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Analysis of oily water two-phase flow between deflected parallel panels of the model oil separator

SUMMARY

In the paper assumptions and course of laboratory tests of oil separation process (concerning both heavy and light fuel oil) with the use of a model oil separator are presented. In the investigations NEPTUN 2.5 device, an existing oil separator was utilized. Model – prototype geometric similarity and kinematic similarity of the oil particle stopped within the separator were maintained. Measurement results of oil concentration at outlet are presented for different designs of calming elements of the form of parallel panels and for different physical parameters of flow. Conclusions and practical recommendations for the producer of the NEPTUN oil separator are included.

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INTRODUCTION

MARPOL 73/78 convention provisions [2] unequivocally determine standards and methods of testing the marine environment protection devices intended to be installed on ships, i.e. oil separators, sewage treatment plants and incinerators. Guidelines for acceptable design, survey and operation within permissible contamination water discharge standards are given in the convention. In view of continued development of shipping and underwater mining the hazard of marine environment pollution by oil still grows. Therefore new oil separators with high operational efficiency are required to cope with these demands. The oil separator of NEPTUN system which is approved by Polish Register of Shipping in accordance with Res. 60/33 MEPC IMO provisions, produced by WARMA Pomeranian Ship Equipment Works, Grudziądz is the only recognized domestic design. The oil separators of the capacities : 0.25, 0.5, 1, 2.5, 5 and 10 m^3/h have been manufactured since 1985. In recent years research work on some outfitting elements of the separators [1] was carried out by Maritime University of Szczecin, whose results are presented in this paper.

LABORATORY TESTS OF THE SEPARATOR

The research work was divided into the following two tasks :

- selection of an optimum insert of coalescent elements to be fitted in the separator cylindrical part (Fig.1, item 1)
- operation analysis of a new design of velour filter placed in the separator bottom part.

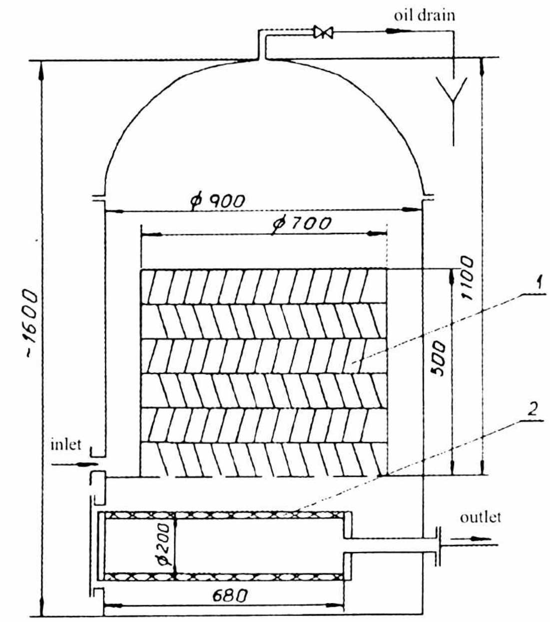

Fig.1. Scheme of NEPTUN 2.5 oil separator : 1- S700 insert, 2- velour filter

The existing test stand and separator model owned by the Maritime University, Szczecin, were utilized for the investigations in question. Model – prototype geometrical similarity was almost maintained, as well as kinematic similarity by maintaining the velocity of oil particle stopped in the separator and assuming the same oils as real ones to be used in the tests. The tests were performed on the existing design of NEPTUN 2.5 A1M oil separator. In Fig.1 and 2 the most important dimensions of the tested oil separator designs are given.

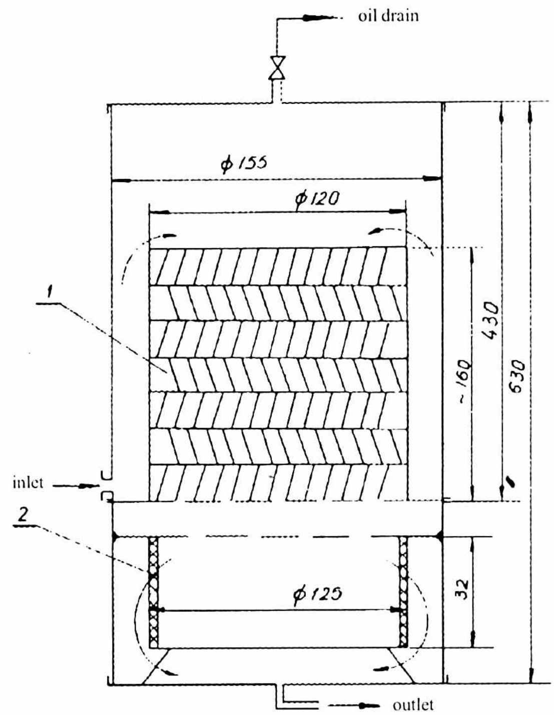

Fig.2. Scheme of the model oil separator : 1 - insert, 2 - velour filter

A 1 mm thick perspex cylinder (in which consecutive layers of plates were arranged orthogonally to each other) was co-axially placed inside the oil separator model (Fig.2) In the bottom part of the separator the velour filter was installed, which was so selected as to maintain the same flow area rating. Its velour whiskers were directed against inflowing liquid. The device for separating the oil-water mixtures [3], presented in Fig.3, has the plates 1 made of oleophilic materials, whose lower part 4 is bent out under the angle of 10° to 45° and the part covers 1/3 to 2/3 height of the plate. The plates are located parallel to each other forming the gaps 2 of 4 mm to 40 mm in size. The plates so situated in several planes form the separating layers in a number dependent upon the flow rate of the oil-water mixture. The separating plates of the second layer 5 are turned by the angle of 90° in respect to the plates in the first separating layer.In particular separating layers the bent parts of the plates are pointed in one and the same direction or situated in such a way as to form mirror reflection in respect to axis of symmetry of the particular separating layers.

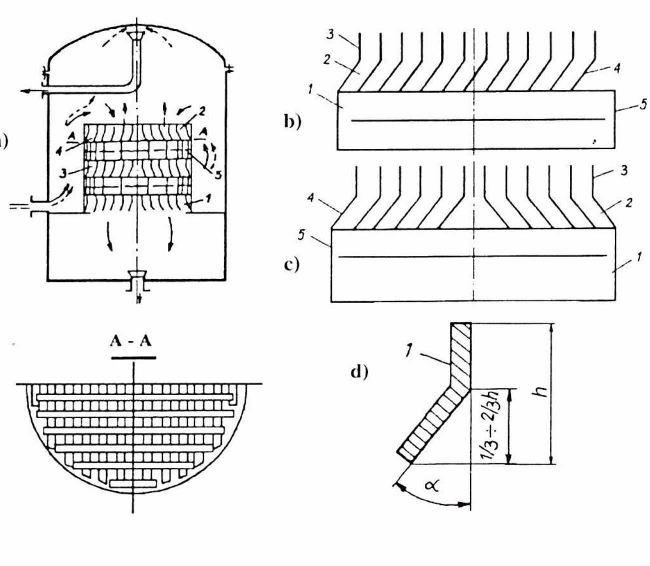

Fig.3. Scheme of the device for separating the oil-water mixtures : a) location within the gravitational stage, b), c), d) design solutions, α = 10°÷ 45° [3]

CALCULATION OF THE OIL SEPARATOR MAIN PARAMETERS

❍ Flow rate :

The flow continuity equation was applied to the space with plate layers :

$$Q_2 = Q_1 \frac{P_2}{P_1} = Q_1 \left(\frac{D_{C2}}{D_{C1}} \right)^2 = 2.5 \frac{0.12^2}{0.7^2} = 0.0735 \ m^3 / h$$

❍ Mean flow velocity :

$$W_1 = W_2 = \frac{Q_1}{P_1} = \frac{2.5 \cdot 4}{\pi \cdot 0.7^2} = 6.5 \ m / h$$

❍ Time of flow through the oil separator (approximate calculation) :

➢ for NEPTUN oil separator

$$\tau_1 = \frac{V_1}{Q_1} = \frac{1.02 \cdot 60}{2.5} = 24.48 \ \text{min}$$

➢ for model oil separator

$$\tau_2 = \frac{V_2}{Q_2} = \frac{12 \cdot 60}{74} = 9.80 \ \text{min}$$

Note: *Lower indices stand for : „1" – of the prototype, „2" – of the model.*

The main parameter values of the model and prototype, i.e. 2.5 NEPTUN oil separator are compared in Tab.1.

***Tab.1.** Main parameter values of the NEPTUN 2.5 and model oil separator*

Parameter	Symbol &Unit	Prototype NEPTUN 2.5	Model	Dimension ratio
Internal diameter	D [m]	0.9	0.155	5.81
Internal diameter of cylinder with plates	D_C [m]	0.7	0.12	5.81
Internal cylinder height (7 layers)	H [m]	0.5	0.16	3.16
Height of calming elements in one layer	h [m]	0.07	0.022	3.18
Plate spacing within layer	s [mm]	20	4	5.0
Plate length within layer	l [mm]	~8000	~1700	4.71
Plate thickness	b [mm]	2	1	2.0
Active area of one plate layer (1/3 h of plate forms a bend)	F [cm^2]	4000	238	16.81
Oil separator volume	V [dm^3]	1020	12	85
Flow rate	Q [dm^3/h]	2500	74	33.8
Flow time of a particle through oil separator	τ [min]	24.4	9.73	2.51
Velocity of flow through space between plates	W [m/s]	1.8×10^{-3}	1.82×10^{-3}	0.99
Area of velour filter	F_f [cm^2]	4272.6	126	33.9

Summing up one can conclude that the assumed model is a part of the prototype in which systems of geometrical similarity are contained and the following similarities maintained :

★ kinematic similarity

★ Archimedean Number :

$$Ar = \frac{d_o^3 g}{\eta_w^2} (\rho_o - \rho_w) \rho_w$$

★ Reynolds Number for a particle :

$$Re = \frac{W_o \cdot d_o \cdot \rho_o}{\eta_w}$$

where *the lower indices stand for : „o" - of oil, „w" - of water.*

A scheme of the test stand is presented in Fig. 4.

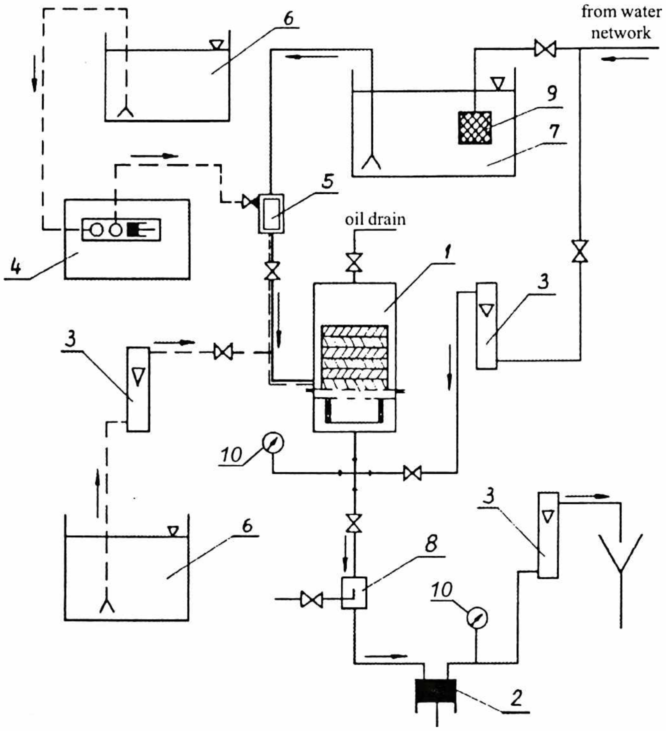

Fig.4. Scheme of the test stand :
1 – oil separator, 2- piston pump, 3- rotameter, 4- metering pump, 5- oil proportioner, 6- oil tank, 7- water tank, 8- sampling, 9- filter, 10 - manometr

Two kinds of oil (fuel oil) of the characteriscs given in Tab.2 were used for the tests.

Tab.2. Characteristics of the oils used for the tests

Properties	Oil kind	
	Light fuel oil	Heavy fuel oil
Density ρ [kg/m³] at t = 15°C	843	944
Density ρ [kg/m³] at t = 50°C	-	922
Kinematic viscosity [cSt]	4.23	280 (at 15°C)
H_2O content [%]	Trace amount	2.2

TEST RESULTS

The diagrams of oil concentration at outlet from versus that at inlet to the separator, $C_k = f(C_p)$ and diagrams of oil concentration at inlet versus mixture flow rate, $C_k = f(Q)$ elaborated on the basis of the performed measurements, are presented in Fig.5 to10. The relationships were obtained by changing the following design parameters of the model oil separator :

- number of plate layers i = 7, 5, 3
- plate spacing within layer s = 4, 6, 8 mm
- plate bend angle α = 20°, 45°

as well as the following physical - mechanical parameter values :

- flow rate Q = 30, 50, 80, 120 and 150 dm³/h
- oil concentration at inlet C_p = 0.1, 0.5, 5, 10, and 25%
- temperature of water t = 15 ÷ 20°C
- kind of oil : light and heavy fuel oil.

Oil separating process was observed parallely to the performed parameter measurements, in particular - drop coalescence on the plates and velour filter.

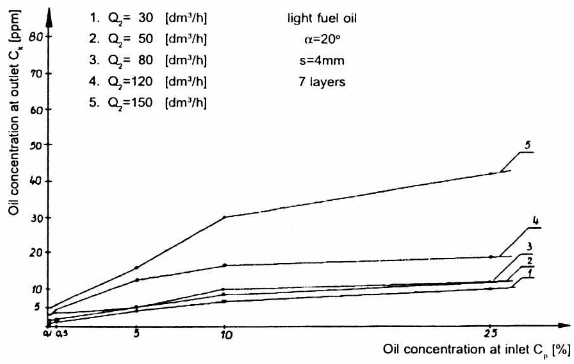

Fig.5. The diagram $C_k = f(C_p)$ for constant flow rate Q

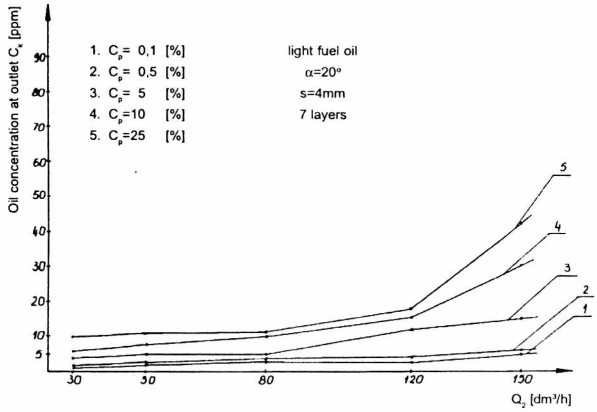

Fig.6. The diagram $C_k = f(Q)$ for constant oil concentration at inlet C_p

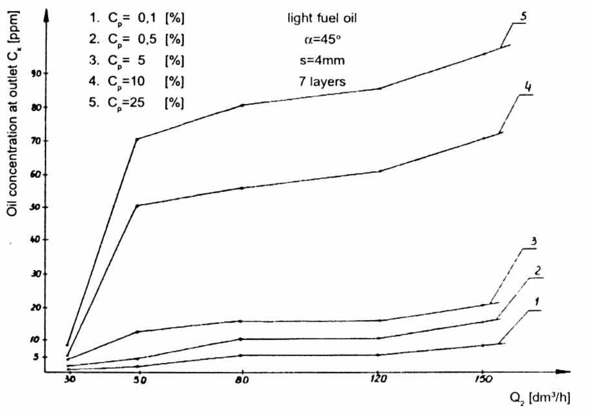

Fig.7. The diagram $C_k = f(Q)$ for constant oil concentration at inlet C_p

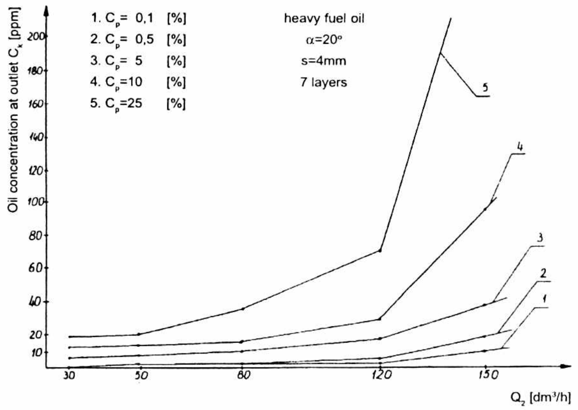

Fig.8. The diagram $C_k = f(Q)$ for constant oil concentration at inlet C_p

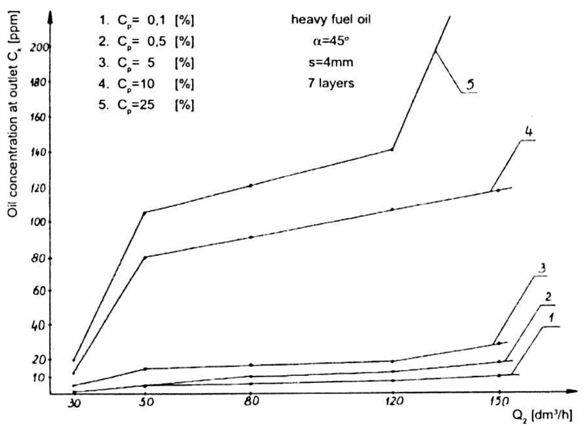

Fig.9. The diagram $C_k = f(Q)$ for constant oil concentration at inlet C_p

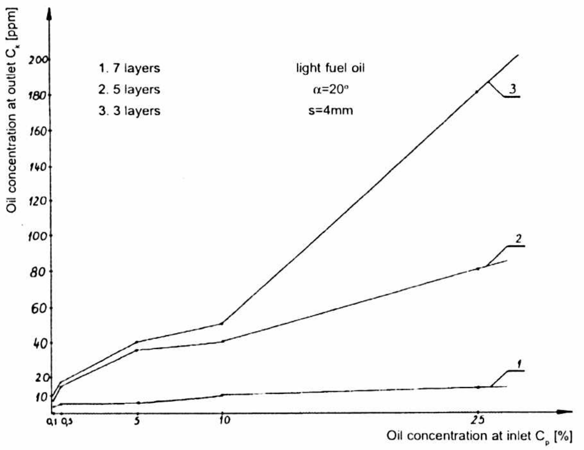

Fig.10. The diagram $C_k = f(C_p)$ for constant flow rate $Q_2 = 80$ dm³/h

ASSESSMENT OF TEST RESULTS

It is possible to determine optimum design parameters of the oil separator by using the diagrams which present the relationships $C_k = f(C_p)$ and $C_k = f(Q)$ at light fuel oil proportioning, when taking into account oil concentration behind the separator. It results from Fig.6 that the measured light fuel oil concentration at outlet amounted less than 15 ppm at Q value lower than 100 dm³/h, at s = 4 mm and $\alpha = 20°$, when dosing $C_p = 25\%$ of oil to the system. However the heavy fuel oil concentration at outlet $C_k = 20$ ppm was obtained at Q value lower than 50 dm³/h (Fig.8).

The diagram $C_k = f(Q)$ at light oil proportioning and the plate bend angle $\alpha = 45°$, is presented in Fig.7. The oil concentration at outlet clearly grows, when dosing $C_p = 10$ and 25% of oil, up to 50 ppm and 70 ppm respectively, at Q = 50 dm³/h. Similarly, respectively higher oil contamination levels were achieved at dosing the heavy fuel oil (Fig.9).

It can be stated, when assessing the influence of plate bend angle, that the oil concentration at separator outlet was the lowest for the plate bend angle $\alpha = 20°$ and dosing either light (Fig.6) or heavy (Fig.8) fuel oil. It was observed from monitoring the oil particle flow through the separator that the particles greater than 0.5 mm were displaced due to buoyancy and separated out gravitationally in result of circulation of liquid in the separator - statical inflow to the space around the cylinder. However the smaller particles, swept away by the stream, flew into the cylinder interior where the plate layers were installed. Separation of the coagulated oil on the bottom surface of the plates was observed practically after 1.5 to 2 h of operation of the separator (depending on an applied oil dose).

The phenomenon can be explained as follows : a local pressure drop on the plate surface appears in the flow due to bend of the plate, the greater the plate bend angle the greater drop. It results in local drag and disturbance of flow within the boundary layer on the plate surface.

The obtained measurement results of oil concentration behind the separator demonstrate that the disturbance of flow between the plates of 45° bend angle diminishes oil separation intensity on the surface of plates.

It results from the relationships $C_k = f(C_p)$ presented in Fig.10 that increasing the number of plate layers leads to lowering the oil concentration at outlet from the separator.

The velour filter applied in the separator favourably influenced the rate of stopping the coagulated oil. During operation the filter became saturated with oil practically on its entire surface. A more intensive oiling up of the filter happened at heavy oil dosing. Rinsing the separator resulted in separation of the stopped oil from the surfaces of the filter and plates. On completion of the test series at 20° bend angle of plates the velour filter was renewed. Post testing examination of the velour revealed that it was oil-clogged and the oil parted out from its surface by washing it with warm water.

CONCLUSIONS

The investigations of oil separating effectiveness carried out with the use of the model oil separator make it possible to state that the lowest oil concentration level behind the separator was achieved at the following design parameter values :

- number of layers : 7
- plate bend angle : 20°
- plate spacing within layer : 4 mm

Comparable results of oil concentration behind the separator were obtained for both light and heavy fuel oil at the flow rate Q = 30, 50, 80 dm³/h. The following can be concluded on the basis of the performed observations :

- It is possible to lengthen the oil particle trajectory (increasing the time spent by the oil particle in the separator) by applying the flow directing elements in the form of cylinders and plates.
- Application of the knitwear velour filter improves escapement of the emulgated oil particles provided that its whiskers are directed against the flow.
- Shortening the plate spacing within the layer improves the oil separating effectiveness.

NOMENCLATURE

d	-	oil particle diameter
D_C	-	internal diameter of cylinder with plates
D_{C1}, D_{C2}	-	internal diameter of cylinder with plates of NEPTUN and model separator, respectively
g	-	gravity acceleration
P	-	cross-section area of cylinder with plates $\left(P = \frac{\pi D_C^2}{4}\right)$
P_1, P_2	-	cross-section area of cylinder with plates of NEPTUN and model separator, respectively
Q_1, Q_2	-	flow rate in NEPTUN and model separator, respectively
s	-	plate spacing within layer
V_1, V_2	-	NEPTUN and model separator volume, respectively
W	-	velocity of flow through space between plates
W_1, W_2	-	velocity of flow through space between plates in NEPTUN and model separator, respectively
α	-	plate bend angle
η	-	dynamic viscosity
ρ	-	density
τ_1, τ_2	-	flow time of a particle through NEPTUN and model separator, respectively

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