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Micro-turbulence of the stream and its connection with the roughness of the pipeline inner surface

Микротурбулентность потока и ее связь с рельефом внутренней поверхности трубопроводов

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Abstract. This study has been aimed at investigating the problems of a fluid stream flowing in an open chute, which imitates a small-diameter gravity pipeline (up to 150 mm) at low rates of sewage. The works on a specially developed hydraulic bench have enabled determination of the conditions of the flow vortex formation (micro-turbulence) by changing the geometric shape of the internal surface of the pipe by placing artificial protrusions (obstacles) on it, which can help to prevent deposition of suspended particles on the pipeline surface and facilitate their efficient removal. The technique of carrying out hydraulic experiments on the bench has been developed. Several types of artificial obstacles have been studied to investigate their activity in creation of micro-turbulence phenomena on the inner surface of the chute near the frontal surface of streamlined obstacles that can contribute to the stable transport capacity of suspended solids in the flow of a moving fluid. As obstacles, provision has been made of single and grouped bars made of metal and polymeric materials in the form of a parallelepiped and a cylinder, a polyhedron in the form of a prism and screw-nuts, as well as obstacles in the form of an inverted spherical segment, etc. Based on the results of study of the fluid stream flow in an open chute, as well as the location of obstacles, the nature of the vortex formation before and after them was revealed, the optimal geometric dimensions of the obstacles have been got and the areas of disturbance zones at low water flow rates (less than 0.4 m/s) have been determined.

Аннотация. Исследованы вопросы течения потока жидкости в открытом желобе, имитирующем самотечный трубопровод малого диаметра (до 150 мм) при низких скоростях течения сточной воды. На специально разработанном гидравлическом стенде выявлены условия, обеспечивающие вихреобразование (микротурбулентность) потока за счет изменения геометрической формы внутренней поверхности трубы путем расположения на ней искусственных выступов (препятствий), что может способствовать предотвращению осаждения взвешенных частиц на поверхности трубопровода и способствовать их эффективному перемещению. Разработана методика проведения гидравлических экспериментов на стенде. Изучено несколько типов искусственных препятствий, создающих явления микротурбулентности на внутренней поверхности желоба вблизи лобовой поверхности обтекаемых препятствий, которые могут способствовать стабильной транспортирующей способности взвешенных веществ в потоке движущейся жидкости. В качестве препятствий рассматривались единичные и групповые выполненные из металла и полимерных материалов бруски в виде параллелепипеда и цилиндра, многогранника в виде призмы и гаек, а также препятствия в форме перевернутого шарового сегмента и другие. По результатам исследования течения жидкости по открытому желобу и расположения препятствий выявлен характер вихреобразования до и после них, установлены оптимальные геометрические размеры препятствий и определены площади зон возмущения при малых скоростях течения воды (менее 0,4 м/с).

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1. Introduction

Increase of the transport capacity of small diameter water discharge gravity pipelines, which contain in the water flow a significant amount of suspended sandy particles, is an urgent task of all city services bearing responsibility of an effective operation of water discharge networks. This problem is the most acute one due to the general tendency of decrease in water consumption in modern cities. At low flow rates, formation of stagnant zones (siltation) is possible due to the accumulation of suspended solids in the chute portion of gravity pipelines. As an exit from this situation provision may be made of creation of the micro-turbulence conditions on the inner surface of the pipeline chute by formation of a special shape of its relief. The above-mentioned issues have been the subject of these investigations. The purpose of the research was to perform a visual description of the emerging vortex structure with a certain arrangement of obstacles, as well as to fix the character of the perturbation zone geometric parameters in front of the obstacles and behind them. When having these results, researchers are able to select the optimal type of structure and location of obstacles in the chute part of the pipeline to ensure the maximum effect of the local micro turbulence. The works on the study of the micro-turbulence, which arises when the stream is flowing over the obstacles (protrusions), have been performed on a hydraulic bench developed by the authors [1]. As obstructions, use has been made of point and linearly stretched obstacles of equal and different size, which can be considered as an artificial roughness, which does not create large hydraulic resistances.

One of the decisive factors that ensure an effective transport capacity of both operating pipelines and those, that have been repaired by applying internal protective coatings, is the condition of the inner surface of their walls [2, 3]. For a long period of time the researchers have had the opinion, that the inner surface of the pipes should be as smooth as possible, because this ensures the absence or minimal amount of precipitating and accumulating components of contaminants of various origins (for example, sand) in the continuously operating water discharge gravity network [4]. The intensity of precipitation of suspended particles in the bottom of a pipeline is related to the flow rate of the waste fluid [5, 6]. If the flow rate remains below the critical (self-cleaning) one within a long period of time, the impurities do not rest in the suspension state and precipitate, forming deposits. Some sediments, mostly the upper layers, can be taken out by the stream during the hours of maximum water consumption in the city, and the caked (as a rule, the core) ones stay in the chute part of the pipe, which ultimately requires periodic cleaning of the pipeline by various methods [7, 8].

The most common are the General sewage systems are the most commonly subject to a high variability of the flow rate. At the night hours, when the water consumption is minimum and there is no rain, the pipelines work at a low filling, i.e. the live section of the pipeline is only partly filled, which leads to a greater amount of deposits [9]. The presence of deposits in sewerage pipelines and even in water supply systems in the form of a variety of sediments and deposits (suspended matter, bio-fouling, metal oxides, etc.) may decrease the efficiency of the pipeline system or need additional costs of overcoming frictional forces due to narrowing of the living section of pipelines.

The accumulated knowledge in creation of self-cleaning surfaces and provision of self-cleaning rates made it possible to forward the idea of working out such a structure of the pipeline inner surface, which would reduce to a minimum the amount of deposed sediments regardless of the velocities and the filling matters in the pipeline [10, 11]. This purposeful work aimed at the efficient transportation of liquid and solid substances through pipelines has been based on the examples of the wildlife, such as the structure of blood vessels of the insects’ wings and the system of transportation of water and nutrient solutions of mineral salts from roots to leaves in the tissues of higher plants, i.e. in the so-called xylem [12-14]. Some researchers have shown, that the effective stirring of the flow and the movement of suspended particles, which have deposed in the chute portion of the pipelines, is observed in the pipes with corrugated internal surfaces made in the form of rectangular needle lips (obstacles) such as a herringbone [15]. With such a structural surface of the chute, the time required for detaching sand deposits from its bottom part due to local turbulence of the water flow in the near-wall area between the obstacles, sediment lifting and their transportation by water should shorten. As shown by investigations on special benches, the effect of the conveying capacity of pipelines can be enhanced by using hydrophobic surfaces that shall be applied to their inner surface by modern trenchless methods [16, 17].

The results of the performed experiments [18] served a scientifically grounded basis for the development of self-cleaning pipeline systems (for example, Self Cleaning Systems), which were implemented into the practice of trenchless renovation using the Trolining method, where internal polymer protective coatings with external and internal corrugated profiles are applied.

However, today there is no general understanding of the surface relief structure, as well as specific technical information on geometric parameters of the corrugated surfaces, in particular the distances between the obstacles, the angles of their location with respect to the axis of the tray and other circumstances.

The aim of these studies is to obtain and complement knowledge on the study of a wide range of obstacles in the form of corrugated pipe surfaces or their internal protective coatings, which are widely used in the practice of the trenchless rehabilitation of technical utility networks [19, 20]. The tasks of the research include: analysis of the different types of obstacles emerging vortex structure, development of the special testing bench, experimental studies with different types of obstacles [21–22].

2. Methods

The research was based on performing hydraulic experiments on an installation, which has been specially installed in the laboratory, and represented a container rigidly coupled to a polypropylene open chute (trench), of 130 mm diameter (Figure 1), which housed various types of protective coatings with structural features in the form of obstacles to the flow of liquid. Retention of the corresponding obstacles on the tray was made by gluing them on the inner surface of the tray or by using a powerful magnet placed under the tray. The slope of the tray was 1/130 = 0.077.

Figure 1 Side view of a special stand in the form of an open inclined chute of 130 mm diameter for performing experiments

The works on the bench were performed according to a specially developed procedure. The method of carrying out experiments for investigation of the micro turbulence consisted in flowing of the design water stream from a measuring container along the chute, fixing the water flow rates and the filled amount.

The experiments were accompanied by filming (Sony HDR-CX250 camera) and continuous multi-frame photography (Sony α550 digital SLR camera, DT 1.8 / 50 SAM lens) using a light-shadow effect to reflect the vortex configurations and backwater in the frontal parts of obstacles. For these purposes, a light source in the form of a lamp with free rotation was mounted on the installation, and a measuring ruler was rigidly fixed in the tray to its upper edge from the inside.

The corresponding flow rate and the stream rate were provided by opening / closing a valve on the pipeline, which supplied water to the measuring vessel. The water consumption was monitored by a volumetric method using a calibration curve describing the dependence of the amount of water flowing out of the chute on time. The rate was determined by the "bobber method", i.e. using a stopwatch and a bobber, triggered into the flow at a certain length of the chute. The values of the wetted perimeter and hydraulic radius were to be calculated.

The final target of the experiments was to determine the optimal configuration of single linearly elongated objects (obstacles), as well as of a set of them, which differ by their location on the tray and dimensions; it allows to get the micro turbulence effect of the flow with small fillings and rates (up to 0.4 m/s). These parameters should provide a stable state of weighing of sediments, which are transported by water due to the created turbulence of the stream.

3. Results

The experiments' results, which have been got by different options (positions 1–9) of single and grouped obstacles on the inner surface of the chute, are given below. Two options are represented by illustrative photos (positions 1 and 2).

1) A single obstacle in the form of a rectangular bar, 1 cm long, 0.3 cm wide and 0.2 cm high

- position in the center at an angle of 45 degrees to the axis of the chute (Figure 2).

A distinct ripple (flow disturbance) is observed in front of the obstacle, nearly1.4-1.6 cm long, with the perturbation area about 1.95 cm^2. The bed of the stream is not really displaced. Behind the obstacle, the disturbance zone covers the whole width of the stream along 2.5 cm due to the formed vortex and has an area about 2.25 cm^2. After the perturbation zone, the width of the stream narrows by nearly 1/3.

Figure 2. A single obstacle in the form of a rectangular bar (with a measuring ruler on the right)

- location with a displacement from the center at an angle of 45 degrees to the axis of the chute (Figure 3).

A distinct ripple is observed in front of the obstacle at a length about 2.9-3.1 cm with a perturbation area nearly 6.8 cm^2. The bed of the stream is displaced somewhat from the axis to the side opposite to the obstacle. The disturbance zone behind the obstacle covers the whole width of the stream due to the formed vortex and makes nearly the same area as in the case with the bar in the center, i.e. 2.25 cm^2. The width of the stream narrows by about 1/3 after the perturbation zone.

Figure 3. Single obstacle in the form of a rectangular bar with displacement

2) Single obstacle in the form of a lying metal cylinder

- location in the center of the chute.

The length of the cylinder is about 1 cm, the diameter is about 1.5 mm. The cylinder is located at the center of the axis of water stream flow, at an angle of 45 degrees. The ripple in front of the obstacle is observed for 1.5–1.7 cm, and after it the swirling of the flow is located at 1.4–1.8 cm.

- location with a small displacement from the center.

The nature of the vortex formation is identical to the position of the cylinder in the center. The areas of the perturbation zone are approximately equal and make about 6.25–6.5 cm^2.

3) A single obstacle in the form of a lying hexagonal prism with location in the center.

The length of the prism is about 2 cm, the maximum width is about 2 mm. It is located at the center of the axis of the water stream flow, at an angle of 45 degrees. Ripples before the obstacle are observed for 2.1–2.6 cm, and after the obstacle – at the length about 3 cm. In contrast to the experiments with cylinders, the area of the perturbation zone makes about 9 cm^2, which is explained by the greater length of the obstacle.

4) Single obstacle in the form of an inverted spherical segment with a displacement from the center.

The diameter at the base of the inverted ball segment is 0.9 cm. Ripples before the obstacle are observed for 2.5–2.9 cm, and after the obstacle the swirl of the stream is a kind of torch with the area of the disturbance zone about 5 cm^2, which distinguishes this obstacle from those previously considered.

5) Double obstacle in the form of inverted spherical segments with a displacement from the center.

The pattern of the ripple distribution and turbulence of the flow is almost identical, as in the case of single obstacles in the form of inverted spherical segments. The areas of the perturbation zones are approximately equal and make about 10 cm^2.

6) Grouped obstacles (Figure 4) in the form of identical polyhedral (screw -nut-type) figures, which are displaced from the axis of the chute.

The maximum obstacle size is 0.8 cm, the height is 0.3 cm, the distance between individual obstacles is about 2 cm. The stream twists have an intense turbulence and are observed from one obstacle to the other in the form of "Karman paths". The area of the disturbance zone is significant and practically covers the entire area of the free surface of the water flow in the chute.

7) Grouped obstacles in the form of identical round (checker-type) figures

The diameter of the obstacle is 0.8 cm, the height is 0.2 cm, the distance between individual obstacles is about 2 cm. Fluctuations of the flow are observed near the axis of the chute in the form of persistent perturbations.

8) Obstacles of different size in the form of round (checker-type) figures in the plan with a strictly perpendicular arrangement as to the axis of the chute.

The diameters of the obstacle are 0.8 and 0.6 cm, the height is 0.2 cm, the distance between individual obstacles is about 2 cm. the swirling of the stream is observed practically over all the entire free surface of the stream.

9) Obstacles of different size in the form of round (checker-type) figures in plan which are positioned at an angle to axis of the chute.

The diameter of the obstacles is 0.8 and 0.6 cm. In this case, a chaotic, practically continuous area of vortices is observed that surrounds the free surface of the water flow in the chute.

Figure 4. Grouped obstacles in the form of identical polyhedral figures displaced from the axis of the chute

4. Discussion

Table 1 (below) presents summary results and interpretation of the vortex formation nature and their geometric parameters, depending on the location of obstacles.

Table 1. Summary results of experiments to determine the nature of the disturbance zones at water flow rates less than 0.4 m/s

Location of obstacles	Vortex formation nature	Averaged geometric dimensions of disturbance zones	
		Lengths before / after obstacles, cm	Areas before / after obstacles, cm^2
1. A single obstacle in the form of a rectangular bar 1 cm long, 0.3 cm wide and 0.2 cm high.			
Center location at an angle of 45 degrees to the axis of the tray	Coherent	1.5 / 2.5	1.95 / 2.25
Location with displacement from the center at an angle of 45 degrees to the axis of the chute	Coherent	3.0 /3.0	6.8 / 2.25
2. A single obstacle in the form of a lying metal cylinder 1 cm long, 1.5 mm in diameter			
Location with a small displacement from the center	Coherent	1.6 / 1.6	6.25 / 6.25
Location with a small displacement from the center	Coherent	1.6 / 1.6	6.25 / 6.25
3. A single obstacle in the form of a lying hexagonal prism with the placement in the center 2 cm long, 2 mm wide (at an angle of 45 degrees)	Coherent	2.4 / 3.0	5 / 9
4. Single obstacle in the form of an inverted spherical segment with a diameter of 0.9 cm with a displacement from the center	Coherent	2.8 / 2.5	7 / 5
5. Double obstacle in the form of inverted spherical segments with a displacement from the center	Coherent	2.8 / 2.5	10 / 10
6. Group obstacles in the form of identical polyhedral figures (nuts) displaced from the axis of the trough; the maximum obstacle size is 0.8 cm, the height is 0.3 cm, the distance between individual obstacles is about 2 cm.	Vortex	Vortex path at the whole length	- / 5
7. Grouped obstacles in the form of identical round figures in plan displaced from the axis of the chute; diameter of obstacle 0.8 cm, height 0.2 cm, distance between individual obstacles about 2 cm	Vortex	Vortex path from obstacle to obstacle	- / 3.5
8. Multiple obstacles of different size in the form of round figures in plan with a strictly perpendicular location to the axis of the chute; the diameter of the obstacle is 0.8 and 0.6 cm, the height is 0.2 cm, the distance between individual obstacles is about 2 cm.	Coherent	Vortex path at the whole length along the chute axis	8 / 8
9. Multiple obstacles in the form of round figures in plan located at an angle to the axis of the chute; the diameter of the obstacles is 0.8 and 0.6 cm.	Coherent	Vortex path at the whole length along the chute axis	8 / 8

Based on the results of the analysis of the vortex formation nature behind individual (items 1–5 in Table 1) and grouped obstacles (items 6–9) and the size of the perturbation zones, additional experiments were carried out with 6 variants of grouped obstacles with such geometric distances between them that provide a stable flow turbulence at relatively low water flow rates (within 0.2–0.4 m/s).

The study was performed for configurations of grouped obstacles in the form of rectangular cross section bars with a height of about 2–3 mm and the length of about 2–3 cm, as well as round objects (diameter in plan about 1 cm) located at the chute:

1) at an angle of 90 degrees to each other

2) crosswise,
3) at an angle of more than 90 degrees (“herringbone”),
4) at an angle of 120 degrees;
5) along the axis of the chute (round obstacles),
6) displaced from the axis of the chute (round obstacles).

In Figure 5, as an example, a typical view of one of the investigated variants of the location of obstacles is presented (item *e*), illustrating the flow turbulence at the water flow rate of 0.4 m/s.

Figure 5 Grouped obstacles in the form of bars of rectangular cross-section, located at an angle of 120 degrees

Below is the interpretation of the results of experiments according to the got photos and film materials.

Variant 1: at the rate of 0.4–0.6 m/s, there is an active disturbance of the flow, thus it can be assumed that the transport capacity of the liquid flow will be increased. At the rate of less than 0.4 m/s, the vortex is weaker, so it can be concluded that this relief of the inner surface of the pipeline will work efficiently at the rates of 0.4–0.6 m/s.

Variant 2: when the rate is less than 0.4 m/s, the formation of vortices is coherent. The active disturbance of the flow began with the rate increase. However, it shall be assumed that the substances precipitating as sediments will not stop in front of the obstacle itself.

Variant 3: the nature of the vortices is stable along the entire flow of the fluid, including in front of the obstacle.

Variant 4: the liquid stagnation is clearly observed when there is a low filling.

Variant 5: at the rate of 0.4 m/s the liquid stagnation is observed in front of the obstacles, so this can entail the accumulation of suspended substances, but after the obstacle in the form of a screw-nut the disturbance of the flow becomes coherent.

Variant 6: the active disturbance of the flow occurs at low rates (0.4 m/s) and remains stable throughout the disposed obstacles even with the rate increase.

For comparison with the results of other authors, other testing benches with similar working models can be mentioned. However, similar experiments with a creation of the micro-turbulence flow with a study of a different type of the obstacles and the interpretation of the vortex formation nature (coherent or vortex) during the transportation of the thin layers of water have been never carried out by other researches.

The closest patent of the known analogs is a device that allows to investigate the hydrophobicity of materials by examining the flow and detachment of droplets from the plane with a change of a slope [23]. This testing bench includes a fixed frame with a movable sliding surface fixed to it, a slope changing system, photo camera for a frontal shooting of drops, dispenser for a dosing of droplets on a surface, which can be one of a various range of materials with hydrophobic properties, and container for droplets collecting.

Also known a device for determining (in the static and dynamic modes) interfacial tension of liquids surface, as well as for determining the angle of wetting of solid surfaces. The device includes an adjustable surface under the sample, dispensers and video devices for checking the position of droplets and the liquid surface tension [24]. The fundamental difference in this case is the lack of slope changing devices, as well as imperfection of the video units.

5. Conclusions

1. On a special hydraulic bench in the form of an open chute with various surface relief, complex studies were conducted to identify the effect of the micro turbulence.

2. Provision has been made for determination of the parameters describing the nature of the vortices and their dimensions both before and after single, double and grouped obstacles of rectangular, cylindrical, prismatic, spherical and circular shapes with their different locations in relation to the axis of the flow (perpendicular to or at an angle).

3. On the basis of the got results, it was ascertained that practically all obstacles to some extent provoke the micro-turbulence of the flow at flow rates less than self-cleaning ones: there were no obvious advantages of any of the obstacle categories.

4. Based on the experimental data, it is suggested to carry out further experiments on revealing the micro-turbulence effect on the basis of the surface relief in the form of grouped obstacles of a rectangular shape, which are located at an angle to the axis of the chute on both sides of it and a free cross-section about 0.2 cm along the axis of the chute.

5. In future, the experiments are planned to be performed for studying the transfer of the sand particles in order to identify the optimal surface relief for the effective movement of suspended solids by the flow of water at low flow rates.

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