Efficiency assessment of waste filtration of motor oils over grainy partitions

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Abstract. The article discusses the further use of used engine oil (UEO). The article presents the types of bulk materials that can be used for cleaning UEO. The advantages and disadvantages of ultrafiltration are considered. It is shown that the filtering material is characterized by a number of parameters that affect both the parameters of the filter and the efficiency of the process of cleaning the treated UEO. The mathematical model determining the dynamics of the filtering material capacity change is obtained. The results of theoretical study of pollution dynamics are compared with experimental studies. The obtained dependencies allow one to determine pressure losses and filter capacity for engineering calculations. The analysis of the influence of Reynolds' criteria and homogeneity on the Euler criterion shows that with the increase of both Reynolds' criterion and homogeneity criterion there is an increase in the Euler criterion, which indicates an increase in pressure loss on the filter due to its contamination.

1. Introduction
One of the effective methods of using used engine oils (UEO) in the conditions of agricultural enterprises is their cleaning from impurities accumulated in them in the process of operation and the subsequent use of purified oils in those units and mechanisms that under operating conditions allow the operation of such oils. As impurities can act mechanical impurities (dust, water, wear products of engine parts) and products of destruction of the oil itself (acids, oxides, carbens, carboids, etc.) particles dimension of not more than 2-3 microns is necessary for subsequent use of purified UEO [1]. For cleaning UEO from mechanical impurities, so-called grain filters can be used. In these filters, used motor oil passes through the granular layer (sand, expanded clay, ash, etc.) and the impurities contained in the oil are deposited in the volume of the granular layer. In defining rational parameters of such filters it is necessary to solve following problems: definition of filtration quality; definition of filtration speed; determination of filter pollution dynamics; determination of filter operating life [2].

2. Problem Statement
Used engine oils are a problem for agricultural enterprises and the main means of environmental pollution with petroleum products [3]. Cleaning of UEO from accumulated mechanical impurities and
products of oil destruction is an effective means of prolonging the life of motor oils through the use of purified oils in those units and mechanisms that under operating conditions allow the use of such oils. Obtaining high quality purified oils is associated with the need to use ultrafiltration. However, ultrafiltration has a significant drawback, consisting in a very small lifetime of such a filter (6-8 hours), depending on the contamination of UEO. To increase the service life it is suggested to use two filters. The first stage filter removes oil particles of contamination with sizes from 4 to 7 microns, as well as products of oil destruction (resins, low and high molecular acids). In the second stage of cleaning, it is offered to use an ultrafilter. As the first stage filter it is proposed to use a bulk filter to remove both mechanical impurities and decomposition products of the oil itself from UEO [4, 5]. Natural granular materials that have different, operational characteristics of natural and industrial origin can be used as filtering materials [5, 6]. These include activated coals, ion exchange resins, and inorganic sorbents. By means of effective cleaning of UEO from dissolved impurities (resins, low and high molecular acids, other organic substances formed in the process of engine operation). The main requirement for the backfill material is its weak interaction with oil molecules at high interaction energy with the molecules of extracted impurities. This requirement is best satisfied by active coals.

In the process of filter operation the initial structure of the backfill changes, which leads to changes in porosity, permeability (filtration coefficient), physical characteristics of the backfill and, as a result, changes in the filtering mode. These deviations can be both useful and undesirable. The material prepared for UEO cleaning is characterized by a number of parameters that affect both the filter design and the cleaning efficiency. The analysis and conclusions [7] indicate that the characteristics (particle-size) of the filter material used for cleaning UEO of required quality should correspond to the assigned technological parameters of the cleaning plant in order to achieve optimal conditions of their operation (required quality of the resulting UEO, the maximum possible mud capacity, minimum operating costs, etc.). For example, in work [6] it is shown that to achieve the required quality of the obtained filtrate, with increasing the rate of filtration or reducing the content of impurities in the treated medium, it is necessary to increase the height of the filtering material layer. And increasing the particle size of the filtering material requires either reducing the rate of filtration or increasing the height of the material layer [8, 9].

3. Research Methods

During the filtration process, impurities accumulate in the granular layer of the partition, resulting in an increase in hydraulic resistance, reduced filtration speed and filter life. Therefore, the change in hydraulic resistance is an indicator that characterizes the dynamics of contamination of the granular layer of the filter. Theoretical study of the dynamics of contamination of the filter granular layer is based on the Navier-Stokes equation system [10]. It is assumed that the filtration process is one-dimensional, i.e. in the direction of one axis:

\[
\frac{\partial u_f}{\partial t} + u_f \frac{\partial u_f}{\partial x} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \frac{\partial^2 u_f}{\partial x^2},
\]

where \(u_f\) - oil velocity in granular layer, m/s;
\(t\) - time, s;
\(x\) - coordinate in the filtering direction, m;
\(\rho\) - oil density, kg/m\(^3\);
\(\nu\) - kinematic fluid viscosity, m\(^2\)/s;
\(\frac{\partial p}{\partial x}\) - pressure drop in direction of axis x, Pa/m;
\(\frac{\partial^2 u_f}{\partial x^2}\) - second derivative of the oil speed in the direction of x, (m/s)/m.  

Using equation (1) and the positions of similarity and dimensional theory, we obtained the following criteria that determine the filtration of oil through the grain layer:
where $R_e, E_u, G$ - dimensionless criteria for Reynolds, Euler and homochrony, respectively;

$\ell$ - typical size, m.

As a characteristic size in the formula (2) took the filter diameter equal to 0.2m.

The process of changing the bandwidth due to contamination of the filter on the data [11, 12] can be described by the equation:

$$Thr = K_n \cdot F \cdot \frac{\Delta P}{\mu u \cdot H}$$

(3)

where $Thr$ - throughput capacity, m$^3$/s;

$K_n$ - aspect ratio, m$^2$;

$F$ - filtration area, m$^2$;

$\Delta P$ - pressure difference, Pa;

$\mu u$ - dynamic oil viscosity, Pa-s; $H$ - height of filter media, m.

To estimate the filter pollution it is necessary to determine the Euler criterion as a functional dependence from the criterion equation including criteria (2) experimentally:

$E_u = f(Re, G)$,

(4)

and then from Euler's criterion formula to determine $\Delta P$:

$$\Delta P = E_u \cdot \rho \cdot u_f^2 = \rho \cdot u_f^2 \cdot f(R_e, G).$$

(5)

Usually in hydrodynamics and heat engineering when searching for functional dependence (4), an unknown function is represented in the form:

$E_u = aR_e^\delta \cdot G^\beta$

(6)

where $a, \delta, \beta$ - experimental ratios.

Taking into account formula (6) the dependence (5) to determine the pressure loss will take shape:

$$\Delta P = aR_e^\delta \cdot G^\beta \cdot \rho \cdot u_f^2.$$

(7)

The dependence analysis (7) shows that the pressure drop depends on the values included in the Reynolds criterion (linearly on the filtration rate and particle diameter, inversely proportional to the viscosity of the UEO; and the values characterizing the homochrony criterion (linearly and $u_f^\beta$ and $t^\beta$) and inversely proportional to the grain size of the backfill.

To determine the coefficients of equation (6) and check the adequacy of the model, a series of experiments were carried out on the experimental setup shown in figure 1. Experimental studies were carried out with filter 1 having homogeneous loading of granulated polyethylene. Diameter of filter $df = 0.2m$, height of backfill $H = 1m$. Initial porosity of filter material is 0.8. Granulated polyethylene GOST 16338-85 was used as a backfill. The sizes of particles of polyethylene 3.5 - 5 micron. Initial UEO for clearing has been received from cartridges of tractors MTZ-80/82, K-701 in various farms of Omsk region.
The experiments were conducted in the following sequence. Collected in farms UEO was pretreated to remove large mechanical impurities and water by setting in the settling tank at a temperature of 100 - 105°C for 24 hours. After draining, the settling tank oil was centrifuged on the unit, collected on the basis of MTZ-80 tractor centrifuge.

There was carried out the analysis of physical-chemical and operational parameters of oil after centrifugation. The results of the analysis are presented in Table 1.

Table 1. Results of the analysis of WMD cleaned by sedimentation and centrifugation

| experience no. | N at 100°C, mm²/s | H₂O, % | pH, mgCON/g | Content of mechanical impurities, % | ρ, kg/m³ |
|----------------|-------------------|--------|-------------|------------------------------------|---------|
| 1              | 11.63             | 0.014  | 6.2         | 0.0134                             | 910     |
|                | 12.26             | 0.011  | 6.3         | 0.0128                             | 907     |
|                | 11.33             | 0.004  | 6.5         | 0.0131                             | 910     |
| average        | 11.74             | 0.009  | 6.33        | 0.0131                             | 909     |
| 2              | 11.87             | 0.076  | 6.1         | 0.0124                             | 903     |
|                | 11.59             | 0.064  | 6.7         | 0.0114                             | 907     |
|                | 11.42             | 0.032  | 7.5         | 0.0122                             | 908     |
| average        | 11.62             | 0.057  | 6.77        | 0.0120                             | 906     |
|                | 15.21             | 0.006  | 6.8         | 0.0097                             | 904     |
| 3              | 12.42             | 0.017  | 7.1         | 0.0099                             | 906     |
|                | 12.34             | 0.011  | 7.6         | 0.0105                             | 902     |
| average        | 13.32             | 0.011  | 7.17        | 0.0100                             | 904     |

The pressure drop at the filters was controlled after 5 hours of filter operation. Pre-cleaned by sedimentation and centrifugation UEO with the content of mechanical impurities from 0.01 to 0.0131% of the tank 1 at open valves 2 and 6 by pump 3 at a given pressure of 0.4 MPa was fed into the filter 7. The output pressure was measured with the pressure gauge 8 at the open valve 9. Therefore, the differential pressure (MPa) at the filter was determined as the difference between the inlet and outlet pressures of the filter:

$$\Delta p_f = p_{in} - p_{out}, \quad (8)$$

where $p_{in}$ - filter inlet pressure, MPa;

$p_{out}$ - filter outlet pressure, MPa.

The exit pressure of the filter was determined by the formula:

$$p_{out} = p_0 + \Delta P, \quad (9)$$

where $p_0$ - environmental pressure, Pa;

$\Delta P$ - pressure loss in the filter.

Figure 1. Installation diagram: 1 - oil tank; 2 - valve; 3 - pump; 4 - pressure regulator; 5 - manometer; 6 - valve; 7 - bulk filter; 8 - manometer; 9 - valve of purified oil.
4. Findings

Processing the results of the experiments allowed us to obtain equation (10) in the following form:

\[ \Delta P = 1.8052 \cdot R_e^{1.3302} \cdot G^{1.0005} \cdot \rho \cdot u_f^2 \]  \hspace{1cm} (10)

The results of the calculations of the dependence of the Euler criterion on Reynolds' criteria and homogeneity are shown in Figure 2.

The analysis in figure 1 of the graphs shows that as Reynolds' criterion increases, so does the Euler criterion. However, the intensity of this increase is not the same. Thus, with an increase in Reynolds' criterion from 0.5 to 10, with the homogeneity criterion equal to 0.5 Euler's criterion changed from 0.9 to 19. With an increase in the homochrony criterion (UEO purification time) and a constant Reynolds Criterion, the Euler Criterion increases more intensively. If Reynolds Criterion 5 and Homogeneity Criterion 0.5 were 7.65, then with Homogeneity Criterion 10 the Euler Criterion increases to 155.63. The Euler Criterion is directly proportional to the pressure drop (2). We have calculated the pressure loss of the filtration capacity depending on the time of filter operation.

Figure 2. Dependence of the Euler criterion on the Reynolds criterion (Re) and the homochrony criterion G: 1 - G = 1; 2 - G = 2; 3 - G = 3; 4 - G = 4; 5 - G = 5; 6 - G = 6; 7 - G = 7; 8 - G = 8; 9 - G = 9; 10 - G = 10

The results of the calculation of pressure losses by formula (10), depending on the filtering speed and medium, are shown in figure 3.

Figure 3. Function Chart 1 - \( \Delta p = f(t, u_f) \): 1 - \( u_f = 0.001 \) m/s; 2 - \( u_f = 0.0009 \) m/s; 3 - \( u_f = 0.0008 \) m/s; 4 - \( u_f = 0.0007 \) m/s; 5 - \( u_f = 0.0006 \) m/s; 6 - \( u_f = 0.0005 \) m/s; 7 - \( u_f = 0.0004 \) m/s; 8 - \( u_f = 0.0003 \) m/s; 9 - \( u_f = 0.0002 \) m/s; 10 - \( u_f = 0.0001 \) m/s
Pressure losses, depending on the criterion of homogeneity, increase practically by a linear law. The degree indicator $\beta = 1.0058$. Reynolds's criterion (degree index $\delta = 1.3302$) has a greater influence on the nonlinearity of dependence $\Delta P = f(t)$.

The analysis shown in figure 3 of the graphs shows that time and speed of filtration have a significant impact on the pressure loss in the bulk filter. At filtration velocities from 0.0001 to 0.0004 m/s (7-10 curves) during 30 hours, the filtration speed has little effect on pressure loss and does not exceed 65 Pa, but with increasing filtration speed pressure loss increases significantly. At a filtration rate of $\text{tsf} = 0.0005\text{m/s}$ they are 200 Pa, and at $\text{tsf} = 0.001\text{m/s}$ they reach 5500Pa. Effect of filtration time is significant in the initial period of filtration (1...2) hours. At this time pressure losses at a given filtration rate reach almost maximum value (approximately 90 - 95%) of the maximum pressure loss. At further process of filtration pressure losses increase insignificantly and make up 5 ... 10 % of total pressure losses.

At calculation of throughput of a bulk filter by the formula (3) for coordination of results of calculation and the experimental data the factor of proportionality $K_n$ was accepted equal $K_n = 1,31\cdot10^{-10}$.

Figure 4 shows the data calculated by formula (3) on changes in the capacity of the bulk filter depending on its height $H$ and pressure loss $\Delta p$.

Figure 4. Dependence of the capacity of the bulk filter on pressure loss $\Delta p$ and the backfill height of the filter $H$: 1 - $H = 0.5\text{m}$; 2 - $H = 1.0\text{m}$; 3 - $H = 1.5\text{m}$; 4 - $H = 2.0\text{m}$; 5 - $H = 2.5\text{m}$; 6 - $H = 3.0\text{m}$

The analysis of the graph $\text{Thr} = f(t,H)$ shows that the filter capacity drops, both when the pressure loss increases and when the filter height increases. At filter height of 3m3 the throughput changes insignificantly from 20.82 m3/h at the drop and pressure equal to 0Pa to 18.86 m3/h. With decreasing backfill height the capacity of the filter increases and at filter height $H = 0.5\text{ m}$ the capacity is more than 120 m3/h, and at pressure loss 4500Pa the capacity of the filter decreases to 113 m3/h.

5. **Conclusion**

1. The obtained dependencies allow to determine with accuracy for engineering calculations pressure losses and filter capacity.

2. The analysis of the influence of Reynolds' criteria and homogeneity on the Euler criterion shows that with the increase of both Reynolds' criterion and homogeneity criterion there is an increase in the Euler criterion, which indicates an increase in pressure loss on the filter due to its contamination.

3. The increase in pressure loss and backfill height leads to the reduction of the filter capacity and the final judgment on the optimal size of the filter and its modes of operation can be made only after the research on the oil refinement.
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