СУДОВЫЕ ЭНЕРГЕТИЧЕСКИЕ УСТАНОВКИ И ИХ ЭЛЕМЕНТЫ (ГЛАВНЫЕ И ВСПОМОГАТЕЛЬНЫЕ)

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Моделирование эффективности очистки моторного масла судовых дизелей с учетом зарастания и блокировки пор фильтровального материала отложениями

Геннадий Петрович Кича, **Андрей Вениаминович Надежкин**, **Константин Николаевич Гога**✉

Морской государственный университет имени адм. Г.И. Невельского, Владивосток, Российская Федерация
✉ konstant.goga@gmail.ru

Аннотация. На базе капиллярной модели фильтрования идентифицирована эффективность очистки технической жидкости (смазочного масла) от механических примесей с учетом зарастания и блокировки пор отложениями. Цель моделирования состояла в формировании условий и механизмов отсева нерастворимых загрязнений, при которых возможности рассматриваемых способов разделения гетерогенных систем с накоплением отложений в порах и на поверхности фильтровального материала использовались бы наиболее полно. Действие внешних сил, вызывающее отклонение траектории движения частиц загрязнения от линий тока дисперсионной среды, и их отфильтровывание объединено и представлено обобщенным показателем – координатой отсева εd. Новизна подхода к исследованию фильтрования заключается в установке такого распределения загрязнений по зонам и механизмам отсева, когда достигается наиболее выгодный компромисс между тонкостью (полнотой) отсева и грязеемкостью (сроком службы) фильтрующих элементов. Показана кинетика очистки и изменения размеров капилляров фильтровальной шторы с нерегулярной поровой структурой при отфильтровании загрязнителя широкого фракционного состава. Полученные закономерности фильтрования могут быть использованы при оценке эффективности отсева нерастворимых загрязнений судовыми фильтровальными установками масла с рабочими элементами (шторами) из поверхностных нетканых материалов.

Ключевые слова: моторное масло, очистка масла, фильтрование, фильтровальный материал, зарастание пор очистителя

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MARINE POWER PLANTS AND THEIR ELEMENTS (MAIN AND AUXILIARY)

Original article

Modelling marine motor lubricating oil purification efficiency accounting deposit buildup in and clogging up of filter material pores

Gennadiy P. Kicha, **Andrey V. Nadezhkin**, **Konstantin N. Goga**✉

Maritime State University named after admiral G.I. Nevelskoy, Vladivostok, Russian Federation
✉ konstant.goga@gmail.ru

Abstract. The efficiency of systems fluid (lubricating oil) purification from foreign solids accounting deposit buildup in and clogging up of the pores has been identified. The modelling goal has been to generate such conditions and mechanisms for insoluble contaminant (IC) screening that would make full use of the capabilities offered by the studied methods of heterogeneous systems separation accompanied by the deposit buildup in filtering material pores and surface. The action of external forces causing contaminant particle trajectories

to deviate from dispersion medium flowlines and their filtering have been combined and represented by a complex index of εd screening coordinate. The novelty of the filtering process study is in establishing such distribution of contaminants by screening zones and mechanisms where the most profitable compromise between the filtering elements' (FE) screening fineness (completeness) and retention capacity (service life) could be reached. Purification kinetics and changes in irregular porous structure filtering diaphragm pore size when filtering contaminants of wide fractional compositions have been shown. The filtering process dependencies obtained can be applied to assessing the efficiency of IC screening conducted by marine motor lubricating filtering installations employing nonwoven fabric filtering elements (diaphragms).
Keywords: motor oil, oil purification, filtering, filter material, clogging up of filter material pores
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Introduction

Full-flow lubricant fine filters employing nonwoven fiber surface-type FE with an irregular pore structure [1,2] have become widely used to ensure resource-saving oil use on ships carrying high-speed and medium-speed diesel engines. The porous (capillary) structure of the multipath filtering diaphragm of these FEs is selected in such a manner that the elements, with a nominal screening fineness of 25–40 μm [3], are continually operational with no oil bypassing the filter. Such performance can be maintained should FE high contaminant retention capacity and long service life be provided with full-flow filtration at low hydraulic friction [3]. These elements' capillary structure and flow dynamics must meet the requirements of its continuous full-flow filtering mode as well as that of oil purifiers.

It is impossible to select the porous structure and filtering modes when solving this problem without considering deposit buildup in the FE. To achieve this goal, development of a kinetic capillary filtration model that will take into account the contamination of the filter material (FM) with screenings and «clogging» its porous space up with deposits is crucial [4]. There have been virtually no theoretical studies of the process in this dimension of filtration [5], which indicates the topicality of the subject matter covered. Refinement of the deterministic capillary filtration model based on the developed approach mode is being proposed that would be of scientific and practical interest to marine power plant professionals.

The most common models of motor lubricating oil (MLO) full-flow fine filtration allow calculating the filtering (screening) characteristics of screening of various pore structures in their initial state only [3, 6]. Their adaptation to assess the kinetics of purifying fuel and lubricant materials from solids in internal combustion engines is carried out using empirical coefficients that take into account the variable efficiency of filters when employed in fuel conditioning and oil cleaning systems [7]. The analysis conducted allowed to establish that it is deposit buildup in FM pores that has the greatest influence on the fractional coefficient and the completeness of contaminant screening in oil purifiers. Taking this influence into account in capillary filtration models is the most challenging task, especially when using porous structures with complex flow dynamics and identifying the action of the adhesive, sedimentation and tribochemical groups of the disperse phase (DP) deposits [1,8]. Filtration kinetic study would require to simplify the models by joint consideration and combination of the main screening mechanisms, accounting the flow dynamics in polyporous structures specified by different distribution laws [4]. Furthermore, when calculating filtration kinetics, the study into the physical and chemical properties of the dispersion medium (DM) while cleaning such a complex suspension as contaminated lubricating oil employed in a diesel engine [8] is crucial.

The proposed refined kinetic capillary model of MLO full-flow filtration, on the basis of screening and gravitation sedimentation as well as the effect of the major retention mechanisms of the interaction between the polydisperse insoluble phase of contaminants and the polyporous structure filtering partition, takes into comprehensive account. The novelty of the approach is in establishing the relationship between the flow dynamics processes and the retention capacity of filter structures contaminated with screenings, considering the deposit buildup in the pores and the clogging individual capillaries up with large particles [4].

Known filtration models' refinement and simplification is in considering the joint action of all retention mechanisms by introducing a generalized screening coordinate ε_d, which is a probabilistic characteristic of DP trajectory deviation from DM flowlines in capillaries. The proposed model, when identifying ε_d, allows for a high-precision estimate of the fractional coefficient and the completeness of purification of contaminated FM in the presence of deposits in the pores and secondary entrainment of DP particles during filtration.

The kinetic capillary model is simple and versatile. It was obtained, based on the Stokes partial differential equation [10], by considering the steady-state motion of a viscous fluid in a cylindrical capillary with a parabolic distribution of DM velocity in the cross section of the pore and its vanishing along the contour of the filter channel. The equation was solved under the supplementary condition that determined the suspension flow rate through the pore for a given pressure drop and FD thickness [1, 4].

Assuming a uniform DP distribution of diameter d throughout the entire volume of the suspension and along the front of the pore, one should take the fractional screening coefficient to be proportional to the ratio of flows through the peripheral zone of the capillary at distance $\varepsilon_d\, d/2$ from its surface to the entire flow through the filter channel of a given size. In this case, the probability of retaining a contaminant particle is represented by a relative share of the suspension flow from which it will be removed when passing through the capillary. With $\varepsilon_d = 1$ the calculated dependencies characterize the screening caused by the action of the mechanical interlocking effect, i.e. contact of the particle with the capillary wall, which is observed when neglecting the action of external forces [10, 11]. When this happens, the coincidence of the trajectory of particle movement along the DM flow lines may occur.

The kinetic capillary model of filtration might become actual on the assumption that contaminants are screened out according to the intermediate (in the terminology of V.A. Zhuzhikov [12]) filtration law. Their share from the FM surface deposits due to gravity sedimentation is determined by constant β_f [4]. Its value, as well as ε_d, depends on the filtration mode, the FM properties and the filter medium. Their detailed theoretical and experimental study and standardization has been presented in contributions [3, 4]. In individual cases of employing nonwoven fabric with an irregular porous structure during LMO purification, nomography of these indicators was carried out [1]. The principles of capillary filtration kinetic model, as presented below, were extracted on the assumption of a uniform distribution of accumulated deposits along the periphery of cylindrical pores with an increase in the crest surface in the FM of the same dimensions by interior diameter as that of the adjacent pores [4, 12].

A feature of the developed filtration kinetic models is giving consideration to the pores' deposit buildup and its impact upon DP particles' screening. The effect of the varying, due to the deposit buildup, pore structure of the FM on the IC sedimentation was studied using the initial and current pore size distribution, identification of buildup in and clogging up of the capillaries of different size groups taking into account the features of their interaction with the contaminant.

Examination of filtration kinetics through a change in the material porous structure allows to obtain universal dependencies for calculating the efficiency of the process fuels and lubricant materials' purification from any IC when using pore structures with different initial screening completeness. The advantage of the proposed approach is the possibility to calculate the FM retention capacity through the initial structure with the correction of its parameters (pore size distribution scale and shape) as deposits build up in the capillaries, taking into account the change in the dispersed composition and contaminant concentration at the filter inlet [1, 4].

Common relationships of deposit building up in filtering porous structure and its impact upon dispersephase particles screening)

A model of motor lubricating oil purification by filtering has been studied, considering deposit buildup in the filter material FM pores and consequent clogging these up with deposits. The retentivety of material with an irregular pore structure has been identified. The dynamics of purification and changes in the pore size of this material with deposit buildup on the filter screen have been shown. Recommendations are given to improve the FM pore structure to achieve the filter element high purification efficiency and maximum retention capacity when filtering marine diesel engine oil.

A feature of the developed kinetic filtration models is accounting the process of the pore deposit buildup and its impact on the DP particles screening. The influence of the filter material variable, due to deposit buildup, pore structure on the filtration of insoluble impurities has been studied through the use of the initial and current pore size distribution, identification of the buildup and clogging up in the capillaries of different size groups, taking into account the characteristics of their interaction with the contaminant.

Consideration of the filtration kinetics through the change in the material pore structure allows us to obtain valid relationships for calculating the efficiency of the process of cleaning fuels and lubricants from any IC when using pore structures with different initial completeness of screening. The advantage of the proposed approach is the possibility of calculating the FM retention capacity through the initial structure with adjustment of its parameters (scale and shape of the pore distribution by size) as deposits build up in capillaries, taking into account changes in contaminant particle size distribution and concentration when entering the filter.

The challenge for modeling the in-line filtration process is in identification of patterns of changes in the FM pore structure depending on the deposit buildup. In case of a capillary model, the change in the diameter D of the capillary due to its layered deposit buildup is proportional to the intensity of screening and can be determined through the proportion of deposits accumulating inside the pore [1].

$$q_D \varphi_{dD} = \frac{\pi \Delta p_{\mathrm{f}} D^4}{128 \mu_{oil} h_{\mathrm{f}}} \left[4\left(\frac{\varepsilon_d d}{D}\right)^2 - 4\left(\frac{\varepsilon_d d}{D}\right)^3 + \left(\frac{\varepsilon_d d}{D}\right)^4 \right]; \tag{1}$$

$$g_D = q_D \varphi_{dD} \rho_{oil} c \tau; \tag{2}$$

$$\delta D = \frac{2 g_D \lambda_f}{\pi h_f \left(1 + \beta_f\right) \rho_f}, \tag{3}$$

where $q_D \varphi_{dD}$ – the fractional intensity of MLO purification by filtration through pores of size D; Δp_f – the oil pressure across the FE; μ_{oil} – the dynamic viscosity of the oil; h_{f} – the FM thickness; ε_d – dimensionless screening coordinate; d – the diameter of the insoluble phase particles; g_D – the deposit buildup in pores with diameter D; ρ_{oil} – the oil density; c – the mass concentration of IC in the oil; τ – the duration of filtering; λ_f – the ratio of the mass of the FD deposits to the amount of IC contained therein; β_f – the proportion of contaminants deposited on the FM surface; ρ_f – the density of the FD deposits.

Utilizing dependencies (1) – (3) an equation for calculating the relative pore deposit buildup $\delta D / D$ when filtering out a monodisperse contaminant becomes:

$$\frac{\delta D}{D\left[1 - \frac{\varepsilon_d d}{D} + \left(\frac{\varepsilon_d d}{2D}\right)^2\right]} = \frac{\Delta p_f \left(\varepsilon_d d\right)^2 \lambda_f \rho_{oil} c \tau}{16 \mu_{oil} h_f^2 \left(1 + \beta_f\right) \rho_f} = \frac{a_{Dd} \tau}{2}, \tag{4}$$

where a_{Dd} – the relative rate of reduction of the cross-sectional area of pores with diameter D when filtering out finely dispersed impurities.

As seen from (4), the relative decrease in the capillary diameter depends on the relationship between the DP particle size and that of the pores. When filtering out the monodisperse phase of dirt with small particles, when $D/d > 6$, the decrease in pore diameter does not depend on the ratio between the sizes of the capillary and that of the particles

$$\frac{\delta D}{D} = \frac{a_{Dd}\tau}{2}. \tag{5}$$

When purifying the oil from finely dispersed contaminants of a wide fractional composition, the change in size D can be determined through the average diameter m_d of the particles of the filered DP ($\varepsilon_d = 1$)

$$\frac{\delta D}{D} = \frac{a_{Dm}\tau}{2}\left(1 - \frac{3m_d}{2D} + \frac{2m_D^2}{\pi D^2}\right), \tag{6}$$

where $a_{Dm} = \dfrac{\Delta p_f m_d^2 \lambda_f \rho_{oil} c\tau}{2\pi\mu_{oil} h_f^2 (1+\beta_f)\rho_f}$.

Where $\delta D/D > 1/4$, the relative change in capillary diameter must be calculated for fine and coarse contaminants, respectively, according to the formulas:

$$\frac{\delta D}{D} = 1 - \sqrt{1 - a_{Dm}\tau}; \tag{7}$$

$$\frac{\delta D}{D} = 1 - \sqrt{1 - \left(1 - \frac{3m_d}{2D} + \frac{2m_d^2}{\pi D^2}\right) a_{Dm}\tau}. \tag{8}$$

Formulas (7) and (8) are valid for systems with $m_D/m_d > 6$ and $\sigma_d/m_d < 1$.Using them for pores with D/m_d being less than 5 results in a large error when calculating $\delta D/D$. When changing $\delta D/D$ over a wide range, it is necessary to correct the rate of the pore clogging up a_{Dm} utilizing multiplying by $(D_\tau/D)^2$ [2].

When dividing the filtration period τ into cycles of duration τ_i, an equation for the relative rate of clogging up the pore cross-section with diameter D_{i-1}during the i-th cycle of filtering the MLO containing finely dispersed contaminants becomes

$$a_{Dmi} = \frac{\Delta p_{f(i-1)} m_{d(i-1)}^2 \lambda_f \rho_{oil} c_{i-1}}{2\pi\mu_{oil} h_{f(i-1)}^2 (1+\beta_{f(i-1)})\rho_f}. \tag{9}$$

If the rate of a_{Dm} is varying, then the relative decrease in capillary area D over n cycles is equal to

$$g_{Dn} = \sum_{i=1}^{n} a_{Dmi}\left(\frac{D_{i-1}}{D^2}\right)^2 \tau_i.$$

When filtering out a polydisperse contaminant with a time-dependent composition, the decrease in the pore diameter at the n-th filtration cycle is determined by the formula

$$\left(\frac{\delta D}{D}\right)_n = 1 - \sqrt{1 - \sum_{i=1}^{n}\left(1 - \frac{3m_{d(i-1)}}{2D_{i-1}} + \frac{2m_{d(i-1)}^2}{\pi D_{i-1}^2}\right)\frac{D_{i-1}^2}{D^2} a_{Dmi}\tau_i}. \tag{10}$$

Dependencies (9) and (10) can be utilized with variable concentrations and disperse composition of the contaminant, but their capabilities, similar to (7) and (8), are limited in the context of small D. In integral estimate β_f, the relative decrease in pore diameter due to the deposit buildup over n filtration cycles without limitation D is recommended to be found using the following formula

$$\left(\frac{\delta D}{D}\right)_n = 1 - \left\{1 - \sum_{i=1}^{n} \frac{\Delta p_f D_{i-1}^2 m_{d(i-1)}^2 \lambda_f \rho_{oil} c_{i-1}\tau_i}{2\pi\mu_{oil} D^2 h_{f(i-1)}^2 (1+\beta_{f(i-1)})\rho_f}\left[1 - \frac{3m_{d(i-1)}}{2D_{i-1}}\operatorname{erf}\frac{\sqrt{\pi}D_{i-1}}{2m_{d(i-1)}} + \right.\right.$$

$$+\frac{2m_{d(i-1)}^2}{\pi D_{i-1}^2}-\left(\frac{\pi D_{i-1}^2}{8m_{d(i-1)}^2}+\frac{2m_{d(i-1)}^2}{\pi D_{i-1}^2}\right)\exp\left(-\frac{\pi D_{i-1}^2}{4m_{d(i-1)}^2}\right)\Bigg]\Bigg]\Bigg\}^{\frac{1}{2}}. \tag{11}$$

The expression under the summation symbol τ_i characterizes the relative reduced rate of diameter D pore clogging up in the i-th filtration cycle. It is equal to the product of a_{Dmi} and the coefficient $(D_{i-1}/D)^2$, which takes into account the reduction of the intensity of pore clogging up relative to the current diameter to the initial one. The cofactor in square brackets determines the impact of the size of the contaminant particles and that of the pores on their clogging up.

Dependencies (8) – (11) take into account the change in the contaminant particle size distribution when entering the pore. Large particles are more susceptible to inertial screening, and their proportion in the FM surface deposit layer is higher. Therefore, the a_{Dm} must be calculated according to the sequential particle retention main mechanisms, leading to deposit buildup and pore clogging up. Under conditions of filtration of suspensions with DP a time-dependent composition, set by any distribution law, the high accuracy of $\delta D/D$ calculation is provided by utilizing the formula

$$\left(\frac{\delta D}{D}\right)_n=1-\left[1-\sum_{i=1}^{n}\frac{\Delta p_{f(i-1)}D_{i-1}^4\lambda_f\rho_{oil}c_{i-1}\tau_i}{32\mu_{oil}D^2h_{f(i-1)}^2\rho_f}\left\langle\int_0^{D_{i-1}}\left\{\left(\frac{2\varepsilon_d d}{D_{i-1}}\right)^2\left[1-\frac{\varepsilon_d d}{D_{i-1}}++\left(\frac{\varepsilon_d d}{2D_{i-1}}\right)^2\right]-\right.\right.$$

$$-\frac{1+\beta_{D(i-1)}}{2}\left(1-\sqrt{1-\frac{16\beta_{D(i-1)}}{\left(1+\beta_{D(i-1)}\right)^2}\left(\frac{\varepsilon_d d}{D_{i-1}}\right)^2\left[1-\frac{\varepsilon_d d}{D_{i-1}}+\left(\frac{\varepsilon_d d}{D_{i-1}}\right)^2\right]}\right)\Bigg\}\times$$

$$\left.\left.\times F_{i-1}(d)dd+\int_{D_{i-1}}^{d_{\max}}\left(1-\beta_{D(i-1)}\right)F_i(d)dd\right\rangle\right]^{\frac{1}{2}}. \tag{12}$$

The characteristics of the dependency (12) allow taking into account the impact of the contaminant particle size distribution on the deposit buildup on the FM surface.

Should the pores be filled with deposits for less than a quarter of the cross-sectional area, the relative decrease in their diameter can be determined by a simplified equation

$$\left(\frac{\delta D}{D}\right)_n=\sum_{i=1}^{n}\frac{\Delta p_{f(i-1)}D_{i-1}^4\lambda_f\rho_{oil}c_{i-1}\tau_i}{16\mu_{oil}D^2h_{f(i-1)}\left(1+\beta_{f(i-1)}\right)\rho_f}\left\{\int_0^{D_{i-1}}\left[\left(\frac{\varepsilon_d d}{D_{i-1}}\right)^2-\left(\frac{\varepsilon_d d}{D_{i-1}}\right)^3+\frac{1}{4}\left(\frac{\varepsilon_d d}{D_{i-1}}\right)^4\right]\times\right.$$

$$\left.\times F_{i-1}(d)dd+\int_{D_{i-1}}^{d_{\max}}F_i(d)dd\right\}. \tag{13}$$

Making use of formula 13 will simplify calculations of changes in pore size due to deposit buildup therein.

Calculation methodology for porous structure drift and nonwoven fabric efficiency when contaminated with deposits

The dependencies (4) – (13) might become actual when revealing functional expressions for β_{fi}, h_{fi}, Δp_{fi}. The first of the indicators characterizes the balance of deposits on the FM surface and the insides. Its value is found according to the statistical processing of a large number of filtering experiments

$$\beta_{fi}=B_f\left(1-\varepsilon_{mi}\right)^{0,42}\left(\frac{m_{di}}{m_{Di}}\right)^{0,12}\mathrm{Re}_{mi}^{0,08}, \tag{14}$$

where B_f – a constant characterizing the perfection of the FM pore structure, B_f = 0.3–2.5 [4]; Re_{mi} – Reynolds number in the *i*-th filtration cycle with suspension flowing through medium-sized pores.

Dependency (14) was also verified by the results of an active experiment that was planned in accordance with generally accepted recommendations [4].

The current deposit-accumulated FM clearance ε_{mi} is determined through the initial ε_{m0} clearance or that of the previous cycle $\varepsilon_{m(i-1)}$ by the equation

$$\varepsilon_{mi} = \varepsilon_{m0}\left(1 - g_{mDi}\right) = \varepsilon_{m(i-1)}\left(1 - a_{mDi}\tau_i\right). \tag{15}$$

The thickness of the FM together with deposits at the end of the *i*-th filtration cycle is equal to

$$h_{fi} = \frac{h_{f0}}{1 - \dfrac{\beta_{f(i-1)}\varepsilon_{m0} g_{mDi}}{1-\varepsilon_{mi}}} = \frac{h_{f(i-1)}}{1 - \dfrac{\beta_{f(i-1)}\varepsilon_{m(i-1)} a_{mDi}\tau_i}{1-\varepsilon_{mi}}}. \tag{16}$$

The FM clearance ε_{mi} and thickness h_{fi}, accounting the deposits should be found at the end of the filtration cycle through the extent of clogging the pores, the sizes of which are set according to the normalized distribution function $\bar{f}_i(D)$ through mathematical expectation.

The FD performance characteristics Δp_{fi} and Δq_{fi} were calculated using the initial and subsequent normalized distribution functions of the pore structure

$$\Delta p_{fi} = \Delta p_{f0} \frac{h_{fi} N_{n0} \int_0^{D_{\max}} D^4 f_0(D) dD}{h_{f0} N_{ni} \int_0^{D_{\max}} D^4 f_i(D) dD}; \tag{17}$$

$$\Delta q_{fi} = \Delta q_{f0} \frac{h_{f0} N_{ni} \int_0^{D_{\max}} D^4 f_i(D) dD}{h_{fi} N_{n0} \int_0^{D_{\max}} D^4 f_0(D) dD}, \tag{18}$$

where N_n – the number of pores per FM unit surface; $f(D)$ – the FM differential pore size distribution function.

The transition from the initial pore distribution to the current one was carried out through the relationship

$$f_\tau(D) = f_0\left[\frac{D}{1 - \dfrac{\delta D}{D}\left(D, \Delta p_f, c, h_f, \beta_f, \tau\right)}\right]. \tag{19}$$

In case of the MLO full-flow filtration, due to the constancy of the filtration rate at the average FE lifetime values Δp_f, m_D, β_f and h_f it is feasible to take $\bar{a}_D$ = const. According to (7) and (19) for the Weibull distribution, the current FM pore structure characteristics are formulated as

$$f_\tau(D) = \frac{p_D D^{p_D-1}}{\left(1-\bar{a}_D\tau\right)^{\frac{p_D-1}{2}} b_D^{p_D}} \exp\left[-\left(\frac{D}{b_D\sqrt{1-\bar{a}_D\tau}}\right)^{p_D}\right]. \tag{20}$$

Normalization of the $f_\tau(D)$ function leads to a distribution law (as per diameter)

$$f_\tau(D) = \frac{p_D D^{p_D - 1}}{b_{D\tau}^{p_D}} \exp\left[-\left(\frac{D}{b_{D\tau}}\right)^{p_D}\right], \tag{21}$$

where the scale parameter $b_{D\tau}$ equals $b_D(1-\bar{a}_D\tau)^{1/2}$

When filtering coarse-dispersed phase contaminated oil, the FM pore structure changes and its dimensional characteristics, provided it is subject to the Weibull distribution in its initial condition, can be fairly accurately described by the equation

$$f_n(D) = \frac{p_D D^{p_D-1} \exp\left[-\left(\dfrac{D}{b_D\sqrt{1-\bar{g}_{Dn}}}\right)^{p_D}\right]}{b_D^{p_D}\left\{1-\sum_{i=1}^{n}\left[\begin{array}{l}1-\dfrac{3m_{d(i-1)}}{2D_{i-1}}erf\dfrac{\sqrt{\pi}D_{i-1}}{2m_{d(i-1)}}+\dfrac{2m_{d(i-1)}^2}{\pi D_{i-1}^2}-\\ -\left(\dfrac{\pi D_{i-1}^2}{8m_{d(i-1)}^2}+\dfrac{2m_{d(i-1)}^2}{\pi D_{i-1}^2}\right)\exp\dfrac{\pi D_{i-1}^2}{4m_{d(i-1)}^2}\end{array}\right]\dfrac{D_{i-1}^2}{D^2}a_{Dmi}\tau_i\right\}^{\frac{p_D-1}{2}}}. \tag{22}$$

where $\bar{g}_{Dn}$ – determined by the braced sum.

Dependency $f_n(D)$ is not normalized and is suitable for calculating generalized, accounting the FM polypore structure, completeness $\bar{\varphi}_f$ and fractional screening coefficient $\bar{\varphi}_{df}$. When determining Δp_{fi} or q_{fi}, it is necessary to know the normalized distribution $\bar{f}_n(D)$. In order to reduce $f_n(D)$ to $\bar{f}_n(D)$, a normalizing multiplier is used. The *n*-th filtering cycle it is found by integrating the expression

$$1 \Big/ \int_0^{D_{\max}} f_n(D)dD.$$

In case of complex dependencies $f_n(D)$ equations (11) and (12) are used to obtain $\bar{g}_{D\tau}$. The representation of the current FM pore structure by equation (12) is universal. It is suitable for any distributions of $f_n(D)$ and $F(D)$ and considers the impact of the varying dispersion of the contaminant on pore clogging-up. Deformed normalized distributions $\bar{f}_\tau(D)$ and $\bar{F}_\tau(D)$ are utilized to calculate, using the expressions given in [6,8], the fractional coefficient $\bar{\varphi}_{df}$ and the filter screening completeness $\bar{\varphi}_f$ at any segment τ of its service time, including at a varying value of the concentration of contaminants c_τ.

The features of nonwoven fabric pore clogging-up, as revealed by the kinetic capillary model (22), are as follows:

– the pore cross-sectional area decreases unequally, large pores accounting for the most significant changes $(D_i/D_0)^2$;

– when filtering out finely dispersed phase contaminant, a_D is constant for almost all *D*;

– as deposits build up, the a_{Dm} increases.

The adequacy of the obtained kinetic filtration model can be proved by comparing the calculated and experimental dependencies of contaminant fractional screening as a function of deposit buildup.

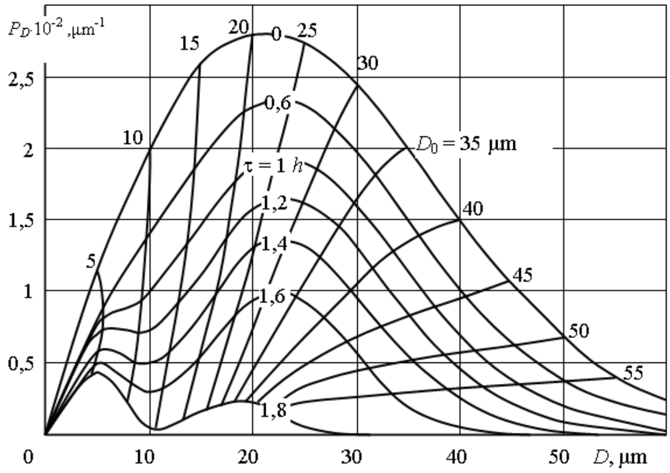

Fig. 1. FM pore structure changes when filtering

Small FM pores, especially with D_0 = 7–12 μm, are more susceptible to clogging up by DP particles when filtering out impurities (fig. 1), which is due to the hydrodynamics of the filtrate flow and the highest concentration of particles of this size in the MLO (contaminant s_{sp} = 1.05 m^2/g). Pores with an initial diameter of less than 20 μm are intensively clogged up and accumulate dirt to a small extent. With D_0 > 50 μm, their cross-sectional area decreases at the highest rate. In the range D_0 = 20–45 μm, the effect of clogging up onto the pore structure is equivalent to that of accumulating dirt up with an increase in the first process for smaller pores and in the second for larger ones.

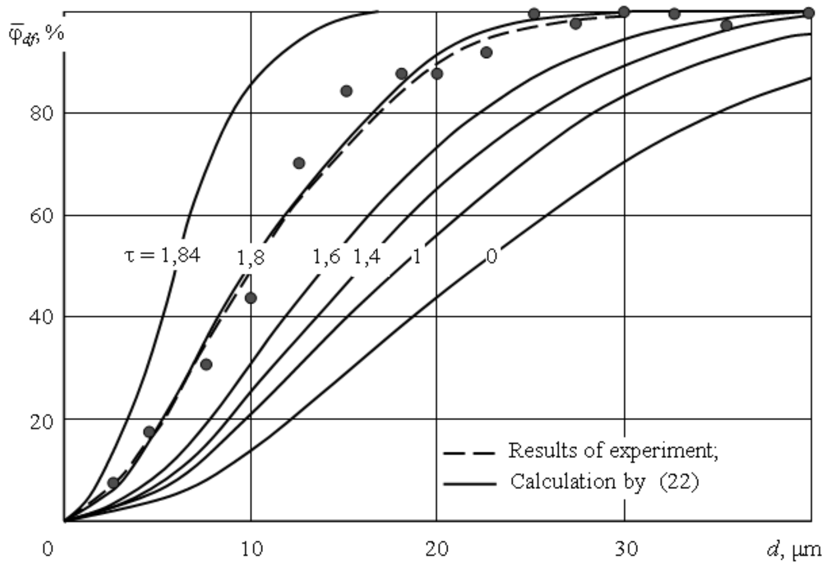

Fig. 2. FM filtration characteristics for screening during pore clogging up and deposit buildup

Filtration kinetics is also characterized by the formation of a bimodal distribution of open partially filled with deposits pores as deposits build up therein (fig. 1). Experiments have proved the adequacy of the mathematical description of the basic filtering kinetic processes [1, 4]. The proof is a good matching of the FM calculated and experimental characteristics $\overline{\varphi}_{df}(d)$ with maximum filling of pores with deposits and complete FE retention capacity (fig. 2). The calculated dependency for the fractional screening coefficient is in the confidential interval of experimental data as per this indicator.

Conclusion

Summing up the results of theoretical studies into the kinetics of mechanical impurities contaminated systems fluids filtration, the following conclusions can be drawn.

1. Kinetic models of sophisticated heterogeneous FM systems with irregular pore structure separation have been developed, allowing:
– to establish the distribution of contaminants by screening zones and mechanisms for various filtering materials;
– to determine the relationship of hydrodynamic processes with the porous structures' retention capacity and to identify the main filtration regularities;
– to consider pore filling up with deposits and clogging these up with DP large particles;
– to calculate the kinetics of the MLO purification from insoluble products of varying contamination disperse and fractional compositions.
2. The updated filtration theory constructs allow:
– to lay a foundation for main directions of MLO purification intensification when contaminated with insoluble products of complex DP;
– to lay down filtering conditions that would provide for the considered methods of heterogeneous systems separation to be utilized to the fullest extent possible;
– to determine the methods of controlling the screening mechanisms in order to achieve multifunctional or selective filter operation;
– to predict methods of settling the controversy or choosing the most profitable compromise between the screening fineness and completeness on the one hand and the FM service life and retention capacity on the other.

ВКЛАД АВТОРОВ | CONTRIBUTION OF THE AUTHORS

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The authors contributed equally to this article. All the authors reviewed the results and approved the final version of the manuscript.

КОНФЛИКТ ИНТЕРЕСОВ | CONFLICT OF INTEREST

Авторы заявляют об отсутствии конфликта интересов.
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ИНФОРМАЦИЯ ОБ АВТОРАХ | INFORMATION ABOUT THE AUTHORS

Кича Геннадий Петрович – доктор технических наук, профессор, заведующий кафедрой, Морской государственный университет имени адмирала Г.И. Невельского (Владивосток, Российская Федерация)

✉ kicha@msun.ru, SPIN: 2469-6099, https://orcid.org/0000-0001-8298-9956

Gennadiy P. Kicha, Doctor of Engineering Sciences, Professor, Head of the Department Maritime State University named after Admiral G.I. Nevelskoy (Vladivostok, Russian Federation)

Надежкин Андрей Вениаминович – доктор технических наук, профессор, Морской государственный университет имени адмирала Г.И. Невельского (Владивосток, Российская Федерация)

✉ nadezkin@msun.ru, SPIN: 7051-7899

Andrey V. Nadezhkin, Doctor of Engineering Sciences, Professor, Maritime State University named after Admiral G.I. Nevelskoy (Vladivostok, Russian Federation)

Гога Константин Николаевич – аспирант, Морской государственный университет имени адмирала Г.И. Невельского (Владивосток, Российская Федерация)

✉ konstant.goga@gmail.com

Konstantin N. Goga, Postgraduate Student, Maritime State University named after Admiral G.I. Nevelskoy (Vladivostok, Russian Federation)

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