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Investigation of Preliminary Dilution Process for Return Water before Discharge into Water Body

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Abstract

One of the methods to intensify the initial dilution process of return water from a sewage treatment facility is to disconnect individual diffuser-type return water discharge devices. It is proposed to perform pre-dilution of return water in a mixer with water from the receiving water body into which they are discharged. The return water should pass into the mixer through the water discharge devices (nozzles) of the distribution pipeline. Empirical research methods were used in this work. The experiments were conducted using the model water. In the hydraulic flume, the water flow was in a calm state, while in the distribution pipeline, the flow regime was turbulent. An increase in return water dilution by 12.2% was achieved by reducing the number of nozzles in the distribution pipeline from seven to four. This confirms the possibility of intensifying the return water dilution by avoiding the interaction between the jets emerging from the discharge devices in the distribution pipeline. If necessary, it is recommended to use the ways of increasing the flow rate of return water from the discharge devices.

Keywords: return water; distributive pipeline; submerged outflow; initial dilution; liquid mixer.

1. Introduction

Water bodies are among the most altered ecosystems in the world, and for almost two centuries, large-scale human use of water bodies has resulted in poor water quality and ecological degradation in these systems [1]. Before the second half of the 20th century, raw sewage was typically dumped directly into a water body, relying on dilution and natural purification processes to treat wastewater [2].

Worldwide, the discharge of treated wastewater (return water) to water bodies is becoming more common as urban populations grow and developing countries increase their use of wastewater treatment plants. Discharge of return water can impair water quality, but also could help restore flow and maintain aquatic state in water-stressed regions [3].

For a water body, to intensify the initial dilution process of return waters, it is proposed to disconnect individual diffuser-type wastewater discharge devices [4]. Because increasing the area ratio of the distribution pipeline leads to greater unevenness in the distribution of liquids along the path [5].

The proposed structure for discharging return waters into a water body [6] (see Fig. 1) involves the following steps. After passing through sewage treatment facilities (STFs), the return water enters a mixer, which is supplied with water from the receiving water body. To ensure preliminary dilution of the return waters in the mixer, a distribution pipeline (DP) with water discharge devices is installed (see Fig. 2). The mixer operates without pressure, while the distribution pipeline is pressurized.

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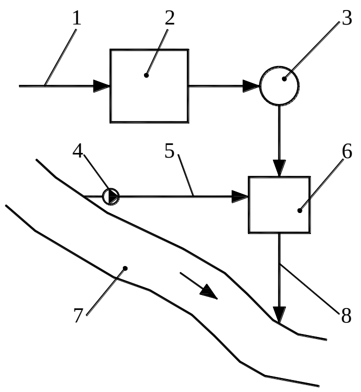

Fig.1. Schematic diagram of facility for discharging the return water into the water body:
1 – pipeline from sewage treatment plant; 2 – regulating tank; 3 – sewer manhole with dosing apparatus; 4 – pump;
5 – pressure pipeline; 6 – mixer of return water; 7 – water body; 8 – outlet of preliminary diluted return water into water body.

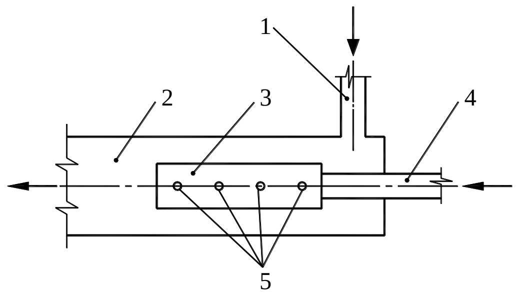

Fig.2. Schematic diagram of mixer with preliminary dilution of return water:
1 – pressure pipeline; 2 – mixer; 3 – distributive pipeline; 4 – pipeline from sewer manhole with dosing apparatus; 5 – water outlet.

2. Formulation of the goal of the paper

The goal of this study is to investigate the hydraulic processes of submerged outflow from a pressurized distribution pipeline with varying numbers of water discharge devices, in order to predict the preliminary dilution of return water. Empirical research methods were employed in this work.

3. Analysis of the recent publications and research works on the problem

The description of the experimental setup and research methodology is provided in reference [7]. The distribution pipeline was installed on flanges at the bottom of the hydraulic flume. To ensure uniform outflow of liquid from the water discharge devices in the DP, it is necessary to adhere to the condition [8] of $\beta \leq 1.2$, where β represents the coefficient of unevenness in liquid outflow [8] and it is calculated as follows:

$$\beta = \frac{q_i}{q_k}, \tag{1}$$

where q_i and q_k are the flow rates through the *i*-th and the terminal (end-point for the flow of wastewater) water discharge device, respectively.

During the design of the DP, the following number of water discharge devices is typically considered [8]: up to 20 devices when *d/D* falls within the range of 0.1 to 0.2, and up to 15 devices when *d/D* is in the range of 0.20 to 0.35, where *d* represents the diameter of the discharge device opening, and *D* is the diameter of the DP.

The distribution pipeline has a rectangular cross-section with internal dimensions of $a \times b$ = 0.100×0.040 m, and there is no end water discharge device (see Fig.3). Its hydraulic diameter D_h is equal to 4*R*, where *R* represents the hydraulic radius of the DP, calculated as:

$$R = \frac{a \cdot b}{2 \cdot (a + b)}. \quad (2)$$

Based on the values of a and b we get R = 0.014 m and D_h = 0.056 m.

The water discharge devices are external cylindrical nozzles with the length of L_n = 4.67 d and the diameter of d = 0.006 m (see Fig. 4). Therefore, d/D_h = 0.107. The number of nozzles can be up to 20 pieces.

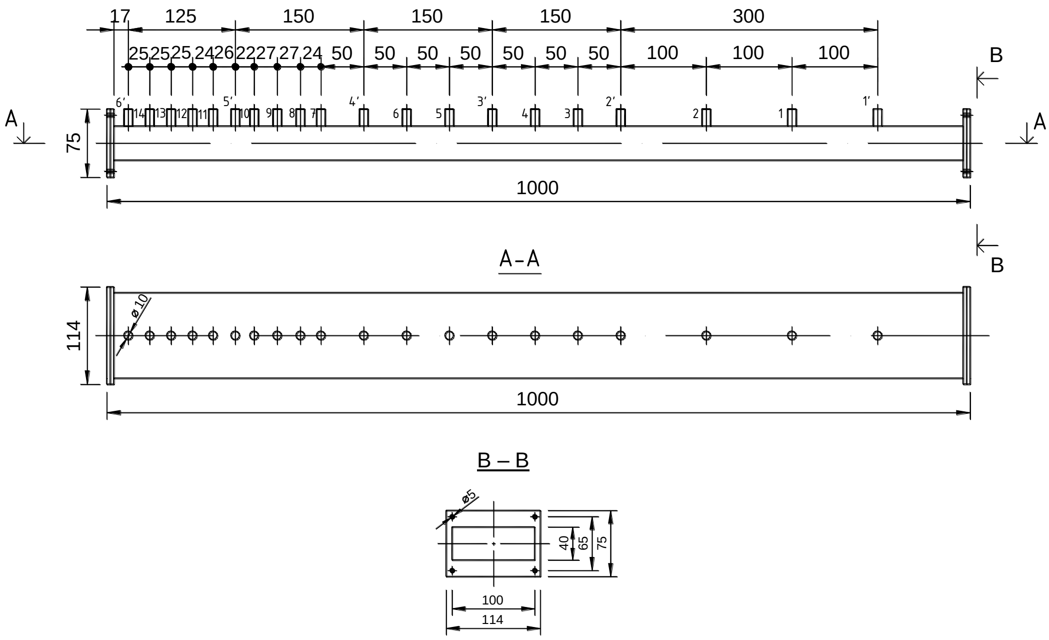

Fig.3. Schematic diagram of distributive pipeline:
1…14 – outlet cylindrical nozzles; 1'…6' – pressure selection tap.

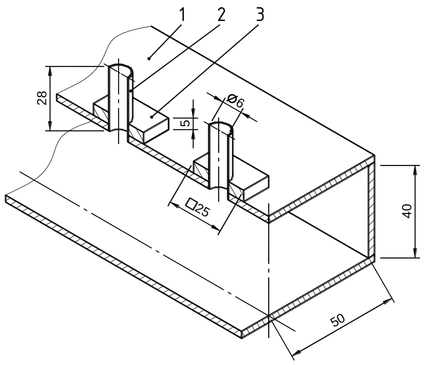

Fig.4. Schematic diagram of nozzles and taps connection to distributive pipeline:
1 – distributive pipeline; 2 – outlet cylindrical nozzle or pressure selection tap; 3 – fastening.

The area ratio of DP is calculated as follows [8]-[10]:

$$f = \frac{n \cdot \omega}{a \cdot b}, \quad (3)$$

where n is the number of nozzles (water release devices in DP); ω is the cross-sectional area of a nozzle.

The cross-sectional area of a nozzle is defined as

$$\omega = \frac{\pi \cdot d^2}{4}. \quad (4)$$

The water flow rate through the *i*-th nozzle is calculated as:

$$q_i = \mu_i \cdot \omega_i \cdot \sqrt{2g(H_p)_i}\ , \tag{5}$$

where μ is the nozzle flow rate coefficient, $\mu = f(\mathrm{Re})$; Re is the Reynolds criterion for the nozzle; H_p is the working pressure in the nozzle cross-section.

The Reynolds criterion is defined as:

$$\mathrm{Re} = \frac{d \cdot \sqrt{2gH_p}}{\nu}\ . \tag{6}$$

The working pressure in the nozzle cross-section, according to [10], is calculated as:

$$H_p = \frac{p}{\rho \cdot g} - h, \tag{7}$$

where $p/(\rho \cdot g)$ is the piezometric pressure in the nozzle cross-section; h is the height from the top of the nozzle to the water level in the hydraulic tray.

The height from the top of the nozzle to the water level in the hydraulic tray is defined as [7]:

$$h = Z_t - a_n, \tag{8}$$

where Z_t is the depth of water in the hydraulic tray; a_n is the height of the nozzles above the bottom of the hydraulic tray; ν is the kinematic viscosity of water as the working fluid.

The kinematic viscosity of water is calculated according to [11]:

$$\nu = \frac{177.5 \cdot 10^{-8}}{1 + 0.0337 \cdot T + 0.000221 \cdot T^2}\ , \tag{9}$$

where T is the water temperature.

The volumetric flow rate of water in the hydraulic tray was determined using the formula [12]:

$$Q_t = m \cdot b_s \cdot H \cdot \sqrt{2gH}\ , \tag{10}$$

where m is the discharge coefficient for a thin-walled spillway; b_s is the width of spillway ($b_s = 0.202$ m [7]); H is the water head at the spillway.

For an unsubmerged spillway without lateral contraction the discharge coefficient is calculated as [12]:

$$m = \left(0.405 + \frac{0.003}{H}\right) \times \left[1 + 0.55 \cdot \left(\frac{H}{H+P}\right)^2\right], \tag{11}$$

where P is the height of the spillway sill ($P = 0.48$ m).

The water head at the spillway is defined as:

$$H = Z - Z_0, \tag{12}$$

where Z and Z_0 are the water levels above the sill and at the sill of the spillway respectively.

The kinematics parameter is calculated as [11], [12]:

$$K = \frac{\alpha V_t^2}{gZ_t}\ , \tag{13}$$

where α is the kinetic energy coefficient (according to [12], α = 1.05…1.10); V_t is the average velocity of water movement in the hydraulic tray.

The average velocity of water movement in the hydraulic tray is defined as:

$$V_t = \frac{Q_t}{Z_t \cdot B}, \tag{14}$$

where B is the width of the hydraulic tray (B = 0.250 m [7]).

4. Presentation and discussion of the research results

The DP is made of transparent plexiglass. The DP has six metal pressure sampling fittings and the number of nozzles is n = 14 (see Fig.3).

In the studies, the water from the closed-loop hydraulic system of the educational laboratory of hydraulics at the Department of Hydraulic and Water Engineering of Lviv Polytechnic National University was used. Its temperature was T = 18 °C, and its quality differed from that of tap water.

The bottom of the hydraulic tray is horizontal, i.e. with zero slope (i = 0).

The experiments were conducted with a constant volumetric flow rate of water in the hydraulic tray (Q_t = const).

Unlike [13], where unsubmerged water outflow from DP under air influence was considered, the water flow in the hydraulic tray was in a calm state (kinematics parameter $K < 1$) and did not significantly affect the submerged outflow of water from the nozzles.

The experiments were conducted for DP with the area ratio of f = 0.0707 and 0.0495. In the first case, nozzles 1, 3, 5, 7, 9–14 were used, and in the second case, 1, 3, 5, 7, 10, 12, 14 and 3, 5, 7, 10, 12–14 (see Fig.3).

The Reynolds criterion for the nozzles $\mathrm{Re} > 2 \cdot 10^4$. Therefore, the discharge coefficient was taken as m = 0.804 = const [11].

The intensity of water detachment in the i-th cross-section of the DP can be represented as [14]:

$$\left(\frac{Q_{tr}}{Q_f}\right)_i = f[(\mathrm{Re}_R)_i], \tag{15}$$

where $(Q_{tr})_i$ is the transit flow rate of water in the i-th cross-section of the DP (see Fig.5); $(Q_f)_i$ is the path water flow rate in the i-th cross-section of the DP; $(\mathrm{Re}_R)_i$ is the Reynolds criterion in the i-th cross-section of the DP.

The transit flow rate of water in the i-th cross-section of the DP is calculated as:

$$(Q_{tr})_i = Q_0 - (Q_f)_i, \tag{16}$$

where Q_0 is the water flow rate at the beginning of the DP, $Q_0 = \sum_{i=1}^{n} q_i$.

The path water flow rate in the i-th cross-section of the DP is defined as:

$$(Q_f)_i = \sum_{j=1}^{i} q_j . \tag{17}$$

The Reynolds criterion in the i-th cross-section of the DP is calculated as

$$(\mathrm{Re}_R)_i = \frac{V_i \cdot R}{\nu}, \tag{18}$$

where V_i is the velocity of water movement in the i-th cross-section of the DP, defined as

$$V_i = \frac{(Q_{tr})_i}{a \cdot b}. \tag{19}$$

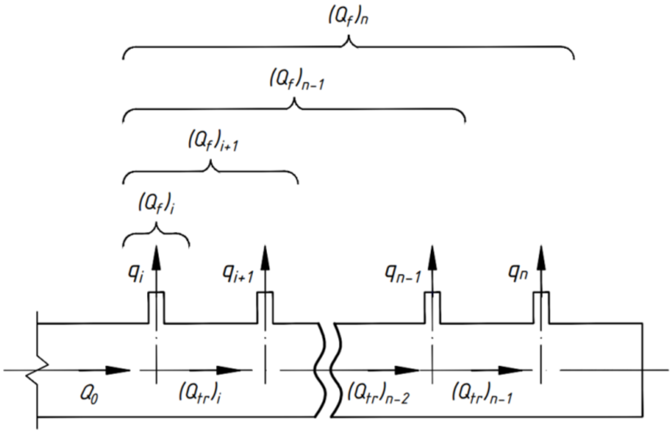

Fig.5. Schematic diagram of the liquid flow in the distribution pipeline and through the nozzles.

Then dependence (15) can be rewritten as:

$$\frac{Q_0}{(Q_f)_i} = 1 + f[(\mathrm{Re}_R)_i]. \tag{20}$$

The intensity of water detachment along the length of the DP was ensured by a constant water flow rate from the nozzles q_i = const. Then, according to formula (1), the discharge non-uniformity coefficient $\beta = 1$. In this case, the DP represented a high-resistance distributor with area ratio of $f \approx V_0 / V$, where V_0 and V are the velocities of water movement at the beginning of the DP and at the nozzle outlet respectively [5].

With uniform distribution of water from the nozzles, $Q_0 = n \cdot q_i$, $(Q_f)_i = i \cdot q_i$, then

$$\frac{Q_0}{(Q_f)_i} = \frac{n}{i}. \tag{21}$$

A different sequence of nozzles used at the same area ratio $f = 0.0495$ almost does not lead to a significant change in the intensity of water detachment along the length of the DP (Fig.6). Therefore, the case with nozzles 3, 5, 7, 10, 12–14 was not further analyzed.

Increasing the number of nozzles in the outer third of the DP for $f = 0.0707$ increases its path flow rate, leading to an increase in the ratio $\sum_{i=1}^{n} q_i \Big/ q_1$ (Fig.7). But in this part of the DP, the nozzles are positioned quite close to each other (Fig.3). This can lead to interaction between the water jets exiting the nozzles, and consequently, to a reduction in the initial mixing of return water [7].

Thus, for nozzles positioned at equal distances from each other, the relative reduction in the mixing of return water [7] is defined as:

$$\Delta N_k = 1 - \frac{\sqrt{k}}{k}, \tag{22}$$

where k is the number of jets interacting with each other.

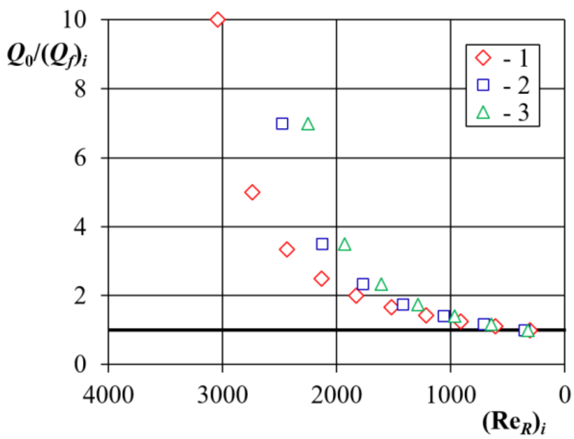

Fig.6. Intensity of water separation along the pass of the distributive pipeline for area ratio $f = 0.0707$ (points 1) and $f = 0.0495$ (points 2 and 3) with outlet nozzles 1, 3, 5, 7, 9–14 (points 1); 1, 3, 5, 7, 10, 12, 14 (points 2); 3, 5, 7, 10, 12–14 (points 3).

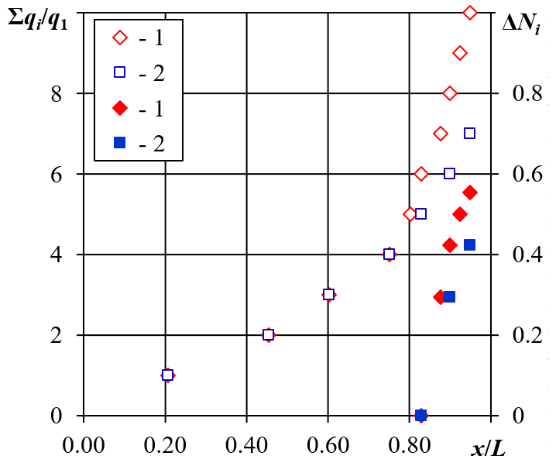

Fig.7. Relative change in the track flow rate in *i*-th cross-section of the distribution pipeline (unshaded points) and the relative decrease in the dilution of return water (shaded points) for area ratio $f = 0.0707$ (points 1) and $f = 0.0495$ (points 2) with outlet nozzles 1, 3, 5, 7, 9–14 (points 1); 1, 3, 5, 7, 10, 12, 14 (points 2).

Let's analyze the relative reduction in the dilution of return water ΔN_k, starting from the relative length of the distribution pipeline $x/L = 0.751$ (Fig.7). So with four jets $\Delta N_4 = 50.0\%$ from the dilution of a single stream for DP with area ratio of $f = 0.0495$; with seven streams $\Delta N_7 = 62.2\%$ – for DP with area ratio of $f = 0.0707$. Therefore, it is better to provide more (in our case by 12.2%) preliminary dilution of return water due to the reduction of their inflow into the mixer with DP at $f = 0.0495$ compared to DP at $f = 0.0707$. Because the ratio $\sum_{i=1}^{n} q_i \big/ q_1$ in the end DP with $f = 0.0495$ is 1.429 times smaller compared to $f = 0.0707$.

So, increase in the dilution of the return water can be achieved by reducing the number of nozzles on the outer third of the DP, bringing its perforation closer to uniform [15].

5. Conclusion

Intensification of the dilution of return water can be achieved by avoiding the interaction of jets with each other, which flow from the distribution pipeline discharge devices. This is achieved by reducing the number of discharge devices regardless of the reduction in the flow rate of return water entering the mixer.

An increase in return water dilution by 12.2% was achieved by reducing the number of nozzles in the distribution pipeline from seven to four.

If necessary, it is recommended to use the ways to increase the flow rate of return water from the discharge devices of the distribution pipeline.

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Дослідження процесу попереднього розбавлення зворотних вод перед скиданням у водний об'єкт

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Анотація

Одним зі способів інтенсифікації процесу початкового розбавлення зворотних вод є відключення окремих водовипускних пристроїв розсіювального випуску зворотних вод. Пропонується проводити попереднє розбавлення зворотних вод у змішувачі водою з водного об'єкта, в який відбувається їх випускання. У змішувач зворотні води повинні надходити крізь насадки – водовипускні пристрої розподільного трубопроводу. В роботі використано емпіричні методи дослідження. Досліди було проведено на модельній воді. У гідравлічному лотку потік води був у спокійному стані, тоді як у розподільному трубопроводі режим руху води був турбулентним. Отримано збільшення розбавлення зворотних вод на 12,2% при зміні кількості насадок розподільного трубопроводу з семи до чотирьох. Це підтверджує можливість інтенсифікації розбавлення зворотних вод завдяки уникненню взаємодії між собою струменів, які витікають з випускних пристроїв розподільного трубопроводу. За необхідності пропонується використовувати способи збільшення витрати зворотних вод з випускних пристроїв.

Ключові слова: зворотні води; розподільний трубопровід; затоплене витікання; попереднє розведення; змішувач рідин.