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COARSE PARTICLES-WATER MIXTURES FLOW IN PIPES*

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The present paper is focused on evaluation of the effect of average mixture velocity and overall concentration on the pressure drop versus the slurry average velocity relationship, on slurry flow behaviour and local concentration distribution. The experimental investigation was carried out on the pipe loop of inner diameter D = 100 mm, which consists of smooth stainless steel pipes and horizontal, inclinable and vertical pipe sections. The frictional pressure drop in the horizontal pipe section were significantly higher than that in the vertical pipe due to the fact, that for stratified flow the contact load produced significant energy losses. The frictional pressure drop of coarse particles mixtures in vertical pipe increased with the increasing mixture concentration and velocity, what confirmed effect of inner friction, inter-particles collision, and the drag due to particle-liquid slip. It was found that for stratified coarse particles-water mixture the frictional pressure drop was not significantly influenced by the pipe inclination, especially for low concentration values. The effect of pipe inclination decreased with increasing mixture velocity in ascending pipe section; the maximum value was reached for inclination between 20 and 40 degrees. Inclination of pressure drop maximum increased with decreasing mixture velocity. In descending pipe section the frictional pressure drop gradually decreased with increasing pipe inclination. The effect of inclination on frictional pressure drops could be practically neglected, especially for low mixture concentration and higher flow velocities. The study revealed that the coarse particle-water mixtures in the horizontal and inclined pipe sections were significantly stratified. The particles moved principally in a layer close to the pipe invert. However, for higher and moderate flow velocities the particles moved also in the central part of the pipe cross-section, and particle saltation [1] was found to be dominant mode of particle conveying.

***Key words*:** hydrotransport, coarse particles pipeline installation, pressure drop, pipe inclination

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The hydraulic transport pipelines are commonly used for transport of bulk materials, like coal, ores, and waste materials. Mostly relatively fine particles are used, which in the turbulent flow are supported by turbulent diffusion in the core of the flow. Near the pipe wall a lift force contributed to particle conveying. Pipeline transport of coarse-grained material is not very frequently used due to the problems of severe wear, energy consumptions, high deposition velocity limit and consequently also operational velocities, and also material degradation. However, pipeline transport of coarse particles in form of heterogeneous mixtures is of potential importance in mining and building industry, dredging and poly-metallic nodules transport from the ocean bottom to the surface [5, 10].

The advanced knowledge of particle-water mixture flow behaviour is important for safe, reliable, and economical design and operation of the freight pipelines. The understanding of the slurry flow behaviour makes it possible to optimize transport parameters and energy requirements, to improve quality, safety, economy and reliability of the transport. Knowledge of the slurry flow behaviour, deposition limit and operational velocities, and the pressure drops associated with the slurry flow in horizontal, vertical and inclined pipe sections is essential to safe and effective design and operation of such pipeline installation [6].

A lot of theoretical or experimental studies have been carried out on transport of sand or fine particles in horizontal pipes [2-4, 10, 11]. However, a relatively little research has been done on hydraulic conveying of gravel or bigger particles, especially in vertical and inclined pipes. A progress in the theoretical description of heterogeneous slurry flow is limited due to the lack of experimental data of the flow behaviour and an inner structure of slurry flow.

The present paper is focused on evaluation of the effect of average mixture velocity and overall concentration on the pressure drop versus the slurry average velocity relationship, on slurry flow behaviour and local concentration distribution. The experimental investigation was carried out on the pipe loop of inner diameter $D = 100$ mm, which consists of smooth stainless steel pipes and horizontal (A), inclinable and vertical (B) pipe sections, see Fig.1.

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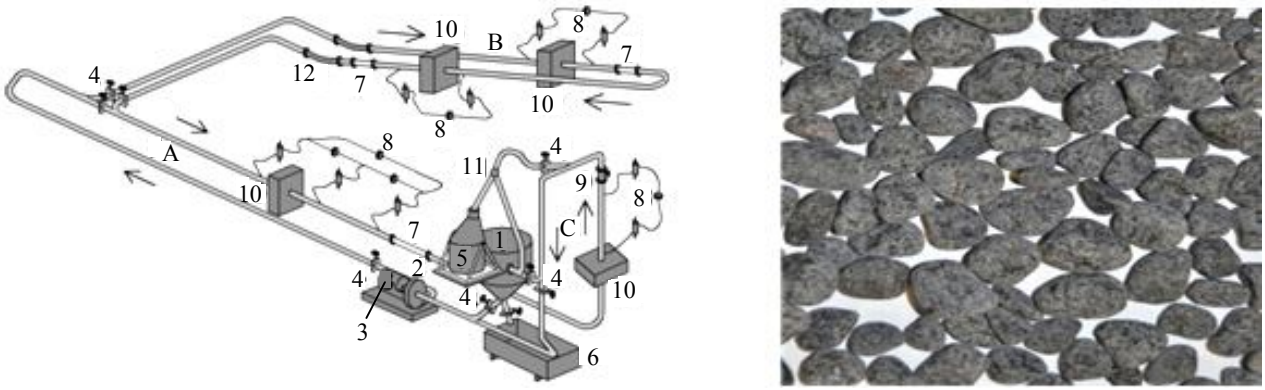


Fig. 1. Experimental test loop D = 100 mm and the used graded basalt pebbles

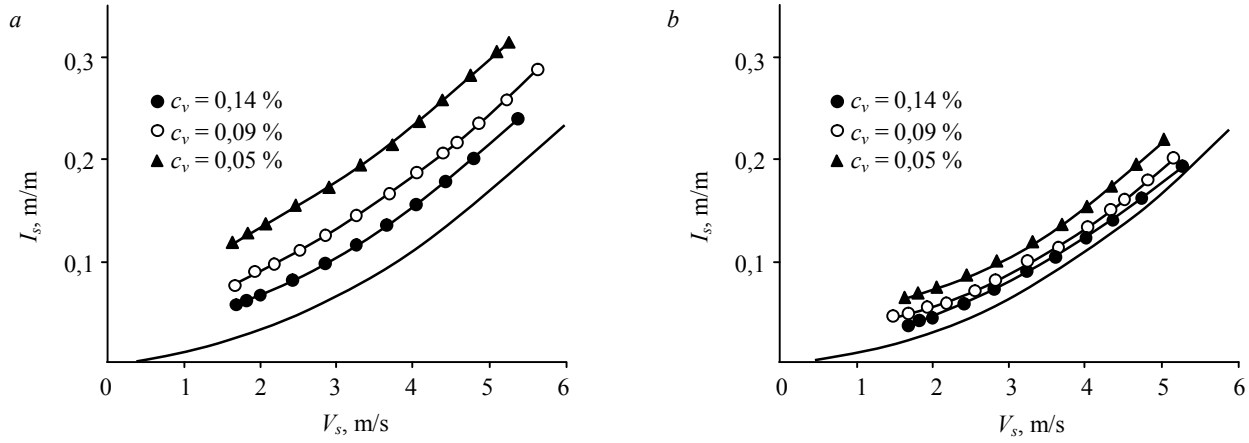


Fig.2. Pressure drop, I_s, in the horizontal (*a*) and vertical (*b*) pipe sections

Slurry was forced from a mixing tank (1) into the test loop by a centrifugal slurry pump GIW LCC-M 80-300 (2) with variable speed drive Siemens 1LG4283-2AB60-Z A11 (3). The pressure drop, I_s, were measured by the differential pressure transducers Rosemount 1151DP (8) over 2-meter long measuring sections, the mean slurry velocity, V_s, was measured in by a Krohne magnetic flow meter OPTIFLUX 5000 (9), mounted in the short vertical section (C) at the end of the loop. In the pipe viewing section (7) the mixture flow was recorded using a high speed digital camera NanoSence MK III+ with a frequency up to 2 000 frames per second, image resolution 1280 × 1024 pixels and frame rate 200 Hz [7]. The vertical *U*-tube (B) enables evaluating the delivered concentration of solid phase. To measure local concentration of solids, the loop is equipped with radiometric density meters (10). Water was used as a carrier liquid and the overall concentration, c_v, ranged from 3 to 15 %. The studied mixtures consist of graded basalt pebbles of narrow particle size distribution (particle diameter, d, ranged from 8 to 16 mm, mean diameter d_{50} = 11.0 mm, density ρ_p = 2 787 kg m^{-3}), see Fig.1.

Effect of mixture concentration and velocity on frictional pressure drop in horizontal and vertical pipe section is illustrated in Fig.2. The hydrostatic effect $\Delta p = (\rho_s - \rho_o)\, g.\, \Delta h$, where ρ_s and ρ_o is density of the mixture and carrier liquid, respectively, and Δh is height of the mixture column, was extracted in Figs.2 and 3. Practically parallel course of pressure over velocity dependence I_s / V_s with that of water confirmed that for stratified flow the main proportion of frictional pressure drop was due to the Coulomb friction between the particles and the pipe [8].

The frictional pressure drop in the horizontal pipe section were significantly higher than that in the vertical pipe due to the fact, that for stratified flow the contact load produced significant energy losses [9, 10]. The frictional pressure drop of coarse particles mixtures in vertical pipe increased with the increasing mixture concentration and velocity, what confirmed effect of inner friction, inter-particles collision, and the drag due to particle-liquid slip.

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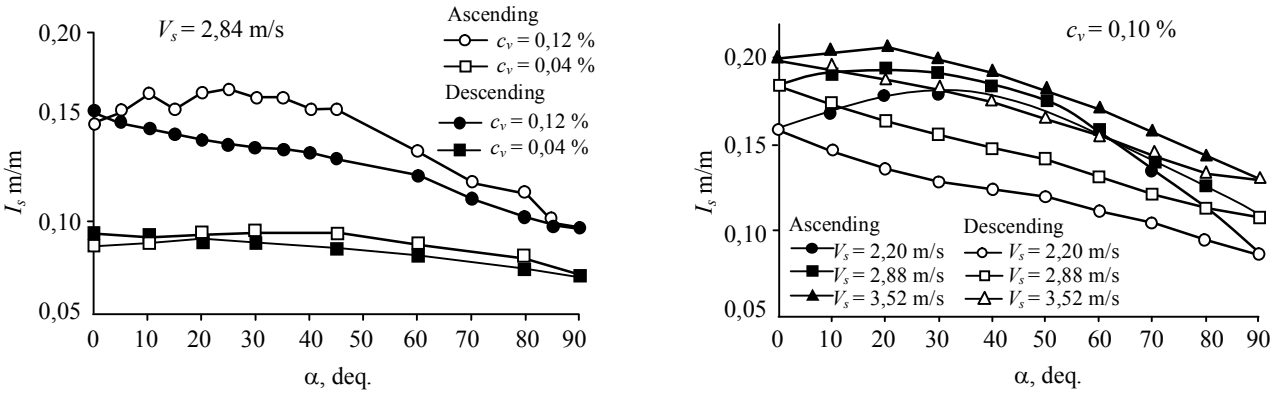


Fig.3. Pressure drop, I_s, in the inclined pipe sections

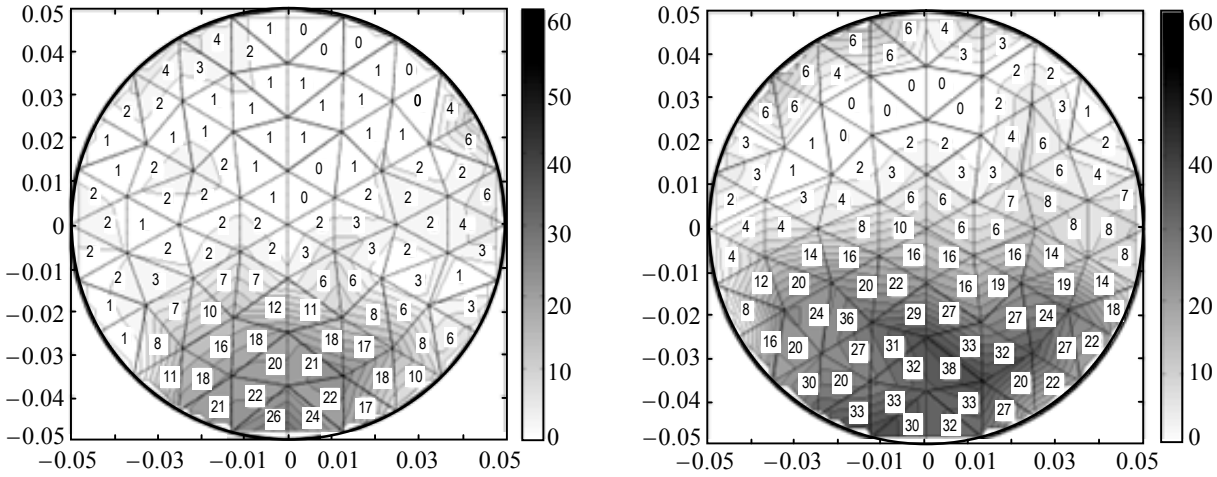


Fig.4. Maps of local volumetric concentration distribution in horizontal pipe section

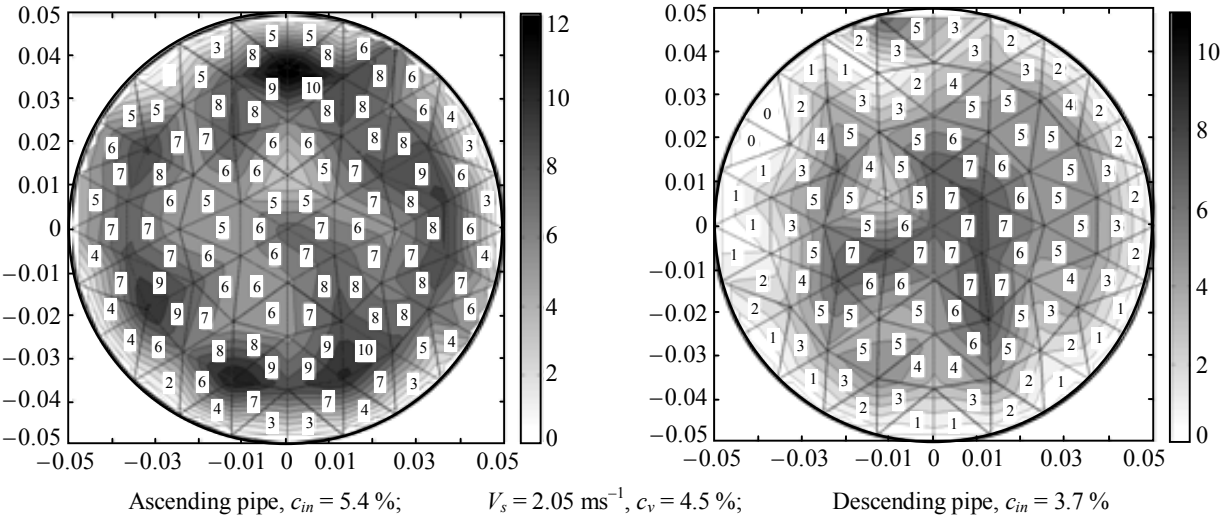


Fig.5. Maps of local volumetric concentration distribution in vertical pipe sec

The pressure drop in inclined pipe sections can be described by well-known Worster and Denny [11] formula, and can be divided into two parts – not recoverable frictional pressure drop, and the hydrostatic pressure difference, in principle change of potential energy. Fig.3 illustrates effect of the pipe inclination, alpha, on pressure drop, I_s, in inclined pipe sections for different values of mixture transport concentration and mean velocity, V_s.

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It was found that for stratified coarse particles-water mixture the frictional pressure drop was not significantly influenced by the pipe inclination, especially for low concentration values. The effect of pipe inclination decreased with increasing mixture velocity in ascending pipe section; the maximum value was reached for inclination between 20 and 40 degrees. Inclination of pressure drop maximum increased with decreasing mixture velocity. In descending pipe section the frictional pressure drop gradually decreased with increasing pipe inclination. The effect of inclination on frictional pressure drops could be practically neglected, especially for low mixture concentration and higher flow velocities.

Local concentration distribution is important for understanding the physical mechanism of the heterogeneous mixture flow; it has a significant effect on both the mixture flow behaviour and pressure drop. The concentration distribution was measured using of a gamma-ray device and the effects of mixture velocity and concentration were analysed.

It is evident from observed local concentration maps that conveyed particles tended to occupy the bottom part of the pipe, see Fig.4. Concentration near the pipe lateral walls was observed slightly less than in central portion of the pipe cross-section. Concentration maps made possible to evaluate the in situ concentration, c_{in}, and compare it with transport concentration, c_v, which depends on particle slip velocity (e.g. velocity difference between particle velocity and carrier liquid velocity).

Local concentration measurement in the vertical pipe section illustrated effect of particle fall velocity on mixture concentration, see Fig. 5. The in situ concentration reached higher value in ascending section than in descending one. The flow pattern and concentration distribution were observed different in ascending and descending pipe section. For descending pipe section the concentration reached maxim in central portion of the pipe, in the direction to the pipe wall local concentration fluently decreased to the pipe wall. In ascending pipe section the maximum concentration was located in an annulus from about $r = 0.15\ D$ to $r = 0.40\ D$, with increasing flow velocity the width of annulus also increases.

The study revealed that the coarse particle-water mixtures in the horizontal and inclined pipe sections were significantly stratified. The particles moved principally in a – layer close to the pipe invert. However, for higher and moderate flow velocities the particles moved also in the central part of the pipe cross-section, and particle saltation [1] was found to be dominant mode of particle conveying.

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