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Coalescence filtration of ship oil bilge water with an nonwoven fabric

Jerzy Gutteter-Grudziński[a,*], Andrzej Moraczewski[b]

[a]*Maritime University of Szczecin, ul. Wały Chrobrego 1/2, 70-500 Szczecin, Poland*
Tel. +48 500472509; email: j.grudzinski@am.szczecin.pl
[b]*Institute of Operational Technologies–State Research Institute; Textile Technology Dpt. in Lodz , ul. Hipoteczna 6, 91-335 Lodz, Poland*

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ABSTRACT

This article examines phenomena occurring in the process of oil-water emulsion flow through a coalescence fabric filter. The authors determined the flow of oil-water mixture through a fabric partition, the efficiency of filtration η_F and the distribution of oil particle size d_o by using a Malvern analyzer gauge. The results, presented graphically and in tables, are considered as satisfactory as they meet the standards of Resolution MEPC 60/(33) IMO for shipboard equipment.

Keywords: Oil-water emulsion; Oil separation; Coalescence fabric barrier filter

1. Oil separation on board ships

Oily water produced in ship operations is one of the essential threats to the marine environment. These wastes find their way to seawater by:

- discharge of ballast water and cargo tank washing water,
- discharge of bilge water,
- ship disasters and machinery failures,
- spillage during oil un/loading operations,
- oil spills from propeller shaft bearings and other oil-lubricated elements that have contact with water [3,4,7,9,17].

All these sources of pollution have a high content of oil products, and their occurrence seems to be practically unavoidable. The oil separator NEPTUN shown in Fig. 1 purifies bilge water. NEPTUN operates in two stages of oil separation: gravity and coalescence. In the former stage separation takes place on the pump suction side where oil is removed by flushing water. The latter stage, where coalescence takes place, is described in detail below. The separator is equipped with necessary fittings and automatic control devices (oil level sensors, oil content gauge etc.,) tested in compliance with MARPOL 73/78 Convention.

Oil particles reaching the oil separator filter can have diameters less than 50 µm and various oil concentration amounting to 10 000 ppm [4,24,25].

The diameter of smallest separated oil particle in the oil separation process taking place on a fabric barrier is a function of many parameters [4]:

$$d_0 = f \quad \rho_w, \rho_0, \eta_w, w, l, F, \varepsilon, g \qquad (1)$$

where w = speed of mix flow [m/s]; F = barrier surface area [m^2]; ε = coefficient of barrier porosity; ρ_w = density of continuous phase (water) [kg/m^3]; ρ_0 = density of dispersed phase (oil) [kg/m^3]; g = Earth's gravity [m/s^2]; η_w = coefficient of water dynamic viscosity [N·s/m^2]; d_0 = diameter of oil particle [m]; l = track of oil particle (length of capillaries or pores) [m].

*Corresponding author.

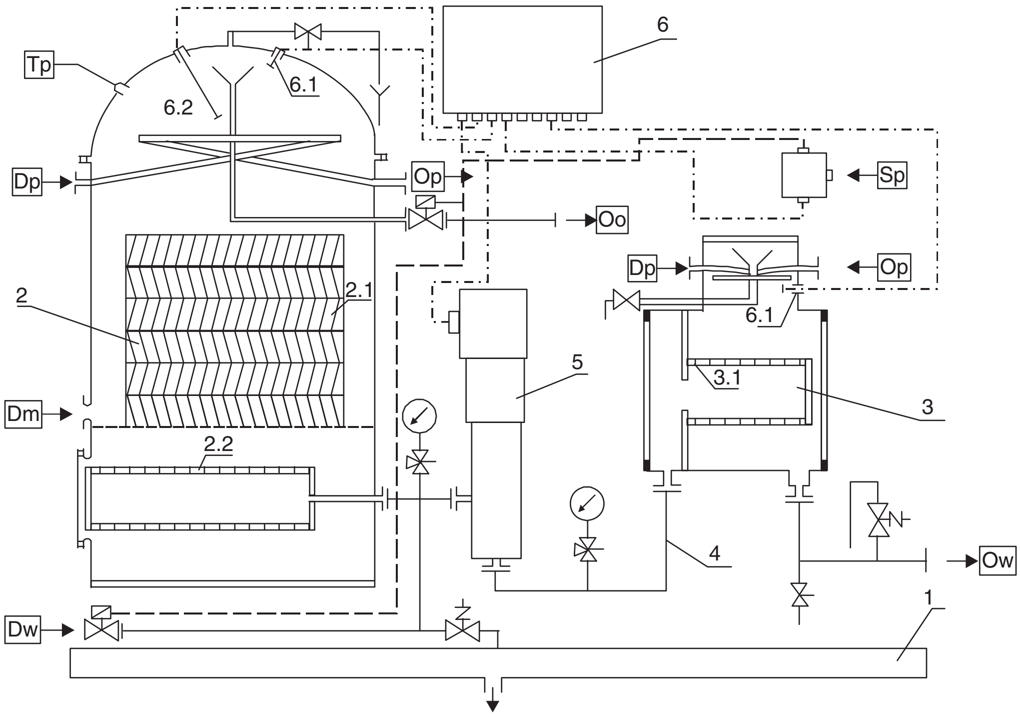

Fig. 1. Schematic diagram of the oil separator NEPTUN (q_v = 2.5 m^3/h); 1 – base, 2 – gravity separator, 2.1 – corrugated plates unit, 2.2 – filter with velours fabric, 3 – coalescence separator, 3.1 coalescence barrier, 4 – pipeline, 5 – pump, 6 – electric control panel, 6.1 – minimum oil level detector, 6.2 – maximum oil level detector; Dw – inlet of tap water, Dm – inlet of oil-water mixture, Tp – control thermostat, Dp – steam inlet, Op – steam outlet, Sp – compressed air, Oo – oil outlet, Ow – outlet of purified water.

An analysis of oil-water emulsion found in a separate porous fabric barrier [4] showed that the diameter of the smallest droplets of oil separated in the filter can be determined as follows:

$$d_0 \geq \left[\frac{4,5 \cdot q_v \cdot \eta_w \cdot d_w}{g \cdot V_c \quad 1-\varepsilon \quad \cdot \quad \rho_w - \rho_0} \right]^{0,5} \tag{2}$$

where q_v = volumetric stream of water [m^3/s]; V_c = volume of sample filtration bed [m^3]; d_w = fiber diameter [m].

One conclusion we can draw from the above relationship is that there are a few measures that can be taken to improve the efficiency of the filtration barrier capturing oil droplets due to coalescence:

- reduce q_v, d_w, ε and ρ_0;
- increase the inner surface area of the barrier;
- increase fabric porosity;
- adjust these flow parameters on an individual basis:
  – barrier parameters,
  – content of oil in the purified liquid.

2. Assumptions for the research and model oil separator design

The research aimed to examine the efficiency of oil coalescence process on a new multi-layer barrier made of chemical fibers. A newly designed and constructed glass oil separator model was used for tests (Fig. 2). Glass fibers used so far in W-5 filters are now prohibited as they posed hazards to human health.

Several assumptions were made before selecting the design solutions:

- the barrier will be horizontal, and oily water will be flowing upwards;
- oil will be stopped on the whole surface area of and inside the barrier, so that it separates in the form of droplets that will be gathering in the upper part of the cylinder;
- outflow of purified water from above the barrier through a connector pipe, mounted so that the collected oil will not get into it.

The oil separator model consists of two glass cylinders (upper and lower) each closed by covers adequately squeezed onto them. To facilitate the exchange of

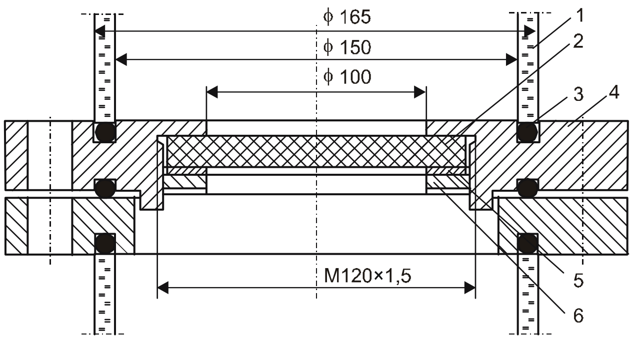

Fig. 2. A model of oil separator with a filtration barrier; 1 – glass cylinder, 2 – tested barrier, 3 – gasket, 4 – flange, 5 – washer, 6 – nut.

unwoven fabric—the filtration barrier—there are easy-to-dismount flanges in the central part.

The intensity of emulsion flow through the filter has to be adjusted so that it corresponds to that in marine filters with D = 140 mm, H = 356 mm, working at q_v = 1 m^3/h, assuming that the kinematic flow will be steady. As the same unwoven fabric barriers are used (the same capillaries) in the model as in marine filters, their Reynolds numbers will be equal:

$$\mathrm{Re}_R = \mathrm{Re}_M \tag{3}$$

$$\left[\frac{w \cdot d_k \cdot \rho}{\eta}\right]_R = \left[\frac{w \cdot d_k \cdot \rho}{\eta}\right]_M \tag{4}$$

where (for denotations, see formula 1), indexes R and M refer to the marine filter and the lab filter.
From Eq. (4) we obtain:

$$\frac{\rho_R}{\rho_M} \cdot \frac{\eta_M}{\eta_R} \cdot \frac{d_{kR}}{d_{kM}} \cdot \frac{w_R}{w_M} = 1 \tag{5}$$

Assuming that parameters ρ, η, d_k do not change, we get:

$$W_R = W_M = 1.77 \cdot 10^{-3}\ \mathrm{m/s} \tag{6}$$

Table 1
Properties of the diesel oil

	Property	Diesel oil
1	density at 20 °C [g/cm^3]	0.8753
2	dynamic viscosity at 40 °C [cP]	14.72
3	kinematic viscosity at 40 °C [cSt]	17.08
4	max. water content [%]	0.10
5	flash point [°C]	101

The volumetric stream in the model filter (Fig. 1, D = 100 mm) depends on the quotient of the barrier surface areas:

$$q_M = q_R \left(\frac{F_M}{F_R}\right) \tag{7}$$

Based on the above considerations, we assumed in the tests that the volumetric stream amounts to q_M = 30–90 [dm^3/h].

Various fabric barriers were placed in the model filter. Each barrier was tested by using the same model water-oil mixture: tap water—diesel oil. The fuel characteristics are shown in Table 1.

2.1. Unwoven fabric filtration barriers

Needled cloth (unwoven fabric) barriers used in the tests were made of hydrophobic polypropylene (PP, 4.1 dtex) and polyester (PES, 1.3; 3.6 dtex) fibers. Their characteristics are given in Table 2. The multilayer FOW† fabric features a layer of thin glass fibers with a diameter of 4 μm. To prevent fabric deformations when the filter is in operation the fabric was strengthened at the manufacturing stage with ET‡ cloth made of PES fibers (elana-2dtex). The needled cloths were then thermally treated to thicken their structure. Characteristic properties of the tested unwoven fabrics are their high strength, low flow resistance, uniform distribution of fibers and pores across the whole volume of the cloth. Besides, these multilayered fabrics can be made with different degrees of layer packing.

2.2. The test stand

The tests were carried out on an upgraded test stand adjusted to the examination of coalescence barriers. The schematic diagram of the test stand is shown in Fig. 2. The tank (7) of 500 dm^3 capacity was fed with tap water. The piston pump (4) with a controllable capacity ranging from 0 to 350 dm^3/h pumped water from the lower part of the tank and passed it to the model oil separator (1) with a volume of 12 dm^3. An oil feeding pump (3) was fitted on the discharge side of the pump before a rotameter (6). Oil was proportioned by a *Dyspenser* 338 type metering pump (capacity q_v = 0–11.5 dm^3/h with a mean accuracy of ±1 mm^3/cycle), that drew oil from the tank (2). The volumetric stream of the mixture was measured with

†FOW is Polish manufacturer's type of oil-separating nonwoven fabric.

‡ET is a type cloth strengthening the external part of FOW fabric.

Table 2
Characteristics of unwoven fabric used for tests of filtration barriers

Lp.	Parameter	Fabric symbol		
		J/PP/1449	FOW	FINET-POP 2
1	Type of filtration barrier	PP-thermally thickened	1. PES (3, 6 dtex) 2. Glass 1–2 μm 3. PP(3, 6–5, 4 dtex) 4. ET fabric	PP-thermally thickened
2	G.S.M.	400 ± 50 g/m^2	650 ± 50 g/m^2 (1030 g/m^2)	300 g/m^2 ± 10%
3	Longitudinal tearing strength	1400 N/5 cm	420 N/5 cm (500 N/5 cm)	350 N/5 cm
4	Transverse tearing strength	1400 N/5 cm	1700 N/5 cm (2000 n/5 cm)	500 N/5 cm
5	Longitudinal elongation	10 ± 10%	163% (170%)	60%
6	Transverse elongation	10 ± 10%	80% (75%)	40%
7	Permeability at 200 Pa [l/m^{2}s]	250 ± 50	150 (200)	200
8	Working temperature	max. 90 °C	max. 90 °C	max. 90 ° C
9	Porosity [%]	39	92	44
10	Mean fiber diameter [μm]	20.2	14.6	20.26
11	Mean pore diameter [μm]	31.2	49.6	28.12
12	Internal surface area coefficient [m^{-1}]	$8.2 \cdot 10^{-4}$	$2.18 \cdot 10^{-4}$	$7.55 \cdot 10^{-4}$

the rotameter. The pressure difference on the model filter was measured with pressure gauges (8) and (9).

The oil content after the oil separator was measured with a HORIBA OCMA-220 analyzer with an accuracy of ±0.5 % of oil content in a sample.

The system was fed with 1000, 2500, 5000 and 10000 ppm (1%) diesel oil by changing the volumetric stream of the emulsion from 30 to 90 dm^3/h. The changes of temperature, pressure drop on the barrier, oil concentration in the purified mixture (at the outlet of oil separator) were recorded. The oil concentration was determined using a Horiba OCMA 220 analyzer.

Besides, the investigation included the distribution of oil particle sizes in the solution after filtration through the oil separator barrier, using an instrument made by MALVERN INSTRUMENTS Ltd., meeting the ISO 13320/01 standard. The method of laser diffraction was employed to find the volumetric and quantitative distributions in the 0.01–2000 μm range.

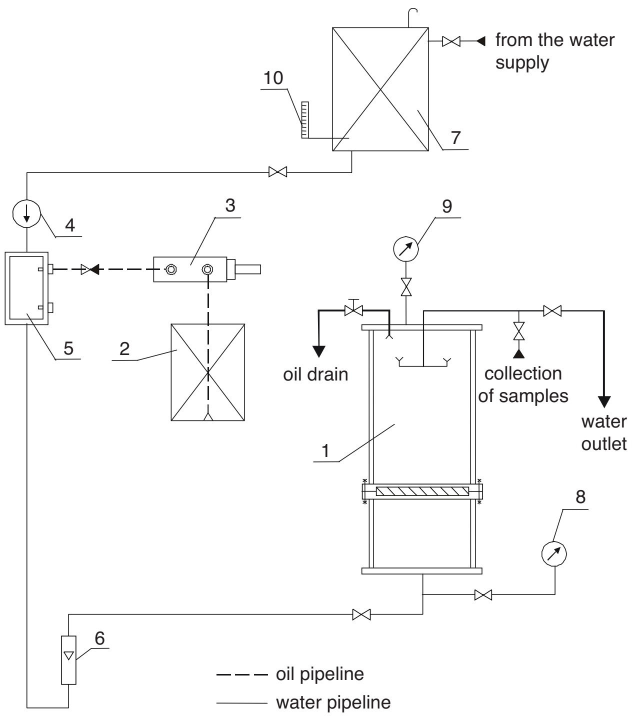

Fig. 3. Test stand diagram; 1 – model filter with the tested barrier, 2 – oil tank, 3 – oil feeding pump, 4 – variable capacity piston pump, 5 – metering system, 6 – rotameter, 7 – water tank, 8, 9 – pressure gauges 0–0.1 MPa, 10 – thermometer.

3. An analysis of oil-in-water emulsion flow through an unwoven fabric barrier

The flow of emulsion through a filtration bed with a multilayered unwoven fabric barrier FOW is shown in Fig. 3. The flow process is characterized by the coalescence of oil droplets from oil-in-water emulsion that takes place inside the barrier pores. Three areas can be identified that differ in the degree of oil dispergation.

We observed that in external layer I the flowing emulsion does not visibly affect the system due to larger pores. The oil dispergation within this layer is the same as outside the barrier. In layer II droplets settle on the bed and on oil previously stopped on the packing structure. The diameter of droplets increases while they slowly move towards the bed center. Large drops coalesce with small droplets and with those that already got bigger. As oil comes closer to the boundary of layer II, capillaries in the bed get filled up by drops contacting each other, but oil still has a discontinuous form. In layer III there is a characteristic flow of consistent oil stream through free space in the bed.

Layer I is only a few millimeters thin. The boundary between layers II and III, depending on a number of factors, shifts either in the direction of oil flow or in the opposite direction. The above description of emulsion flow through the bed is based on the assumption that the whole oil phase undergoes coalescence and leaves the bed in the form of drops much larger than those found in the emulsion.

One conclusion that might be drawn from the above is that pure water flows in capillaries of layer III not occupied by oil. However, this is not so, as part of the oil does not coalesce. Consequently, it will flow out of the bed together with the water phase in the form of very diluted emulsion. After coalescence, the droplet size increases. When a droplet is large enough, it will be pushed away from the fabric as an effect of resistance force acting against the flowing liquid. Once out of the bed, large drops can be easily removed by gravitational separation.

3.1. The efficiency of oil separation by coalescence

If we start from the oil mass balance on the barrier and assume that the oil concentration at the inlet is constant (Fig. 3):

$$m_d = m_z + m_k + m_o \tag{8}$$

where m_d = mass of dispersed phase before the barrier; m_z = mass of dispersed phase stopped on the barrier; m_k = mass of dispersed phase released as droplets from the barrier; m_o = mass of dispersed phase remaining in the stream after the barrier.

Then the efficiency of filtration can be adopted as:

$$\eta = \frac{m_k}{m_d} = 1 - \frac{m_o}{m_d} \tag{9}$$

When oil concentration is introduced [2,6]:

$$\eta = 1 - \frac{C_o}{C_d} = 1 - e^{-\frac{4\beta\eta_i l}{d_w(1-\beta)}} \tag{10}$$

where C_o = oil concentration at the barrier inlet [ppm]; C_d = oil concentration at the barrier outlet [ppm]; $\beta = V_w / V_c$ = density coefficient of filter packing structure; V_w = fiber volume in the filter [m^3]; V_c = filter volume [m^3]; η_i = efficiency of filtration on the surface area of a single fiber; d_w = fiber diameter [m].

The efficiency of coalescence filtration (capturing oil droplets on a single isolated fiber) [6] is defined as the ratio of cross-section of part of the stream from which oil droplets will be separated to the cross-section area of a fiber set at a right angle to the flow direction (Fig. 4):

$$\eta_i = \frac{l \cdot 2l_p}{l \cdot 2r_w} \tag{11}$$

where η_i = filtration efficiency of a single fiber; l = fiber length [m]; l_p = width of the cross-section stream part from which all oil droplets will be separated [m]; r_w = fiber radius [m].

The filter packing density equals:

$$b = V_w/V_c \tag{12}$$

(for denotations see formula 10),
and the flow speed in filter pores $\bar{w}$:

$$\bar{w} = \frac{W}{1-\beta} \tag{13}$$

If the length of parallel cylindrical fibers in a filter volume unit is:

$$L_w = \frac{\beta}{\pi\ r_w^2} \tag{14}$$

then the amount of mixture water and oil filtered by a filter with thickness db:

$$Q_i = 2l_p\bar{w}L_w \mathrm{d}b = 2l_p\bar{w}\frac{\beta}{\pi\ r_w^2}\mathrm{d}\,b \tag{15}$$

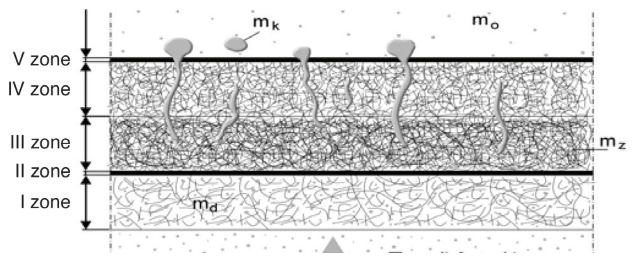

Fig. 4. Emulsion flow through the unwoven fabric bed and oil coalescence; m_d – oil (emulsion) mass before the barrier, m_z – mass of oil captured on the barrier, m_k – mass of oil droplets released from the barrier; m_o – mass of oil (emulsion) flowing through the barrier [4].

A change of oil particle concentration in the flowing emulsion can be expressed as follows:

$$-\frac{dc}{c} = \frac{\beta}{\pi\ r_w^2}\frac{2l_p\bar{w}\ db}{W} = \frac{\beta}{\pi\ r_w^2}\frac{2l_p\ db}{1-\beta} \tag{16}$$

After integration, we obtain:

$$\frac{c}{c_0} = \exp\left[\frac{-2\beta\eta_i b}{\pi\ r_w\,(1-\beta)}\right] \tag{17}$$

For the adopted layer of cylindrical parallel fibers and for mono-dispersed oil, we can express the efficiency of filtration in the form of the filtration Eq. (10):

$$\eta = \frac{c_0 - c}{c_0} = 1 - \exp\left(-\alpha_f\right) \tag{18}$$

where η = efficiency of filtration (purification) of the fibrous layer; $\alpha_f = \dfrac{2\beta b\eta_i}{\pi\ r_w\,(1-\beta)}$ – coefficient of filtration of the fibrous layer.

The separation of oil particles from the flowing mixture of oil and water in the fabric layer occurs when:

- oil contacts the fiber surface,
- there exist forces holding oil particles in fiber surfaces.

Oil particles get in contact with fiber surface when their tracks come across the fiber surface. Several forces can be identified that cause oil particle tracks to diverge from the direction of water flow:

- inertia,
- water viscosity,
- diffusion,
- electrostatic,
- others: magnetic, terrestial gravity, thermoforesis etc.

Forces due to water viscosity tend to keep oil particles along the stream direction, while the other forces counteract it—make oil particles deviate from the stream line.

The efficiency of purification (formula 18) determines the quality of the filtration process. The accuracy of filtration is characterized by the mean size of contaminant particles stopped by the filter.

3.2. Results of oil separation efficiency tests and volumetric and quantitative distribution of oil droplets in unwoven fabrics

Figs. 5–8 include the results of oil separation efficiency $C_0 = f(q_v)$ and $\eta_0 = f(q_v)$ obtained from two types of barriers FOW and POP2.

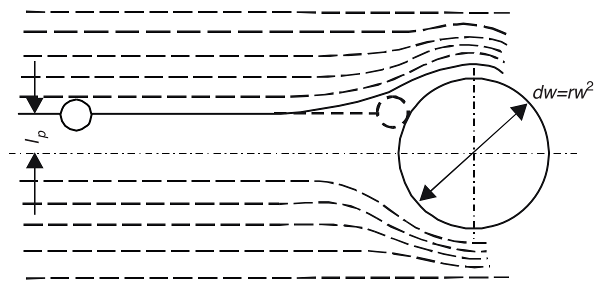

Fig. 5. The efficiency of filtration of a single fiber.

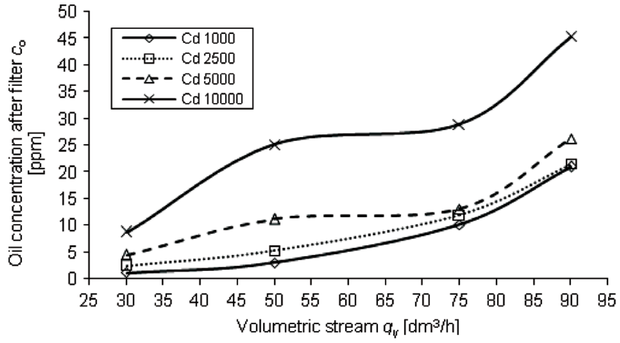

Fig. 6. The efficiency of oil separation by a FOW barrier FOW; $c_0 = f(q_v)$.

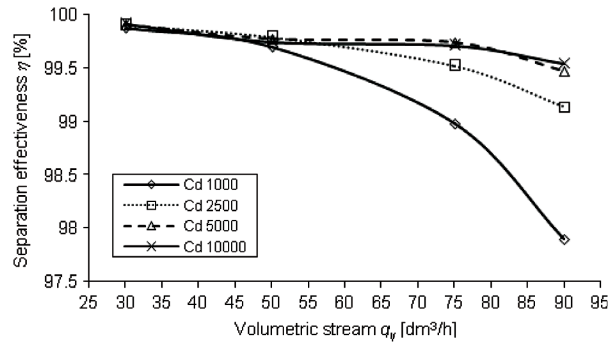

Fig. 7. The efficiency of oil separation by a FOW barrier; $\eta = f(q_v)$.

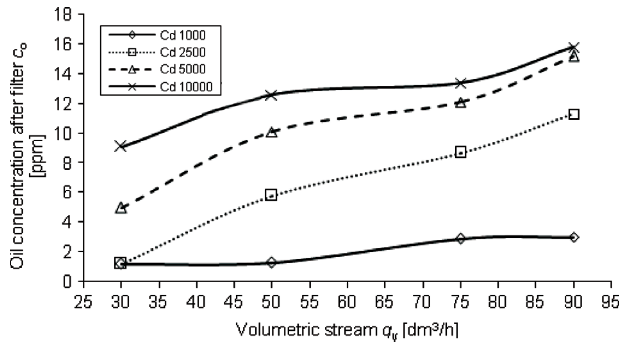

Fig. 8. The efficiency of oil separation by a FINET POP2 barrier; $c_0 = f(q_v)$.

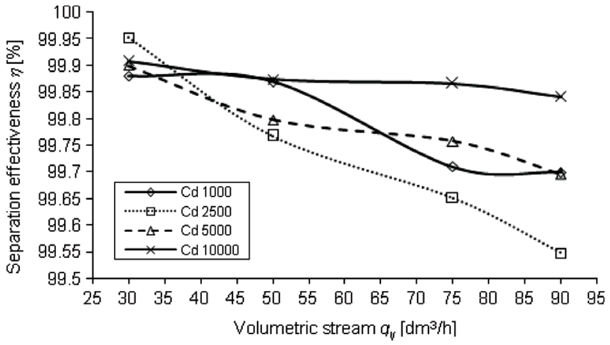

Fig. 9. The efficiency of oil separation by a FINET POP2 barrier; η = *f*(*qv*).

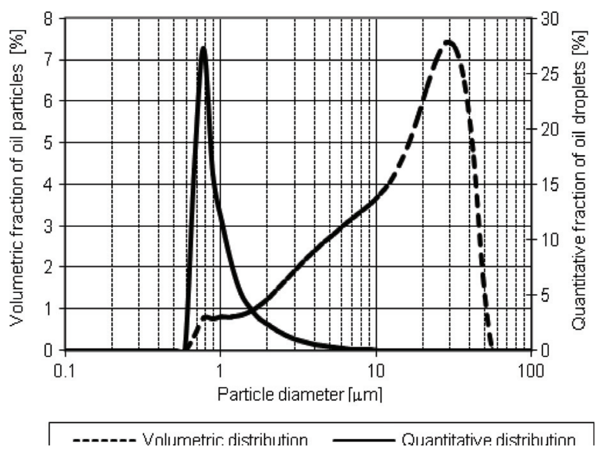

Fig. 10. Distributions of oil particles after the filter, FINET POP 2 barrier.

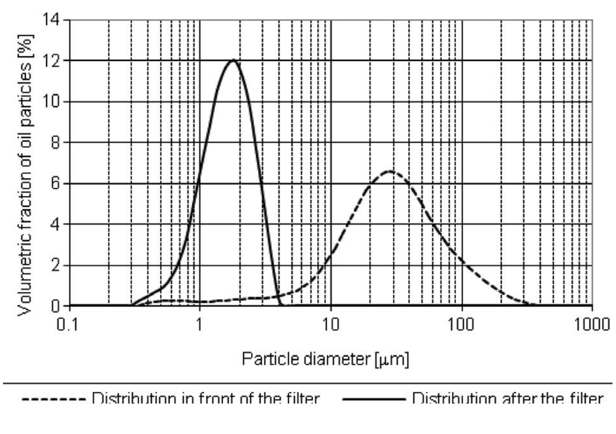

Fig. 11. Comparison of the volumetric distribution of oil particles on the FOW barrier.

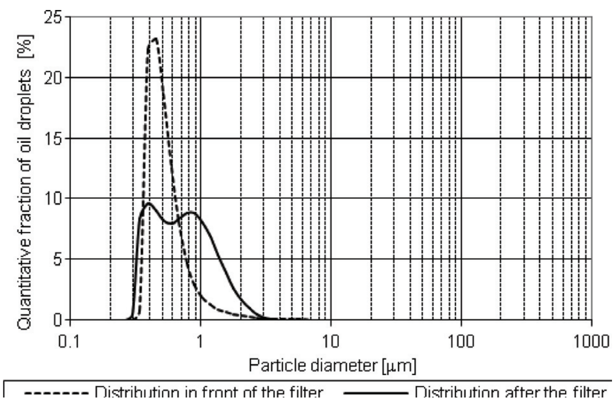

Fig. 12. Comparison of the quantitative distribution of oil particles on the FOW barrier.

The values of oil concentration after the fibrous barriers do not exceed 50 ppm (FOW) and 16 ppm (FINET POP2) at 1% oil concentration before the barrier, while at 0.1% oil concentration, the figures at the outlet ranged from 4 to 20 ppm (Figs. 5–8).

The analysis of oil separation efficiency obtained on coalescence fibrous barriers of FOW and POP2 type leads to an observation that the following factors affect filter performance [1,3,4,7,8,22,23]: filtration bed properties (of the fabric itself, form of structure packing), process parameters (Δp in the bed, R_e), properties of oily water (c_d, ρ_0), volumetric distribution of oil particles, presence of SPC, mechanical contaminants.

The distributions of oil-in-water emulsion particles measured at the fibrous barriers FINET POP2 and FOW are given in Figs. 9–11.

4. Conclusions

The tests show that FOW and FINET POP 2 barriers can yield satisfactory efficiency of oil separation (Figs. 5, 6, 8) at q_v = 30 dm³/h with oil concentration at the inlet 1000÷10 000 ppm. Higher concentrations result in correspondingly higher oil-in-water content after the barrier, ranging from 23.8–45.5 ppm, more than the standard requirement 15 ppm.

It follows from the above observations that unwoven fabric barriers can perform well as diesel oil separators when volumetric stream of the flow does not exceed, respectively 50 and 75 dm³/h, which guarantees relatively efficient work of the oil separation device.

Another advantage observed in the tests was a low flow resistance (over the entire range of tests), which translated into pressure drop of not more than 0.03 MPa.

An analysis of the distributions of oil droplet size for two barriers POP 2 and FOW (Figs. 9–11) has shown that in terms of quantity particles with a diameter of 0.87 µm make up 7.5%, while those with a 30 µm diameter occupy 27% of the total oil volume (Fig. 9).

The measured efficiency of 99.7% for both barrier types is comparable and does not differ significantly from other porous barriers [1,4,5,7,8,13,15,22,23].

A filtration unit fitted with such barrier is capable of efficiently separating oil even at very high concentrations of oil (diesel oil) at the inlet, as confirmed by the lab tests.

As unwoven fabric is inexpensive, fabric filters in oil separators do not have to be reconditioned.

References

[1] J. Chien, E. Glooyna and R. Scheeliter, Device for evaluating coalescence of oil emulsions, J. Environ. Eng., Division (1977).

[2] A. Ciborowski, Fundamentals of Chem. Eng., (in Polish), WNT, Warszawa (1970).

[3] J. Grudziński, Testing the effect of shipboard washing chemicals on oil separation efficiency (in Polish), *Studia* No 21, WSM, Szczecin (1994).

[4] J. Grudziński, Coalescence filters with unwoven fabric barrier for oily bilge and ballast water separation on ships, Doctoral dissertation (in Polish), *Raport* 61/85, Wrocław University of Technology, Wrocław (1985).

[5] M. Gryta and K. Karakulski, A. Morawski, Purification of oily waste water by hybrid UF/MD, Water Res., 35 (15) (2001) 3665–3669.

[6] Hebda et. al., Filtration of oil, fuel, air in engines (in Polish), WNT, Warszawa (1979).

[7] J. Hupka, Introduction to the use of coalescence in barriers for waste water purification (in Polish), Post-doctoral dissertation, Gdańsk University of Technology, Gdańsk (1988).

[8] P. Jeater, E. Rushton, and G.A. Davies, Coalescence in fiber beds, Proceedings of the Filtration Society Birminham Filtration and separation, IV (1980).

[9] G.V. Jeffreys and I.L. Hauskley, AIChEJ., 11 (1965) 413.

[10] W.M. Langdon and D.T. Wasan, Separation of organic dispersions from aqueous medium by fibrous bed coalescence, Recent Developments in Separation Science, CRC Press Inc., West Palm Beach, Florida, V (1979) 159–182.

[11] M. Malaczyński, Methods of protection against pollution from ships (in Polish), Wydawnictwo Morskie, Gdańsk (1979).

[12] International Convention on Prevention of Pollution from Ships (MARPOL 73/78), PRS, Gdańsk (2007).

[13] A. Moraczewski, Materials for air and water filtration (in Polish), *Ochrona Powietrza* 3 (1986).

[14] New Helsinki Convention, HELCOM, *(Polish) Journal of Laws* no 28 para 346, of 14.04.2000.

[15] Pat. PL 1400038 (1987).

[16] Pat. RFN 2609847.

[17] Pat. RP 130413 (1987).

[18] Pat. USA 3969719.

[19] Materials from: FRAM, VOKES, VAMAG Werke GmbH.

[20] Materials from: KORDES, AWAS, Passavant, AWK Unikom System.

[21] Materials from MITPOL Sp. z o.o., Łódź (2003).

[22] L.A. Spelman and S.L. Goren, Experiments in coalescence by flow through fibrous mats, Ind. Eng. Chem. Fund. 1 (1) (1972).

[23] L.A. Spielman and Su. Yeang-Po, Coalescence of oil in water suspensions by flow through porous media, Ind. Eng. Chem. Fund., 16 (2) (1977).

[24] A. Wiewióra, Environmental protection in ship operations (in Polish), *Fundacja Rozwoju WSM w Szczecinie*, Szczecin (2005).

[25] A. Wiewióra, Z. Wesołek and J. Puchalski, Crude oil in maritime transportation (in Polish), Trademar, Gdynia (2004).