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Wind-driven waves
Threshold velocity
Wave absorption
Oil pollution

Interrelationship between the process of surface wave generation caused by an air stream and wave attenuation process on water covered with a monolayer of crude oil derivative*

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Abstract

Viscoelastic properties of oil monolayers, determined on the basis of acoustic investigations, made it possible to define the conditions of loss of surface flow stability of a liquid, caused by an air stream. The values of monolayers surface concentrations for which a stabilization maximum occurs, have been determined. The values of these concentrations approach those, at which the maximum attenuation of a surface capillary layer is observed. The presence of a crude oil derivative on the water surface (in the form of a monolayer) results in the increase of the threshold stream velocity, capable of wave generation, by a factor of 5–18, depending on the surface concentration of the monolayer.

1. Introduction

Investigation of the stability of a moving liquid surface (for one velocity component different from zero) by means of an analytic model is connected with the names of Orr and Sommerfeld, remaining at the border line of turbulent flow theory [11]. It consists in the imposition of slight periodic disturbances on the known solutions of flow equations (exact or approximate). The form of the disturbances is assumed by relating it to the boundary conditions of flow. For the amplitude of these disturbances, approximate equations, differentially normal (usually linearized) are obtained; their solutions have the form of exponential functions. A range is being sought for the quantities dependent on the flow, in which the real part of the exponent in a function describing the relationship between the disturbance and time is positive. From this, a range of laminar flows, usually defined by the Reynolds'

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number, and a range of introduced disturbance frequencies, for which the flow ceases to be stable, are found. For different types of flow, we obtain areas of stability and areas of instability on a diagram, in which on one axis we mark the Strouhal's number [11] ($S_t = U_\infty T/L$; U_∞ = liquid velocity in undisturbed flow, T = characteristic time, L = characteristic linear dimension), and on the other—the Reynolds' number and other related quantities which describe the flow. A change in the character of flow from laminar to turbulent corresponds to a certain critical Reynolds' number (which corresponds to a minimum of function $S_t = S_t(R)$).

Theoretical investigations of the problem of generation of wind-driven waves on a surface of liquid were carried out by Hanratty and Engen [8], Cohen and Hanratty [3], and Craik [5]; they were experimentally verified by van Rossum [20]. Craik observed two kinds of instability closely related to the thickness of the liquid layer. From the point of view of practical applications, the most interesting is the instability of thick liquid layers. It is determined by the action of the normal component of surface stresses being in phase with the steepness of the wave.

The considerations presented further on in this paper, dealing with the loss of flow stability, are analysed by a method similar to that of Cohen and Hanratty [3] and are based on the work of Craik [5]. As a result of adsorption, surface-active agents form on the surface of a liquid a monolayer with certain viscoelastic properties. They may be expressed in the form of two parameters: the dilational surface elasticity modulus and expansion surface viscosity modulus [15].

Both parameters appear in boundary condition dilational for tangential and normal components of surfaces stresses in the theory of surface capillary waves propagation. Since surface stresses determine the conditions of the stability loss, the type and amount of the surface-active agent used are directly connected with the process of wind undulation formation, and especially with the threshold velocity of the air stream capable of generating waves.

Stability equations derived by Craik were supplemented by the values ε_d and η_d, obtained by separate measurements of properties of monolayers formed on the water surface by crude oil. The measurements were performed for five fractions of crude oil: ethyl gasoline 78, kerosene, Diesel oil, Extra 15 engine oil, and Marinoll 111 gear oil. The presence of a surface-active agent in the form of a monolayer results in an increase of attenuation of a surface capillary wave. The attenuation reaches its maximum for relatively low values of surface concentrations (mass/surface) [7, 14]. In the case of monolayers of crude oil derivatives, it is also present [17–19]. A comparison of the relationship between the surface capillary wave attenuation coefficient and surface concentration of the monolayer of crude oil derivative with the threshold velocity of the air stream capable of generating a surface wave at the same value of concentration enables an assertior concerning close correspondence between the processes of flow stability loss and surface wave attenuation. A maximum of surface stabilization corresponds—with a good approximation—to a maximum of wave attenuation. Craik's suggestion [5] concerning an interdependence between both processes is confirmed by a moderate agreement between theoretical predictions and experimental data.

2. Generation of waves caused by an air flow on a surface with various viscoelastic properties

The above situation is presented in Figure 1. A layer of liquid with thickness h covering an immovable bed is subjected to an air flow. We assume that the motion of the liquid is laminar, and its reaction to small turbulent fluctuations in the air

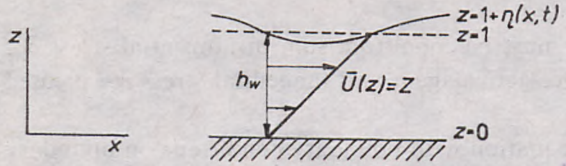

Fig. 1. Generation process of wind-generated waves

flow is considered small. If the depth of the air phase is large, compared to the layer thickness, the velocity profile inside the liquid changes linearly with depth [4]. All parameters introduced further on are dimensionless with respect to the liquid layer thickness h, liquid surface velocity V_c (velocity of airdrift caused by an air stream) and liquid density ρ.

We define the Reynolds' number for the liquid surface as follows [5]:

$$R = V_c h / \nu, \tag{1}$$

where v is the kinematic viscosity of liquid.

The displacement of the liquid surface perpendicularly to the direction of propagation has the following form [5]:

$$z(x, t) = A\, e^{i\alpha(x-ct)} \tag{2}$$

where:

α – dimensionless angular wave number (we assume it is a real value),

C – dimensionless surface wave phase velocity, generally consisting of a real part c_r and conjugate part c_i,

A – dimensionless surface wave amplitude.

The air stream creates on the liquid surface tangential σ_{xz} and normal σ_{zz} tensions, represented by parameters Σ and Π, respectively [4]. They are conjugated, and the r and i notation will be used to determine their real and imaginary parts, respectively.

The liquid surface in an undeformed state is under the influence of a uniform tension equal to mean surface tension γ. The value of its dimensionless form is [5]:

$$T_0 = \gamma(\rho V_c^2 h)^{-1}. \tag{3}$$

After deformation, the difference between stresses across the surface is proportional to the curvature of the surface according to Laplace equation [1]. [11]

Tangential stress $\bar{\sigma}_{xz}$ resulting from the deformation of a surface with certain viscoelastic properties characterized by a pair of quantities (ε_d and η_d) [15] can be presented [2] in the form:

$$\sigma_{xz} = -[T_1 + i\alpha(1-c)K_d]\alpha^2 \hat{x}z(x, t), \tag{4}$$

where: $T_1 = \varepsilon_d(\rho V_c^2 h)^{-1}$; $K_d = \eta_d(\rho V_c^2 h^2)^{-1}$.
Parameters ε_d and η_d determine respectively the dilational surface elasticity modulus and dilational surface viscosity modulus of the monolayer and are closely associated with the structure and type of surface-active crude oil derivative adsorbed on the liquid surface.

Tangential stress on the surface must be equal to a sum of tangential stress $\bar{\sigma}_{xz}$ caused by the presence of the surface-active agent and tangential stress σ_{xz} created as a result of air flow.

Comparing the fluid movement equation with boundary conditions on boundary surfaces and supplementing them with conditions for surface stresses we obtain the problem of stability of surface layer flow limited for the Orr-Sommerfeld equation of the fourth order (expression (2.5) in [5]). As a result we obtain relations between c and α in the form of terms containing parameters, which characterize the following system:

(i) R and G, where $G = ghV_c^{-2}$(g – acceleration due to gravity)-determining the properties of liquid.

(ii) Π and Σ – determining the intensity and character of air flow.

(iii) T_0, T_1, K_d – resulting solely from the nature of the surface and its viscoelastic properties.

If we assume that the values of T_1 and K_d are equal to zero, we will have a situation, when the liquid surface is free from any surface-active agents.

Four independent linear solutions of the stability equation were found by Miles [16] and Lin [11]. By introducing them into equation (4), we obtain the following expression [5]:

$$\begin{aligned}(\alpha^{-1}Rc_j+2)[2\alpha\coth\alpha(c_r-1)+1] - \left(\frac{s}{c_f}-2\right) + \left(\frac{\alpha R}{2c_r}\right)^{1/2} \operatorname{cosech}^2\alpha(c_r-1)^2 \\ + o\{c_j(\alpha R)^{1/2}, c_j RT_1, \Omega, \Xi, \operatorname{cosech}^2\alpha\} = \\ = q_r\alpha^{-2}(c_r-1)^{-2}|1-Y|^{-2}\{R[(1-Y_r)\Sigma_r - Y_j\Sigma_j] - (2\alpha R|c_r-1|)^{1/2} \\ \times[\alpha\coth\alpha(c_r-1)+1][\Omega^2+\Xi+\Xi^2]\}\end{aligned} \tag{5}$$

where dimensionless viscosity and elasticity parameters Ω and Ξ were introduced [5]:

$$\Omega = \left(\frac{\alpha R}{2|1-c_r|}\right)^{1/2} \frac{T_1}{|1-c_r|}; \quad \Xi = \left(\frac{\alpha R}{2|1-c_r|}\right)^{1/2} \alpha K_d, \tag{6}$$

$$Y_r = \Omega - \Xi; \quad Y_j = \frac{1-c_r}{|1-c_r|}(\Omega + \Xi), \tag{7}$$

$$|1-Y|^2 = 1 + 2(\Xi - \Omega) + 2(\Omega^2 + \Xi^2). \tag{8}$$

Stability curves $R=R(\alpha)$ can be obtained from equation (5) when we assume that $c_i=$ $=0$ and neglect terms containing Σ_r and Σ_i together with other small terms.

Viscoelastic properties of the liquid surface can be characterized by the value of the following expression [5]:

$$j=\frac{2(\Omega^2+\Xi+\Xi^2)}{|1-Y|^2}. \tag{9}$$

The surface of clean liquid ($\varepsilon_d=\eta_d=0$) corresponds to the value of $j=0$, $j=1$ characterizes a surface seriously contaminated with surface-active agents (with $\Omega\gg1$ or $\Xi\gg1$), and $j=2$ corresponds to a maximum of stabilization (with $\Omega=1$ and $\Xi=0$).

3. Results and discussion

Each monolayer of a surface-active agent has certain viscoelastic properties characterized by means of parameters ε_d and η_d. They were determined for five crude oil derivatives: ethyl gasoline 78, kerosene, Diesel oil, Extra 15 oil, and Marinoll 111 oil. Their values were determined for a full range of surface concentrations Γ (mass/surface). Parameter $\varepsilon_d=-d\gamma/d\ln\Gamma$ was determined on the basis of dependence $\gamma(\Gamma)$ obtained by Wilhelmy plate method [1, 10]. In order to form a monolayer, the oil derivative was dissolved in ethyl ether and a required amount of this solution was introduced onto the surface of distilled water. Surface viscosity (η_d as a function of Γ) of all tested substances was determined by means of a torsion pendulum according to the method suggested by Fourt [9]. The values of ε_d and η_d may be expressed in a dimensionless form T_1 and K_d according to the relationship (4). We then derive new parameters of surface elasticity Ω and surface viscosity Ξ (6) and (7), occurring directly in the flow stability equation (5). As a result we connect the problem of the flow stability loss with measurable quantities determining the degree and type of crude oil pollutants in the form of a monolayer. Equation (5) can be written in the form of an implicit function of two variables α and $R(\alpha)$:

$$f(\alpha, R(\alpha))=0. \tag{10}$$

Finding a minimum we obtain values α_{min} and R_{min} corresponding to the point of flow stability loss and the origin of capillary wave generation on the surface. Value R is associated with constant shear stress τ_0 caused on the surface by an air stream and with an air velocity [5]:

$$\tau_0=R\rho v^2h^{-2}=\rho_a c_f U^2, \tag{11}$$

where: $\rho_a=$ air density, $c_f=$ friction coefficient of the air stream.
Assuming that $\Omega=\Xi=0$, we obtain in a similar way values α_{min}, R_{min} and U_0 from equation (5) for an unpolluted surface.

The values of parameters Ω and Ξ depend on the assumed conditions of wave formation, kind of liquid, its depth, and the length of the surface wave. Figures 2 and 3 present parameters Ω and Ξ as a function of surface concentrations for the following assumed values of parameters: $\alpha=4.3$; $C_r=2.16$; $h=0.01$ m, $R=1095$. The values assumed for ρ and ν correspond to clean distilled water. Figure 2 presents

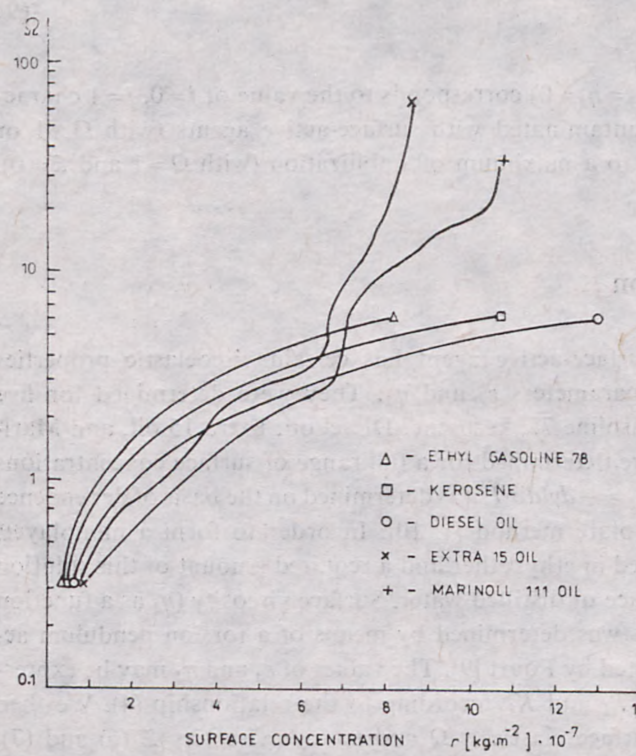

Fig. 2. Dependence of surface elasticity on surface concentration Γ

the dependence $\Omega(\Gamma)$. In the state of maximum monolayer compression (limiting values of Γ), the parameter assumes the values of the order of 10 for ethyl gasoline 78, kerosene, and Diesel oil, while for Marinoll 111 and Extra 15 oils—the values of the order of 100. These values are much larger than one, which is characteristic of strongly polluted surfaces. Figure 3 presents the dependence $\Xi(\Gamma)$; the values assumed by this parameter are lower by several orders of magnitude than the values of parameter Ω, which indicates the insignificant role of surface viscosity η_d in the flow stabilization process. The stabilizing properties of a surface with viscoelastic properties can be expressed by means of parameter j (9)—containing both parameters presented above, Ω and Ξ—on a conventional scale from 0 to 2.

The relationship $j(\Gamma)$ (Fig. 4) reaches its maximum in case of all derivatives for relatively low surface concentrations. The value is close to $j=2$, which corresponds to a maximum stabilization (in which case $\Omega=1$ and $\Xi\simeq0$), which—in turn—is in

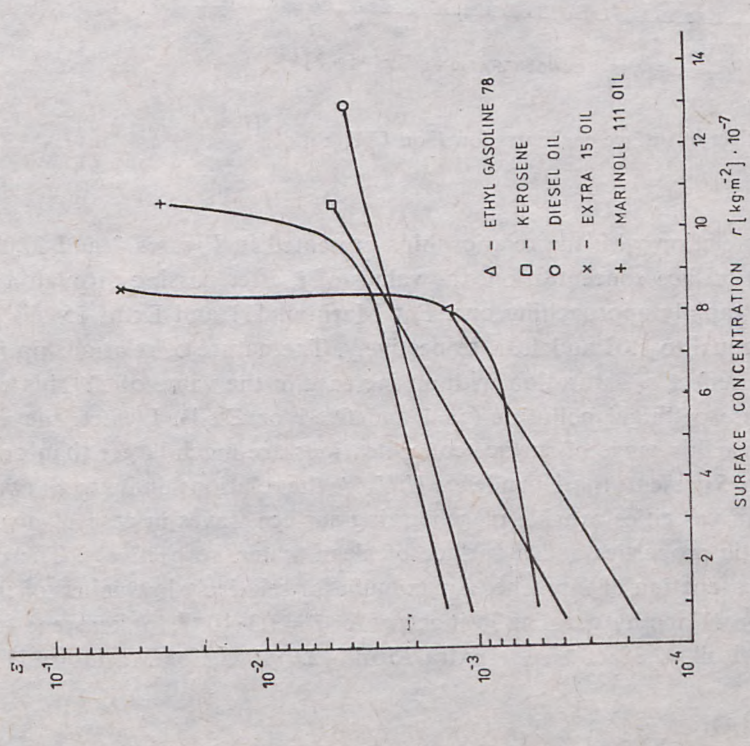

Fig. 3. Dependence of surface viscosity on surface concentration Γ

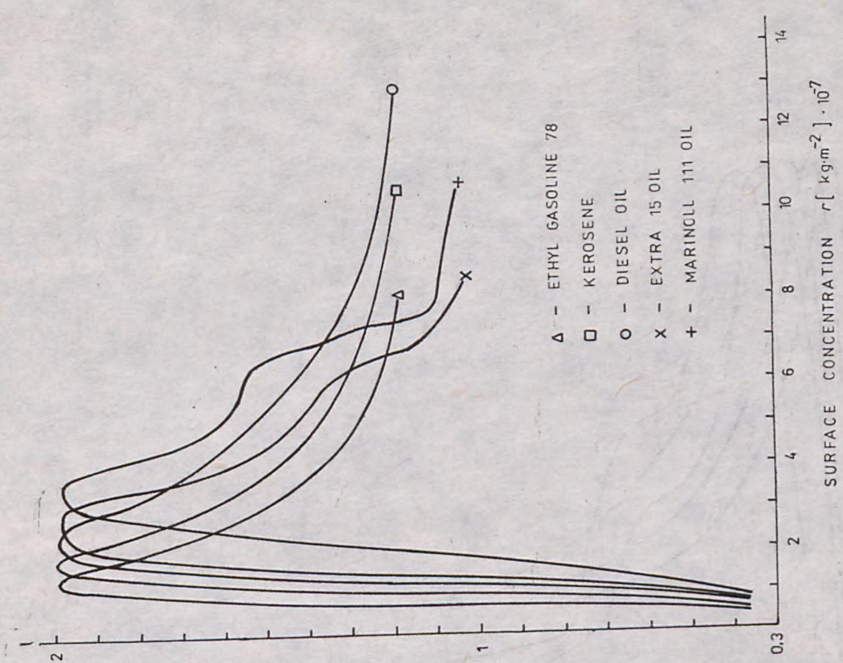

Fig. 4. Dependence of j (9) on surface concentration Γ

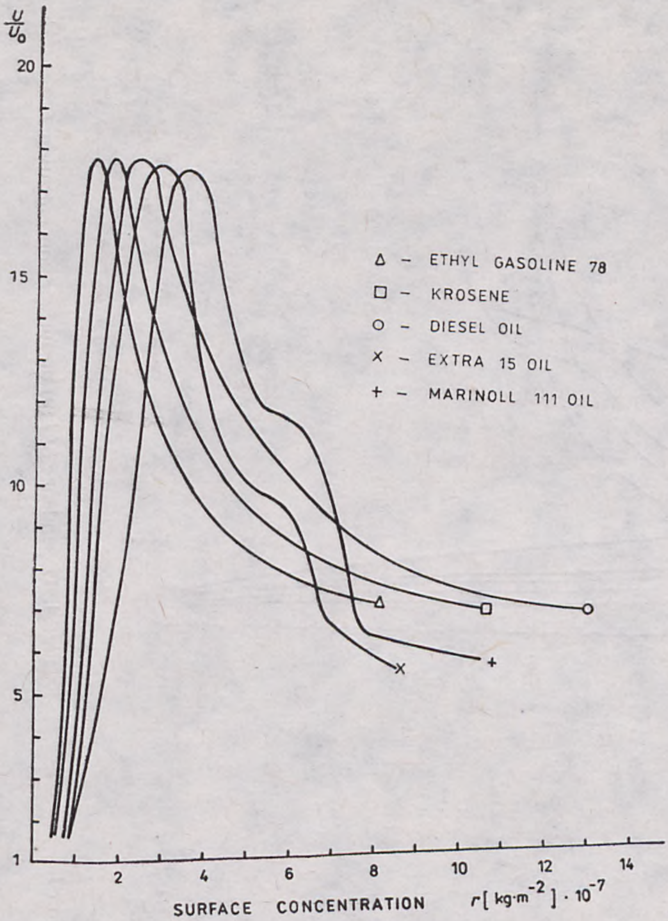

Fig. 5. Effect of surface concentration Γ on U/U_0 ratio

good correlation with the relationships presented in Figures 2 and 3. With an increase in surface concentration, the values of j, after passing through a maximum, decrease rapidly approaching one. For Marinoll 111 and Extra 15 oils, the values of j are equal to 1.03 and 1.01, respectively. The nature of relationship $j(\Gamma)$ reveals a marked effect of saturation with an increase in the value of Γ. This corresponds to the case of 'high' pollution ($j=1$ and $\Omega \gg 1$ or $\Xi \gg 1$). In fact, the values of Ω (Fig. 2) for this range of surface concentrations are much larger than one.

Figure 5 presents the dependence U/U_0, *ie* the relationship between two threshold air stream velocities capable of generating surface waves in case of a surface with viscoelastic properties and a surface of clean water, respectively. The dependence U/U_0 as a function of Γ reaches a maximum for relatively low values of surface concentrations. For ethyl gasoline 78, it occurs for $\Gamma = 1.3 \cdot 10^{-7}$, for kerosene $- 1.75 \cdot 10^{-7}$, for Diesel oil $- 2.32 \cdot 10^{-7}$, for Extra 15 oil $- 2.9 \cdot 10^{-7}$, for Marinoll 111 oil $- 3.55 \cdot$

$\cdot 10^{-7}$ [kg $\cdot$ m^{-2}]. Beyond the maximum, the threshold velocity is increased for the highest surface concentrations by a factor from the interval 5.8–7.3 for the investigated crude oil derivatives.

Attenuation of a surface capillary wave with a frequency $f = 30$ Hz was investigated experimentally on water covered with a monolayer of crude oil derivative.

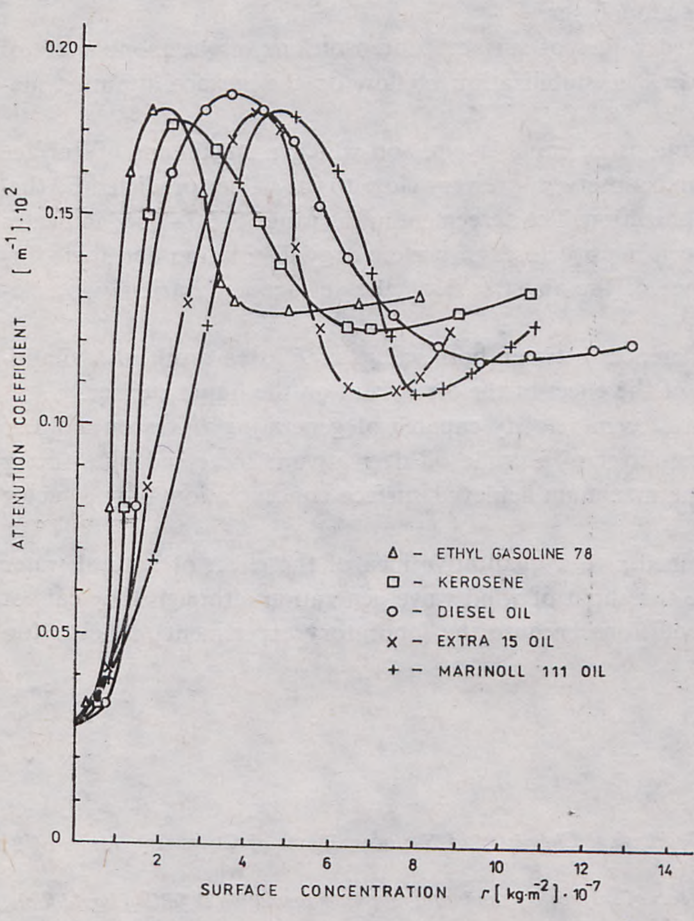

Fig. 6. Dependence of capillary wave attenuation coefficient on the type and concentration of surface pollutant in water

Measurements were carried out for five different fractions of crude oil mentioned above. The attenuation coefficient α_1 of a surface capillary wave as a function of surface concentration of the monolayer, presented in Figure 6, was determined by the acoustic pulse method [12, 13]. In the case of all the investigated substances, the dependence reaches a maximum for relatively small values of surface concentrations. These concentrations are as follows: for ethyl gasoline 78 – $1.90 \cdot 10^{-7}$, for kerosene – $2.31 \cdot 10^{-7}$, for Diesel oil – $3.52 \cdot 10^{-7}$, for Extra 15 oil – $4.12 \cdot 10^{-7}$, for Marinoll 111 oil – $4.73 \cdot 10^{-7}$ [kg$\cdot$m^{-2}].

4. Conclusions

(i) The stabilizing properties of a water surface covered with a monolayer of crude oil derivative and under the influence of an air stream depend on the type of derivative and surface concentration.

(ii) A decisive role in the stabilization process is being played by expansion surface elasticity ε_d of the monolayer.

(iii) For strictly defined values of surface concentrations of the monolayers of the investigated substances, the stabilization of flow on the surface attains a maximum value.

(iv) Surface concentrations of monolayers, for which a maximum of surface capillary wave attenuation is observed, are very close to the values predicted by theory for the maximum stabilization. The agreement in the range of $30-55\%$ indicates a close dependence between the processes of wave energy dissipation and their formation under the influence of the air stream on the surface and various viscoelastic properties.

(v) The observed differences between both values of Γ are a result of a simplified and idealized model of the effect of the air stream on the liquid surface.

(vi) The threshold air stream velocity capable of generating waves on a water surface covered by a monolayer of a crude oil derivative is increased by a factor of about 18, while for the maximum achieved surface concentrations—by a factor of 5–7.5.

(vii) The results obtained give a qualitative idea of the effect of natural water surface pollutants on the threshold of wind wave generation although they cannot be applied to natural conditions because the laboratory experiment model is too idealized.

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