Wastewater treatment plant for the preparation of industrial water for waterflooding of oil reservoirs using pressure hydrocyclones

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Abstract. To increase the oil recovery of productive oil-bearing reservoirs, the method of increasing reservoir pressure is used. It consists of pumping process water into the oil-bearing horizons. To increase the long-term intake capacity of injection wells, this water is purified from the suspended substances.

This article presents treatment facilities for the preparation of industrial water, including the use of pressure hydrocyclones and various hydrocyclone installations for its treatment. The paper presents the results of the research on water purification from suspension in pressure cylinders of Kazan State University of Architecture and Engineering. The settling time for water purification from suspended substances, which was pre-treated in pressure hydrocyclones, was determined.

The results obtained allow us to design treatment facilities with devices of the «block hydrocyclone-sump» type, in which the reagent-free preparation of technical water used for flooding productive horizons is carried out.

Studies of water purification processes from suspension in hydrocyclone installations are of high scientific and practical significance for the oil fields of Russia.

Keywords: industrial water, suspended substances, treatment facilities, pressure hydrocyclones, block hydrocyclone-ump, settling time.

1 Introduction

To increase oil recovery of productive horizons, the method of increasing reservoir pressure is used. When using this method, natural water from surface sources or oilfield effluents that are formed during primary oil treatment in oil fields are injected into special absorption wells [1-4]. To ensure the possibility of long-term operation of injection wells, it is necessary to purify process water injected into productive oil-bearing horizons from solid suspended substances. The degree of purification of this water from suspension is determined individually for each oil field. For example, for the oil fields of the Republic of Tatarstan, the suspension content in the pumped technical water is 10-50 mg/L.

For the oil fields of PJSC «Tatneft», water for flooding productive horizons is supplied from the Kama river, or rather from the Nizhnekamsk reservoir. Water intake is carried out by the Kama water intake located in Naberezhnye Chelny and owned by PJSC «Tatneft». At the Kama water intake, river water is prepared, at which the content of suspended substances is reduced from 15-20 to 1.5-2 mg/L. Then the water flows through pressure pipelines to oil fields located at a distance of about 100 km from the Kama river in various regions of the Republic of Tatarstan. During long-term movement through pressure pipelines, secondary contamination of process water occurs. At the same time, the concentration of suspension in the water increases to 10-30 mg/L, which makes it unsuitable for flooding productive horizons.

At the enterprise of “Udmurnteft”, technical water is taken from the Siva river. The concentration of suspended substances in river water reaches 400 mg/L. Figure 1 demonstrates the technological
scheme of installation of reagent preparation of technical water used for flooding of oil-bearing horizons. The plant capacity reaches 1200 m$^3$/day.

![Flow diagram of the technical water treatment plant at the “Siva” water intake.](image)

This unit consists of microfilters 1, vortex mixers 2, horizontal settling tanks 3, equipped with built-in aerofloculators and shelf units, a clean water tank 4, a coagulant preparation unit 5, a flocculant preparation unit 6, connecting pipelines, shut-off and control valves, pumps and compressors.

The technical water treatment unit of the Siva intake works as follows. Through the pipeline 8, water from the water pumping station of the first lift enters the microfilters 1, from where the purified water is fed by gravity to the faucets 2 through the pipeline 9. Washing of microfilters is carried out with purified water, which is supplied from the clean water tank by P-1 pumps through the pipeline 10. Polluted wash water is diverted via pipeline 11 to the treatment facilities for wash effluents. In block 5, an aqueous solution of coagulant is prepared, which is used as a reagent of the «Aqua-Aurat-30» type. The coagulant solution is fed to the vortex mixers 2 by the P-2 metering pump through the pipeline 12. The water treated with coagulant is fed through the pipeline 13 to the settling tanks 3. In block 6, a flocculant solution is also prepared, which uses a reagent of the «Praestol 2515» type. The coagulant solution is fed to the settling tank 3 by the P-3 metering pump through the pipeline 14. Mixing of the treated water with the flocculant is carried out in the aerofloculators of the settling tanks 3, where compressed air from the compressors is supplied via the pipeline 15. The sediment formed in the settling tanks 3 and the sludge from the vortex mixers 2 through the pipeline 16 enters the thickener, from where it is diverted to dewatering in vacuum filters. The treated water flows through the pipeline 17 to the clean water reservoirs, from where it is fed by pumps P-4 through the pipeline 18 to the injection wells. This installation reduces the concentration of suspension in process water to 30 mg/L.

The use of reagents for the preparation of industrial water significantly increases operating costs and complicates the process of its purification.

Reagent-free treatment of industrial water from suspended substances is possible using horizontal and vertical settling tanks of different types and modifications [5-7].

Water purification from suspended substances in fast and super-fast filters with granular loading gives good results [8-12]. These filters can operate in pressure or non-pressure modes. Membrane filters are used for water purification from suspension [13-17].
Often suspended substances from natural waters are removed using open hydrocyclones. There are studies on water purification from suspended substances in pressure hydrocyclones of various designs [18-23]. Kazan State University of Architecture and Engineering (KSUAE) has developed installations of the «block hydrocyclone – sump» type designed for water purification from suspension and consisting of several pressure hydrocyclones and sumpers operating in pressure or non-pressure mode.

In a pressure hydrocyclone, under the action of the forces of the centrifugal field that occurs due to the tangential entry of liquid into this apparatus, suspended substances, as a heavier phase, are thrown to the walls of the hydrocyclone body and, together with part of the water, are carried out through its lower drain hole. The purified water, together with a part of the suspended substances, is carried out by an ascending axial flow through the upper drain hole of the pressure hydrocyclone. If the water from the discharge of hydrocyclones enters a reservoir working under excessive pressure, it is considered that these devices work with counter-pressure on the drains. If the water is poured from the drains into the atmosphere or into a tank operating in a non-pressure mode, it is considered that the hydrocyclone operates with a free flow [24]. The pressure at the entrances to the hydrocyclone must be greater than the back pressure at its drains by at least 0.2 MPa.

The effect of purification of process water in pressure two-product cylindrical-conical hydrocyclones of the KSUAE design from suspended substances reaches 55-65% when these devices operate with back pressure at the drains.

Figure 2 shows the scheme of the installation for natural water purification from suspended substances, developed in KSUAE.

![Figure 2. Flow diagram of a hydrocyclone installation of process water.]

This unit contains a battery pressure hydrocyclones design KSUAE 1, thin-layer horizontal pressure sump 2, block filter 3 comprising a vertical pressure fast filters with two-layer (crushed anthracite and silica sand) or super-fast pressure filters loaded with quartz sand, piping, and valves.

Water from surface sources is supplied for treatment under pressure through pipeline 4. Water from the lower discharge holes of pressure hydrocyclones (lower drain) is diverted via pipeline 5 to sand platforms or to sand bunkers under excessive pressure. Water from the upper drain holes of hydrocyclones (upper drain) under excessive pressure through the pipeline 6 enters the thin-layer sump 2. After treatment process water is carried out in the filtration unit 3, where water from the sump 2 under excessive pressure enters the pipeline 7. Sediment from the sump 2 is periodically discharged under excessive pressure through the pipeline 8. The filtration unit is supplied with flushing water along line 9, which after flushing the filters is discharged through the pipeline 10. If super-fast filters are placed in block 3, compressed air must be supplied to this block. The treated water under residual pressure is diverted via pipeline 11 to the reservoir pressure maintenance system. The installation allows reducing the concentration in natural water from 1000 to 10 mg/L. This technological scheme was implemented at the Bugulma porcelain factory. This unit does not require the use of reagents for water treatment, it is quite compact and can be easily automated.
For the preparation of process water pumped into productive horizons a hydrocyclone filtration system can be used (Figure 3).

This unit contains a battery pressure hydrocyclones design KSUAE 1, thin-layer horizontal pressure sump 2, block filter 3 comprising a vertical pressure fast filters with two-layer (crushed anthracite and silica sand) or super-fast pressure filters loaded with quartz sand, piping, and valves.

![Figure 3. Technological scheme of the hydrocyclone-filtration plant.](image)

Water for treatment is supplied under excessive pressure through the pipeline 4 to the pressure hydrocyclones 1. After processing it in these devices, the upper discharge of hydrocyclones (purified water) under excessive pressure through the pipeline 5 is fed to the rapid pressure filters 2. The water in them moves from top to bottom. The bottom discharge of hydrocyclones under excessive pressure is diverted through the pipeline 6. Part of the treated water from the filters 2 under residual pressure through the pipeline 7 enters the container 3, and part through the pipeline 8 is diverted to the reservoir pressure maintenance system. Flushing of filters 2 is carried out with water, which is supplied to these devices by pumps P-1 through the pipeline 9. Contaminated wash water under residual pressure is diverted from filters 2 through the pipeline 10. The installation reduces the concentration of suspended substances in water from 110-130 to 10 mg/L.

The use of hydrocyclone installations for the preparation of industrial water allows increasing the efficiency of its purification from suspended substances.

2 Materials and methods
KSUAE conducted experimental studies of water purification processes from suspended substances in order to improve hydrocyclone treatment plants for process water injected into oil-bearing horizons. For this purpose, an experimental setup was developed (Figure 4).
Figure 4. Scheme of the experimental installation: 1-pressure hydrocyclone; 2-calming tank; 3-pressure capacity of the lower drain; 4-pressure capacity of the upper drain; 5-cylinders for settling; 6-water supply for cleaning; 7-lower drain of the hydrocyclone; 8-upper drain of the hydrocyclone; 9-water supply to glass cylinders; 10-water drainage to the sewer.

The calming tank 2 is used for modelling the connection of a pressure hydrocyclone to a large-diameter pipeline. Tanks 3 and 4 are used to create back pressure on the corresponding discharge of hydrocyclones. Glass cylinders 5 are designed to determine the settling time of water treated in pressure hydrocyclones. The diameter of the cylinder is 50 mm, the height is 600 mm. There are two marks on the cylinder wall: mark A is at a height of 400 mm, mark B is at a height of 200 mm from the bottom of the cylinder. The inlet pressure of the hydrocyclones is governed by the pressure gauge \( P_{g1} \), and the backpressure on the words of these vehicles according to the testament pressure gauges \( P_{g2} \) and \( P_{g3} \). The initial water is supplied to the experimental plant under excessive pressure. The sampler S-1 is used for obtaining samples of source water, the sampler S-2 is used for sampling purified water in pressure hydrocyclones. Water purified in pressure hydrocyclones is fed to cylinders 5 to determine the settling time.

Geometric characteristics of hydrocyclones used for natural water treatment are shown in Table 1. The taper angle of the studied hydrocyclones is 5 degrees.

| The designation of the hydrocyclone | Diameter, mm | Height of the cylindrical part, \( H_{cyl} \), mm | Total height of the hydrocyclone, \( H_{tot} \), mm |
|------------------------------------|--------------|------------------------------------------|------------------------------------------|
| HC-40-I                            | 40           | 15                                       | 5                                        | 40                         | 565                        |
| HC-80-I                            | 80           | 20                                       | 10                                       | 80                         | 745                        |
| HC-100-I                           | 100          | 20                                       | 10                                       | 100                        | 1120                       |
The experimental setup works as follows. We set the required pressure at the entrance to the hydrocyclone, as well as the back pressure on it drains. 15 minutes after the start of the experimental installation, when the water movement has become steady, samples are taken from the S-1 and S-2.

The concentration of suspended substances in the samples was determined by the weight method [25, 26].

The effect of water purification from suspended solids in the hydrocyclone $E_{HC}$, %, was defined by the formula:

$$E_{HC} = \frac{C_0 - C_{up,d}}{C_0} \cdot 100 \quad (1)$$

where $C_0$ - concentration of suspended substances in the water supplied for treatment, mg/L, $C_{up,d}$ - the concentration of suspended substances in the treated water (from the upper discharge of hydrocyclones), mg/L.

The water temperature was determined using a mercury thermometer with a division price of 0.1 °C.

The water flow from the discharge of hydrocyclones was measured using a volumetric method with a stopwatch and a 1- liter measuring cylinder with a division price of 0.01 L.

3 Results and Discussion

The results of experiments on water purification in pressure hydrocyclones are presented in Tables 2-2a.

Analysis of the results of experimental studies allows us to draw the following conclusions:

a) the suspension content in the source water was 46-56 mg/L;

b) the concentration of suspension in the treated water did not exceed 16-26 mg/L;

c) with increasing pressure at the entrance to the hydrocyclones, the efficiency of natural water purification from suspension increases, and with increasing back pressure at the drains, it decreases;

d) with increasing pressure at the entrance to the hydrocyclones, the performance of these devices increases, and with increasing back pressure at their drains, it decreases;

e) to purify natural waters from suspended substances, it is advisable to use a hydrocyclone of the HC-80-II type, which has a sufficiently high efficiency and productivity.

The volume of the sump for the preparation of natural water used in reservoir pressure maintenance systems, $W$, $m^3$, is:

$$W = Q_p \cdot T \quad (2)$$

where $Q_p$ – the calculated flow rate of water supplied for treatment, m$^3$/h; $T$ – required water retention time in the sump, h.

Value $T$, h, is:

$$T = t_2 \left( \frac{H}{h_2} \right)^n \quad (3)$$

where $H$ – the working depth of the sump; $t_2$ – the time required to achieve the desired effect of cleaning from suspended substances $E_d$ in a cylinder with a water depth of $h_2 = 0.4$ m, h; $n$ – the degree indicator.

Value is:

$$n = \frac{\lg t_2 - \lg t_1}{\lg h_2 - \lg h_1} \quad (4)$$

where $t_1$ – the time required to achieve the desired effect of cleaning from suspended substances $E_d$ in a cylinder with a depth of $h_1 = 0.2$ m.
Table 2. Results of research on natural water treatment in pressure hydrocyclones.

| The designation of the hydrocyclone | Water temperature, ºC | Pressure, MPa | Water consumption |
|------------------------------------|-----------------------|---------------|-------------------|
|                                    |                       | at the entrance to the hydrocyclone | on drains of hydrocyclones | through the upper drain of the hydrocyclone | through the bottom drain of the hydrocyclone |
| HC-40-I                            | 19.8                  | 0.3           | 0.1              | 0.24          | 0.05          |
|                                    |                       | 0.4           | 0.1              | 0.26          | 0.06          |
|                                    |                       | 0.4           | 0.2              | 0.24          | 0.05          |
|                                    |                       | 0.5           | 0.1              | 0.28          | 0.09          |
|                                    |                       | 0.5           | 0.2              | 0.27          | 0.08          |
|                                    |                       | 0.5           | 0.3              | 0.25          | 0.07          |
|                                    |                       | 0.6           | 0.1              | 0.35          | 0.14          |
|                                    |                       | 0.6           | 0.2              | 0.31          | 0.12          |
|                                    |                       | 0.6           | 0.3              | 0.29          | 0.1           |
|                                    |                       | 0.6           | 0.4              | 0.27          | 0.09          |
| HC-90-I                            | 20.1                  | 0.3           | 0.1              | 1.15          | 0.27          |
|                                    |                       | 0.4           | 0.1              | 1.33          | 0.29          |
|                                    |                       | 0.4           | 0.2              | 1.28          | 0.27          |
|                                    |                       | 0.5           | 0.1              | 1.54          | 0.37          |
|                                    |                       | 0.5           | 0.2              | 1.5           | 0.35          |
|                                    |                       | 0.5           | 0.3              | 1.47          | 0.33          |
|                                    |                       | 0.6           | 0.1              | 1.71          | 0.43          |
|                                    |                       | 0.6           | 0.2              | 1.69          | 0.41          |
|                                    |                       | 0.6           | 0.3              | 1.66          | 0.4           |
|                                    |                       | 0.6           | 0.4              | 1.63          | 0.32          |
| HC-100-I                           | 20.2                  | 0.3           | 0.1              | 2.4           | 0.37          |
|                                    |                       | 0.4           | 0.1              | 2.26          | 0.45          |
|                                    |                       | 0.4           | 0.2              | 1.90          | 0.43          |
|                                    |                       | 0.5           | 0.1              | 2.42          | 0.58          |
|                                    |                       | 0.5           | 0.2              | 2.29          | 0.51          |
|                                    |                       | 0.5           | 0.3              | 1.92          | 0.44          |
|                                    |                       | 0.6           | 0.1              | 2.47          | 0.61          |
|                                    |                       | 0.6           | 0.2              | 2.44          | 0.59          |
|                                    |                       | 0.6           | 0.3              | 2.42          | 0.56          |
|                                    |                       | 0.6           | 0.4              | 2.4           | 0.43          |
Table 2a. Results of research on natural water treatment in pressure hydrocyclones.

| The designation of the hydrocyclone | The concentration of suspended solids, mg/L | The cleaning effect of the mist, $E_{HC}$, % |
|------------------------------------|---------------------------------------------|------------------------------------------|
|                                    | in the source water, $C_0$ | in purified water, $C_{up,d.}$ | |
| 1                                  | 7                           | 8                          | 9                     |
|                                    | 52                          | 22                         | 58                    |
|                                    | 49                          | 17                         | 65                    |
|                                    | 47                          | 19                         | 60                    |
|                                    | 54                          | 16                         | 70                    |
|                                    | 48                          | 16                         | 67                    |
|                                    | 46                          | 17                         | 63                    |
|                                    | 51                          | 17                         | 67                    |
|                                    | 49                          | 18                         | 63                    |
|                                    | 55                          | 22                         | 60                    |
|                                    | 56                          | 24                         | 57                    |
| HC-40-I                            | 54                          | 26                         | 52                    |
|                                    | 49                          | 20                         | 59                    |
|                                    | 51                          | 25                         | 51                    |
|                                    | 53                          | 20                         | 63                    |
|                                    | 48                          | 19                         | 60                    |
|                                    | 47                          | 21                         | 55                    |
|                                    | 55                          | 18                         | 67                    |
|                                    | 53                          | 19                         | 64                    |
|                                    | 54                          | 20                         | 63                    |
|                                    | 52                          | 21                         | 60                    |
| HC-90-I                            | 56                          | 29                         | 48                    |
|                                    | 54                          | 26                         | 52                    |
|                                    | 51                          | 26                         | 49                    |
|                                    | 49                          | 21                         | 57                    |
|                                    | 52                          | 24                         | 54                    |
|                                    | 53                          | 26                         | 51                    |
|                                    | 48                          | 17                         | 65                    |
|                                    | 54                          | 20                         | 63                    |
|                                    | 55                          | 21                         | 62                    |
|                                    | 52                          | 21                         | 60                    |
| HC-100-I                           | 56                          | 29                         | 48                    |
|                                    | 54                          | 26                         | 52                    |
|                                    | 51                          | 26                         | 49                    |
|                                    | 49                          | 21                         | 57                    |
|                                    | 52                          | 24                         | 54                    |
|                                    | 53                          | 26                         | 51                    |
|                                    | 48                          | 17                         | 65                    |
|                                    | 54                          | 20                         | 63                    |
|                                    | 55                          | 21                         | 62                    |
|                                    | 52                          | 21                         | 60                    |

Value $E_{ed}$, %, is:

$$E_d = \frac{C_{aw} - 10}{C_{aw}} \cdot 100$$  \hspace{1cm} (5)$$

where $C_{aw}$ – the average concentration of suspension in the water poured into the cylinders before settling, mg/L.

10 – the desired concentration of suspension in water after settling, mg/L.

Figure 5 shows the scheme for determining the values $t_1$ and $t_2$. 
Figure 5. Determination of settling time in cylinders: 1 – dependence $E = f(t)$ at the depth of settling $h_1$; 2 – dependence $E = f(t)$ at the depth of settling $h_2$.

Value of $C_{av}$, mg/L is:

$$C_{av} = \frac{\sum_{i=1}^{5} C_{up.d.}^i}{5}$$  \hspace{1cm} (6)

where $C_{up.d.}^i$ – the concentration of suspension in the sample taken from the upper drain of hydrocyclones before filling the cylinders for settling, mg/L.

A 10 mL water sample is taken from the S-2, in which determines the concentration of the suspension ($C_{up.d.}^i$). Fill the cylinders for settling: one to mark B, and the second-to mark A. After 10 minutes, using a siphon, water samples are taken from each cylinder to determine the concentration of the suspension ($C_{k}^i$).

Effect of water purification from suspensions by settling $E$, %, is determined according to the formula:

$$E = \frac{C_{up.d.}^i - C_{k}^i}{C_{up.d.}^i} \cdot 100$$  \hspace{1cm} (7)

The above actions are repeated when the settling time in the cylinders is equal to 20, 30, 60 and 120 minutes.

Dependences $E = f(t)$ are constructed for the depth of settling $h_1 = 200$ mm and $h_2 = 400$ mm.

The results of the determination time $T$ at $H=1.5$ m are presented in Tables 3, 4. Thus, the time spent in the sump to reduce the concentration of suspension in natural water to 10 mg/L is 50-60 minutes at $H=1.5$ m.
Table 3. Determination of the time of settling.

| The designation of the hydrocyclone | Water temperature, °C | Pressure, MPa at the entrance to the hydrocyclone | The average concentration of suspended solids in the water before settling, $C_{av}$, mg/L |
|------------------------------------|-----------------------|-----------------------------------------------|-----------------------------------------------|
| HZ-40-I                           | 20.1                  | 0.4                                           | 20                                           |
| HZ-80-I                           | 19.8                  | 0.4                                           | 24                                           |
| HZ-100-I                          | 19.9                  | 0.4                                           | 25                                           |

Table 4. Determination of the time of settling.

| $E_d$, % | $t_1$, min | $t_2$, min | $n$ | $H_s$, mm | $T_s$, min |
|----------|------------|------------|-----|------------|------------|
| 6        | 7          | 8          | 9   | 10         | 11         |
| 50       | 18         | 25         | 0.47| 1500       | 47         |
| 58       | 16         | 24         | 0.6 | 1500       | 53         |
| 60       | 17         | 26         | 0.6 | 1500       | 57         |

4 Conclusion

Methods of purification of industrial water from suspended substances in pressure hydrocyclones, as well as settling tanks after processing natural water in these devices are studied. Technological processes of natural water purification from suspension in pressure hydrocyclones are investigated. Geometric characteristics of these devices for natural water purification from suspended substances are determined. In the course of research, the settling time required for cleaning water from surface sources from suspended substances, which was pre-treated in pressure hydrocyclones, was determined. All this makes it possible to design installations of the "block hydrocyclone-sump" type for the preparation of process water used in oil fields for flooding productive horizons.

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