

# Perforation of oil and gas wells by a high-velocity jet of polymer solution

## Perforacja odwiertów ropnych i gazowych za pomocą strumienia roztworu polimeru o dużej prędkości

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**ABSTRACT:** The work is devoted to the development of a technological process for perforating oil and gas well casing strings by a high-velocity jet of a polymer solution. The proposed method of well perforation refers to methods for the secondary opening of productive deposits in the well by hydrojet perforation of the casing strings, annulus cement ring (stone) and rock. The new knowledge about the dynamics of polymer solutions under the conditions of flow through the jet-forming nozzles of a hydroperforator, which create a high-velocity jet, became the main scientific basis for this method of hydroperforation of oil and gas well casings. The study of the reaction of polymer solutions to the hydrodynamic effect with stretching led to the formulation of a structural concept, the “common denominator” of which is a strong deformation effect of the hydrodynamic field on macromolecular coils, which in terms of nonequilibrium thermodynamics generates a kind of rubber-like high elasticity. The peculiarities of the hydrodynamic behaviour of aqueous solutions of polyethylene oxide (PEO) during flow under the conditions of various nozzle jets were modelled, and the regularities of the influence of the resulting dynamic structures on the efficiency of hydrojet water–polymer perforation were established. The mechanism of hydrojet water–polymer perforation of casing columns in oil and gas wells was clarified. The mechanism of the large destructive capacity of a high-velocity polymer solution jet is not due to the reduction of turbulent friction by small polymer additives (the Toms effect), but consists in the destructive action of the dynamic pressure of the water–polymer jet “reinforced” by highly developed macromolecular coils and the dynamic structures formed under the action of extended flow in the inlet section of the hydroperforator nozzles. The method of perforating oil and gas well casings comprises the exact determination of the perforation zone in lowering on production tubing a hydroperforator with 2–4 jet flow-forming nozzles for directing hydrojet to the zone of perforation, sealing the inside cavity of tubing pipes and the jet operators, actuating a ball valve at the bottom of the jet operators, sealing the annulus with a self-sealing gland and supplying the working cutting fluid to the tubing – which differs in that the aqueous solution of PEO used as a working cutting fluid has a molecular weight of  $6 \cdot 10^6$  and a concentration 0.003–0.007% by weight and a working pressure of 100–300 MPa. The PEO additives are very environmentally friendly because this polymer is not harmful to humans or the environment. Experimental and industrial testing of this method of well perforation, which was carried out during the secondary opening of a reservoir at a well in the Carpathian oil- and gas-bearing region, confirmed the practical and economic feasibility of its use.

**Key words:** hydroperforator, casing strings, polymer solution, supramolecular structures, nozzles, Toms effect.

**STRESZCZENIE:** Praca poświęcona jest opracowaniu procesu technologicznego perforacji kolumn rur okładzinowych odwiertów ropnych i gazowych za pomocą strumienia roztworu polimeru o dużej prędkości. Zaproponowana metoda perforacji odwiertów odnosi się do metod wtórnego udostępniania złóż produkcyjnych za pomocą hydroperforacji kolumny rur okładzinowych, płaszcz cementowego (kamień) i skały. Uzyskana nowa wiedza na temat dynamiki roztworów polimerów w warunkach przepływu przez dysze strumieniowe hydroperforatora, które tworzą strumień o dużej prędkości, stała się główną podstawą naukową dla tej metody hydroperforacji rur okładzinowych w odwiertach ropnych i gazowych. Badanie reakcji roztworów polimerów na efekt hydrodynamiczny z naprężeniem pozwoliło na sformułowanie koncepcji strukturalnej, której podstawą jest silny wpływ odkształcenia pola hydrodynamicznego na kulki wielkocząsteczkowe, co w warunkach termodynamicznej nierównowagi generuje swego rodzaju „podobną do gumy” wysoką elastyczność. Zbadano osobliwości hydrodynamicznego zachowania się wodnych roztworów tlenku polietylenu (PEO) w modelowych warunkach podczas przepływu przez różne dysze tworzące strumień oraz ustalono prawidłowości dotyczące wpływu utworzonych struktur dynamicznych na efektywność hydroperforacji strumieniem woda–polimer. Wyjaśniono mechanizm hydroperforacji kolumn rur okładzinowych strumieniem wodno-polimerowym w odwiertach ropnych i gazowych. Mechanizm dużej zdolności niszczącej strumienia roztworu polimeru o dużej prędkości nie wynika ze zmniejszenia oporów w warunkach przepływu turbulentnego przez małe dodatki polimeru (efekt Tomsa), ale polega na niszczącym działaniu ciśnienia dynamicznego strumienia woda–polimer „wzmocnionego” przez silnie rozwinięte wiązki makromolekularne i struktury dynamiczne powstające w wyniku działania wydłużonego przepływu w sekcji wlotowej dysz hydroperforatora. Metoda perforacji rur okładzinowych odwiertów ropnych i gazowych polega na dokładnym określeniu

strefy perforacji, opuszczaniu na rurach wydobywczych aparatu perforacyjnego z 2–4 dyszami formującymi strumień w celu skierowania przepływu w strefę perforacji i uszczelnieniu wnętrza rur wydobywczych. Następnie operatorzy perforatora uruchamiają zawór kulowy umieszczony w jego dolnej części, następuje uszczelnienie przestrzeni pierścieniowej samuszczelniającą dławnicą i doprowadzenie cieczy roboczej do rur. Jako płyn roboczy używany jest wodny roztwór tlenu polietylenu o masie cząsteczkowej  $6 \cdot 10^6$  i stężeniu 0,003–0,007% wag. i pod ciśnieniem roboczym 100–300 MPa. Dodatki PEO są bardzo przyjazne dla środowiska, ponieważ polimer ten nie jest szkodliwy dla ludzi ani środowiska. Doświadczalne i przemysłowe testy tej metody perforacji odwiertów, które przeprowadzono podczas wtórnego udostępnienia złoża ropno-gazowego w jednym z odwiertów rejonu karpackiego, potwierdziły zasadność jej wykorzystania pod względem praktycznym i ekonomicznym.

Słowa kluczowe: hydroperforator, kolumny rur okładzinowych, roztwór polimeru, struktury supramolekularne, dysze, efekt Tomsa.

## Introduction

The method of hydro-sandblasting perforation (HSP) of oil and gas well casing strings is a fairly effective (Chornyj et al., 2013), but this method has significant disadvantages: in the process of HSP, the inner surfaces of the tubing, fittings and equipment used in the water–abrasive perforation fluid are subject to strong hydro-abrasive wear; as a result of this hydroabrasion, the diameter and profile of the nozzle holes increases, forming a perforation jet, which in turn leads to a gradual decrease in its velocity and to weaker perforation and longer total execution time; due to the hydro-abrasive wear of the sandblasting machine nozzles, there is a need to periodically replace the nozzles, which causes additional costs for the nozzles, which are made by powder metallurgy of hard alloys, and due to an increase in the number of round-trip operations; there is intense wear on the pipes, meaning they need to be replaced; the abrasive sand particles penetrate deep into the rock in the channels which are formed, impairing the productivity of the formation. All this leads to more resources being necessary in the hydroperforation of oil and gas well casing strings.

The problem of developing a highly efficient, innovative method for hydroperforating oil and gas well casings can be approached by taking advantage of certain anomalies in the hydrodynamic behaviour of polymer solutions in longitudinal flow. That is, the cutting hydro-abrasive jet in the inlet section of the hydroperforator nozzles must be replaced by a polymer solution jet (Ivaniuta et al., 1985). The polymer must be a safe substance which is approved for use in the oil and gas industry. Such polymers include PEO, polyacrylamide (PAA) or hydrolysed polyacrylamide (HPAA). For example, PEO is a safe substance that is used as a flocculent to purify and disinfect drinking water, as a thickener in the food industry, in pharmaceuticals and more (Diment et al., 1976; Salyanov et al., 1978).

## Theoretical analysis

An analysis of the literature data shows that modern ideas about the behaviour of macromolecules under the conditions

of convergent flow – as in the entrance area of the jet-forming nozzle of a hydroperforator – are far from perfect. Currently, we are transitioning from an accumulation of experimental information to an understanding of its physicochemical essence and to establishing the basic patterns of its rubber-like, high-elasticity manifestation. New knowledge is needed to understand the rheophysics of several anomalies during the flow of polymer solutions through the nozzle of a hydroperforator, which would allow very efficient perforation of the casing strings of oil and gas wells with a high-velocity polymer solution to be developed.

Of particular scientific and practical interest is the study of transitions, which result in structures that are far from equilibrium. Non-equilibrium thermodynamics proves that non-equilibrium phase transitions are possible. These transitions have only been thoroughly studied in concentrated polymer solutions, while the dynamic phase transitions in dilute polymer solutions are only studied in a longitudinal field, which is created by the superposition of two coaxially located streams (Keller and Odell, 1985; Brestkin, 1987; Brestkin et al., 1989). It has long been suggested that such transitions are impossible under the conditions of convergent flow of dilute polymer solutions. It was previously proved that convergent flow is a superposition of currents under tension and shear forces (Pogrebnyak et al., 2017). This is primarily due to the interest in work on the dynamics of polymer chains in convergent flows, because a strong deformation effect on macromolecular balls must take place in the inlet of the nozzle of the hydroperforator (Pogrebnyak A.V. et al., 2021).

The most significant results in the study of the structural changes in polymer solutions under the action of a homogeneous longitudinal hydrodynamic field were obtained by Brestkin (1987). The main result of this work is the proof that in the conditions of a homogeneous longitudinal hydrodynamic field, dynamic phase transitions are possible. However, this finding refers to a homogeneous longitudinal field and not to convergent currents, which takes place in the inlet area of a drill nozzle. This indicates the relevance of research on the anomalous phenomenon of the high destructive capacity of a water–polymer jet. According to the results of the review of

convergent (Pogrebnyak et al., 2017) and turbulent flows of polymer solutions (Povkh et al., 1979) and the use of polymer additives in cutting materials ((Pogrebnyak and Naumchik, 1995; Kuzmin et al., 2002), it has been established that the process of perforating oil and gas well casing strings with a stream of polymer solution requires further study. It becomes obvious that the development of a highly efficient process for hydroperforating oil and gas well casing strings can be approached using features of the hydrodynamic behaviour of polymer solutions observed in a longitudinal flow, which occurs in the inlet section of hydroperforator nozzles.

The aim of the study is to develop an efficient, innovative method of perforating oil and gas well casing strings with a high-velocity stream of polymer solution that conserves resources and energy and meets the requirements for environmentally friendly hydrocarbon production.

### Experimental part

The perforation work was performed on laboratory stands. A laboratory hydraulic stand based on an URG-3020 unit – with an operating pressure of up to 500 MPa, had a jet diameter at the nozzle of 3 mm and a function for controlling both the integral and differential parameters of the process of material destruction by a water–polymer jet – was used as the source of high-speed fluid flow. A model was created for the obstacle (target) to test the effectiveness of perforation: a kind of “sandwich” which contained a 10-mm-thick sheet of steel – with a strength category of D according to GOST 632-80, which simulated a casing – a concrete layer, 20-mm-thick ring and a layer of rock (compressive strength: 600 kg/cm<sup>2</sup>) with a total thickness of 800 mm.

We also used an industrial water jet, which provided 450 MPa of pressure in the jet-forming nozzle, an average jet velocity of up to 350 m/s and had a jet diameter at the nozzle of 10 mm. A detailed description of the hydrodynamic part of the water jet, its characteristics and the methods for determining the average speed, momentum and energy of the jet can be found in Atanov (1987), (Pogrebnyak and Naumchuk, (1995) or Brenner et al. (2000). To qualitatively assess the energy capabilities of the jet in the experiments, we studied the interaction between the jet and the obstacle installed on a physical pendulum. The barrier was made of steel (category of S 3) sheets with dimensions of  $220 \cdot 220 \cdot 3 \cdot 10^{-3}$  m with mounting holes. There was a gap of  $5 \cdot 10^{-2}$  m between the plane of the obstacle and the body of the physical pendulum.

An optical–mechanical complex and a polarisation–optical installation (Azzam et al., 1981) were used to study the peculiarities of the flow of polymer solutions under model condi-

tions of jet-forming nozzles, as were the dynamics of polymer macromolecules in the inlet section of hydroperforator nozzles.

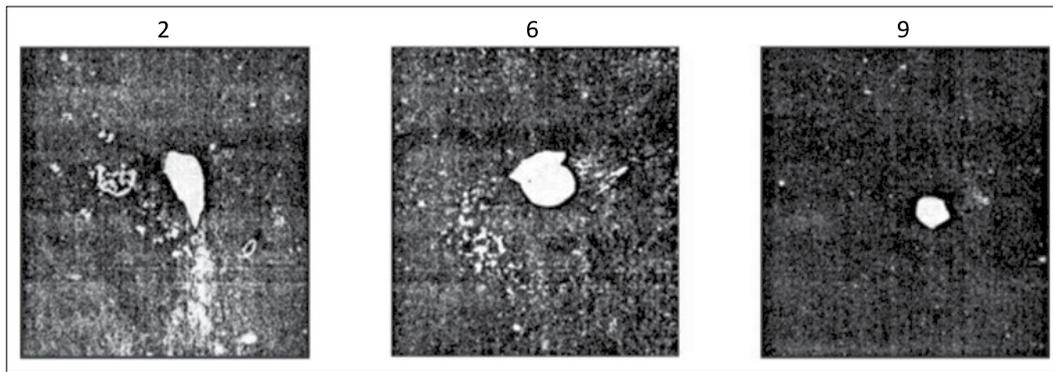
Solutions with a completely dissolved polymer were prepared by diluting to the desired concentration of a prepared 0.1% polymer solution. Because aqueous solutions of PEO (as well as other polymers) have significantly different properties during long-term storage, 0.05% potassium iodide is used as a stabilizer in aqueous solutions of PEO, which almost completely eliminates the ageing of PEO in water during storage and does not affect its hydrodynamic activity (Pogrebnyak et al., 2017). PEO solutions with intrinsic viscosities of 2.42 and 1.72 kg/m<sup>3</sup> and molecular weights of  $6 \cdot 10^6$  and  $4 \cdot 10^6$  were used.

The novelty in the design and components of this research is the comprehensive study of the reactions of polymer solutions to the hydrodynamic effect of tension, i.e. under the conditions of the jet-forming nozzle of a hydroperforator. Complexity is a necessary condition for solving not only fundamental scientific problems, but also technical ones (from basic research to a specific technological process).

### Results and discussion

Establishing the nature of the destructive capacity of a polymer solution jet is important for the development of an efficient, innovative method of perforating oil and gas well casings with a high-speed polymer solution jet. Contradictory opinions have been put forward about the mechanism of the destructive power of a high-velocity jet of a polymer solution. Some researchers believe that the increased destructive capacity of the water jet when small polymers are added is caused by the Toms effect during the flow of the working fluid through the nozzle that forms the jet (Kuzmin et al., 2002). Based on this, it is argued that the jet with polymer additives has a higher speed and dynamic pressure than a jet of pure water at the same operating pressure and nozzle diameter, and therefore destroys more of the material. In other words, it is assumed that associates of polymer molecules are formed in a water–polymer jet (without experimental proof) (Kudin, 1972). In Pogrebnyak (2008), the high destructive capacity of a high-velocity jet of a polymer solution is associated with the deformation effects that occur during the flow of aqueous solutions of polymers under tension. Therefore, we discuss the experiments that were set to clarify the peculiarities of a polymer solution jet’s destructive capacity, which is based on the idea that a strong deformation of the hydrodynamic field occurs on macromolecular bundles in the inlet of the nozzle.

This experiment was conducted using a hydraulic stand of industrial manufacture. The experimental data are presented in Figure 1 and Table 1. It can be seen that the maximum distance



**Figure 1.** Photos of the target obstacle after interaction with jets of water and an aqueous solution of PEO: 2 – water; 6 –  $M_{PEO} = 6 \cdot 10^6$ ;  $C_{PEO} = 0.0004\%$ ; 9 –  $M_{PEO} = 6 \cdot 10^6$ ;  $C_{PEO} = 0.0008\%$

**Rysunek 1.** Zdjęcia docelowej przeszkody po interakcji ze strumieniem wody i wodnego roztworu PEO: 2 – woda; 6 –  $M_{PEO} = 6 \cdot 10^6$ ,  $C_{PEO} = 0,0004\%$ ; 9 –  $M_{PEO} = 6 \cdot 10^6$ ,  $C_{PEO} = 0,0008\%$

from the jet-forming nozzle of the hydrostand to the target obstacle, when the target obstacle puncture is still observed, is 1.5 m for water and 2.5 m for a 0.0008% aqueous polymer solution; the effectiveness of PEO additives was observed in concentrations starting from 0.004%; and that PEO impurities reduced the average jet velocity.

**Table 1.** The effect of PEO concentration and distance from the nozzle to the target obstacle on the interaction with a jet of PEO solution

**Tabela 1.** Wpływ stężenia PEO w roztworze wodnym oraz odległości pomiędzy dyszą a docelową przeszkodą na charakter oddziaływania ze strumieniem roztworu PEO

$C_{PEO}$	Distance to the target	Average velocity of jet flow	Nature of target obstacle
[%]	[m]	[m/s]	
0	1.50	255	Diameter of a hole (15–18) · 10 <sup>-3</sup> m
0	1.75	250	No puncture
0	2.50	250	No puncture
0.0004	1.50	240	Diameter of a hole (15–18) · 10 <sup>-3</sup> m
0.0004	2.00	235	No puncture
0.0008	2.50	230	Diameter of a hole (8–10) · 10 <sup>-3</sup> m

The experimental data are fully explained by a strong deformation effect of the hydrodynamic field on molecular bundles of the polymer. In a previous study (Pogrebnyak et al., 2019), the transition of the bundle-expanded chain at a convergent flow (in the model conditions of the nozzle of the hydroperforator) of aqueous solutions of PEO was experimentally revealed. It is shown that the hydrodynamic field, which arises under conditions of convergent flow, leads to a significant degree of expansion of polymer molecules (60–70%) and to a bundle-to-chain transition.

The longitudinal velocity gradient, which occurs in the contraction cone nozzle of the hydrostand, can be calculated as not exceeding  $2 \cdot 10^3 \text{c}^{-1}$ . Therefore, despite the high speeds (250 m/s) and resulting large shear velocity gradients, the conditions of deformation of polymer macromolecules in the conical nozzle of the water jet and in the inlet section of the model nozzle are almost the same. This indicates that during the flow of an aqueous polymer solution in the nozzle of the water jet, the PEO macromolecules are subjected to strong deformation of the longitudinal hydrodynamic field. All this supports the claim that the high-velocity water–polymer jet is “reinforced” by highly developed macromolecular chains of the polymer, and – considering the results from Pogrebnyak et al. (1992) – then supramolecular structures. Part of the energy goes to the structural adjustment of the flow (Ivanyuta et al., 1985; Pogrebnyak et al., 2019), which lowers the average flow rate of the aqueous polymer solution and improves the quality of its formation, as a jet with small polymer additives is more compact (has a smaller diameter) than water (see Figure 1 and Table 1). This contributes to an increase in the maximum distance from which the destruction of the steel barrier/target can occur.

The data of the experiments which are presented in Table 1 convincingly testify that the high destructive capacity of a high-velocity water jet with small polymer additives is not due to the Toms effect. This is confirmed, first of all, by the 8–10% reduction in the average jet velocity of the aqueous PEO solution relative to the water jet’s velocity at the same operating pressure and nozzle diameter. Thus, despite the lower flow rate of the polymer solution, its destructive capacity was much higher than that of the water jet.

The conclusion that the large destructive capacity of the high-velocity water jet with dissolved small polymer impurities was not due to the Toms effect also follows from the analysis of turbulent fluid flow presented below. In the case of near-wall

turbulence, its structure should be affected by highly uncoiled macromolecular chains (Pogrebnyak et al., 1991; Kryvenko and Perkun, 2017). To do this, there must be certain conditions in the turbulent flow, namely, the longitudinal velocity gradients and the time of deformation in them must be greater than  $0.5/\theta_c$  and  $\theta_c$ , accordingly (where  $\theta_c$  is the relaxation time of the polymer solution). At some fairly high dynamic velocities, when the formation and destruction of tensile zones occur at a high frequency, as follows from the work by Cantwell (1981), increasing the strain rate should reduce the strain factor by decreasing the time of the longitudinal velocity gradient. This is due to small-scale turbulence, the percentage of which increases sharply at high velocities (Bredshou, 1974; Cantwell, 1981). Also, the degradation of polymer solutions significantly reduces the Toms effect at high velocities (Pogrebnyak et al., 2017). Therefore, in high-velocity turbulent flows, the hydrodynamic activity of PEO should decrease due to the discrepancy between the characteristic relaxation times of the aqueous PEO solution, the time scale of the flow (emissions) and the degradation of the PEO macromolecules.

To confirm the correctness of the above approach, it is necessary to conduct a detailed study of the polymer solution's flow through the nozzles of a hydroperforator. At the same time, there are obvious advantages of using currents in the model of nozzles forming a stream in order to research the macromolecules' interaction with a hydrodynamic field in connection with the possibility of studying experimentally the features of a polymer solution stream forming under controlled conditions.

Before proceeding to the discussion of the experimental data, let us consider the parameters that will characterise the dissipative processes in flow model systems of jet-forming nozzles. The energy dissipated per unit of time during the flow of a liquid is equal to

$$W = \Delta P \cdot q \quad (1)$$

where  $\Delta P$  is the pressure drop in the system or in its individual sections at a given flow rate  $q$ . This is the work that must be spent per unit of time to push the liquid through the jet-forming nozzle. Equation (1) is valid for any type of flow (shear, longitudinal or the superposition of one and the other – convergent) and any shape of jet-forming nozzle. Energy dissipation can be represented as

$$W = (\eta_{ef} \cdot q^2) / k_{fs} \quad (2)$$

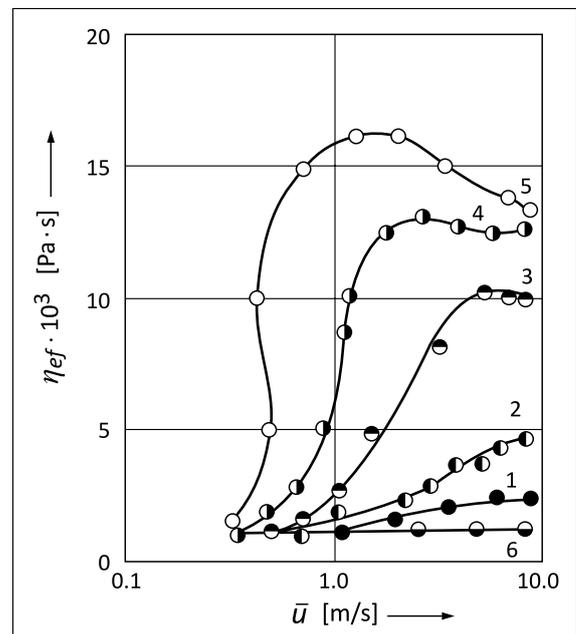
where  $k_{fs}$  is the constant of the flowing system and  $\eta_{ef}$  is the effective viscosity which characterises the resistance of the continuous environment to irreversible changes in form at various sites in a current and is calculated by expression

$$\eta_{ef} = k_{fs} \cdot (\Delta P / q) \quad (3)$$

The constant  $k_{fs}$  is determined experimentally by using Newtonian fluids with known viscosities.

From Equation (2) it follows that dissipation at a liquid stream can be characterised using effective viscosity. For a Newtonian fluid, it always coincides with the shear viscosity, whereas the effective viscosity of a non-Newtonian medium depends on the flow regimes and is an average characteristic. The latter is due to the fact that the viscosity of such a medium is different at points in space with different rates of deformation (Pogrebnyak V.G. et al., 2021).

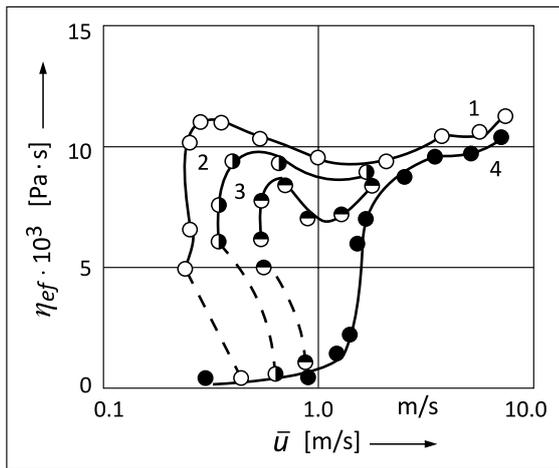
The data that characterise the influence of outflow velocity through a nozzle on effective the viscosity of PEO aqueous solutions of various concentrations for molecular weight  $6 \cdot 10^6$  are given in Figure 2.



**Figure 2.** Dependence of an aqueous PEO solution's effective viscosity on its average flow through a nozzle with a square inlet:  $d_{noz} = 0.12 \cdot 10^{-3} \text{m}$ ;  $M_{PEO} = 6 \cdot 10^6$ ;  $C_{PEO}$ : 1 – 0.0005%, 2 – 0.001%, 3 – 0.002%, 4 – 0.003%, 5 – 0.004%, 6 – water

**Rysunek 2.** Zależność efektywnej lepkości wodnego roztworu PEO od średniej prędkości przepływu przez dyszę o kwadratowym przekroju wlotowym:  $d_{noz} = 0.12 \cdot 10^{-3} \text{m}$ ;  $M_{PEO} = 6 \cdot 10^6$ ;  $C_{PEO}$ : 1 – 0,0005%, 2 – 0,001%, 3 – 0,002%, 4 – 0,003%, 5 – 0,004%, 6 – woda

The error of viscosity measurement did not exceed 2%. It is seen that at relatively low velocities, the solutions behave like Newtonian fluids and their viscosities are close to the viscosity of the solvent (water). At the critical threshold value,  $\bar{u} = u_{cr}$ , the viscosity of the solution begins to increase; the sharper the increase, the higher the concentration of the polymer. The absence of growth of effective water viscosity with growth suggests that the specified effect is not connected with inertial turbulence. The data describing the influence of the diameter of the nozzle's aperture on the effective viscosity of PEO solutions show (Figure 3) that increasing the diameter of the nozzle essentially increases the critical speed.



**Figure 3.** The influence of the nozzle diameter on the effective viscosity of PEO aqueous solutions:  $C_{PEO} = 0.02\%$ ;  $M_{PEO} = 4 \cdot 10^6$ ;  $d_{noz.}$ : 1 –  $0.34 \cdot 10^{-3}$  m, 2 –  $0.42 \cdot 10^{-3}$  m, 3 –  $0.52 \cdot 10^{-3}$  m, 4 –  $0.6 \cdot 10^{-3}$  m)

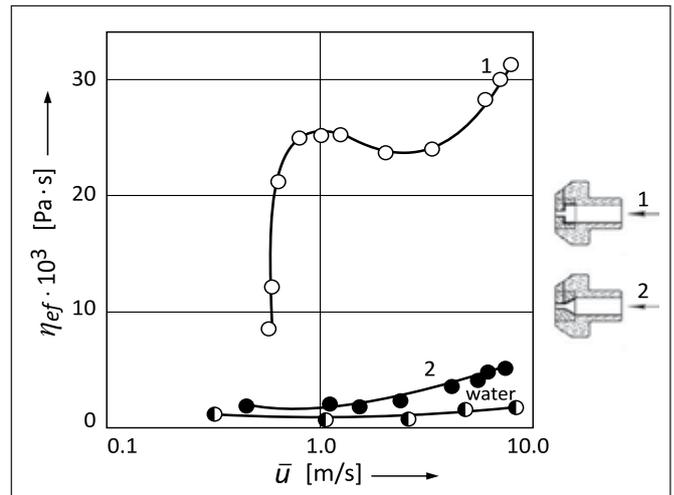
**Rysunek 3.** Wpływ średnicy dyszy na efektywną lepkość wodnych roztworów PEO:  $C_{PEO} = 0,02\%$ ;  $M_{PEO} = 4 \cdot 10^6$ ;  $d_{noz.}$ : 1 –  $0,34 \cdot 10^{-3}$  m, 2 –  $0,42 \cdot 10^{-3}$  m, 3 –  $0,52 \cdot 10^{-3}$  m, 4 –  $0,6 \cdot 10^{-3}$  m

These experimental results (Figure 3) allow us to assume that the observed changes of viscosity with growth  $\bar{u}$  due to first of all at the expense of a difficult structure of the hydrodynamic field at the entrance section of the jet-forming nozzle (not at the expense of the macromolecules' adsorption). Studies of solutions in a stationary Kuett field have shown that they can detect a decrease in viscosity only with increasing velocity gradient (Frenkel et al., 1970) and only in turbulent motion do they show certain anomalies (Pilipenko, 1980). Therefore, the change in the geometry in the inlet walls of the jet-forming nozzles (i.e. the conditions of solution deformation) should change the nature of the dependence of  $\eta_{ef}$  on  $\bar{u}$ .

Figure 4 shows the curves that reflect the influence of conditions (inlet angle) of the polymer solution's flow through the jet-forming nozzle with an inlet angle of  $180^\circ$  and  $45^\circ$  (smooth inlet and a standard factory nozzle) on the effective viscosity. It can be seen that the flow of the PEO solution in the first case (curve 1) is highly dissipative, while in the second (curve 2) it is slightly dissipative. At the same time, for a Newtonian liquid (water), the angle of entry into the nozzles does not play a significant role. A similar conclusion follows from the analysis of the data in Figure 5, which shows the results of experiments to identify the effect of the angle of entry into the nozzle and the PEO concentration on the effective viscosity of polymer solutions.

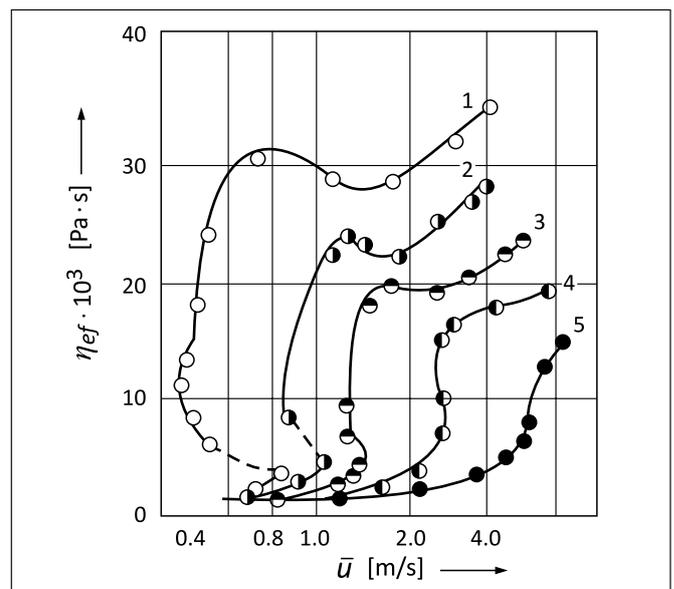
The experimental data characterise the peculiarities of the flow of PEO aqueous solutions through the model nozzles of a hydroperforator.

From the experiments regarding the detection of the influence of the entrance angle into a nozzle on the effective viscos-



**Figure 4.** The influence of conditions of the entry into the nozzle on effective viscosity:  $M_{PEO} = 6 \cdot 10^6$ ;  $C_{PEO} = 0.1\%$ ;  $d_{min} = 0.53 \cdot 10^{-3}$  m; 1 – rectangular entry ( $180^\circ$ ); 2 – smooth entry ( $45^\circ$ )

**Rysunek 4.** Wpływ warunków wlotowych do dyszy na lepkość efektywną:  $M_{PEO} = 6 \cdot 10^6$ ;  $C_{PEO} = 0,1\%$ ;  $d_{min} = 0,53 \cdot 10^{-3}$  m; 1 – rectangular entry ( $180^\circ$ ); 2 – smooth entry ( $45^\circ$ )



**Figure 5.** The influence of the inlet angle on the effective viscosity when the PEO aqueous solutions flow through the nozzles:  $M_{PEO} = 6 \cdot 10^6$ ;  $C_{PEO} = 0.1\%$ ;  $\beta$ : 1 –  $180^\circ$ , 2 –  $150^\circ$ , 3 –  $98^\circ$ , 4 –  $65^\circ$ , 5 –  $35^\circ$

**Rysunek 5.** Wpływ kąta dopływu na lepkość efektywną podczas przepływu wodnych roztworów PEO przez dysze:  $M_{PEO} = 6 \cdot 10^6$ ;  $C_{PEO} = 0,1\%$ ;  $\beta$ : 1 –  $180^\circ$ , 2 –  $150^\circ$ , 3 –  $98^\circ$ , 4 –  $65^\circ$ , 5 –  $35^\circ$

ity of PEO solutions, it is clear that there are phenomena that are typical for such flows, yet not for purely viscous environments. At some critical values of  $u_{kp}$ , the effective viscosity begins to increase sharply, and the sharper this increase, the higher the concentration of polymer in solution and the wider the angle of entry into the nozzle. The highest value for  $\eta_{ef}$  was observed for a nozzle with an inlet angle of  $180^\circ$ , i.e. when there was

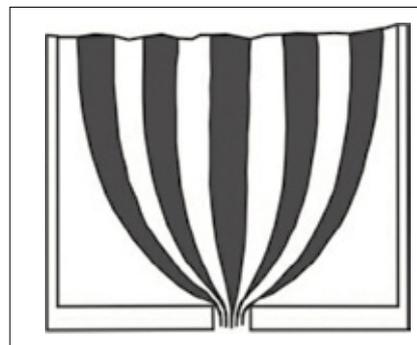
a sudden narrowing. Reducing the angle of entry into the hole of the nozzle leads to a decrease in  $\eta_{ef}$  and displacement of the critical (threshold) speed in the direction of large values.

The ambiguity of the effective viscosity's dependence on  $\bar{u}$  (one velocity can correspond to two values of viscosity, see Figures 3 and 5) testifies to the difficult nature of these currents and, naturally, studying only integral characteristics of a flows draws attention not enough to understand the observed phenomena. As mentioned above, in a previous study (Pogrebnyak et al., 2019) the transition of the bundle-unfolded chain at a convergent flow (in the model conditions of the hydroperforator nozzle) of aqueous solutions of PEO was experimentally revealed. It has been established that the water-PEO system at convergent flow under certain regimes is self-regulating with negative feedback. It has been shown that increasing longitudinal velocity gradients leads to deformation of the macromolecular coils, which in turn causes a rearrangement of the flow structure and increase the time of influence of the longitudinal velocity gradient on the macromolecular chains. The hydrodynamic field, which occurs under conditions of convergent flow, leads to a significant proportion of the polymer molecules unfolding, hence the peculiarities of the convergent flow of even dilute solutions due to the ability of the macromolecules to easily change the shape of these molecular coils under the action of the complex structure of the hydrodynamic field that arises in the inlet nozzle of the hydroperforator and due to the increased molecular interactions at the molecular-supramolecular level caused by these changes. Therefore, experiments proving the possibility of supramolecular structure formation during the flow of an aqueous solution of PEO in a model of jet-forming nozzles of a hydroperforator are fundamental in terms of solving the destroying of nature, which causes the destructive power of a high-speed water-polymer jet. Below we turn to such experiments.

Experimental studies (Ivanyuta et al., 1985, Pogrebnyak and Naumchuk, 1992) have demonstrated that self-organisation in space and time can be observed in aqueous solutions of PEO in the inlet section of the nozzle, which forms a jet (flow under tension). Therefore, to create a hydrodynamic field under tension, a convergent flow of water into a small hole in the plate (a model of a nozzle) with a diameter of  $3 \cdot 10^{-4}$  m was used. Streams of PEO solution with a molecular weight of  $6 \cdot 10^6$  were introduced into the water stream at a sufficient distance from the hole. The range of concentrations studied was 0.001–0.1%. The speed of the aqueous solution of PEO at the points of introduction of jets coincided with the speed of the main flow of water. Visualisation of the flow in the inlet area of the hole was carried out using admixtures of dye in the injected aqueous solutions.

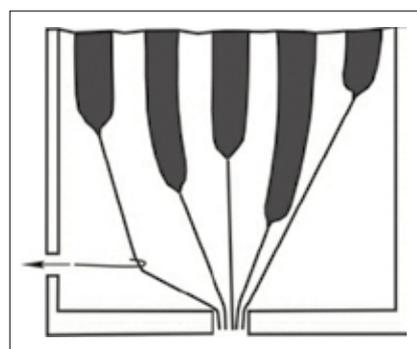
At low flow rates, the coloured streams of PEO aqueous solution visualised the flow lines of the main stream (Figure 6).

The behaviour of the streams of PEO solutions was no different from the behaviour of streams of pure water injected into the convergent stream. When a critical water flow through the outlet of the nozzle was reached, the nature of the flow of jets of aqueous solution changed dramatically. Quite thick streams of PEO aqueous solution were transformed into thin threads, the length of which changed over time (Figure 7).



**Figure 6.** The flow in the inlet section of the model nozzle when the PEO aqueous solutions were injected into water:  $M_{PEO} = 6 \cdot 10^6$ ;  $C_{PEO} = 0.03\%$ ;  $\bar{u} < u_{cr}$

**Rysunek 6.** Obraz przepływu w sekcji wlotowej modelowej dyszy podczas wtlaczania wodnych roztworów PEO do wody:  $M_{PEO} = 6 \cdot 10^6$ ;  $C_{PEO} = 0,03\%$ ;  $\bar{u} < u_{cr}$



**Figure 7.** The flow at the moment of wire probe effecting a polymer thread spun by hydrodynamic field:  $M_{PEO} = 6 \cdot 10^6$ ;  $C_{PEO} = 0.03\%$ ;  $u = 2.5$  m/s;  $\bar{u} < u_{cr}$

**Rysunek 7.** Obraz przepływu w momencie działania sondy na nitkę wodno-polimerową wytworzoną przez pole hydrodynamiczne:  $M_{PEO} = 6 \cdot 10^6$ ;  $C_{PEO} = 0,03\%$ ;  $u = 2.5$  m/s;  $\bar{u} < u_{cr}$

When observing the dynamics of the formation and destruction of individual threads (this is the oscillating nature of the movement of flooded streams of PEO solution) the following pattern is revealed. Initially, as the jets of PEO solution approached the hole, they were observed to bend smoothly towards the hole. At the same time, their velocity along these curvilinear trajectories began to increase more and more noticeably, as evidenced by the decrease in the thickness of the streams. Near the hole there was an abrupt decrease in the thickness of the streams of aqueous PEO solution, and they were transformed into a thin thread. The area of transformation

of the thick stream into a thin thread began to move up the streams, which led to an increase in the length of the threads. Since the streams of the aqueous solution of PEO approached the hole at the same time, at each time the length of the threads spun by the flow from the individual streams of aqueous solution was different.

When a critical length was reached, the thread in the immediate vicinity of the hole broke. After that, the thread remaining at the top lost elasticity and sagged, i.e. one of the lines of the main flow of water. When the stream of aqueous PEO solution again approached the hole, everything repeated. The observed behaviour of flooded streams of aqueous PEO solution during tensile flow is due to the development of many PEO coils under the action of a hydrodynamic field. Rolling out molecular chains of PEO led to a decrease in their flexibility, which under certain conditions caused phase separation under the action of a hydrodynamic field, i.e. leading to the formation of a dynamic supramolecular structure.

The following experiment can confirm this formation of a dynamic supramolecular structure under the action of a tensile hydrodynamic field. In the subcritical modes of main water flow leakage in the inlet area of the hole, a thin wire-probe with a device for capturing the thread of an aqueous solution of PEO was introduced. The movement of this probe wire in a plane perpendicular to the jets did not change the flow pattern, as the jets of the aqueous PEO solution in these flow regimes are permeable to it. If the same experiment is repeated in the supercritical mode of water leakage, it is possible to capture one or more a polymer threads at the time of their growth and move aside, as shown in Figure 7. This is only possible in the presence of a sufficiently strong interaction between PEO molecules, i.e. in the emergence of a supramolecular structure, which is formed in this case under the action of a tensile hydrodynamic field. The minimum concentration of aqueous PEO solutions, when it was still possible to divert the aqueous solution of PEO, was 0.008%, which corresponds to the region of dilute solutions when the intrinsic viscosity  $[\eta]_0$  multiplied by the concentration of PEO  $C_{PEO}$  was less than 1 (Frenkel et al., 1970).

These results and those given above suggest that aqueous solutions of PEO can be divided into at least three regions of concentration. This is the region of dilute aqueous PEO solutions, where PEO macromolecules under the action of a hydrodynamic field are subjected to strong deformation effects (expansion of macromolecules), but still weakly interact with each other in the expanded state. The second is the region of semi-dilute aqueous PEO solutions (intermediate), when in subcritical flow regimes the solutions are diluted, and in the supercritical ones – already concentrated in the result of the formation of supramolecular structures under the action of a hydrodynamic field. These dynamic structures should be

considered the type of dynamic phase transitions dealt with by the theory of dissipative structures (Hlesdorf and Prigogin, 2003). The last region is the region of concentrated aqueous solutions of PEO ( $[\eta]_0 \cdot C_{PEO} > 1$ ), when significant interactions between PEO molecules exist without the action of a hydrodynamic field. It should be noted that the first two areas relate to the concentrations of the manifestation of great destructive power of a high-velocity jet of an aqueous solution of PEO. Thus, when aqueous solutions of PEO flow through the nozzles, forming a high-velocity jet, there may be a dynamic supramolecular structure that is subject to Prigogine's principles of self-organisation (Hlesdorf and Prigogin, 2003). These results are crucial for elucidating the nature of the great destructive capacity of a high-velocity water-polymer jet.

By elucidating the dynamics of macromolecules in the hydrodynamic field of a jet-forming nozzle and experimentally proving the formation of a dynamic supramolecular structure in the inlet section of the nozzle, we can obtain reasonable ideas to explain the mechanism behind the destructive capacity of a water-polymer jet.

Analysis of the concentration dependence of the destructive capacity of polymer solutions and the results indicating on formation of dynamic supramolecular structures in polymer solutions suggest that approaching the optimal concentration of polymer ( $C \geq C_{opt}$ ), the destructive capacity of water generates anisotropic supramolecular formations that have a lifetime 10 times longer than the relaxation time of the macromolecule (Pogrebnyak et al., 2019). A further increase in the PEO concentration led to the creation of conditions for the interaction between individual molecules of PEO, even without the action of a hydrodynamic field. This leads to a sharp increase in the usual viscosity and, of course, to a relatively strong decrease in the flow rate of the aqueous solution. The consequence of this is a decrease in the destructive capacity of the water-polymer jet when reaching a relatively high concentration of PEO in aqueous solution.

To substantiate and systematise the physical laws of the fracture mechanism in the process of perforating the casing strings of oil and gas wells with a stream of polymer solution and the relationship of the individual phenomena that occur, it is important to develop schemes for calculating basic technological parameters and rational modes of a hydroperforator. The experimental data show that the process of water-polymer perforation of oil and gas well casing strings is complex and has specific features which contrast with the perforation of the water jet and hydro-abrasive jet.

The subject of the work – to develop a highly efficient innovative method for perforating oil and gas well casing strings – can be achieved through a method of hydrostream perforation of the well that includes directing the jet to the place

of perforation, sealing the inner cavity of the tubing and jet apparatus, actuating the ball valve located at the bottom of the jet apparatus, sealing the annulus with a self-sealing gland, and supplying the tubing pipe with cutting fluid, that is, an aqueous solution of PEO with a molecular weight of  $M = 6 \cdot 10^6$  at a concentration of  $C_{PEO} = 0.003\text{--}0.007\%$  by weight and with an operating pressure of 100–300 MPa. These parameters are the innovative technological feature in the function of this cutting fluid.

Perforation works were performed in the laboratory using a hydraulic stand based on aURG-3020 installation. The model of the obstacle (target) on which the perforation efficiency was tested is described in the experimental part. The results of the destruction of the model barrier by a water–polymer jet with PEO concentrations of 0.0025–0.008% and a PEO molecular weight of  $6 \cdot 10^6$ , a leakage pressure of 200 MPa, a nozzle diameter of  $3 \cdot 10^{-3}$  m and a perforation time of 10 min are provided in Table 2.

**Table 2.** The effect of PEO concentration on the length of the channel formed in the model obstacle

**Tabela 2.** Wpływ stężenia PEO na długość kanału utworzonego w modelowej przeszkodzie

N° of research	$C_{PEO}$	Length of formed channel
	[%]	[mm]
1	0.0025	0.245
2	0.0030	0.385
3	0.0050	0.405
4	0.0070	0.430
5	0.0080	0.435

**Table 3.** The effect of the pressure of the destructive fluid on the length of the channel formed in the model barrier with a 0.005% concentration of PEO in the water–polymer stream

**Tabela 3.** Wpływ ciśnienia płynu niszczącego na długość kanału utworzonego w modelowej barierze dla stężenia PEO w strumieniu woda–polimer równego 0,005%

N° of research	Pressure of cutting fluid	Length of formed channel
	[MPa]	[mm]
6	75	225
7	100	380
8	200	405
9	300	420
10	350	425

The tests were also performed with a concentration of PEO aqueous solution of 0.005%, but the pressure of the destructive fluid changed. These results are presented in Table 3.

Decreasing the pressure below 100 MPa reduced the perforation efficiency, while raising it above 300 MPa caused a slight increase in the length of the channel; however, in a production

environment there are technical difficulties in maintaining such high pressures. Comparative perforation works were performed on a similar model of the obstacle using HSP (sand fractional composition: 0.5–1.2 mm; concentration: 30–50 kg/m<sup>3</sup>; leakage pressure: 200 MPa). In the case of HSP, the length of the channel in the obstacle model was 320 mm.

The results presented in Tables 2 and 3 show that PEO additives in the selected range of concentration and flow regimes will lead to greater channel formation efficiency during the perforation of oil and gas well casings, which will allow more efficient use of oil and gas fields' potential.

Experimental and field testing of the proposed method of perforating the casing columns of oil and gas well casing strings– using a jet of PEO aqueous solution – which was carried out during the secondary opening of the productive reservoir at a well in the Carpathian oil-and gas-bearing region, confirmed the practical and economic feasibility of its use. The environmental friendliness of PEO additives should be noted, because this polymer is not harmful to humans and does not harm nature.

## Conclusions

1. The mechanism behind the destructive power of a high-velocity jet of polymer solution has been discovered. It is not due to the Toms effect, but consists in the destructive action of the dynamic pressure of the water–polymer jet, “reinforced” by highly developed macromolecular chains and dynamic anisotropic supramolecular structures formed under the action of expanding flow in the inlet section of the hydroperforator nozzle that forms the high-velocity jet flow.
2. Research and field testing of the method of hydrojet perforation of well casings that uses aqueous solutions of PEO confirmed that the process of well perforation is more efficient, environmentally friendly and resource-saving than hydro-sandblasting perforation.
3. The new data on the influence that different jet-forming nozzles have on the hydrodynamic behaviour of aqueous polymer solutions during their flow through the nozzles and the established patterns of the influence that the structures have on the efficiency of well perforation – aimed at developing a highly efficient process for perforating oil and gas well casing strings with a high-velocity stream of polymer solution – are innovative, relevant and promising.

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