Проведеними дослідженнями встановлено можливість отримання водних вогнегасних речовин, здатних знижувати гідравлічний опір (володіють ефектом Томса) шляхом використання гуанідинових похідних.

Для проведення експериментальних досліджень використовували катіонну поверхнево-активну речовину полігексаметиленгуанідину гідрохлорид молекулярною масою 10000–11000 а.о.м.

Показано, що додавання незначних концентрацій (0,03–0,290 %) полігексаметиленгуанідину гідрохлориду, що належить до IV класу токсичності та є ефективним інгібітором біокорозії, збільшує витрати водної вогнегасної речовини у 1,20–1,78 раз під час використання пожежного ствола РСК-50.

Експериментально встановлено збільшення витрат водної вогнегасної речовини полігексаметиленгуанідину гідрохлориду з дренчерних зрошувачів в діапазоні концентрацій (0,3–1,4 %) вздовж досліджуваного трубопроводу (1 м та 13 м) на 1,86–7,69 %. За цих умов можливим є підвищення величини тиску на 2–6 % в порівнянні з початковими значеннями.

Використаний полімер володіє властивостями «біологічно м'якої» поверхнево-активної речовини та відповідає високим екологічним вимогам охорони навколишнього середовища і раціонального використання природних ресурсів. Може бути використаний для розробки рецептур екологічно прийнятних водних вогнегасних речовин як підґрунтя їх застосування в практиці пожежогасіння.

Таким чином, є підстави стверджувати про можливість спрямованого використання солей полігексаметиленгуанідину гідрохлориду для зменшення гідравлічних втрат в системах водяного пожежогасіння. Це може бути використано для удосконалення інженерно-технічних заходів попередження та ліквідації наслідків надзвичайних ситуацій

Ключові слова: полігексаметиленгуанідину гідрохлорид, водна вогнегасна речовина, пожежогасіння, гідродинамічна активність, ефект Томса

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IMPROVING THE EFFICIENCY OF WATER FIRE EXTINGUISHING SYSTEMS OPERATION BY USING GUANIDINE POLYMERS

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1. Introduction

Water fire extinguishing systems are the most effective. They make it possible to quickly respond to the occurrence of fire [1]. The movement of liquid in pipelines in such systems has several features. An important task is to provide necessary conditions of movement of water extinguishing agents through pipelines to maximize the flow of fluid, a range of jets, etc. with minimal efforts [2].

The use of hydrodynamically active substances in liquid flows makes it possible to increase the efficiency of fire extinguishing systems without using additional means and significant changes in their design [3].

However, the effectiveness of modern fire extinguishing agents is insufficient to provide an adequate level of environmental and fire safety [4]. Therefore, studies aimed at further improvement of the technology of water fire extinguishing systems, including the use of environmentally friendly water extinguishing agents, are expedient.

The aim of this study is further improvement of the technology of water fire extinguishing systems, including the use of environmentally friendly water extinguishing agents.

2. Literature review and problem statement

Work [5] reported the results of studies obtained over the last seventy years on the reduction of hydraulic resistance in pipelines at the addition of small amounts of polymer. It covers fundamental knowledge and classical theories comprehensively. In addition, the author tries to focus on a new vision of classical theories in the field of research. The authors of paper [6] showed that polymers cause a decrease in resistance in horizontal turbulent flows in pipes. They established a connection between a decrease in resistance and variables of a turbulent flow [6]. They showed that local values of some variables of a turbulent flow correlate with measured levels of a resistance decrease, regardless of the Reynolds number. At the same time, issues of the control of variables of turbulent flow to obtain the lowest resistance in horizontal turbulent flows remained unresolved.

Work [7] showed that the addition of polymers reduced friction resistance but it did not affect the initial growth of turbulence. However, it stabilized the primary structure of the vortex flow. The work showed that losses of turbulent kinetic energy (as a result of the elastic transformation of polymer) were comparable with viscous dissipation for large values of the Weissenberg number. However, since the Weissenberg effect takes place not only in solutions of high-polymers but also in any dispersed systems with some elasticity of a form, there is a question of what exactly stabilizes the primary structure of vortex flow. The authors of work [8] took steps to understand turbulent dynamics in case of the presence of polymers and to develop new strategies for liquid flow control to reduce friction effectively.

The authors of paper [9] analyzed a laminar-turbulent transition and a decrease in resistance due to the addition of polymers to the Newtonian liquid. Reduction in friction resistance achieved its maximum near a boundary of the laminar mode in a Newtonian flow. The authors proposed an asymptotic boundary, at which the turbulence inferior to a laminar flow disappeared, for the appropriate choice of polymer parameters. However, the laminar state became unstable at higher polymer concentrations. It led to fluctuations in the flow. In addition, the mechanism of laminar-turbulent transition and reduction of resistance at the addition of polymers to a non-Newtonian liquid was unclear.

Review [10] examined studies on reduction of resistance and elastic turbulence, as well as modification of heat transfer in natural convection. Authors attempted to explain basic mechanisms, which operated in a system of resistance reduction and were described by other authors of various theoretical approaches and explanations in this field.

Work [11] showed that water-soluble macromolecules of both natural and synthetic polymers, in particular polyethylene oxide, polyacrylic acid, polyacrylamide and poly N-vinyl formamide, are effective for the development of anti-turbulent agents, among the promising compounds of the last decade.

However, the issues related to a dosage of polymers in fire hoses, preparation of solutions of an appropriate concentration of powders, and reduction of hydrodynamic activity during storage of homogeneous solutions, in particular polyethylene oxide and polyacrylamide, remained unresolved [12].

The causes are objective difficulties associated with a need to prepare homogeneous solutions of powders in advance. It requires cumbersome equipment, and the dissolution process is time-consuming. In addition, sticking of parts that are not soluble may occur during the mixing of powder. And obtaining solutions with a concentration of more than 0.2 % is technically difficult due to the hygroscopicity of polyacrylamide [11]. However, it is not clear what authors meant by the effective mixing of components of a solution of high molecular weight polymer and how to provide such mixing.

An option to overcome the corresponding difficulties may be the use of gels or concentrated solutions. The authors of paper [14] applied this approach.

All the above confirms the expediency of the study on a search for easy-to-use concentrated solutions of hydrodynamically active polymers capable of retaining their properties for a long time.

3. The aim and objectives of the study

The objective of this study is to determine optimal conditions for the reduction of hydraulic losses in pipe and hose lines for water extinguishing agents based on polyhexamethyleneguanidine hydrochloride during firefighting and emergency response.

We set the following tasks to achieve the objective:

– to investigate the presence of hydrodynamic activity in water solutions of polyhexamethyleneguanidine hydrochloride;

– to investigate the dependence of pressure changes in drencher distributors at a fixed flow rate of tap water and polyhexamethyleneguanidine hydrochloride water extinguishing agent from them along a pipeline;

– to investigate the flow rate of tap water and polyhexamethyleneguanidine hydrochloride water extinguishing agent from nozzles in the investigated concentration range;

– to investigate the concentration range of the presence of hydrodynamic activity of water solutions of polyhexamethyleneguanidine hydrochloride when using the RSK-50 fire barrel.

4. Materials and methods to study the hydrodynamic activity of polyhexamethyleneguanidine hydrochloride

4. 1. Materials and equipment used in the experiment

We used tap water (a total rigidity of 3.70 mgeq/dm^3) and water solutions of polyhexamethyleneguanidine hydrochloride (PHMG-HC) with a molecular weight of 10,000–11,000 u.

A sample of PHMG-HC was synthesized according to method [15] with a low content of residual amount of monomer for experimental studies.

We prepared experimental water solutions by dissolving of accurate samples of PHMG-HC in distilled water and leaving the solutions for 24 hours at 25±5 °C until complete dissolution.

The indicators of water extinguishing agent were determined by using a pump unit. Fig. 1 shows its scheme.

The pump unit consisted of a power module (1–6), a barrel positioning module, a system of pipelines with distributors, feeding and distribution hoses, and a container for water and water solutions. The pump unit included an asynchronous three-phase 18 kW electric motor and a centrifugal liquid pump, which could deliver flow rates up to 800 l/min with a head up to 100 m. The pump unit gave a possibility to study the flow of viscous liquids in the nozzles of various types and fire barrels.

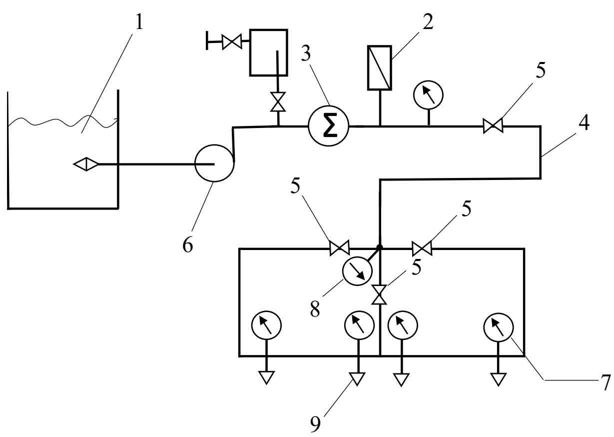


Fig. 1. Scheme of the pump unit: 1 – 1 m^3 tank for water intake (water extinguishing agent); 2 – analog pressure converter; 3 – liquid flow converter; 4 – PE 80 Ø35 water pipe; 5 – Ø50 mm valve; 6 – centrifugal pump; 7, 8 – manometers; 9 – Ø 8–10 mm drencher

The pump unit consisted of a system of plastic pipelines with drencher distributors placed on it. A centrifugal pump with a capacity of 1 m^3 delivered water to distributors. Water was supplied to a circular net to distributors placed on it. A conditional passage of distributors could vary and it was 8 or 10 mm.

The pump unit was connected to nozzles (fire barrels) through a hydraulic system (a flowmeter, a pressure transducer, pressure lines). Nozzles could be mounted at different angles with respect to the horizon due to a special system of precise positioning of a fire barrel.

4. 2. Methodology for determining the indicators of water extinguishing agent

The instrumentation used in the control system of the pumping unit gave the possibility to measure the main parameters of a flow in a supply pipe, depending on parameters of received jets (coefficients of speed and flow) [16].

The study involved two stages. We investigated changes in pressure in nozzles depending on the fixed flow along the pipeline, which reproduced hydraulic branched water automatic fire extinguishing systems, at the first stage.

The pressure was determined by using manometers installed opposite the nozzles. We measured the flow of water extinguishing agent from drencher distributors by the volumetric method using the pump unit.

The flow of water extinguishing agent was determined using the RSK-50 manual fire barrel at the second stage.

5. Results of studying the effectiveness of water fire extinguishing systems using water extinguishing agents based on polyhexamethyleneguanidine hydrochloride

5. 1. Studying the presence of hydrodynamic activity in water solutions of polyhexamethyleneguanidine hydrochloride by the establishment of the dependence of pressure changes in drencher distributors

We prepared water extinguishing agents by mixing tap water with pre-prepared concentrated PHMG-HC water solutions of known concentration in the tank for water intake of the pumping unit.

A pump supplied water and water extinguishing agents from the water intake tank along a 125 mm diameter hose line that was constructed of pressure-suction fire hoses (GOST 7877-75) to drencher distributors installed at a distance of 1, 5, 9, 13 m.

The dependences were derived from the changes in pressure in the drencher distributors on the fixed flow from them along the pipeline based on the experimental data (Table 1). We carried out statistical processing of data and obtained the dependency in the form of a polynomial. The reliability of the approximation of experimental data depending on the polynomial order was 93.47–99.98 %.

Since the obtained approximation accuracy was 99.98 %, one could state that there was a pressure increase at a fixed flow of polyhexamethylene guanidine hydrochloride by 2–6 % comparing to tap water. The studies with discrete flow showed that the minimum polymer concentration when we observed hydrodynamic activity, was 0.3 %. There was no increase in pressure and discrete flow at the test unit below this concentration.

Table 1

Dependences of pressure changes in nozzles on the fixed flow of tap water and 0.3 % PHMG-HC solution of water extinguishing agent

Polynomial order	Dependences of pressure change in nozzles on the fixed flow of tap water	R^2 (%)	Dependences of pressure change in nozzles on the fixed flow of 0.3 % PHMG-HC solution of water extinguishing agent	R^2 (%)
2	$y=0.003x^2-0.0873x+1.1038$	95.87	$y=0.0019x^2-0.0693x+1.0904$	93.47
3	$y=0.001x^3-0.0184x^2+0.0287x+0.9887$	99.98	$y=0.0012x^3-0.0233x^2+0.0676x+0.9545$	99.98

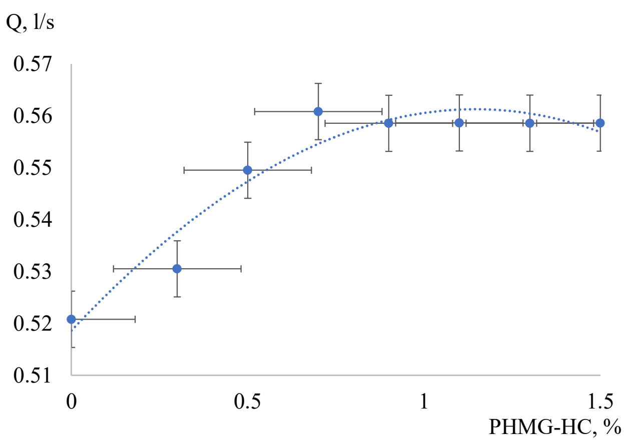
5. 2. Studying the presence of hydrodynamic activity in water solutions of polyhexamethyleneguanidine hydrochloride by determining the flow from drencher distributors

The pump supplied water and water extinguishing agents from the water tank along the hose line similar to chapter 5. 1.

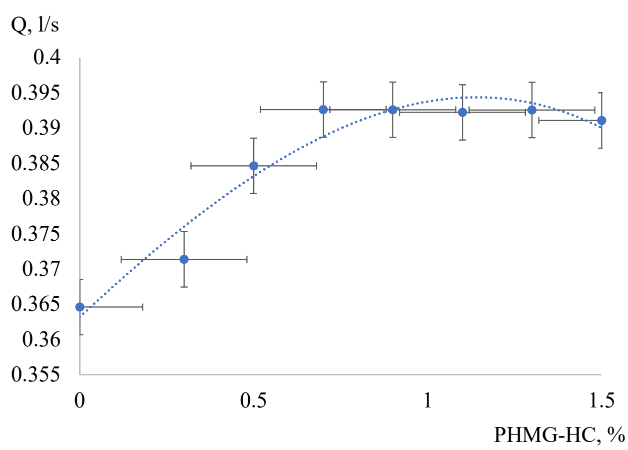
A water flow rate was 0.52083 l/s in the hose line from the first drencher distributor (installed at a distance of 1 m) during the test. There was an increase in the flow of extinguishing liquids for water solutions of the investigated polymer due to the reduction of the hydrodynamic friction resistance in the hose line. It was: 0.53055; 0.54955; 0.56085;0.55859; 0.55866; 0.5586; 0.55863 l/s.

The water flow rate was 0.36458 l/s in the hose line from the drencher distributor installed at a distance of 13 m during the test. It was 0.37135; 0.38462; 0.3926; 0.39257; 0.3922; 0.39254; 0.39106 l/s for water PHMG-HC solutions.

The obtained increase in the flow rate of fire extinguishing agents with polymer additives (Fig. 2) indicates that the hose line and the drencher distributors worked under the mode of reduction of hydrodynamic resistance. Under these conditions, the maximum magnitude of the effect of reduction of the hydrodynamic resistance under optimal conditions at a polymer concentration of 0.7 % was 7 %.



a



b

Fig. 2. Flow rate of water extinguishing agent of polyhexamethyleneguanidine hydrochloride: *a* — a pipeline with a length of 1 m; *b* — a pipeline with a length of 13 m

We carried out statistical processing of data and obtained the dependence in the form of a polynomial. It made it possible to calculate the dependence of the flow rate on the concentration of polymer.

The reliability of the approximation of experimental data depending on the order of a polynomial was 94–99 %. Table 2 shows the dependence of the flow rate on the polymer concentration and the reliability of the approximation of experimental data depending on the order of the polynomial.

Table 2

Dependence of the flow rate on the polymer concentration and the reliability of the approximation of experimental data depending on the order of the polynomial

Order of a polynomial	Dependence of the flow rate on the polymer concentration	R^2 (%)	Dependence of the flow rate on the polymer concentration	R^2 (%)
	a pipeline with a length of 1 m		a pipeline with a length of 13 m	
2	$y=-0.0324x^2+0.0744x+0.5185$	93.12	$y=-0.0237x^2+0.0543x+0.3625$	94.28
3	$y=-0.0017x^3-0.0287x^2+0.0723x+0.5186$	93.12	$y=-0.0065x^3-0.009x^2+0.0461x+0.3632$	94.57
4	$y=0.1018x^4-0.3088x^3+0.2586x^2-0.0105x+0.5204$	97.71	$y=0.0658x^4-0.205x^3+0.1766x^2-0.0074x+0.3643$	98.22
5	$y=-0.2221x^5+0.9539x^4-1.4572x^3+0.8915x^2-0.1283x+0.5208$	99.75	$y=-0.1481x^5+0.634x^4-0.9708x^3+0.5987x^2-0.086x+0.3646$	99.94

We analyzed data in Fig. 2, *a*, *b* and the dependence of the flow rate on the concentration and the length of the pipeline. And one can state that the positive effect of reduction in the hydrodynamic resistance appears immediately at the initial section of the pipeline. Further, the effect persists and even increases slightly.

We determined the initial (minimum) concentrations of a polymer, which provides a decrease in hydrodynamical losses on the drencher distributors and carried out further studies using RSK-50 fire barrel at polymer concentrations less than 0.3 %.

5. 3. Studying the presence of hydrodynamic activity in water solutions of polyhexamethyleneguanidine hydrochloride using RSK-50 manual fire barrel.

The pump supplied water and water extinguishing agents from the water intake tank along the hose line similar to chapter 5. 1.

RSK-50 fire barrel was connected to the pump unit and the water tank (water extinguishing agent) with a volume of 1 m^3.

Table 3 shows the results of the determination of the flow rate of tap water and PHMG-HC water extinguishing agent using RSK-50 fire barrel (diameter of the nozzle was 13 mm, an angle of the torch of a spray jet was 30°, working pressure was 3 bar).

Table 3

The flow rate of water extinguishing agent using RSK-50 fire barrel

Type of fire extinguishing agent	Flow rate of water extinguishing agent, l/s	Coefficient of water flow rate, *k*
Water	2.80	1
PHMG-HC 0.290 %	4.99	1.78
PHMG-HC 0.035 %	3.37	1.20

Experimental studies showed that the addition of polymer at concentrations less than 0.3 % led to an increase in the flow rate of the investigated solutions of water extinguishing agent. We took a water flow rate coefficient as 1 and calculated the consumption coefficients of the PHMG-HC water extinguishing agent. It was 1.20 and 1.78 for the concentrations of PHMG-HC of 0.035 % and 0.29 %, respectively.

The obtained increase in the flow rate of PHMG-HC solutions indicated that the hose line and fire barrel worked under the mode of reduction of hydrodynamic resistance almost 2 times.

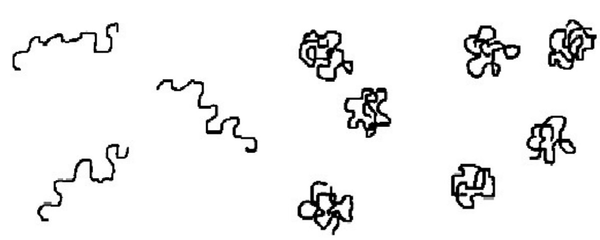
6. Discussion of results of the hydrodynamic activity of polyhexamethyleneguanidine hydrochloride

It is known that one of the reserves for increasing the efficiency of water fire extinguishing systems is the use of the phenomenon of reduction of hydrodynamic resistance due to the use of small quantities of soluble macromolecular polymers. Our study investigated the possibility of reduction of hydrodynamical losses using guanidine polymers, which have a long storage life (5 years), in contrast to solutions of polyethylene oxide and polyacrylamide, the use of which is widely described in the literature. Prerequisites for the use of the investigated polymers in firefighting, in addition to a long storage life, are the safety of guanidine preparations, which are widely used in medicine and food industry as antiseptic, antibacterial and therapeutic agents and belong to class IV class of toxicity [16].

A significant advantage of guanidine polymers is a lack of volatility, good solubility in water, absence of odor and color, non-aggressiveness to various materials and ability to exhibit inhibitory properties of biocorrosion [16, 17].

The reasons for a decrease in hydrodynamic resistance by guanidine polymers may be the presence of a polyelectrolyte effect in dilute solutions and/or adsorption of polymer macromolecules on walls, which leads to a decrease in friction. The substantiation of such mechanisms of action is as follows.

The used PHMG-HC is a linear polymer. It belongs to the class of strong polybases and it is a polyelectrolyte. Its electrolytic dissociation leads to the formation of macroions and counterions. Ionogenic guanidine PHMG-HC groups give polymer properties of cationic polyelectrolyte, which has a polyelectrolyte effect in dilute solutions and the effect of swelling of macro clubs under the action of positive charges on a macromolecule chain (Fig. 3).



a *b*

Fig. 3. Confirmation of PHMG-HC macromolecules: *a* – unfolded in a dilute solution; *b* – rolled up in a concentrated solution

Polymer molecules with concentrations less than 1 % swell a lot in water and have a thread-like structure. It causes them to be pulled along the flow by the flow of liquids, which enhances fluidity at wall regions and, possibly, is able to reduce hydraulic losses when using PHMG-HC water solutions (Fig. 2, Table 3).

An increase in the concentration (from about 1.0 to 3.0–5.0 wt. %) can lead to conformational changes in PHMG-HC macromolecules, such as macromolecules adopt an increasingly convoluted conformation: firstly, they become loose fluffy statistical tangles (Fig. 3, *a*), and, with an increase in the concentration, - statistical macromolecular tangles begin to overlap and compress (Fig. 3, *b*), decreasing in size and forming more compact macromolecular tangles. As a result, there is a gradual decrease in the hydrodynamic activity at concentrations greater than 1.4 % (Fig. 2, *a*, *b*). We established experimentally an increase in the flow rate of water extinguishing agents using RSK-50 fire barrel at the concentration of polyhexamethyleneguanidine hydrochloride less than 1 % (Table 3). Under these conditions, the hydrodynamic resistance decreases almost 2 times.

There was no significant increase in the flow rate of PHMG-HC water solutions detected in the studied range of concentrations of PHMG-HC (0.035–0.29 %) using RSK-50 fire barrel. The reason is, probably, a decrease in a surface tension value and obtaining the droplet of smaller diameter that has less kinetic energy. One can apply this to precipitate combustion dust products, reduce heat radiation, and reduce environmental impact during firefighting.

Adsorption on walls of the pipeline of PHMG salts in presence of a secondary amino group in the guanidine group with the formation of a sufficiently stable adsorption layer can also have a significant effect on the reduction of hydrodynamic resistance by guanidine polymers. Thus, macromolecules of polymer increase the wall (laminar) layer on the inner surface of pipes [18, 19]. And, since each PHMG macromolecule is covered by water tetramers (due to association), their interaction with the formation of hydrogen bonds can lead to water structuring and also to an increase in fluidity (Table 3) at wall regions. The main regulators of the process are the amount of polymer and peculiarities of the formation of a wall layer (drencher units, fire barrels, and primary fire extinguishers). Therefore, a choice of a method for supply of water extinguishing agents (primary fire extinguishers, fire barrels, etc.) has a significant influence on reduction of the hydrodynamic friction resistance, since we achieve the optimal reduction of hydraulic losses using RSK-50 fire barrel (Table 3), drencher distributors (Fig. 2), fire extinguishers [16] in a certain concentration range. Therefore, it is necessary to approach the determination of the required amount of polymer and a method of supply reasonably, depending on set tasks (reduction of hydraulic losses, a distance of supply, improvement of fire-fighting properties, etc.).

Such uncertainty imposes some restrictions on the use of the obtained results. We can interpret them differently in the context of the study, which gives rise to a potentially interesting direction for further research. A focus of further research, in particular, can be the detection of the concentration parameter of PHMG-HC, from which the hydrodynamic activity of its solutions begins to decrease. Such discovery will give a possibility to investigate transformations beginning at this time and to determine concentration limits at which we observe a “negative” effect of PHMG-HC on the hydrodynamic activity of water solutions.

In addition, it is necessary to choose the optimal concentration of hydrodynamically active polymer for each case of use. Depending on the scope, it is necessary to take into account other parameters, such as surface tension, foaming, stability and multiplicity of foam, the pH of a solution, etc.

7. Conclusions

1. It has been established that water solutions of polyhexamethyleneguanidine hydrochloride exhibit hydrodynamic activity in the studied range of concentrations of PHMG-HC (0.3–1.4 %).

2. We have determined experimentally the increase in pressure of polyhexamethyleneguanidine hydrochloride water extinguishing agent by 2–6 % in comparison with tap water at the fixed flow rate from the drencher distributors. It has been shown that the maximum increase in the flow rate of extinguishing liquids with polymer additives through drencher distributors occurs at a polymer concentration of 0.7 %.

3. It has been established experimentally that the flow rate of the water-extinguishing agent of polyhexamethyleneguanidine hydrochloride from drencher distributors in the studied concentration range along the pipeline of 1–13 m increased by 1.86–7.69 % depending on the concentration and length of the pipeline.

4. Showed that the addition of insignificant concentrations (0.035–0.290 %) of polyhexamethyleneguanidine hydrochloride increased the flow rate of water extinguishing agent by 1.20–1.78 times when using the RSK-50 fire barrel. It was found that the hose line and fire barrel worked under the mode of reduction of the hydrodynamic resistance almost by 2 times at polyhexamethyleneguanidine hydrochloride concentrations of 0.290 %.

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