The research of tubular mixer with improved design

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Abstract. Modern technological schemes in water supply for clarifying surface water include using reagents as coagulants, flocculants, etc. To mix them with the source water on plants usually use different types of mixing devices. Tubular mixer is one of such devices. Our research work involves the study of a tubular mixer with improved design, which can mix several reagents with source water. The paper presents theoretical and experimental studies of the tubular mixer with improved design for mixing several reagents with natural water. It is theoretically and experimentally substantiated the feasibility of using this tubular mixer for mixing several reagents with natural water over a short mixing time. The improved design of tubular mixer can mix several reagents with natural water in a short mixing time, intensify the mixing process and improve quality of water after treatment.

1. Introduction
The most important sectors that determine the level of urban development are: water supply, water and wastewater treatments. Nowadays, a big problem is to supply clean water with high drinking quality to consumers. Water clarification becomes crucial in the integrated system of water supply in cities and villages. Modern technological schemes in water supply for clarifying surface water include using reagents before sedimentation and filtration [1-5]. To mix them with the source water on plants are usually used different types of mixing devices. [6,7]. Tubular mixer is one of such devices. The efficiency of these facilities influences on the efficiency of water clarification. A very important condition for improving the efficiency and depth of coagulation is the rapid and intensity of mixing process in the mixer. Therefore, mixing the source water with the reagents should be complete and rapid. Tubular mixers are widely used in water treatment [8-12], but they have got disadvantages. They are used to mix only one reagent with water and can’t adjust the intensity of mixing process. Therefore, increasing the efficiency of mixing process is a very important task.

We proposed a tubular mixer with improved design [13]. This tubular mixer consists of four sections: two sections for supply and distribution reagents, another two sections have got mixing elements. They are made from porous polymer concrete and have got different thickness, material and size of aggregate.

The aim of the research is to study the tubular mixer with improved design for mixing reagents with water.

2. Material and Methods
A method was proposed to intensify the mixing process for water with reagents. Design changes and the possibility of entering several types of reagents in one mixer will improve the efficiency of water clarification at water treatment plants [13].
The phenomenon of water velocity in porous surroundings in hydraulics is called water filtration. Filtration can be laminar and turbulent.

For laminar filtration, the main dependency is the Darcy equation [14]:

\[ V = k \cdot i, \] (1)

where, \( V \) is filtration velocity, cm/s; \( k \) is filtration constant, cm/s; \( i \) is piezometric level.

We use the dependence (1) if:

\[ Vd < 0.01 \div 0.07, \] (2)

where, \( d \) is average size (diameter) of particle, sm. Filtration takes place through this particles.

If the condition (2) is not implemented, then turbulent filtration takes place.

Filtration velocity is the part of flow which rate to the the intersection area of the porous surroundings where filtration takes place.

The equation (2) shows that the critical velocity for laminar filtration can’t be more than:

\[ V = \frac{0.01+0.07}{d}, \] (3)

At an average size of gravel material of porous surroundings of 2.5 and 3.0 cm, the critical velocity for laminar filtration will accordingly be: 0.004 - 0.028 cm/s and 0.0033 - 0.0233 cm/s.

In this case, when the porous surroundings are placed in the tubular mixer and water velocity in it is more than 0.028 cm/s, then turbulent filtration will occur.

For turbulent filtration conditions, its velocity (m/s) is determined by the equation:

\[ V_t = K_t \cdot \omega^{0.5}, \] (4)

where, \( K_t \) is coefficient of turbulent filtration m/s; \( I \) is hydraulic level.

Based on the calculation of pressure filter mounds we have decided to use the equation of turbulent filtration flow with uniform motion [14]:

\[ Q = K_t \cdot \omega \sqrt{I}, \] (5)

where \( Q \) is water flow rate through the filter embankment, m³/s; \( \omega \) is the living area of the intersection of the filter embankment, m².

Equations (4) and (5) show that:

\[ Q = V_T \cdot \omega \] (6)

If we know water flow rate (Q) and living area of the intersection (\( \omega \)) of the filter embankment, that it is possible to determine the rate of turbulent filtration:

\[ V_T = \frac{Q}{\omega} \] (7)

And after that we can use the equation (4) to determine the hydraulic level:

\[ I = \left( \frac{V_T}{K_T} \right)^2, \] (8)

where, \( K_T \) is determined by the follow equation (cm/s):

\[ K_T = 18\rho \sqrt{d}, \] (9)

where, \( \rho \) is coefficient of porosity. For gravel this coefficient is \( \rho = 0.4 \); \( d \) is diameter of filter material, cm.

Thus, the head loss in the porous polymer concrete partition can be determined by the equation:

\[ \Delta h = \left( \frac{V_T^3}{K_T^2} \right) \cdot \delta, \] (10)
where $\delta$ is thickness of porous polymer concrete (cm).

All mixing devices should satisfy the efficiency and intensity of mixing process, but there is another economic issue. In this case, this is the head loss in the porous area, which influences on pressure of pumps.

The intensity of mixing process is the energy $N_P$ that must be spent on mixing an unit of volume ($N_P/V$) or mass ($N_P/\rho Q$) of liquid per unit time to obtain the desired quality of the mixture.

The energy $N_P$, which can be used for mixing process in a porous area, we can find by the follow equation:

$$N_P = \Delta P \cdot V,$$

where $\Delta P$ is pressure drop, Pa; $V$ is volumetric flow rate, m$^3$/s.

Therefore, the mixing intensity in the porous area depends entirely on the pressure drop:

$$I = \frac{N_P}{V} = \frac{\Delta P \cdot V}{V} = \Delta P$$

In this way, the greater loss of head in a porous area is, the greater the intensity of mixing process will be.

3. Experimental and numerical database

For experimental research, we have created a model of a tubular mixer with a constant diameter of 100 mm in the laboratory of the Department of Water Supply, Sewerage and Hydraulics of Kharkiv National University of Civil Engineering and Architecture. The scheme of the experimental setup is shown in Figure 1.

![Figure 1. Scheme of the experimental setup.](image)

This scheme includes: a tubular mixer (1) which has four sections: first section (2) is for distribution part of sulfuric acid aluminum; the second section (3) is the first mixing element, which made from porous polymer concrete with a gravel aggregate with average size ($d_{ave} = 25$ mm) and a length of 80 mm; third section (4) is for distribution another part of sulfuric acid; fourth section (5) is the second mixing element, which made from porous polymer concrete with gravel aggregate ($d_{ave} = 30$ mm) and a length of 120 mm and Mariotte vessel (6). The hoses (7) regulate the flow of coagulant (8). Tap water through the pipe (10) supplies to the tank (11) and from there by the pump (12) is transported into the tubular mixer (1). Through the pipe (13) volume of water moves into the collecting tank (23). From there by the submerged pump 14 through the pipeline 15 is discharged into the sewer. The tubular mixer (1) has a sampler (16), pressure gauges (17) and a return water supply line (18). The mixer is equipped with
a shut-off valve (19) and a water counter (20). All sections of the tubular mixer is connected with the flanges (21). The pipe (22) is used to mix the water in the tank (11).

The experiments were carried out at a water temperature of from 7 to 17 °C (at different times of the year). The flow speed in the mixing elements was from 0.6 to 1.2 m/s. Suspended solids concentration in source water was from 50 to 140 mg/dm³. The silt was from the Siverskyi Donets River and we used them as an opacifier. Mixing elements were made from gravel on epoxy resin brand ED - 20. This material is characterized by high strength, good chemical resistance to the aggressive effect for water with reagents, and, finally, permitted by the Ministry of Health of Ukraine for using in water supply systems.

The first stage of the research was carried out to determine the pressure loss in the mixing elements. They were determined by the difference between the values of manometers (17), which were installed before and after the mixing element (Fig. 1). Water from the tank (11) was transferred by the pump (12) into the mixer (1), and then through the pipes (18) again returned to the tank (11).

The second stage of this research was to determine the efficiency of the tubular mixer. In the tank (11) was added the sludge and the pump (12) mixed it with water. After mixing, we determined the dose of coagulant (sulfuric acid aluminum) using the device “Drop” for trial coagulation.

Experimental studies were performed according to the method, which described in the work [13].

The experimental dependences of the pressure drop on the flow velocity in the tubular mixer are shown in Table 1. A Table 2 shows the experimental and theoretical databases of the pressure drop in the mixing elements. The theoretical values of the pressure drop in the mixing elements were determined by equations (7), (9) and (10).

The Table 1 shows that with increasing velocity of water the pressure drop increases and reaches considerable values. The water temperature slightly affects the viscosity of the water. Unfortunately, it was not possible to fix it with the help of gauges. To reduce the magnitude of the pressure drop in the mixing elements, materials with high porosity should be used as a filler for porous polymer concrete.

### Table 1. Experimental values of pressure drop in tubular mixer and in mixing elements

| The water velocity in the mixer, m/s | Temperature, °C | Manometer readings, kPa | Pressure drop kPa | Pressure drop kPa in the mixer |
|-----------------------------------|----------------|-------------------------|------------------|-----------------------------|
|                                   |                | 1  | 2  | 3            | 1st mixing element | 2nd mixing element |
| 1                                 | 0.6            | 7  | 69.6 | 46.6 | 12.1 | 23            | 34.5        | 57.5        |
| 2                                 | 0.6            | 9  | 69.7 | 46.4 | 12.1 | 23.1        | 34.5        | 57.6        |
| 3                                 | 0.6            | 14 | 69.4 | 46.3 | 12.1 | 23.1        | 34.2        | 57.3        |
| 4                                 | 0.6            | 17 | 69.4 | 46.5 | 12.1 | 22.9        | 34.4        | 57.3        |
| 5                                 | 0.8            | 7  | 105.0 | 63.9 | 12.9 | 41.1        | 51          | 92.1        |
| 6                                 | 0.8            | 9  | 104.6 | 64  | 12.9 | 40.6        | 51.1        | 91.7        |
| 7                                 | 0.8            | 14 | 104.7 | 63.8 | 12.9 | 40.9        | 50.9        | 91.8        |
| 8                                 | 0.8            | 17 | 104.8 | 63.9 | 12.9 | 40.9        | 51          | 91.9        |
| 9                                 | 1.0            | 7  | 157.1 | 93.5 | 14.2 | 63.6        | 79.3        | 142.9       |
| 10                                | 1.0            | 9  | 157.2 | 93.7 | 14.2 | 63.5        | 79.5        | 143.0       |
| 11                                | 1.0            | 14 | 157.0 | 93.5 | 14.2 | 63.5        | 79.3        | 142.8       |
| 12                                | 1.0            | 17 | 156.9 | 93.5 | 14.2 | 63.4        | 79.3        | 142.7       |
| 13                                | 1.2            | 7  | 222.1 | 130.0 | 15.8 | 92.1        | 114.2       | 206.3       |
| 14                                | 1.2            | 9  | 222.0 | 130.0 | 15.8 | 92.0        | 114.2       | 206.2       |
| 15                                | 1.2            | 14 | 222.1 | 130.1 | 15.8 | 92.0        | 114.3       | 206.3       |
| 16                                | 1.2            | 17 | 222.0 | 130.1 | 15.8 | 91.9        | 114.3       | 206.2       |

The Table 2 shows that the experimental and theoretical values of the pressure drop in the mixing elements has difference (from 4.4 to 5.6%), but remain constantly above the theoretical. This can be
explained by the fact that pore channels, in the connected porous structure, have a smaller diameter than the bulk material.

### Table 2. Experimental and theoretical values of the pressure drop in the mixing elements

| The water velocity in the mixer, m/s | Experimental determination of pressure drop, kPa | Theoretical value of the pressure drop, kPa | Deviation, % |
|-------------------------------------|-----------------------------------------------|---------------------------------------------|--------------|
| 1                                   | 23 23.5 21.8 32.7 5.2 5.2                   | 1                                           | 2            |
| 2                                   | 23.1 34.5 21.8 32.7 5.6 5.2                   | 2                                           | 3            |
| 3                                   | 23.1 34.2 21.8 32.7 5.6 4.4                   | 3                                           | 4            |
| 4                                   | 22.9 34.4 21.8 32.7 4.8 4.9                   | 4                                           | 5            |
| 5                                   | 41.1 51.0 38.8 48.4 5.6 5.1                   | 5                                           | 6            |
| 6                                   | 40.6 51.1 38.8 48.4 4.4 5.3                   | 6                                           | 7            |
| 7                                   | 40.9 50.9 38.8 48.4 5.1 4.9                   | 7                                           | 8            |
| 8                                   | 40.9 51.0 38.8 48.4 5.1 5.1                   | 8                                           | 9            |
| 9                                   | 63.6 79.3 60.5 75.7 4.9 4.5                   | 9                                           | 10           |
| 10                                  | 63.5 79.5 60.5 75.7 4.7 4.8                   | 10                                          | 11           |
| 11                                  | 63.5 79.3 60.5 75.7 4.7 4.5                   | 11                                          | 12           |
| 12                                  | 63.4 79.3 60.5 75.7 4.6 4.5                   | 12                                          | 13           |
| 13                                  | 92.1 114.2 87.2 108.9 5.3 4.6                 | 13                                          | 14           |
| 14                                  | 92.0 114.2 87.2 108.9 5.2 4.6                 | 14                                          | 15           |
| 15                                  | 92.0 114.3 87.2 108.9 5.2 4.7                 | 15                                          | 16           |
| 16                                  | 91.9 114.3 87.2 108.9 5.1 4.7                 | 16                                          |              |

Table 2 is the 1st mixing element; 2 is the 2nd mixing element and 3 is tubular mixer

Based on the Table 1 we have made graphs of the dependence of the pressure drop in the mixing elements and in the tubular mixers on the flow velocity in the device, which is presented in Figure 2.

**Figure 2.** Dependences of the differential pressure $\Delta P$ in the mixing elements and in the tubular mixer on the flow velocity $V$ in the mixer
From the Figure 2 we have concluded that results connect well with the theory. The pressure drop is proportional to the square of the fluid flow velocity.

In the Table 3 results of experiments that were conducted to determine the efficiency of the tubular mixer is shown.

| Turbidity of source water, (NTU) | Temperature of the water in a mixer (°C) | The velocity of water in a mixer (m/s) | Turbidity of clarified water (NOC) | Coefficient of deposition efficiency, $K$ |
|----------------------------------|------------------------------------------|--------------------------------------|----------------------------------|----------------------------------------|
|                                  |                                          |                                      | $C_y$                            | $C_t$                                  |
| 1                                | 171.0                                    | 17                                   | 0.9                              | 13.6                                   | 11.8                                   | 1.15                                  |
| 2                                | 86.0                                     | 17                                   | 0.9                              | 13.7                                   | 11.8                                   | 1.15                                  |
| 3                                | 223.6                                    | 15                                   | 0.9                              | 14.6                                   | 12.8                                   | 1.14                                  |
| 4                                | 240.8                                    | 12                                   | 0.9                              | 16.8                                   | 14.7                                   | 1.14                                  |
| 5                                | 103.2                                    | 10                                   | 0.9                              | 22.5                                   | 19.9                                   | 1.13                                  |
| 6                                | 137.6                                    | 7                                    | 0.9                              | 24.0                                   | 21.4                                   | 1.12                                  |
| 7                                | 171.0                                    | 17                                   | 1.0                              | 13.0                                   | 11.1                                   | 1.17                                  |
| 8                                | 86.0                                     | 17                                   | 1.0                              | 13.1                                   | 11.2                                   | 1.17                                  |
| 9                                | 223.6                                    | 15                                   | 1.0                              | 14.3                                   | 12.3                                   | 1.16                                  |
| 10                               | 240.8                                    | 12                                   | 1.0                              | 16.2                                   | 14.0                                   | 1.16                                  |
| 11                               | 103.2                                    | 10                                   | 1.0                              | 21.8                                   | 18.8                                   | 1.16                                  |
| 12                               | 137.6                                    | 7                                    | 1.0                              | 23.3                                   | 20.3                                   | 1.15                                  |
| 13                               | 171.0                                    | 17                                   | 1.1                              | 13.5                                   | 11.8                                   | 1.14                                  |
| 14                               | 86.0                                     | 17                                   | 1.1                              | 13.5                                   | 11.8                                   | 1.14                                  |
| 15                               | 223.6                                    | 15                                   | 1.1                              | 14.8                                   | 13.0                                   | 1.14                                  |
| 16                               | 240.8                                    | 12                                   | 1.1                              | 16.5                                   | 14.6                                   | 1.13                                  |
| 17                               | 103.2                                    | 10                                   | 1.1                              | 24.4                                   | 21.8                                   | 1.12                                  |
| 18                               | 137.6                                    | 7                                    | 1.1                              | 22.8                                   | 20.4                                   | 1.12                                  |

The Table 3 shows that the efficiency of the tubular mixer is almost constant in the range of velocity of $0.9 \text{ ÷ } 1.1 \text{ m/s}$ and temperature of $7\text{ - }17 \text{ °C}$, but a slightly better effect is observed at a velocity of $1 \text{ m/s}$.

4. Discussion

These studies are continuing of previous studies on this topic. They considered increasing the efficiency of mixing process of water and reagents. It can effect on clarifying water and get water with high-drinking quality after water treatment plant [16, 17].

5. Conclusion

A tubular mixer with improved design in which it is possible to enter several types of reagents for mixing with water and control the intensity of mixing is proposed and investigated. The expediency of using the tubular mixer with improved design for water velocity $1 \text{ m/s}$ has been experimentally confirmed. The expediency of using materials for aggregate bound porous structures of mixing elements of a tubular mixer with improved design with materials of high density is shown. This structure can significantly reduce the pressure drop in the mixer.

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