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Open flow damper in effluent control system

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Abstract. Nowadays, there are enterprises that use a direct-flow cooling system without treatment of used water before discharging it into a water body. Most of these enterprises use outdated equipment in the cooling system (including oil cooling systems). As a result, there is a high probability of oil products getting into the natural water body. An oil product in a stream of water can be dissolved and undissolved (emulsion). The design of the flow damper proposed in this work is part of a functioning industrial water quality control system. The flow damper is designed to register undissolved oil products in the water flow from the cooling system of a CHP plant. Measurements are conducted at the control points. The research model includes the development of a solid model of the flow damper (including the analysis of its use in a natural environment modelled by software package with the possibility of CFD analysis) and the calculation of oil particles ascent time inside the damper. The result of the study is the design of the flow damper, which ensures oil film detection in the cooling system effluents discharged into the water body.

1. Introduction

Nowadays the environmental protection issues are significant for water resources consumers [1–8], and especially for enterprises that discharge effluents into water bodies [9]. The State Duma of the Russian Federation conducts an active policy on improving the environmental situation, and in particular the state of water bodies, by increasing fines for legal entities and individuals [10].

Active consumers of water resources are combined heat power stations (CHP), which use water to cool oil-filled equipment that is part of the CHP cooling system [11]. Some CHP plants have a flow-through cooling system, where water is taken from a water body (river, lake, etc.) by a pumping station, used as cooler for equipment and finally is discharged back into the water body after passing through the circuits of cooling system. At the same time, the cooling system includes oil chillers which ensure the operation of turbine generators, feed pumps and other parts of the CHP. In this units the natural water could have a contact with industrial oil. Oil cooler is a shell and a tube or plate type heat exchanger which is pumped with water that removes heat from the oil circuit. Oil cooler maintain the set temperature of the lubricating oil that is necessary to support the set oil pressure in equipment. It should be noted, that oil chiller is subject to high depreciation and as a result, it needs repairing. Most often reasons of repairing on oil chiller occur due to several causes: corrosive destruction of heat exchange tubes, violations of the tightness of rolled joints of tubes with tube sheets, some factory defects formed during their manufacture or installation. The number of oil chillers depends on the power of the CHP and can reach several dozen. At the same time, the disruption of the operation of oil chillers can lead to serious environmental consequences, such as discharge of a large volume of oil products into the used water body, which in turn leads to serious economic consequences for enterprises.

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In case of using water resources without constant pollution monitoring, there is a probability of an emergency when water body will inevitably suffer and be polluted by oil products [12]. Therefore, according to the materials [13–14], CHPs with a flow-through cooling system are sources of oil products (TP-22S turbine oil [15]) entering the water body used as a source of cooling water. The discharge of oil products into a water body leads to inevitable environmental consequences [16] in the framework of pollution of both water and land resources [17].

Nowadays, for example, the Russian normative document determining the control mode of CHP's waste water is [18], according to which the sampling schedule for CHP effluents is approved by local regulatory organizations. As known, the regular oil products control in the effluents of the CHP is carried out once every few days (from three to ten). Such method excludes the possibility of oil products operational monitoring of wastewater.

Thus, it is necessary for CHP plants with a direct-flow cooling system to control oil contamination level in water which is discharged from the flow-through cooling system. In particular, the wastewater should not contain traces of industrial oil. Industrial oil serves as an intermediate heat carrier in the cooling systems of equipment and can get into water due to malfunction of heat exchangers.

Today, such technologies as digital twins and internet of things (IoT) are developed actively. In terms of Industry 4.0 technologies, using automatic monitoring of oil concentration in effluent of the CHP cooling system is strongly recommended. In future, industrial water control systems could be part of global environmental monitoring system [19–22].

The literature review has shown that the main gap in problem of prevention of water bodies pollution by CHP is development of effective monitoring of the CHP sewage water [12–14]. To ensure online monitoring of the cooling system effluent, at present, the employees of Russian company ELITA-Petersburg LLC have developed and commissioned industrial water control system that provides continuous monitoring of oil products in effluents of CHPs cooling system [23].

One of the parameters for the effluents control by this system is the control of oil films on the surface of effluents discharged into a water body at the spillway with laser oil detector. Laser technologies could be also use to create building information models [24–26].

To ensure proper control, the authors developed the element to soothe the flow.

Created damper is used in the cushion pools were effluents outfall to local water-system area. The damper is necessary for the operation of the oil detector device. This is due to the need for a water surface with an angle of inclination of waves less than 20° [27]. Otherwise, the reflected laser beam from the oil film will not fall into the receiving area of the device.

Objectives of the work are:

– design of flow damper for calming the open flow which ensures the operation of the oil film detector to notify the presence of oil products;
– modeling of damper work with program of CFD analysis;
– justification of the principles of the damper operation.

2. Materials and Methods

2.1. Oil film registration method

To date, the presence of an oil product in a fluid stream can be detected by registration of oil films on the surface of the analyzed water [27]. Instrumentally, the fixation of the presence of an oil product occurs due to the difference in reflectivity (reflection coefficients) of water and oil product. In this project Russian-made device was used to identify the presence of oil stains on the surface of the liquid (which was previously applied to control the presence of oil stains on the river Neva [28]).

This method is based on laser detection of the water surface with a laser beam directed vertically downward (wavelength – 0.65 μm) with measurement frequency < 30 s. The difference in reflection coefficients for oil products and water makes possible to detect oil films. This method allows detecting oil spots with a thickness from 0.5 microns (the more the oil thickness, the more is reflected light intensity, and as a result the registered signal is higher).

In practice, in the places where the oil film detector is installed, there are differences in elevations of water conduit structures, due to which there is a destruction of the water surface and the formation of disturbances that destroy the structure of the formed oil spots [29].

The effective functioning of the oil film detector requires ensuring the optimal flow mode of the analyzed liquid. In this mode, due to the difference in densities, emulsified particles of the oil float to the surface and form oil films. These oil films are available for detector.

Often, the essence of the structure that provides “calming” of the flow is to change the vector of the fluid velocity and its direction along the profile of the water conduit (tube), thereby eliminating the vortex movement. Usually, such structures are used in closed pipelines [30]. Also, structures are known that carry out pressure damping in open reservoirs [31]. Their significant disadvantage is the destruction of the all-liquid flow including surface. That is unacceptable in the case of the task of water quality control using the selected detector, in which it is necessary to locally provide conditions for the formation of an oil slick from emulsified oil particles in the flow with the possibility of them, by a device that performs laser beam reflection from the water surface inside the structure being developed. The main principle of operation of the designed flow damper is to reduce the speed inside it, due to the diversion of a part of the flow by perforation in the damper channels. The area with a reduced flow rate inside itself provides for the appearance of particles of emulsified oil located at the surface of the liquid, due to the difference in density of oil and water.

Thus, the basic task of the damper of soothing the flow in the water control system is: to ensure the proper residence time of the liquid inside the damper, corresponding to the time of formation of oil films from emulsified particles of oil.

The time required for the ascent of emulsified oil particles in the flow of the analyzed water depends on the rate of their ascent to the surface of the liquid due to the difference in the densities of waste water and oil product. In this study, the ascent rate is determined similarly to the principle of the design of treatment facilities for removal of oil products from the storm water sewage.

The control points, where the flow soothing damper is used is the chamber with a cross section of 6×6 m at the discharge point in the local river, see Fig. 1.

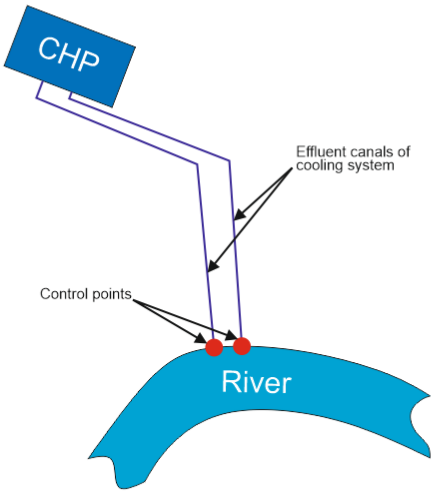

Figure 1. Placement scheme of dampers.

2.2. Basic parameters of flow soothing method

The required time within the flow inside the damper is determined by terminal ascent rate of particles of oil products according to the Stokes formula:

$$\vartheta_{em} = \frac{g d_{oil}^2 \left(\rho_w - \rho_{oil}\right)}{18\mu}, \quad (1)$$

where d_{oil} is diameter of oil product particle; ρ_{oil} is density of oil product (TP-22S); ρ_w is water density; μ is dynamic coefficient of water viscosity.

Ascent time is defined as the ratio of the path of a particle of oil from the flow to the water surface (l) to its rate ϑ_{em}:

$$t = \frac{l}{\vartheta_{em}} \quad (2)$$

The ascent depth is taken as 0.05 m. Due to the difference in the densities of the oil and water, the oil products will accumulate in the upper part of the stream and weak oil concentration could be detected because the oil detector's lower level is 0.5 microns.

To calculate the ascent rate, the following parameters are defined (see Table 1):

Table 1. Data for calculating the ascent rate of oil particles.

№	Parameter	Value	Note
1	d_{oil}, μ	300	See [32]
2	ρ_{oil}, kg/m3	0.87	See [15]
3	ρ_w, kg/m3	1.0	See [32]
4	μ, g/cm s	0.0131	See [32]

Based on (1) and the data from Table 3, the ascent rate is defined as:

$$\vartheta_{em} = 0.0049\, {}^{m}\!/_{s}.$$

Based on (2), the time is determined:

$$t = 10.3s.$$

A certain time characterizes the minimum required time for the fluid flow inside the flow damper of designed size.

The flow rate inside the damper is based on the ratio of the area of the flow damper (in perpendicular projection to the flow movement) to the perforations area inside the damper:

$$n = \frac{W_1}{W_2}. \quad (3)$$

The speed inside the damper is equal to the ratio of the estimated flow speed to the coefficient *n*.

$$\vartheta_2 = \frac{\vartheta_1}{n} \cdot (1 - c), \quad (4)$$

where c is the shape resistance coefficient [33].

2.3. Flow soothing damper

Based on certain parameters, a flow damper design has been developed, shown in Fig. 2.

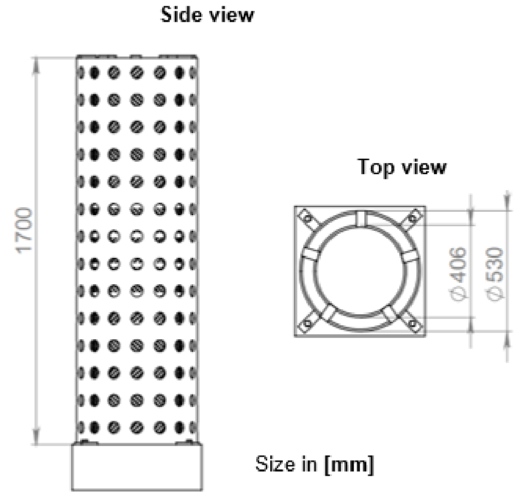

Figure 2. Flow damper device design.

The existing design of the flow damper is based on the separation of part of the fluid from the existing flow (by passing of water through the perforations) and damping the flow energy when it interacts with the damper walls by creating a large local resistance.

The device shown in Fig. 2 is constructed of two cylinders located one in the other. In this design, cylinders with radii of 406 mm and 530 mm are used, the dimensions of the cylinders are selected based on the convenience of mounting the equipment through a standard sewer manhole [34].

Due to various perforations size with a decrease in their area in the section plane to the center of the structure, a significant decrease in the flow rate is achieved.

External perforations are holes with a diameter of 50 mm, arranged in increments of 120 mm to prevent clogging of the inner part of the damper with a smaller fraction of trash shown in Fig. 3.

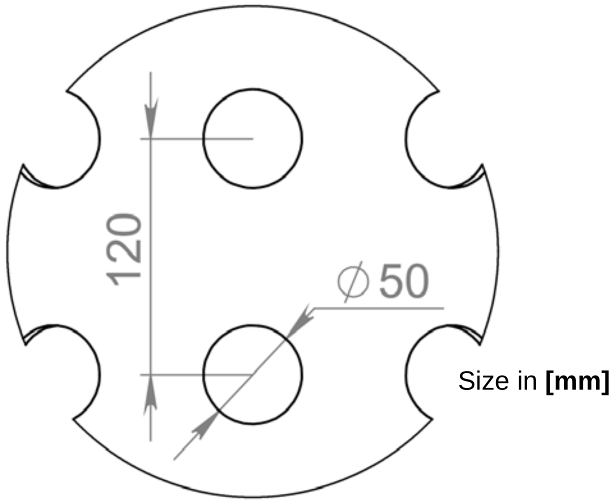

Figure 3. External punch perforations.

The internal perforation of the flow damper consists of parallel slots, 3.2 mm wide and 110 mm high, arranged at an angle of 45° with a pitch of 15 mm. Vertical perforations on inner cylinder have different directions, for more efficient quenching of flow energy, shown in Fig. 4.

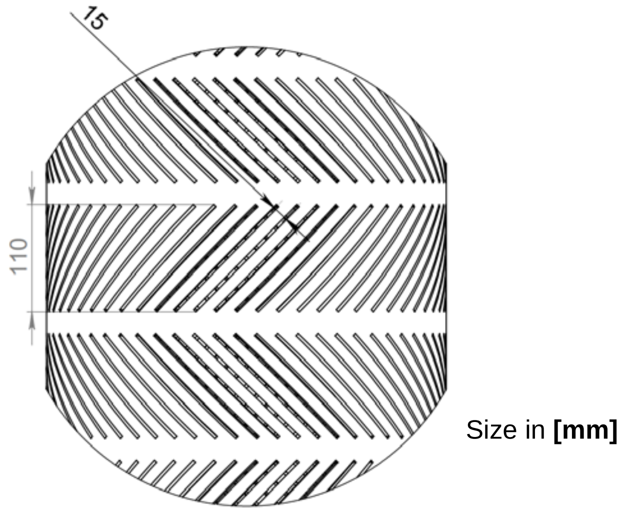

Figure 4. Perforation of the inside of the damper.

The construction is additionally equipped with a concrete load to ensure stability and resistance to the fluid flow.

3. Results and Discussion

The construction of the flow-damping device was developed with 3d-modeling software packages using computational fluid dynamics simulation packages (Solid works Flow Simulation), which makes it possible to evaluate the performance of this unit in an environment close to the actual operating conditions.

Construction designed with using dynamic simulation packages witch usually uses for solving whole host of hydraulics issues [35–40].

In our task the boundary conditions were:

- mass flow rate of liquid 16 000 m^3/h;
- environmental pressure – atmospheric;
- liquid – water with a temperature of 5 °C;
- roughness:

concrete (cushion pool) – 1 mm;

damper (used steel with paint) – 0.2 mm.

Total number of cells in the grid: 131 678.

After the statement of the problem and its solution, the following results were obtained Fig. 5 shows the diagram of the water flow velocity distribution (side view).

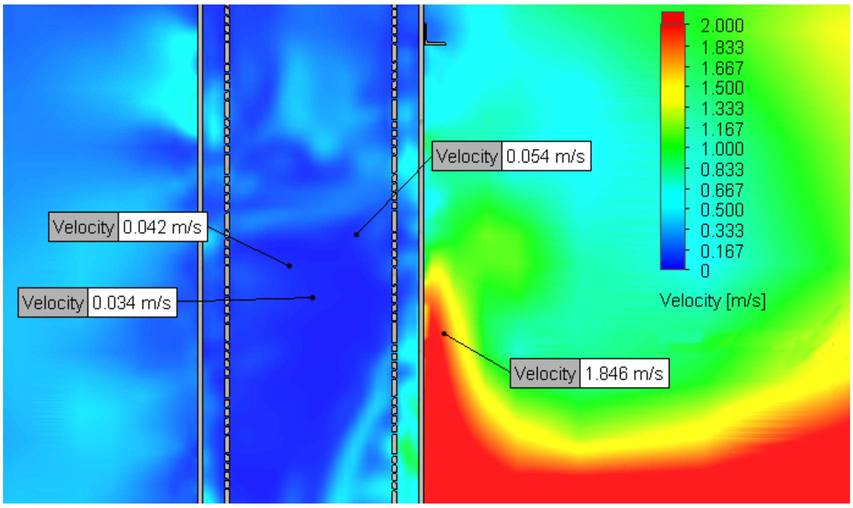

Figure 5. Velocity distribution diagram (side view).

As seen from the Fig. 5, the flow velocity inside the damper is much less than beyond its borders, so values greater than 1 m/s are observed in front of the damper. The high flow velocity outside the damper is based on a high-water flow rate (up to 16 000 m^3/h) passing through the damper installation site – a stilling chamber installed at the place where the wastewater from the CHP cooling system is discharged into the local river.

In Fig. 6 a plot of the plane is presented at a distance of 1.2 m from the bottom of the chamber (at this level the flow surface was established in the problem being solved).

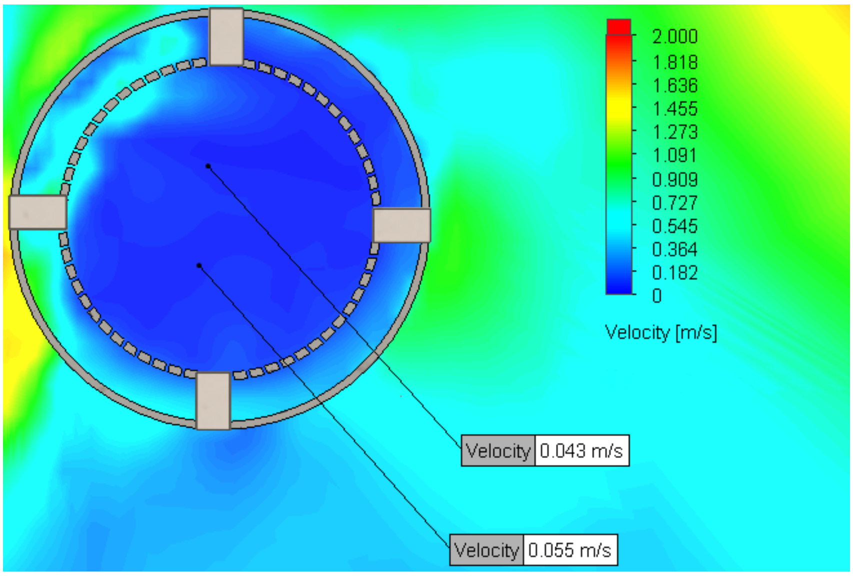

Figure 6. Velocity distribution diagram in a stream (top view).

As seen in this diagram, the velocities on the surface of the liquid are 0.034–0.055 m/s.

Fig. 7 shows a graph of the distribution of water speed along an axis passing from the center of the flow damper.

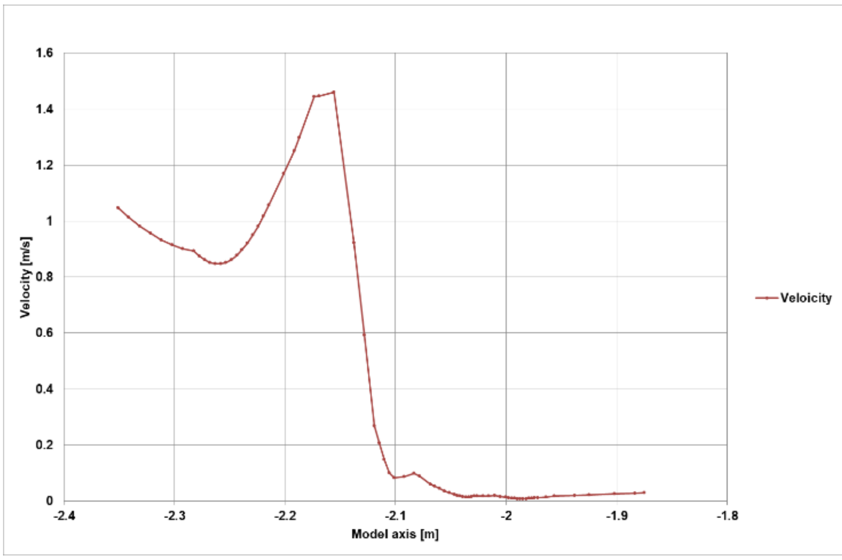

Figure 7. The graph of the distribution of speeds before the damper and inside it.

Damper's damping plate is located on points – 2.078 m and – 2.140 m and point – 1.875 m is the center of the damper.

The effectiveness of the damper is clearly visible outside speed is 0.85–1.45 m/s, while inside the damper is less than 0.1 m/s.

It should be noted that in this chamber the flow damper not only reduces the speed inside itself, but also provides a smooth surface of the liquid to reliably determine the presence of oil films on its surface. Installed opposite the spillway collector, it provides damping of the waves generated when the liquid leaks from the collector into the water intake chamber.

Considering the theoretical indicators of speed inside the damper when installing it in a chamber with a cross section of 6×6 m, we take the depth of filling of the chamber as 1.2 m (from the simulation results). By formula (3) we find the ratio of the area of the damper to the total area of perforations for a given depth of coverage of the body of the damper (at a depth of 1.2 m, 7 levels of inclined perforation are covered).

$$n = \frac{0.64}{0.076} = 8.42.$$

By the formula (4) we determine the flow rate inside the damper.

$$\vartheta_2 = \frac{0.61}{8.42} \cdot (1 - 0.46) = 0.042\, {}^{m}\!/\!{}_{s}.$$

At a given speed, the time spent by the particles inside the damper is:

$$t = \frac{0.530[m]}{\vartheta_2} = 12.6s.$$

This time of flow located inside the damper will ensure the detection of oil emulsified particles and the formation of the oil layer, visible to the device of oil films.

The theoretical value of the speed differs from the calculated one due to neglect of the following parameters:

- orientation of perforations to the direction of flow;
- surface characteristics;
- the form resistance coefficient does not take into account perforation;
- the distance from the outlet manifold to the damper (speed distribution during outflow to the pool).

Thus, in this work, the efficiency of the developed damper is graphically and computationally presented.

4. Conclusions

In order to ensure the operation of the online detector for registration of oil products in CHP effluents the method and device for calming of the water flow is proposed.

The functioning of the device is based on ensuring low speeds of fluid movement inside. As a result, in the presence of oil in wastewater, a smooth calm film of oil products is formed on the water surface. This allows to determine oil products by a detector based on laser beam reflection from the surface.

Simulation of the operation of this device under conditions close to real is considered and the theoretical basis for calculating the speed inside the flow damper is given.

The rational design of the flow damper is selected and justified by the program simulation results.

5. Acknowledgement

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