of Northeast Petroleum University (No. JYCX_CX05-2018, No. JYCX_JG05-2018).

Symbols

A_H — Hamaker constant
c_{eff} — Effluent concentration of particles
c — Influent concentration of particles
d_0 — Pore diameter
D_{BM} — Brownian diffusivity
d_c — collector/media diameter
d_p — Suspended particle diameter
e_f — Relative permittivity of fluid
e_0 — Permittivity in vacuum
I — Ionic concentration
k_B — Boltzmann constant
L — Filter height
N_{DL} — Double layer force parameter
N_{E1} — First electrokinetic parameter
N_{E2} — Second electrokinetic parameter
N_{E3} — Third electrokinetic parameter
N_{Fr} — Froude number
N_G — Gravitational parameter
N_{LO} — London force parameter
N_{Pe} — Peclet number
N_R — Interception parameter
N_{Re} — Reynolds number
N_{Rtd} — Retardation parameter
T — Absolute temperature
t — Operation time
u — Filtration rate
v — Superficial velocity
α — Adhesion efficiency
ε — Bed porosity
ε_0 — Initial bed porosity
ε_d — Deposit porosity
η — Transport efficiency
η_0 — Initial or clean bed transport efficiency
η_D — Transport efficiency of diffusion
η_e — Transport efficiency of the experiment
η_G — Transport efficiency of sedimentation
η_I — Transport efficiency of interception
η_m — Transport efficiency of model
κ — Reciprocal of the electric double layer thickness
λ — Filtration coefficient
λ_0 — Initial or clean bed filtration coefficient
λ_e — Filtration coefficient of the experiment
λ_m — Filtration coefficient of the model
λ_w — Wavelength of electron oscillation
μ — Fluid viscosity
ξ_g — Surface (zeta) potentials of collector
ξ_p — Surface (zeta) potentials of particle
ρ — Fluid density
ρ_p — Particle density
σ — Specific deposit
ϕ — Sphericity of filter material
DEM — discrete phase method
DPM — discrete element model
LHR — lipophilic-hydrophilic ratio
UBE — Unit bed element
WPF — Wastewater from polymer flooding

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