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IMPROVEMENT OF LABOUR SAFETY AND SAFETY OF LIFE ACTIVITIES BY INCREASING THE EFFICIENCY OF WATER FIRE EXTINGUISHING SYSTEMS

Enhancing the level of occupational safety and safety of life activities for civil protection workers, such as firefighters and rescuers, is a priority task, especially during emergency response at industrial facilities. These specialists are frequently exposed to hazardous factors, notably high temperatures and intense thermal radiation. In this context, the search for ways to improve the efficiency of fire extinguishing systems is highly relevant. This work focuses on investigating opportunities to enhance water-based fire extinguishing systems through the application of polymer additives capable of reducing hydrodynamic drag, which, in turn, allows for an increase in the range and intensity of the fire extinguishing agent delivery.

During the research, the regularities of behavior and manifestations of elastic deformations in the flows of aqueous polymer solutions were studied. The experimental conditions were maximally approximated to the real conditions that occur in fire hoses during their operation on the territories of industrial enterprises. Analysis of the obtained data convincingly demonstrates that when developing and implementing technologies for reducing hydrodynamic drag by injecting polymer solutions into the boundary layer of the flow, it is necessary to consider the effects of elastic deformations of macromolecules. These deformations can significantly affect the final efficiency of the drag reduction process.

It was established that the observed decrease in the efficiency of fluid drag reduction when a polymer solution is supplied into the boundary layer of a fire hose is a complex result. It is caused by a combination of the deformational effect of the longitudinal hydrodynamic field, which is inevitably present in the polymer delivery system (pumps, injectors), and the specific molecular-concentration properties of the polymer solution itself (polymer type, its molecular weight, concentration). Uncontrolled deformations can lead to partial degradation of polymer chains or changes in their conformation, which negatively affects their ability to effectively suppress turbulent pulsations.

Understanding these processes is important not only for fire extinguishing systems but may also find application in other fields where high-velocity fluid jets with polymer additives are used, for example, in water-polymer perforation technologies, particularly in oil and gas wells.

Based on the conducted analysis, the paper outlines practical ways to increase the efficiency of systems for supplying polymer solutions into fire hoses. This includes recommendations regarding the design of injection units and the selection of optimal parameters for polymer solutions. The implementation of the proposed approaches will allow for an increase in the tactical and technical capabilities of water-based fire extinguishing systems, thereby improving the working conditions and safety of rescuers.

Key words: *occupational safety, water-polymer perforation, oil and gas wells, fire, polymer solution.*

Погребняк А. В., Перкун І. В., Погребняк В. Г., Шиманський В. Я. Підвищення рівня охорони праці та безпеки життєдіяльності шляхом удосконалення ефективності водяних систем пожежогасіння

Підвищення рівня охорони праці та безпеки життєдіяльності працівників цивільного захисту, таких як пожежники та рятувальники, є пріоритетним завданням, особливо при ліквідації надзвичайних ситуацій на промислових об'єктах. Ці фахівці часто піддаються впливу небезпечних факторів, зокрема високих температур та інтенсивного теплового випромінювання. У зв'язку з цим, актуальним є пошук шляхів підвищення ефективності систем пожежогасіння. Дана робота зосереджена на дослідженні можливостей удосконалення водяних систем пожежогасіння шляхом застосування полімерних добавок, здатних знижувати гідродинамічний опір, що, в свою чергу, дозволяє збільшити дальність та інтенсивність подачі вогнегасної речовини.

У ході дослідження було вивчено закономірності поведінки та прояви пружних деформацій у потоках водних розчинів полімерів. Експериментальні умови були максимально наближені до реальних умов, що виникають у пожежних рукавах під час їх експлуатації на територіях промислових підприємств. Аналіз отриманих даних переконливо демонструє, що при розробці та впровадженні технологій зниження гідродинамічного опору шляхом інжекції полімерних розчинів у примежовий шар потоку необхідно враховувати ефекти пружних деформацій макромолекул. Ці деформації можуть суттєво впливати на кінцеву ефективність процесу зниження опору.

Було встановлено, що спостережуване зменшення ефективності зниження опору рідини при подачі полімерного розчину в примежовий шар пожежного рукава є комплексним результатом. Воно зумовлене поєднанням деформаційного впливу поздовжнього гідродинамічного поля, яке неминуче присутнє в системі подачі полімеру (інжектори), та специфічними молекулярно-концентраційними властивостями самого полімерного розчину (тип полімеру, його молекулярна маса, концентрація). Неконтрольовані деформації можуть призводити до часткової деградації полімерних ланцюгів або зміни їхньої конформації, що негативно позначається на їхній здатності ефективно гасити турбулентне тертя.

Розуміння цих процесів є важливим не тільки для систем пожежогасіння, але й може знайти застосування в інших галузях, де використовуються високошвидкісні струмені рідин з полімерними добавками, наприклад, у технологіях водополімерної перфорації, зокрема нафтогазових свердловин.

На основі проведеного аналізу в роботі окреслено практичні шляхи підвищення ефективності систем подачі полімерних розчинів у пожежні рукави. Це включає рекомендації щодо конструкції вузлів введення та вибору оптимальних параметрів полімерних розчинів. Реалізація запропонованих підходів дозволить підвищити тактико-технічні можливості водяних систем пожежогасіння, тим самим покращуючи умови праці та безпеку рятувальників.

Ключові слова: *охорона праці, водополімерна перфорація, нафтогазові свердловини, пожежа, розчин полімеру.*

Statement of the problem. Open fire is one of the dangerous factors, especially on the territories of industrial facilities. It is also considered to be quite an important environmental factor, which under certain circumstances leads not only to deterioration of working conditions of operational personnel at a particular facility, but also to severe environmental pollution. This is especially true of firefighters, rescuers and other civil protection workers who are subjected to harmful effects of high temperature, thermal radiation, as well as hazardous combustion products while eliminating emergency situations [1,2]. Improvement of working conditions during emergency rescue operations can be achieved by reducing their conduct time, as well as by increasing a distance between a rescuer and ignition point. This can be achieved by increasing the efficiency of water fire extinguishing systems. An increase of work efficiency of the fire extinguishing systems is one of important engineer- technological measures that allows to decrease the influence of the combustion products on a biosphere and to increase level of safety on the territories of industrial facilities. Reduction of hydrodynamic resistance of fire hoses and pipelines allows to improve the efficiency of water-based fire-suppression systems which are the most widespread and feasible methods of the fire-fighting on the territories of industrial facilities [1].

Among the well-known methods of the decrease in the hydrodynamic drag resistance through the artificial modification of the boundary layer of the fire hoses, the method of the introduction of the polymer solutions is almost unique, and certain practical results have been achieved in its development. The study has shown that the introduction of small amounts of polyethylene oxide (PEO) and polyacrylamide (PAA) into the fire-suppression liquids (water and water solutions of surfactants) make it possible to significantly (down to 80%) reduce the hydrodynamic drag resistance [1–6]. This reduction (when other parameters of the hydraulic system are unchanged) ensures that the capacity of the fire-fighting systems is 1.5–2 times higher, or the length of the fire hoses may be 3–5 times higher, or the pump power consumption may be decreased by 60–70%, or the diameter of the fire-suppression pipes may be decreased by 15–20%. Besides, it has been shown that the additions of the polymers to water or surfactant solutions considerably improve their fire-suppression properties [1,2].

This study relates to the hydrodynamics of the polymer solutions in the pipelines and problem of the improvement of the introduction devices. The hydrodynamics of polymer solutions at the polymer introduction into the boundary layer of the fire hoses has not been examined properly. It is assumed that in case of the flow of polymer solutions through the slots and other elements of the introduction systems, essential "anomalies", which could considerably affect the Toms effect, cannot be observed [1–5]. Such a conclusion is based on the analysis of the data obtained from the study of the shear laminar flows where the effects of elastic deformations are insignificant. In the introduction systems a complex flow is dominant and it consists of superposition of the shear and predominantly longitudinal (with stretching) flow. In case of such complex flows, the effects of elastic deformations become so significant that it may result in lessening the potential effect of the polymer additives, especially at high velocities of the flow of the fire-suppressing liquids.

Presentation of the main material. Water solutions of polyethylene oxide with the molecular masses 2 10^6 and 4 10^6 were investigated. The mass fraction of polymer was varied from 0 to 0.3%, temperature during experiments – 25°C. To achieve the required temperatures polymer solution, utilized customized termostatization [7,8]. The temperature stabilization was maintained at the specified level with precision up to ±0.1°C.

Solutions of fully dissolved polymer were prepared in dark vessel by dissolving the ethanol-polymer suspension in distilled water at room temperature during 2–3 days or by dilution of the previously prepared solutions of polymer (0.1%, 0.2% and 0.5%) during 7–8 days before the desired concentration. Since water solutions of PEO significantly change properties at the upon prolonged storage, conformities to law of their aging process in water were preliminary studied and stabilizers to exclude it were chosen. The addition of 0.05% by mass potassium iodide solution in the PEO and PAA, which almost completely eliminates the aging of these polymers in water during storage and does not effect on the hydrodynamic activity, are used as such stabilizer [8].

We used a special hydrodynamic bench that allows achieving the exhaust velocities of the water flow through its channel of up to 35 m/s; the channel's length was 8.5 m. Orifices for measuring the pressure and for the sensors of friction force were placed on the lower wall of the channel. The injection system consisted of a dosing unit, underslot chamber ensuring different conditions of the deformation of the polymer solution (by changing the entrance angle) at the entrance to the slot. The angle between the injected polymer stream and the wall did not vary. The following characteristics have been variable: the angle of the opening of the slot β (the angle of the entrance to the slot), concentration of the injected polymer solution, velocity of the injection, molecular mass, polymer brand, and velocity of the fire suppressing liquid (water).

The purpose of the article. The aim of this paper is to investigate methods for improving water-based fire extinguishing systems by utilizing polymer additives. This research specifically focuses on how these additives can reduce hydrodynamic drag in fire hoses, thereby increasing the projection range and intensity of the extinguishing agent. The study explores the behavior and manifestations of elastic deformations within aqueous polymer solution flows, under conditions closely simulating real-world scenarios in fire hoses at industrial facilities. A key objective is to understand how these elastic deformations impact the overall efficiency of the drag reduction process. Ultimately, this work seeks to provide insights that will contribute to enhancing the occupational safety of firefighters and rescuers during emergency operations.

Results and discussion. This paper regularities and manifestations of the elastic deformations of the polymer flow are investigated under conditions close to that of the real flows of the fire hoses in the territories of industrial facilities (at oilfield territories). The experiments described below were conducted in order to establish the conformities to law of manifestation of elastic deformations in the flow of polymer solutions under conditions typical for the internal problem in relation to the fire hoses and pipelines.

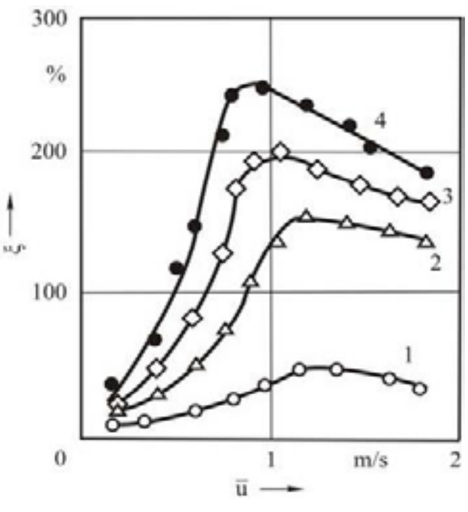

Fig. 1. Influence of u and angle of entrance into a slot on the relative pressure differential

Note: Mol. mass: 4·10⁶, C_{PEO}=0.1%; β°: 1 – 9°, 2 – 13°, 3 – 22°, 4 – 34°

In figure 1, the experimental data related to the flow of polyethylene oxide (PEO) water solutions through the underslot camera are shown. It is clear that the phenomena, unusual for purely viscous mediums, are inherent for such flows. At a certain critical (threshold) average exhaust velocity $\bar{u}$, the relative pressure differential ξ'

increases sharply, and it is sharper at the higher polymer concentrations. The characteristics of the dependence $\xi' = f(\bar{u})$ indicate the high dissipation of energy in the polymer solutions flow through the injector, i.e. the increased hydrodynamic drag resistance is served at the supercritical flow rates.

The presented experimental data corresponds to the results obtained from the study of the flow of the polymer solutions under the simulated conditions such as through short capillary tubes and slots. These flows were thoroughly investigated in paper [6]. There should be stressed the most important moments of the elastic stress effects in the polymer solution flows with stretching. Transition to a flow mode with increased energy dissipation is accompanied by formation of so called “inlet flooded jet” as a “cord” or “fillet” enclosed by secondary flows in the shape of ring- shaped vortex. In case of the supercritical flow mode for polymer concentrations ranged from very diluted to moderately concentrated, the hydrodynamic field causes rather strong deformation effects on molecular chains. The uncoiled part of a polymer chain may be as large as 60–70% [9]. In half-diluted and moderately concentrated polymer solutions, the relaxation times of the fully stretched and slightly deformed individual chains differ more than by 2 orders of magnitude. The reason for such a large time for the curling of the polymer chain is supermolecular structures formed in the hydrodynamic field. This is reflected in the decrease of turbulent friction if the lifetime of supermolecular formations in the polymer solution at the moment of its introduction to the boundary layer is comparable to the residence time in the fire hose at industrial territories.

The results of the polymer solution injection onto the lower wall of the channel through the underslot chambers with varying angles of the entrance to the slot shows (figure 2), that when the polymer solution is introduced onto the inner surface of the fire hose at low angles of the entrance to the slot, the drop in the tangent stresses of friction is exhibited practically right behind the point of the introduction of the polymer to the flow.

If the polymer solution is introduced into the boundary layer through the chamber with a large angle of the entrance, there is a delay in development of hydrodynamic activity of the polymer molecules.

It should be mentioned that the distribution of the tangent stresses and relative pressure losses along the channel correlate with each other. As it follows from the results shown in figure 2, the change of the mode of the polymer introduction through the under slot camera from weakly dissipative to strongly dissipative by modification of the entrance conditions results in double decrease in the drag resistance coefficient.

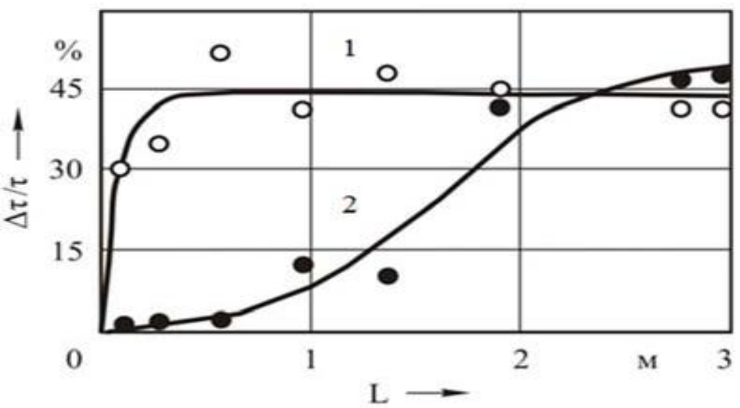

Fig. 2. Influence of the angle of the entrance to the slot on the distribution of the decrease in the tangent stresses along the lower wall of the channel for the injections of PEO solutions

Note: Mol. mass: $2 \cdot 10^6$, C_{PEO}= 0.3%, V_0 = 16.5 m/s, Q = 50 sm³/s; β°: 1 – 7.8°, 2 – 165°

There has been (figure 3) registered a considerably larger divergence in the plots of the drop of the resistance versus the changing concentrations of the polymer in case of the introduction of the polymer onto the inner surface of the fire hose under conditions of strong deformation effect of the hydrodynamic field on the injected solution, compared to the weak gradient effect.

The visualization of the flows of the polymer solution in the underslot chamber shows that the conditions of the entrance render influence on the drop of hydrodynamic resistance only when there is a loss of stability of the flow caused by the formation of the dynamic supermolecular structures which sharply increase the dissipatedness of the flow. The reduction of efficiency of the polymeric solution due to the deformation effects in the introduction system may be as large as 25% or higher at V_0>15 m/s. The increase in the rate of the water flow results in the expansion of the area with the reduced hydrodynamic activity of the polymer.

The significance of the area with the reduced hydrodynamic activity of the polymer introduced into the boundary layer is the more, the less is the length of the fire hose. It may be explained by the fact that the lifetime of the derivative structures under conditions of the flow with stretching is in the order of magnitude of 0.1–0.2 s or higher. This is the time during which the polymer after leaving the slot in the fire hose has reduced activity due to its memory. Obviously, the higher is the velocity of the water flow, the larger is the area behind the slot filled with the polymer solution under this condition, and its size is defined as:

$$l_{\lambda} = \theta_{sw} \cdot V_0 \qquad (1)$$

where θ_{sw} – time of structural relaxation of the supermolecular formations,

V_0 – velocity of the filling flow.

Hence, for the velocity of the water flow of 25 m/s, this area should extend downwards along the stream to 2.5m, if θ_{sw} = 0.1s. The estimated size of the area with the reduced hydrodynamic activity of the polymer is in good correlation with the experimentally obtained results.

Specific concentration was used to plot a chart (figure 3)

$$\gamma = Q \cdot \frac{C_{PEO}}{\Omega \cdot V_0} \qquad (2)$$

where Q –volume flow rate of the injected liquid,

C_{PEO} – concentration of the injected polymer solution (kg/m^3),

Ω – moistened surface,

V_0 – velocity of the filling flow.

The results of the experiments with the introduction of the polymer solutions of the various concentration through the underslot camera with the changing angle of the entrance (figure 3) show that for the given specific average concentration of the polymer in the boundary layer the efficiency of the reduction of drag resistance is decreased with the growth of the concentration of the injected polymer solution, and it is the stronger, if the angle of the entrance is higher.

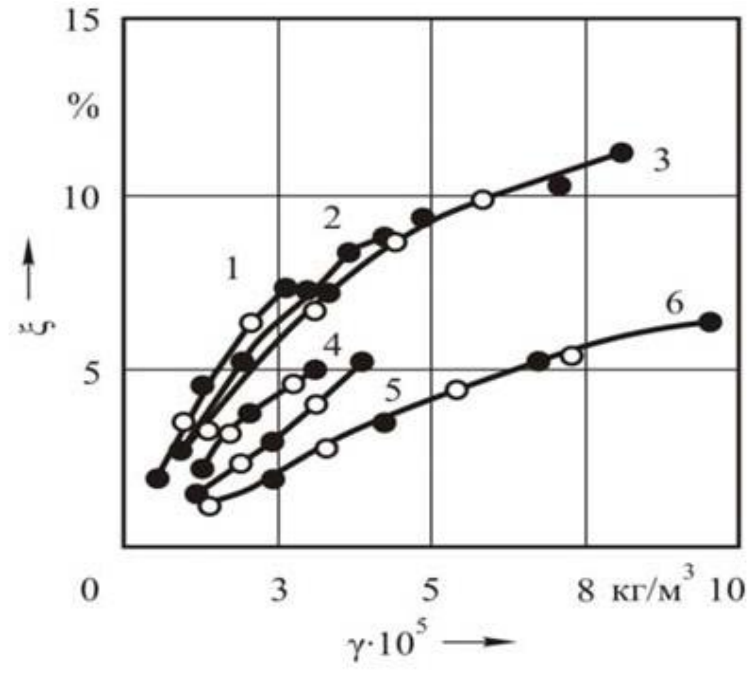

Fig. 3. Plot of the general pressure losses along the channel versus the specific concentration of PEO

Note: Mol. mass: 2·10^6, V_0: ● = 16.5 m/s, o = 25 m/s; β° = 7.8° (1, 2, 3), β° = 165° (4, 5, 6); C_{PEO}: 1 and 4 – 0.05%, 2 and 5 – 0.1%, 3 and 6 – 0.3%

In [10], it was outlined a hypothesis that viscoelastic effects (swelling of the jet) near the slot strengthen the pull of the polymer solution by the external boundary layer and result in a faster decrease in the concentration of the polymer on the inner surface of the pipeline. The results obtained in [11] make us reconsider this hypothesis because the visualization of the flow behind the slot and the actual concentration of the polymer in the boundary layer have not evidenced to the increased diffusion of the polymer. Most feasible is the explanation based on the impact of the effective viscosity (taken in its broad sense) that does not contradict to the results of the studies on the hydrodynamic activity of the polymers under conditions of the introduction of the polymer solution to the fire suppression pipeline.

The dynamic structures of the polymer formed in the hydrodynamic field cause its compression, and this, of course, should cause a decrease in the diffusion of the polymer in the boundary layer.

The detected regularities of the manifestation of elastic deformations at the introduction of the polymer solution to the fire-suppression pipeline allow suggesting a method for evaluation of the flow resistance of the fire suppressant liquid with the polymer additives in it. The flow resistance of the liquid in the pipeline at the introduction of the polymer solution to the boundary layer caused by the elastic deformations can be determined as:

$$X = \int_{0}^{\ell_\lambda} \chi(x)\tau_{wo} dx + \int_{\ell_\lambda}^{\ell_p - \ell_\lambda} \chi(x)\tau_{wc} dx, \qquad (3)$$

where χ is the perimeter of the pipeline cross-section,

τ_{wc} , τ_{wo} – tangential stresses with the introduction of the polymer to the boundary layer and without it,

ℓ_p – length of the pipeline,

ℓ_λ –length with the reduced hydrodynamic activity of the polymer.

The data obtained in this study shows that in solving the problems of drag reducing of the fire suppressing liquid in the fire hoses and pipeline by injecting the polymer solutions in the boundary layer, for the development of the optimum system of the introduction, it is necessary to take into account possible effects of the elastic deformations. The decrease in the effect of drag reduction at the introduction of the polymer solution into the boundary layer of the fire hose is due to the combination of the deformational effects of the longitudinal hydrodynamic field developed in the system of the injection and molecular-concentration characteristics of the polymeric solution.

Conclusions. This paper demonstrates the ways to improvement of labour safety and safety of life activities true of firefighters, rescuers and other civil protection workers who are subjected to harmful effects of high temperature, thermal radiation, as well as hazardous combustion products while eliminating emergency situations on the territories of industrial facilities by increasing the efficiency of water fire extinguishing systems.

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