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STUDY OF HYDROPHOBICITY AND TEXTURE OF THE GRAVITY TRAY SURFACES TO IMPROVE THEIR TRANSFER CAPACITY

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Abstract

The article reveals a study of open trays transporting water and gravity. The study focuses on a new design patented small-size hydraulic benches, which allow investigating of the hydrophobicity degree of the materials intended for manufacture of open trays, as well as the efficiency of the tray internal surface textures to increase the transporting capacity of the streams containing solid inclusions. The wetting of protective coatings in dynamic conditions has been studied on a small hydraulic bench by creating a mini-flow and registering its characteristics with photo and video equipment. The study results on the liquid transfer in the trays of small-sized installations are given for two modes: single-phase (water) and two-phase (water with mineral inclusions). Exploratory studies have been performed to fix the vortex formation in the flow based on the chiaroscuro effect, when the filling has been made according to the tray surface corrugated texture, in a wide range of water flow velocities, as well as well as at calculated fillings corresponding to the actual operating conditions of trays and pipelines. The article estimates the pipeline surface structure influence on formation of the turbulence zones in different points of the obstacles. There were texture roughness characteristics given, which provide the most effective fluid flow transfer capacity by the mass of dispersed inclusions of various granulometric composition (sand-based) have been revealed. The velocity increasing ranges (below self-cleaning velocities), which provide the transfer capacity of the trays due to the textured surfaces, were established.

Keywords: chiaroscuro effect, gravity pipelines, hydrophobicity, surface texture, transfer capacity

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1. Introduction

Modern approaches to the management of water supply and water discharge pipeline systems should ensure a trouble-free operation of engineering networks. This can be achieved through the introduction of new technical solutions designed to facilitate the unobstructed water transfer through pipeline networks under any negative circumstances (Kuliczkowski, 2004). One of the ways to solve the problems of the pipeline transport effective operation is to improve the hydraulic characteristics of the inner surface of free-flow water discharge pipelines and open trays for storm water discharge (Arolla and Desjardins, 2015). The modern construction market offers a wide range of polymer and composite materials for protective coatings (cladding, insulation, etc.) with low hydraulic resistances (Houghtalen et al., 2016).

Rapid application of such coatings to the inner surface of old pipelines using trenchless repair methods improve efficiency of drainage systems (Kuliczkowski et al., 2000). It also intensifies the discharge water transfer, including the water containing foreign inclusions without their gravity deposition in the pipe tray parts (Zakharov and Orlov, 2017). According to the legislative acts of the Russian Federation, the use of open drainage utilities and facilities (trays) is allowed on the territory of one or two-storey buildings, in the parks and recreation areas (SP 104, 2017). Analysis of the foreign regulations shows that the drainage trays are not prohibited in any

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areas (DIN EN 1433, 2005). The trays are widely used, mainly in the pedestrian zones, as well as in the areas with low-speed traffic (Rudolph and Blok, 2001).

The calculations made for trays located in a limited water collecting area having a waterproof covering shall be guided by determination of the design flow according to the methods given in the Norms SP 30.13330.2016, as the calculations for a roof. The choice of material of pipes and trays (concrete, polymer concrete, metal, polymer etc.) is determined depending on the climatic zone, the maximum dynamic and static loads on them (Rameil, 2007).

Hydrophobicity/hydrophilicity as indicators of working surfaces nowadays stand alone (Boinovich and Emelyanenko, 2008) in the studies of intensification of wastewater transfer, and more precisely in the studies of physical and chemical properties of the pipeline tray inner walls or their protective coatings. That was the key factor during the described experimental studies. Thus, the list of scientific tasks included the study of the nature of water contact with hydrophobic working surfaces and the determination of the influence of surfaces topology (artificial roughness) on the dynamics of the fluid flow and its transferring capacity within wide range of velocities (Grossmann and Lohse, 2017). However, the studies have mostly been carried out only for thin mini-channels on the ultra-hydrophobic surfaces (Oner and McCarthy, 2000). The relevance of these studies results in determination the conditions that provide additional turbulence (micro-turbulence) of the flow due to a geometric shape and location of artificial protrusions (obstacles) on the inner surface of pipelines and trays. The improved tray surface texture may prevent deposition of the suspended particle and stimulate their transportation by the liquid flow (Kuehner et al., 2019; Zhao et al., 2019).

The objectives of the work were to study the possible use of hydrophobic and textured linings in open trays as protective coatings with corrugated surface to provide an efficient transfer of water with suspended solid inclusions without their deposition. The theoretical and practical significance of the work consists in the study of hydraulic parameters of textured coverings of the inner surfaces of trays applied using trenchless technologies. The most well-known and significant publications on this subject are the following (Afonin et al., 2007; EN, 2001; Verstraten et al., 2017), which reflect the complex issues of design and operation of open trays. The problems of possible improvement of open trays, as the sewer outlets from the multi-storey buildings, without people safety violation, the threat of flooding and water logging of the territories remain the unsolved.

2. Material and methods

The investigation methods consisted of hydraulic tests and processing of their results in order to search the optimal texture of the trays and pipes inner surface, which improves the liquid transportation. The features of the three applied investigation methods have been tested consistently on small-size hydraulic benches of new design as follows:

2.1. Methods, installations, equipment and automation means for calculation of the hydrophobicity degree of the internal surfaces of the trays

The basic method of bench-scale studies consisted of the performance of hydraulic experiments on a small-size bench. A simplified scheme of the bench for the liquid mini-stream flow dynamic studies is presented in Fig. 1 (Bryanskaya, 2013; Orlov et al., 2015). On the bench, dosed drinking water was used as a liquid for the formation of a critical mass of the water mini-flow on the gutter of variable slope. This allowed simulating the operation of the bottom part of the drainage system open tray of a semicircle shape or gravity drainage pipes (Fig. 2).

The surfaces of the tray were the most common materials of pipes and protective coatings: polypropylene, polymer sleeves of foreign firms "Per Aarsleff" (Denmark) and "Wawin" (Holland), protective films of "3M" (USA), etc. In addition, the “Smart Surface” coating, developed by FUJIFILM HUNT (Belgium), which was originally classified as a hydrophobic one, has been subject to the hydrophobicity investigation. The choice of surfaces was determined by the assumption that old drains and gravity pipes should be restored with modern repair materials (new pipes, protective coatings), which are used in trenchless technologies (Ariaratnam and Sihabuddin, 2009).

The film and photo cameras, installed in the bench, served as the equipment for fixing the results of bench studies and enabled frontal and coaxial shooting of the mini-flow in the tray. In particular, Sony digital video camera (HDR-CX250E model) and a Sony 550 digital SLR camera (equipped by a DT 1.8/50 SAM lens with a Kenko Extension tube macro-ring system) were used operating in continuous multi-frame shooting mode.

The method of the experiments consisted in frontal and coaxial photo and video shooting of the mini-flow, determination of its dimensions (Fig. 2): the heights of the upper H and lower h lenses, the edge angles α, the areas of the lenses S (for example, for the upper lens S_v =2aH/3) and other parameters that allow assessing the hydrophobicity degree of the material and, if possible, identifying its relationship with the mini-flow geometric parameters. A mathematical description of the outlines of the mini-flow elements has been made, and the equations of the upper lens and the tangent to it at the intersection with the horizontal plane, in particular.

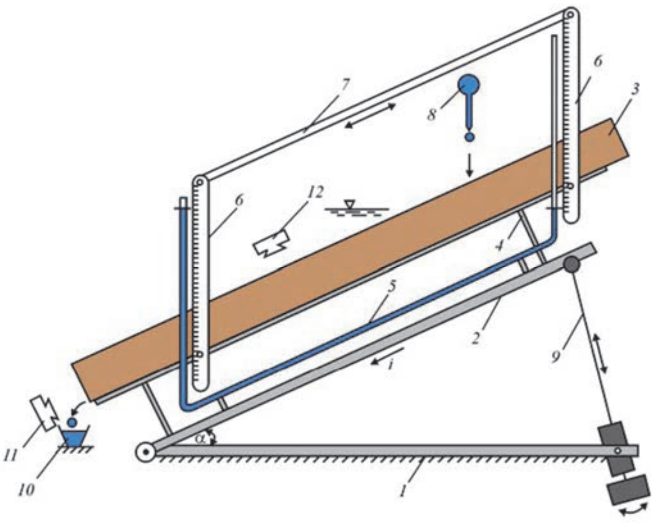
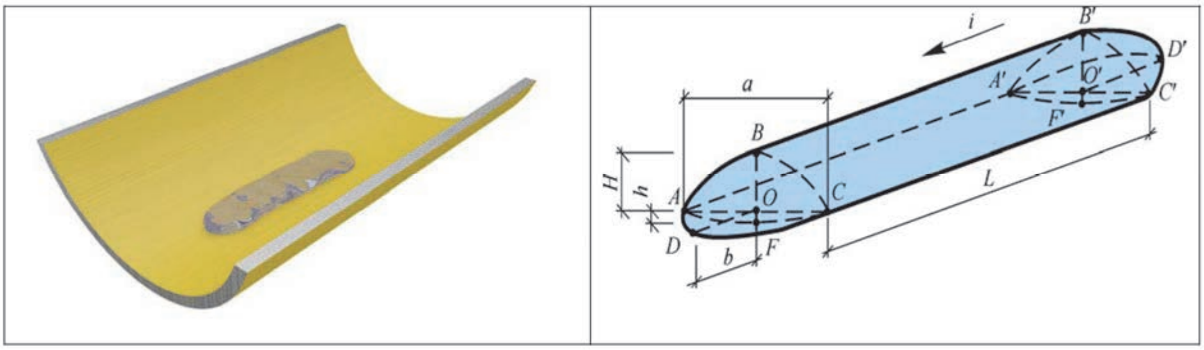


Fig. 1. Scheme of the bench at the maximum slope of the semicircle tray (d=130 mm): 1-support frame; 2-trestle; 3 - tray [L=1 m]; 4-rack; 5 - system of communicating vessels; 6-dimensional rulers; 7-control bar; 8-dosing pipette with water; 9 - rod mechanical Jack; 10-liquid collector; 11, 12- front and coaxial cameras respectively



(a) (b)

Fig. 2. Axonometric scheme of the mini-flow: i – variable slope of the gutter; a, L - average values of the width and length of the mini-flow compact part, respectively; N, h - the projection heights of the upper and lower lenses on the vertical plane, respectively; b - the height of the half of the mini-flow head ball segment; AFC, AA`C`C, respectively, the wetted perimeter and the surface of the mini-flow compact part (Sm_{cm}): (a) represents general view of mini-flow in the semicircle tray; (b) represents geometric characteristics of mini-flow elements

2.2. Methods, facilities and utilities for exploratory experimental investigations to study the tray inner surface texture providing the vortex formation in single-phase flows with small fillings

The search experiments aimed at studying the most effective texture (shape and location of artificial obstacles) on the inner surface of the trays were carried out on a small-size test bench (Fig. 3) (Orlov et al., 2018). The principle of the bench operation is that liquid flows from a reservoir to the tray, which is installed with a slope and has a certain surface relief. Artificial obstacles are placed to form a vortex at both lower and upper limits of working fillings (small and large fillings) of pipelines of the corresponding diameter. During the flow movement a source of light was switched on and cameras recorded the flow front (layer height, filling), nature and geometric dimensions (length, width and area of turbulence zones) at different options of the tray slope.

"Small fillings" meant herein the tray fillings being provided according to the size of possible artificial obstacles (1-4 mm), which do not have a significant impact on the hydraulic performance of the flow in the pipelines. The small fillings were a necessary condition to track the appearing Karman vortex tracks on the bottom of the tray and clarify kinematic characteristics of the turbulent flow with the help of photo and video filming (Orlov et al., 2018). The conducted experiments consisted in confirmation of hypothesis that the arising vortices are the accomplice of those forces, which allow increasing the transfer efficiency of solid (for example, sand) inclusions without their deposition onto the bottom part of trays or pipes.

One of the distinctive features of the bench is provision of a light source, which created the chiaroscuro effect, allowing a productive capture of the flow vortex formation using the photo and film equipment.

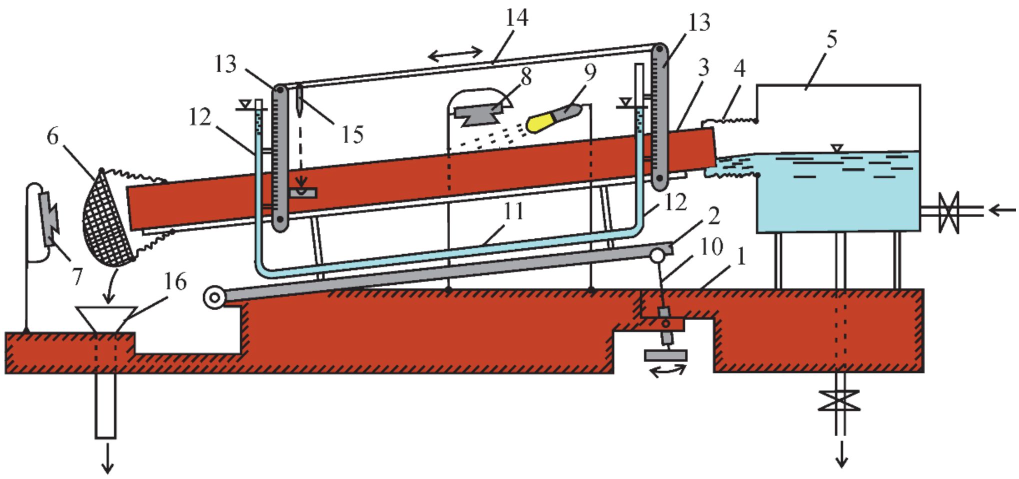


Fig. 3. Test bench to study turbulence and transport capacity of the flow: 1 - fixed frame; 2 - movable platform; 3 - open tray; 4 - rubber corrugated pipe; 5 - storage tank for liquid; 6 - removable mesh catcher of foreign dispersed inclusions; 7, 8 – cameras, respectively, frontal and coaxial shooting; 9 - light source; 10 - mechanical Jack; 11 - water main; 12 - flexible transparent communicating tubes; 13 - movable measuring rulers; 14 - strap; 15 - laser plumb; 16 - receiving measuring reservoir

Fig. 4. Samples of surfaces with artificial roughness. From left to right: round-shaped obstacle; cylindrical bars; cruciform bars arranged in the form of a parallelepiped; ditto with a round obstacle in the middle; corners (at the top) and double obstacles in the form of consecutive wedges (at the bottom)

There were bars in the form of a parallelepiped and a cylinder, prisms and nuts, as well as obstacles in the form of an inverted ball segment and other 12 types in total used as obstacles forming the artificial texture of the inner surface of the tray. Some types of trays with an artificial textured surface are shown in the Fig. 4. Metal and polymer obstacles were located both in the center of the tray and with a relative displacement (small and large) from the axis of the tray to identify the size (nature, length, width, area of the disturbance zone) of the vortices (behind the object) and the support in the form of ripples in front of the obstacle.

2.3. Methods, utilities and equipment for the study of vortex formation of single-phase and two-phase flows in order to increase the transfer capacity of open trays with a corrugated surface for the movement of solid fractions of different granulometric composition

Turbulization studies of single-phase and two-phase flows with the assessment of their efficiency to transfer solid fractions of different granulometric composition were carried out on the bench shown in the Fig. 5 (Orlov et al., 2019). The operation of this bench to some extent repeats the work on the bench shown in the Fig. 3. The difference is that the liquid containing solids inclusions is fed directly to the tray with the design surface relief. When the flow is moving, cameras record its front (layer height, filling), character and geometric dimensions (length, width and area of turbulence zones). Based on the chiaroscuro effect, the efficiency of the flow transfer capacity is subject to an analysis with regard to its ability to remove various foreign objects of different dispersive composition.

Experimental bench studies have been aimed at describing the vortex processes in the liquid when encountering obstacles. It should be noted that the theoretical definition of hydrodynamic characteristics presents great difficulties not only in mathematical terms, but also in the formulation of the hydrodynamic problem. Hence, theoretical methods require a number of assumptions and the introduction of a number of simplifications. During the experiments, the vortex flows within the obstacles were studied in the form of a visual fixation of the Karman vortex streets. To control the vortex formation more stringently during the experiments, there were the refraction effect of the shadow line reflected on the water surface used, which has occurred due to the parallel placement of two lamps of a special illuminator. As a result, the phenomenon of vortex formation has been fixed in the form of the shadow line deformation, classifying it as laminar, vortex or coherent. The experiments were carried out both when the coaxial film camera was stationary and when it was moved in the direction of the flow to identify the areas of the greatest turbulization in the tray between the obstacles.

3. Results and discussion

3.1. Assessment of the hydrophobicity degree

The dynamic experiments resulted in the mini-flow imaging in the frontal and coaxial planes on a tray made of polypropylene (Fig. 6) and other materials.

Similar results, illustrating the mini-flow behavior on other surfaces (polymer sleeves and protective films with clearly expressed hydrophilic and hydrophobic characters), in the dynamic stream flow conditions allowed estimating the hydrophobicity degree of the surfaces not by the size of the edge angle, as it is done in statics with a drop of liquid (Urazaev, 2006), but by determining the hydrophobicity relative coefficient, K_{hr} (Eq. 1).

$$K_{hr} = S_v /(S_{gs} \cdot i) \quad (1)$$

where: i is the slope of the gutter; S_v – the area of the upper lens (*ABCOA*), mm^2; S_{gs} - the wetting area of the gutter surface (*AA`C`C*) by the *L* compact part of the mini-flow along the width of the wetted perimeter arc (*AFC*), mm^2.

During dynamic bench studies aimed to determine the hydrophobicity degree of the "Smart Surface" coating it was detected, that the flow width *a*, the heights of the upper *H* and the lower *h* lenses depend on the mini-flow mass *N* in wide ranges of the gutter slope *i*, which made from 0.01 to 0.11.

As follows from the graphs in Fig. 7, automated data processing showed linear dependencies. Concerning the changes in geometric parameters, such as the average flow width *a* and the height *h* of the lower lens within the investigated range of the drop mass *N*, it can be stated that these values practically do not change and the compensation of the increasing mass *N* entering the gutter is reflected in the length *L* of the mini-flow compact part resulting in the increase of the latter.

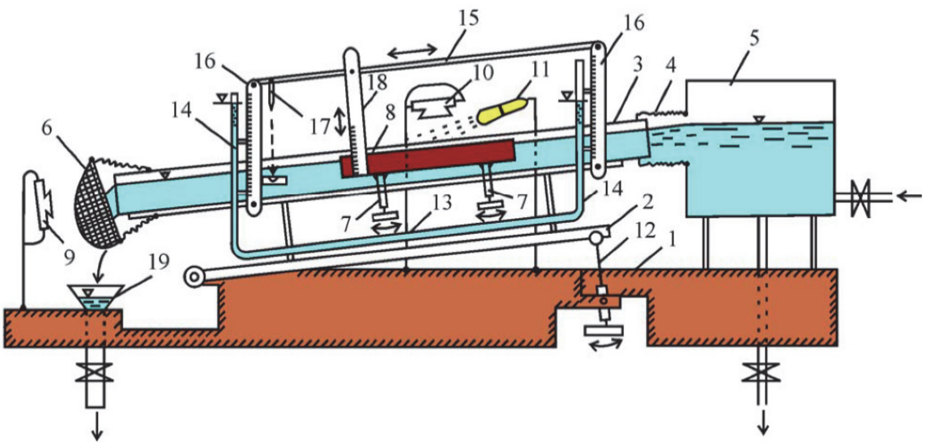
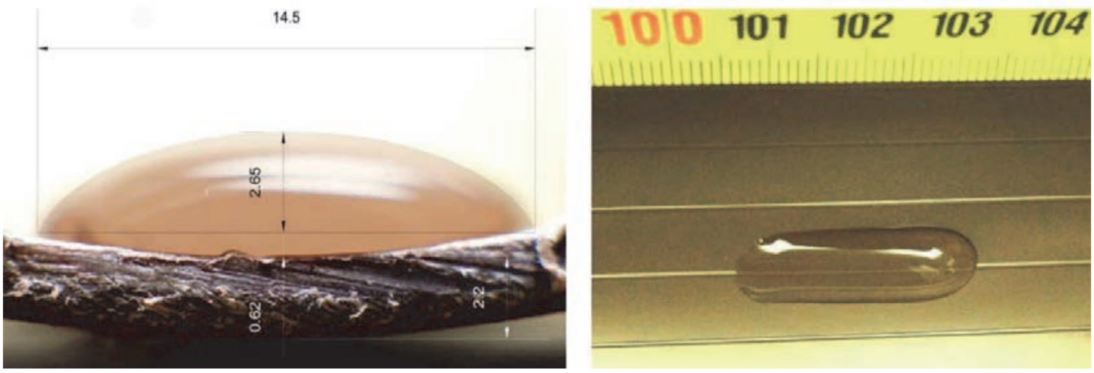


Fig. 5. Test bench for investigation of the transfer capacity of open trays having different texture of the inner surface: 1 - fixed frame; 2 - movable platform; 3 – gutter; 4 - rubber corrugated pipe; 5 - storage tank; 6 - removable mesh catcher; 7 - small mechanical Jacks; 8 - tube module in the form of an open tray; 9, 10 - front and coaxial cameras, respectively; 11 - light source, 12 - large mechanical Jack; 13 - water - filled main; 14 - communicating flexible transparent tubes; 15 – strap; 16 - movable dimensional rulers; 17 - laser plumb; 18 - retractable measuring ruler; 19-receiving measuring reservoir



(a) (b)

Fig. 6. Photos of the mini-stream in a polypropylene tray: (a) selective front photo; (b) coaxial photo

The nature of the change *H=f (N)* shows that for small values of *N*, the height of *H* is greater than for large *N*, i.e., the greater the mass *N* of the mini-flow, the lower the height *H* of the upper lens. The reason is a kind of "leveling" of the height *H* due to changes in the average length *L* of the mini-flow compact part, which can be characterized as the mini-flow evolution.

It shall be concluded from the analysis of dependencies *a=f(N), H=f (N)* and *h=f(N)* that the experiments on determination of the hydrophobicity degree of the materials in the bench investigations can be carried out at any slope of the gutter with possible formation of a relatively stable length *L* of the mini-flow compact part within shorter time. The limit states are determined by the total mass of water in the mini-stream and its compactness, the slope of the trough and the geometric characteristics of the mini-stream.

Using the geometric dimensions and average velocities of the mini-flow obtained during the experiments, the entire spectrum of the necessary hydraulic parameters of the studied protective coatings was determined with the final output to the roughness coefficient of the corresponding protective coating "n".

The algorithm for hydraulic parameters estimate is to determine: the filling (*h/d*) and the wetted perimeter (the arc length *AFC*) of the mini-flow; the average hydraulic radius *R*; the speed of the mini-flow *V* and the path *П* traversed by the head part of the mini-flow during the time *T*; the Chézy coefficient *C* and the coefficient of relative roughness *n*. Following the presented calculation method, the roughness coefficient "n" by Manning for polypropylene according to the results of experiments made n=0.0132 with a relative hydrophobicity coefficient of $K_{rel.}$=1.0655. For other hydrophilic protective coatings, the roughness coefficient varied in the range of 0.009-0.0098, and the relative hydrophobicity coefficients respectively in the range of 1.075-1.098 (for Smart Surface hydrophobic coating it was 1.098). Thus, a correlation was found between the coefficients of the relative hydrophobicity and the roughness: the smaller the roughness of the material, the higher its hydrophobicity.

Complex hydraulic calculations during experiments on different types of coatings required the creation of an automated program (Orlov et. al, 2017b). The results of the software complex with the assessment of the dynamics of changes in hydrophobicity indices are presented in the article (Orlov et al., 2017a). Results of experiments on a smooth hydrophobic surface, as well as with texturized fragments, gave the following conclusions. The mini-flow has the form of a "snake" on a smooth surface, and in the presence of corrugations (obstacles), it tends to protrusions, which may be characterized as an artificial roughness. As the speed increases, the mini-flow begins to straighten, and artificial roughness protrusions lead to an increased turbulization, which can contribute to a bigger transfer capacity of the flow in trays and pipelines (Fig. 8). This assumption has been confirmed in subsequent experiments.

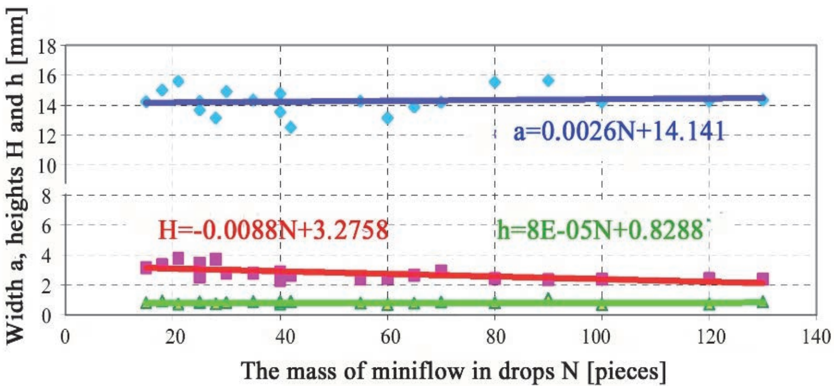


Fig. 7. Diagrams of the parameter dependences of the width **a**, heights **H** and **h** on the mini-flow mass **N** in wide ranges of the gutter slopes *i*

(a) (b)

Fig. 8. Fragment of the mini-stream flow: (a) mini-stream flow at low velocities on a hydrophobic surface; (b) flow straightening with gravity to roughness projections when the flow rate increases

3.2. Analysis of vortex formations in single-phase flows at small fillings

As a result, the peculiarities of creating vortex zones for each type of obstacles were revealed. Fig. 9 shows a photo with a pronounced Karman vortex street in the presence of obstacles to the water flow in the form of nuts with a height of 4 mm (with a distance between obstacles circa 20 mm).

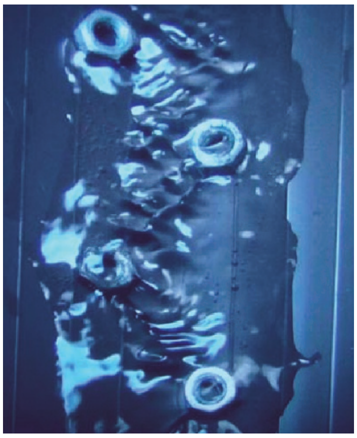


Fig. 9. Polyhedron obstacles on the right and on the left of the tray axis

The measurements showed that the disturbance zone between individual obstacles is significant (about 5 cm^2) and practically covers the entire free surface area of the water flow in the tray. This flow can be attributed to the category of a vortex one, since a trace is formed behind the streamlined bodies, containing persistent vortex paths directed from obstacle to obstacle. In this case, the vortex path will increase the flow transfer capacity at low flow rates.

Fig. 10 shows a shortened version of the interpretation of the three results on the study of vortex formation on other textured surfaces and forecasts of increasing the transfer capacity of trays with different textures to move foreign inclusions in the case of two-phase flow. With relatively wide and short obstacles (2x11x2 mm size), located at an angle of 90º to each other (Fig. 10a), it follows that at the velocity of 0.4 – 0.6 m/s there is an active perturbation of the flow, thus it can be assumed that the transfer capacity of the liquid flow to move suspended particles can increase.

For the case of using narrow bars (Fig. 10b) of rectangular cross-section (1x11x1 mm), located cruciform, at a rate of less than 0.4 m/s, the character of the vortex formation is coherent (with separation of jets); an active perturbation of the flow began with an increase in speed from 0.3 m/s; however, it should be assumed that due to the backup potentially precipitating substances will not be removed from the interface zone of the cruciform obstacles.

For the case of grouped obstacles (Fig. 10c) being of identical round-in-plan shape (4 mm diameter and 2 mm height), which are displaced from the gutter axis, the active disturbance of the flow occurs at low rates (0.4 m/s) and remains stable over the entire length of the obstacle location at the increased rates. This type of the obstacle location can be estimated as a promising one for increasing the tray transfer capacity.

3.3. Analysis of the vortex formation of single-phase flows and the movement of solid fractions of different granulometric composition in two-phase flows at different fillings

According to need to fix the vortex formation in the form of refraction of the shadow line (shadow track) from special lamps, which reflects on the water surface, the experiments have been carried out in two modes, i.e. using single- and two-phase flows.

When conducting experiments in the first mode, a significant number of artificial obstacles were studied. The experiments were carried out both at a fixed location of the movie camera (the first stage), and when it was moving along the flow (the second stage).

Fig. 11 shows visual characteristics of the flow on an open tray with mini-pyramid-type obstacles (dimensions of the sides 4x4mm, height 3 mm) with a reflected shadow path in the laminar flow mode (V=0.166 m/s), the turbulent one (V=0.222 m/s) and the coherent one (V=0.303 m/s).

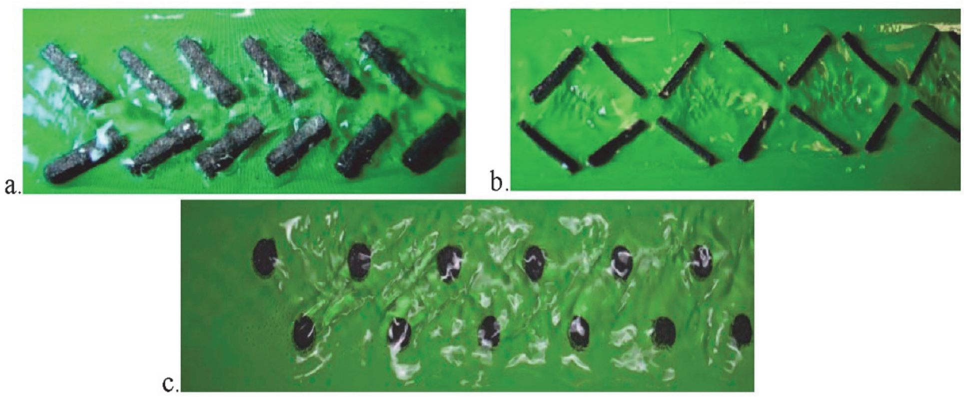
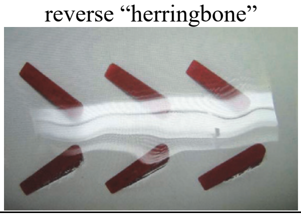
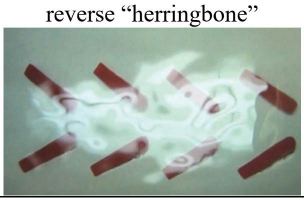


Fig. 10. Turbulence of the flow on three types of obstacles: (a) wide and short obstacles; (b) narrow bars; (c) grouped obstacles

(a) (b) (c)

Fig. 11. Visual dynamics of the shadow track deformation: on the left-laminar motion; in the middle part – turbulent (vortex) motion; on the right – coherent (with separation of vortices) motion: (a) laminar motion; (b) turbulent (vortex) motion; (c) coherent (with separation of vortices) motion

Table 1. Micro-turbulence studies using the chiaroscuro effect on the obstacles of direct and reverse "herringbones"

Test number	***Indices of time, flow rate, water level height and filling***				
	Time T_{av} [s]	***Average velocity V_{av} [m/s]***	***Height h_{av} [mm]***	***Filling [h/d_{av}]***	***Shape of the position on the tray***
1a	9	0.111	14	0.108	reverse "herringbone" 
1b	9	0.111	14	0.108	direct "herringbone" 
2a	3.5	0.285	35	0.269	reverse "herringbone" 
2b	3.5	0.285	35	0.269	direct "herringbone" 
3a	3.0	0.333	40	0.308	reverse "herringbone" 
3b	3.0	0.333	40	0.308	direct "herringbone" 

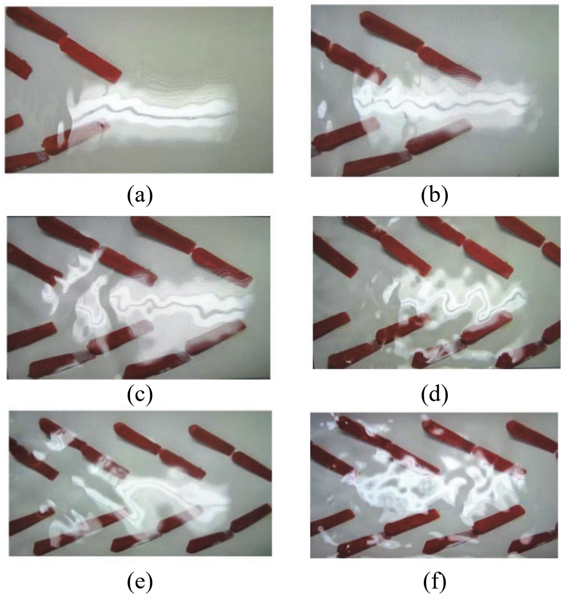


Fig. 12. Visual dynamics of vortex formation on a textured surface when moving the camera: (a) represents laminar flow motion, (b) represents slight deformation between the first obstacles, (c) and (d) represents large scale of deformation, (e) represents strong deformation, but without torn vortices, (f) represents appearance of a coherent motion (vortex rupture)

According to the experimental data presented in the Fig. 11, a significant turbulence of the flow at this type of obstacles is possible at the flow rates about 0.3 m/s. The first stage of the micro-turbulence assessment is presented in the Table 1. Table 1 shows the flow time T_{av}, average velocity V_{av}, height of the water layer in the tray h_{av}, and filling h/d_{av}. There are the data of the flow hydraulic characteristics during its movement through a structured surface, which is formed by two similar obstacles in the form of polyethylene wedges (H=1-4 mm, L=20 mm). The obstacles were located by their frontal and pointed parts towards the flow as "straight" and" reverse" herringbone.

Visual observation of the fluid flow behavior on textured surfaces with a fixed coaxial location of the movie camera testify that fundamental differences almost do not occur in the nature of the fluid flow both at the location of the obstacles in the form of direct or reverse “herringbone“ (see pairs of the experiments 1a and 1b, 2a and 2b, 3a and 3b). This conclusion served a strong argument for expanding the range of studies of the solid inclusions transfer along a double-level structure with obstacles combining direct and reverse “herringbones “.

When performing the second stage of the first mode, i.e. moving the movie camera in the direction of stream flow along the tray (from the right to the left), many types of obstacles were used, including a "two-storey" arrangement of obstacles in the form of wedges (Fig. 12). The results of the visual observation are presented by a number of photographs at the filling of 0.185 and the flow rate of 0.3 m/s in the tray.

The results of the experiments presented in the Fig. 12 showed, that the shadow line is smooth in front of the obstacle, which testifies a laminar flow motion (Fig. 12a). Next, the shadow line has a slight deformation between the first obstacles (Fig. 12b). When reaching the third and the fourth rows of obstacles (Figs. 12 c, d) there is a large degree of deformation, and in Fig. 12e there is a strong deformation, but there are no torn vortices. Fig. 12f indicates the appearance of a coherent motion (vortex rupture) and, thus, intensification of the flow turbulization. This testifies that at the rate about 0.3 m/s and higher it is possible to ensure the vortex formation on a textured surface, which will facilitate the removal of potentially precipitating impurities in the form of sand and other materials from the bottom of the trays.

The results of the experiments on two-phase flow (the second mode) are presented at Fig. 13. Provision has been made there of studying the sand removal dynamics (the sand of 0.3 mm fraction) in the presence of the second layer of obstacles, i.e. the combined arrangement of the obstacles (direct and reverse "herringbone") and flow rates in the tray within 0.1-0.35 m/s (Fig. 12a) with a step of 0.05 m (Fig. 13).

Visual results of the experiments showed that the removal of sand occurs by forming a ridge at the water's edge point between the second row of obstacles (Figs. 13 a, b). The sand mass starts to be flushed (Fig. 13c) except for the caked sand (Fig. 13d) along the axis of the tray. When the flow rate increases to 0.3 m / s, there is a complete removal of sand in the second row (Fig. 13e) and almost complete removal at the rate of 0.35 m/s (Fig. 13f). When performing the experiments with the sand fractions of 1.5 and 2.5 mm diameter, the nature of its removal practically did not change, but the process took place at higher rates (about 0.5 m/s).

Thus, the availability of a structured surface makes it possible to transfer the sand inclusions, that have fallen in the bottom part, at the rates, which are two times lower than the self-cleaning ones (0.7 m/s).

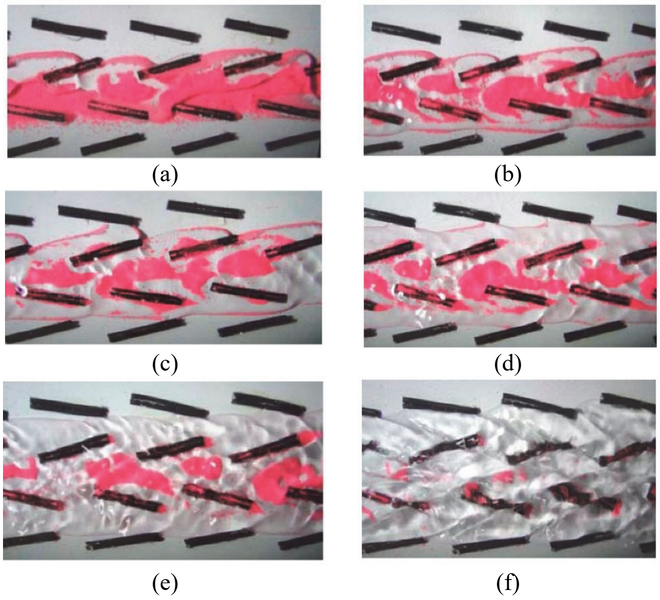


Fig. 13. Visual dynamics of sand inclusions removal from a textured surface depending on the flow velocity: (a) and (b) represent forming a ridge at the water's edge point between the second row of obstacles (velocity is 0.1 m/s and 0.15 m/s correspondingly); (c) represents sand mass starts to be flushed (velocity is 0.2 m/s); (d) represents caked sand along the axis of the tray (velocity is 0.25 m/s); (e) represents complete removal of sand in the second row (velocity is 0.3 m/s); (f) represents almost complete removal at flow velocity of 0.35 m/s

4. Conclusions

Three new designs of small-size experimental benches and an automated program of calculation of hydraulic parameters have been presented. They provided the studies with the tray transfer capacity based on a chiaroscuro effect using the coverings of the internal surface of the trays, including special textured ones in the form of obstacles forming vortexes in a liquid flow.

Within the research there has been new investigation made of the nature of the mini-flow movement along hydrophobic and hydrophilic surfaces inclined in the form of an open gutter with natural and artificial roughness in the form of obstacles of different size and location. The mini-flow geometry of the front and coaxial projections has been studied, as well as its geometrical dimensions and hydraulic characteristics of the surfaces under investigation; the concept of the hydrophobicity degree of the sliding surfaces has been formulated.

It has been established, that when the inner surface of the trays is made as a hydrophobic structure and has an artificial roughness, the flow turbulence is enhanced with the attraction of vortices to the protruding elements of the artificial texture, which results in a higher removal efficiency (transfer) of foreign inclusions (e.g., sand of various fractions) without their deposition in the tray part of the pipe.

Provision has been made herein of the study results on the dynamics of changes in the nature of a single-phase flow with different textured trays, as well as removal of foreign inclusions in a combined arrangement of the obstacles in the case of two-phase flow, taking into account the deformation of the shadow line created by a lamp. The possibility of increasing the transfer capacity of trays due to textured surfaces at the rates below the self-cleaning ones is defined. The texture of trays and gravity pipelines may be improved during repair and restoration works by applying polymer protective sleeves with the appropriate surface relief.

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