

Experimental study of the hydrodynamically active reagent for energy saving

Taras Nyzhnyk¹, Tetiana Mahlovana², Tatyana Strikalenko³, Denis Kolesnikov⁴, Oleh Zemlianskyi⁵, Serhiy Stas⁶, Dmytro Kopytin⁷

¹ Department of Inorganic Substances Technology and General Chemical Technology, Faculty of Chemical Technology, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Prospect Beresteyskyi, 37, Kyiv, 03056, Ukraine

² Department of Ecology, Faculty of Technologies, Construction and Rational Nature Management, Cherkasy State Technological University, Shevchenko Boulevard, 460 Cherkasy, 18006, Ukraine

³ Department of hotel and restaurant business, Odesa National University of Technology, Kanatnaya Str., Odesa, 65039, Ukraine

⁴ Department of Fire Prevention in Settlements, National University of Civil Defence of Ukraine, Onoprienko St., 8, Cherkasy, 18034, Ukraine

⁵ Department of Automatic Safety Systems and Information Technologies, National University of Civil Defence of Ukraine, Onoprienko St., 8, Cherkasy, 18034, Ukraine

⁶ Department of Engineering and Rescue Machinery, National University of Civil Defence of Ukraine, Onoprienko St., 8, Cherkasy, 18034, Ukraine

⁷ Scientific and Editorial Activity Division of the Scientific and Innovation Center, National University of Civil Defence of Ukraine, Onoprienko St., 8, Cherkasy, 18034, Ukraine

* Corresponding author's e-mail: maglovana_t@ukr.net

ABSTRACT

The paper deals with the topical, however controversial issue of the impact on the hydrodynamic resistance of polymer solutions of certain reagents that have proven to be already used in water supply for water disinfection, have anticorrosive activity and are safe for humans and the environment. The practical significance of this theoretical problem is that its solution can positively influence the achievement of energy saving at water supply companies without significant engineering or technical operating costs, as well as the management of environmental risks in extreme situations requiring significant water consumption (fires, human-caused accidents, etc.). The studies were carried out using tap water (with a total hardness of 3.70 mg-eq/dm³ polyhexamethylene guanidine hydrochloride (PHMG-HC) aqueous solutions. The pipeline model comprised fire hoses connected to a manual fire-hose nozzle RKS-50. In the modelling studies, a pumping unit with adjustable water flow rate and supply pressure was used, i.e., measurement of the main flow parameters in the feed pipeline depending on the parameters of the resulting jets. The results of statistical data processing are presented in figures and in the form of a polynomial. It was experimentally established that PHMG-HC aqueous solutions in the concentration range of 0.001% to 0.3% exhibit hydrodynamic activity, and their flow rates depend on the polymer concentration in the solution and the pressure in the hose line. Thus, when adding PHMG-HC aqueous solution, the maximum increase in fluid flow occurs at a pressure of 2 bar and reaches ~10% to 11% (taking into account the error of laboratory set-ups and metrological equipment). The obtained research results allow assuming that the hose line and fire-hose nozzle under these conditions operated in the mode of reducing hydrodynamic resistance by almost 10%, which, according to the authors, is due to a decrease in the friction of the fluid surface in the fluid pumping system. In order to specify the conditions under which effective practical use of PHMG-HC aqueous solutions is possible, as evidenced by preliminary assessments of technical and economic efficiency, it is planned to conduct field tests.

Keywords: hydraulic resistance, hose line, water transportation, guanidine polymers, hydrodynamically active substance.

INTRODUCTION

Among the energy-saving measures currently being considered for water supply systems, the prevailing recommendations include reducing the number of accidents and water losses during its transportation, increasing the time of pipeline operation or significantly changing their design, technical retrofitting of energy-intensive and existing technological equipment, and introducing the latest technical solutions and advanced treatment technologies, including water disinfection, etc. [Liberanore et al., 2003; Stupin et al., 2013; Simonenko et al., 2012; Yasniuk et al., 2018]. Taking into account the requirements of a systemic approach, solving energy efficiency problems should be aimed at both achieving economic efficiency and reducing the environmental impact of energy-saving technologies.

One of the approaches to minimise the complexity of water transport conditions by reducing corrosion and biofouling [Ryu and Yoon, 2021; Qiu et al., 2023] in the pipeline network is currently considered to be the use of hydrodynamically active substances in water flows, which can change the hydraulic resistance and water transport speed in water supply systems as well as increase the service life of pipelines. After all, the reduction of the internal cross-section of pipes due to the development of corrosion and biofouling can initiate a significant increase in energy costs for water transportation through the water supply network and increase the cost of water for its consumers. Therefore, the research aimed at improving water supply technology using a hydrodynamically active substance, in particular a representative of guanidine polymers, polyhexamethylene guanidine hydrochloride (PHMG-HC), and its impact on the environment and the possibility of energy saving, is considered relevant and timely.

The analysis of information sources was conducted in the following areas:

- corrosion and biofouling of the pipeline inner surface and anti-corrosion properties of PHMG-HC [Choi et al., 2017; Nikkola et al., 2013; Obratsov et al., 2013; Qiu et al., 2023; Farh et al., 2023];
- environmental impact of PHMG-HC and indicators of epidemiological safety and harmlessness of water [Vointseva, 2011; Mariievskiy et al., 2009; Wang et al., 2020];

- the effect of hydrodynamically active substances on the hydraulic resistance in pipelines (Toms effect) [Picardo et al., 2023; Baakeem et al., 2024; Graham, 2014];
- justification of the feasibility of conducting experimental studies on the technology of PHMG-HC use and its technical and economic efficiency [Prokopov et al., 2020; Ministry of Health of Ukraine, 2010].

Corrosion and the formation of biological film on the internal surfaces of pipelines are serious problems for all water transport systems and technological equipment operating in the water environment [Farh et al., 2023]. Such changes in pipelines are caused, in particular, by an acidic environment, oxygen dissolved in water, oxidants, microflora, etc.

They also contribute to the deterioration of the chemical composition and epidemiological safety of water supplied to consumers (population, food, and other industries), deep damage to metal structures and communications, an increase in the number of accidents and water losses during transportation, and, ultimately, significant economic costs. Corrosion processes are significantly accelerated when traditional oxidising biocides (chlorine and chlorine-containing reagents) are used for water disinfection. It should be noted that the chlorine resistance formed by some water microorganisms is often combined with the resistance of these microorganisms to antibiotics, which does not contribute to the epidemic safety of water, and the by-products of water chlorination worsen its toxicity [Mariievskiy et al., 2009; Prokopov et al., 2020; Vointseva, 2011].

Studies carried out under laboratory and industrial conditions [Vointseva et al., 2018; Obratsov et al., 2013; Nikkola et al., 2013] have shown that the macromolecular nature of PHMG-HC, as well as the presence of positively charged biocidal guanidine groups in its composition, determine the ability of the polymer to form strong, non-washable biocidal films on metal surfaces that protect the metal surface from corrosion and biofouling. An important conclusion is that the replacement of oxidising reagents in the water treatment process with a disinfectant based on PHMG-HC helps to clean old pipelines from the accumulation of biocenosis components and Fe salts.

An overview of classical approaches and theories justifying the use of methods for reducing hydraulic resistance in pipelines (Toms effect)

is given in [Baakeem et al., 2024; Picardo et al., 2023; Xi, 2019; Zhang et al., 2021; Kamel and Shah, 2009; Graham, 2014]. It has been shown in [Bizotto and Sabadini, 2008; Soares et al., 2020], stating that water-soluble macromolecules of some natural and synthetic polymers, in particular polyethylene oxide, polyacrylic acid, polyacrylamide, and poly N-vinylformamide, are effective among the promising compounds of recent decades that can be used as anti-turbulence reagents. However, objective difficulties in their use (e.g., toxicity to humans and the environment in effective concentrations, rather rapid degradation in pipes and during storage) [Edson, 2020; Pereira and Soares, 2012; Hashlamoun et al., 2023; Liberatore et al., 2004] do not allow their use in the domestic drinking water supply.

For the first time in 2019, a hypothesis was formulated regarding the ability of PHMG-HC-based reagents to exhibit hydrodynamic activity in aqueous solutions and the possibility of using PHMG-HC to reduce hydrodynamic resistance in the water supply network [Nizhnik et al., 2019]. The presence of even small amounts of high-molecular-weight polymers in fluids significantly reduces flow resistance. These polymers can be used in firefighting, primarily due to the reduced energy required for water pumping [Figueredo and Sabadini, 2003; Zhartovsky and Maglyovana, 2020].

In laboratory viscometric studies, it has been shown that the hydrodynamic activity of PHMG-HC in aqueous solutions can be caused by conformational changes in the PHMG-HC macromolecules during the movement of the solution in the flow [Nizhnik et al., 2019]. Since PHMG-HC is a polyelectrolyte, its macromolecules have a significant positive charge, which is compensated in aqueous solution by mobile counter-ions (chloride ions). The effect of water structuring at high flow rates can prevent the formation of turbulence in the flow and lead to a decrease in hydrodynamic resistance in the flow.

The unresolved issues of the mechanism of action of polymer solutions as reagents capable of changing the hydrodynamic resistance in pipelines seriously limit the use of such polymers in the operation of water supply systems in normal and extreme situations. Therefore, the study of the mechanism of reducing hydraulic resistance in pipelines is of both theoretical and practical, technological importance and is relevant for the companies that operate water supply systems under normal and extreme conditions.

While analysing this problem, the authors focused on PHMG-HC, one of the guanidine polymers, as the possibilities of their use to reduce hydraulic resistance [Maglyovana et al., 2020] can be combined with other known properties of PHMG-HC, as already mentioned in this review of information sources: anticorrosive properties [Vointseva et al., 2018], stability during use and storage for more than 1 year [Ministry of Health of Ukraine, 2010], pronounced antibacterial and virucidal activity [Choi et al., 2017; Wang et al., 2020; Zhou et al., 2015], safety for humans and the environment, availability of permits from the Ministry of Health of Ukraine for the domestic PHMG-HC-based reagent for use in drinking water treatment technologies and approved methodological documents for the implementation of such use [Ministry of Health of Ukraine 2013].

To improve the engineering and technical measures for the operation of water supply systems under normal conditions and in the aftermath of emergencies, it is advisable to conduct model and field tests of the effect of adding a reagent, the active ingredient of which is PHMG-HC, to analyse the conditions under which its effective use for public water supply and energy saving at enterprises is possible.

MATERIALS AND METHODS

For the experimental studies, tap water (with a total hardness of 3.70 mg-eq/dm³) and aqueous solutions of PHMG-HC, which is the active ingredient of the complex action reagent “Aquat-10”, were used.

The polymer (PHMG-HC, average molecular weight 12 000), obtained by a patented synthesis technology [Nyzhnyk et al., 2007] (manufactured by LLC STC “Ukrvodbezpeka”, Ukraine, Kyiv), allows obtaining a polymer with macromolecular parameters typical for hydrodynamically active polymers, was used in the study. The Ministry of Health of Ukraine has approved Aquat-10 reagent for use in the treatment of water and water supply systems, capping of mineral water sources, containers at food industry enterprises, etc. [Ministry of Health of Ukraine 2013].

Experimental studies were conducted using the laboratory equipment of the National University of Civil Defence of Ukraine.

PHMG-HC aqueous solutions were prepared by mixing tap water with pre-prepared

concentrated PHMG-HC aqueous solutions of known concentration in a water intake tank of the pumping unit. The latter were used 24 hours after dissolving the exact PHMG-HC weight quantities in water.

Under laboratory conditions, the pipeline model was a 140 m long fire hose, which, according to the literature [Kolesnikov et al., 2014], exhibits the same phenomena as conventional pipelines, namely, pressure loss along the length, water hammer, etc.

Water and PHMG-HC aqueous solutions were supplied by a pump from a water intake tank (with a volume of 1 m³) through a hose line (with a diameter of 125 mm), which was collected from pressure-suction fire hoses to hand-held fire-hose nozzle RSK-50 (with a nozzle diameter of 13 mm, a spray nozzle angle of 30°, an operating pressure of 3 bar).

The used pumping unit (Fig. 1) allows conducting the research related to the fluidity of liquids and to record the indicators controlled in the experiments. An 18-kW asynchronous three-phase electric motor and a centrifugal liquid pump in the system can provide water flow rates of up to 48 m³/h with a pressure of up to 1 MPa and conduct research with various types of hydraulic hand-held firefighting equipment.

The electric motor is controlled by a Danfoss VLT 6000 HVAC frequency converter, which allows obtaining the required fluid pressure value. Pressure measurement: KRT-Ex pressure transmitter with a measuring limit of 2.5 MPa, accuracy class 1.

Flow rate measurement (Fig. 2): SDM 1022 electromagnetic liquid flow rate transducer

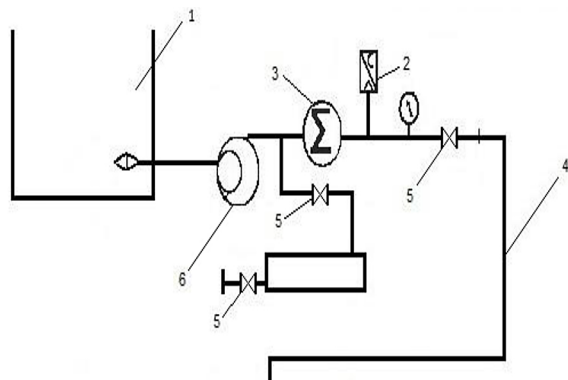


Figure 1. Scheme of the pumping unit: 1 – 1 m³ tank; 2 – analogue pressure transducer; 3 – electromagnetic fluid flow rate transducer; 4 – Ø51 mm hose; 5 – shut-off valves; 6 – centrifugal pump

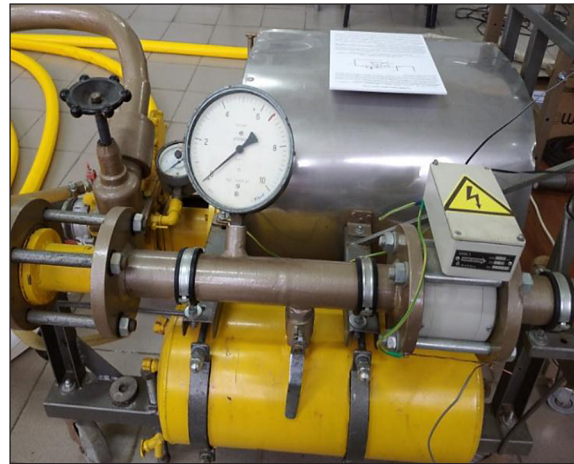


Figure 2. Photo of the pumping unit

(maximum relative error at a flow rate of 0.65 m³/h is ~2%; accuracy class 2), which can operate in the flow rate range from 0.26 m³/h to 65 m³/h.

The instrumentation used in the control system of the pumping unit made it possible to measure the main parameters of the flow rate in the feed pipeline depending on the parameters of the resulting jets (velocity and flow rate coefficients) [Kolesnikov et al., 2014; Zhang et al., 2020].

The study was conducted in two stages. At the first stage, the changes in the flow rate of water and PHMG-HC aqueous solutions were determined at a constant pressure value in the hose line and at different concentrations of the polymer in water. The pressure value was determined by pressure gauges with a pressure transducer. At the second stage, the changes in the flow rate of water and PHMG-HC aqueous solutions were studied at different pressure values in the hose line (Figure 3).

RESULTS AND DISCUSSION

The generalised results of determining the flow rates of tap water and PHMG-HC aqueous solution at a constant pressure value in the hose line of fire-hose nozzle RSK-50 are shown in Figure 4.

As it can be seen from Figure 4, the flow rate of PHMG-HC aqueous solution at a constant hose line pressure (3 bar) increases significantly with increasing polymer concentration and is maximum at a PHMG-HC concentration of 0.2%. Statistical data processing allows presenting this dependence in the form of a polynomial (Table 1, where R² is the reliability of the approximation of experimental data depending on the polynomial degree).



Figure 3. Photo of the hose line L = 140 m

The next stage of the study was to determine the changes in the flow rate of water and PHMG-HC aqueous solutions at different pressure values in a 140 m long hose line (Fig. 3). The concentration of PHMG-HC in the studied aqueous solutions was 10 mg/L.

It was experimentally established that the fluid flow rate increased when using PHMG-HC aqueous solutions at different values of pressure

in the hose line, which suggests the presence of a certain decrease in the hydrodynamic friction resistance in the hose line.

Thus, when using PHMG-HC aqueous solution (10 mg/L), depending on the pressure, its flow rate increases by 3% to 10% (compared to water, Fig. 5).

The maximum increase in the flow rate of PHMG-HC aqueous solution by 10% to 11% was found at a pressure of 2 bar. That is, under these experimental conditions, the hose line “operated” in the mode of reducing hydrodynamic resistance by almost 10% to 11%.

The obtained results of experimental studies allow making rather cautious assumptions about the possibility of industrial use of reagents based on PHMG-HC for water treatment, which can decrease (by ~10% to 11%) electricity consumption for pumping and transporting water.

Such assumptions are made by the model chosen for the research, namely, fire hoses, during the operation of which the same phenomena inherent in conventional pipelines (pressure loss along the length, water hammer) are observed.

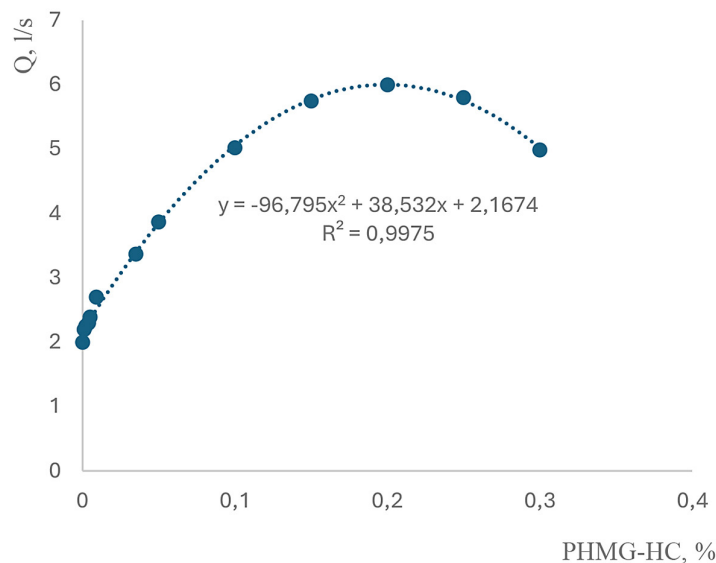


Figure 4. Dependence of PHMG-HC aqueous solution flow rate on the polymer concentration in water when using fire-hose nozzle RSK-50 (with a nozzle diameter of 13 mm, a spray nozzle angle of 30°, an operating pressure of 3 bar)

Table 1. Dependence of the flow rate of PHMG-HC aqueous solution on the polymer concentration

Polynomial degree	Dependence of the flow rate of PHMG-HC aqueous solution on the polymer concentration	R ²
2	$y = -96.795x^2 + 38.532x + 2.1674$	0.9975
3	$y = -5.5201x^3 - 94.405x^2 + 38.289x + 2.1694$	0.9975
4	$y = -608.75x^4 + 349.97x^3 - 157.42x^2 + 41.61x + 2.1534$	0.9978
5	$y = 5774x^5 - 4833.5x^4 + 1414.1x^3 - 263.53x^2 + 45.025x + 2.1426$	0.9979

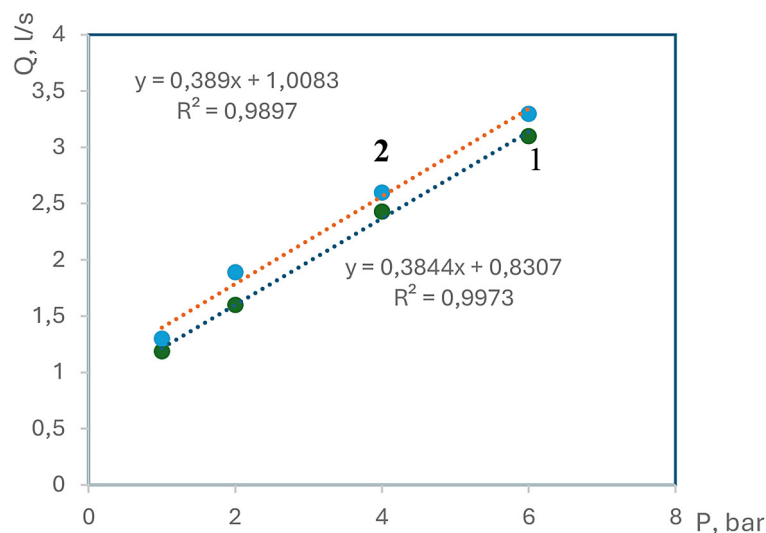


Figure 5. Flow rates of water (1) and PHMG-HC aqueous solution (2) at different pressure values when using the hose line of fire-hose nozzle RSK-50

Also, the data from literature sources and own research, the analysis of information sources shows the positive impact of PHMG-HC on the surface condition of pipelines, since corrosion and bio-fouling occur during pipe operation, and the use of PHMG-HC helps to minimise them on pipes made of different materials.

Taking into account the positive experience of using PHMG-HC-based reagent in water treatment, its safety for humans and the environment, the availability of permits from the Ministry of Health of Ukraine for a domestic reagent based on PHMG-HC for use in drinking water treatment technologies and approved methodological documents for the implementation of such use, it was considered appropriate to carry out the next stage of work.

The need for full-scale testing of the effect of the reagent, the active ingredient of which is PHMG-HC, is due to the importance of analysing and specifying the conditions under which it can be effectively used for water supply to the public and energy saving at enterprises, i.e. improving engineering, technical and sanitary and anti-epidemic measures for the operation of water supply systems.

Furthermore, the application of water transport systems using the studied polymer can be used to manage environmental risks in extreme situations related to the elimination of the consequences of human-caused accidents and disasters, localisation of toxicants in the lithosphere, reduction of dust pollution during firefighting and emergency situations.

CONCLUSIONS

On the basis of the research results, the following conclusions were presented:

1. It has been experimentally established that aqueous solutions of polyhexamethylene guanidine hydrochloride (PHMG-HC) (in the studied concentration range of 0.001% to 0.3%) exhibit hydrodynamic activity.
2. The flow rate of PHMG-HC aqueous solution when using the fire-hose nozzle RSK-50 depends on the polymer concentration in the solution and the pressure in the hose line.
3. In laboratory studies, it was found that the flow rate of PHMG-HC aqueous solution at a constant pressure in the hose line (3 bar) is maximum at a concentration of PHMG-HC of ~0.2%.
4. According to the results of experimental studies, it was found that when adding PHMG-HC aqueous solution, the maximum increase in fluid flow rate occurs at a pressure of 2 bar and reaches ~10% to 11%, taking into account the error of laboratory set-ups and metrological equipment.
5. The obtained research results suggest that the hose line and fire-hose nozzle in the presence of PHMG-HC (10 mg/L) in the water and at a pressure of 2 bar operated in the mode of reducing hydrodynamic resistance by almost 10%.

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