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GLOBAL AND LOCAL CHARACTERISTICS OF ASH MIXTURE FLOWS

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ABSTRACT

The results of flow experiments for several kinds of ash are presented. The experiments were carried out on the two laboratory stands at the Institute of Environmental Engineering, Agricultural University of Wroclaw. The pressure drop, limit deposit velocity, mixture density distribution in a cross-section of pipeline and pump characteristics are measured during these experiments. The measurements of density distribution were carried out by means of a device based on radiometric scanning, which enables us to determine these parameters without causing disturbances in the flow. The problem of limit concentration between Newtonian and non-Newtonian behaviour of mixtures is also discussed.

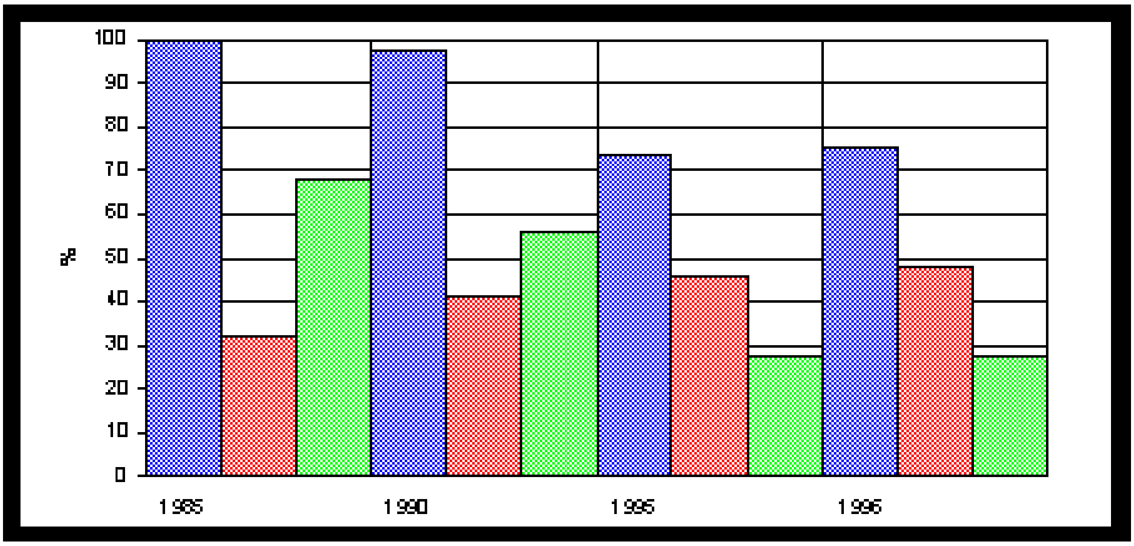
The results of investigations into parameters of hydrotransport of ash and brine mixture in pipelines (80 and 100 mm) are presented. The investigations were carried out on the test laboratory installation at the Silesian Technical University of Gliwice. The results can be used for the design of a hydraulic backfill installation in a coalmine.

Key words: ash, mixture flow, pipeline, density distributions.

INTRODUCTION

In Poland, nearly 100% of electrical and thermal energy is produced from hard coal and lignite. As a result of this production, waste material is formed – ashes and slugs. Ashes and slugs are used for economic purposes, or stored in special storage areas. In recent years, there has been a visible increase in the industrial utilization of this waste material, with a simultaneous drop of their quantity (Figure 1). In this figure all quantities are expressed in relation to waste production in 1985 (100%).

Fig. 1. Quantities of ashes and slugs in Poland relative to a production in 1985 -100% (columns - global production, industrial utilization, stored)



Ashes and slugs are utilized in hard coal mining for backfill and in hydraulic engineering for dyke and dam construction. This waste material is also used for building roads. The highest ash quantities are currently used in hard coal mining for backfill and for filling mine voids.

The ashes are transported to mine voids hydraulically through pipelines. Depending on the sort of coal and its combustion technology, the ashes have different physico-chemical and chemical properties, which influence the flow characteristics of ash-water mixtures in pipelines.

These flow characteristics for several kinds of ash-water mixtures were the matter of experimental investigations conducted in the laboratories of the Institute of Environmental Engineering of Agricultural University, Wrocław, the Institute of Mining Technology of Silesian Technical University in Gliwice, and the Measurement-Research Plant of Power Engineering in Katowice.

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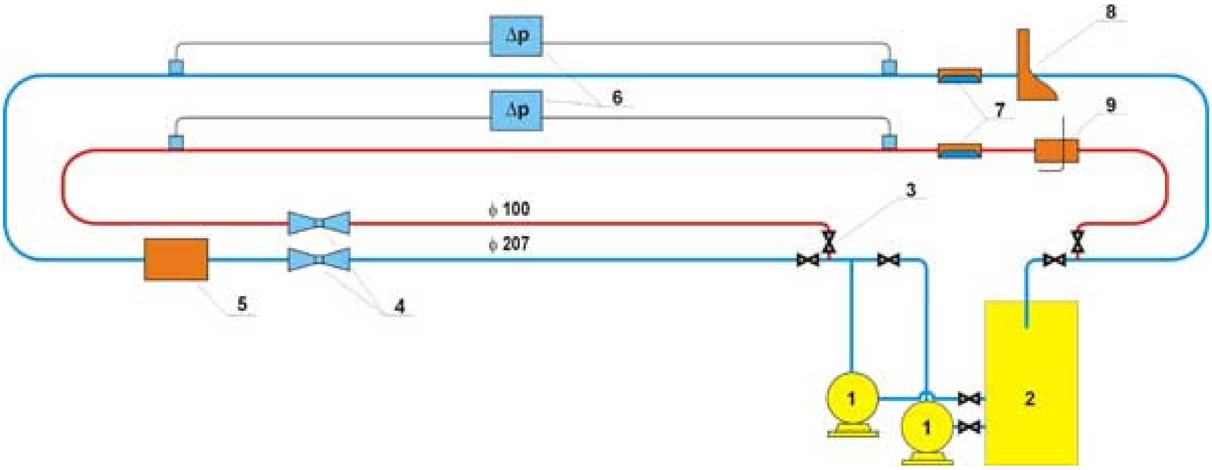
TEST-LOOPS AND ASH CHARACTERISTICS

The hydraulic gradient measurements for the mixture flow with ash labeled A and B were carried out in pipelines with a diameter of 50, 100 and 207 mm in the laboratory of the Department of Water Engineering and Hydrotransport, Agricultural University, Wrocław. The scheme and view of the installations is presented in Figure 2.

Fig. 2. Test loops at the Department of Water Engineering and Hydrotransport, Agricultural University of Wrocław
a - scheme of 100 and 207 mm loops (1-pumps, 2-suction tank, , 3-valves ϕ 200, 4-Venturi tube, 5-inductive flowmeter, 6 – pressure drop measure device, 7-transparent window, 7-scaning device, 8-Jufin-Orlov tube)



b - view of 50 mm loop

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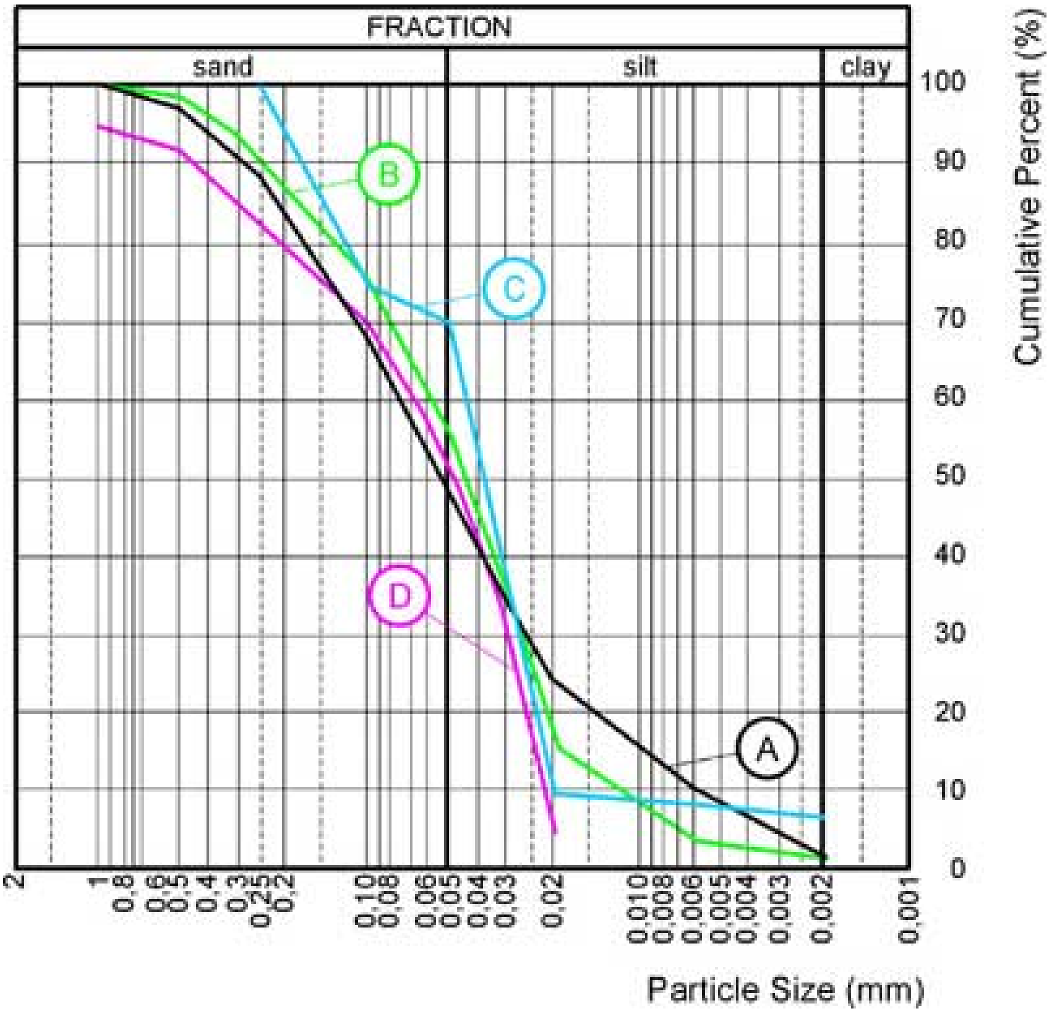
The measurements for the mixture of water and ash labeled C were performed in pipelines with a diameter of 36, 52 and 90 mm. These tests were conducted in the laboratory of the Measurement-Research Plant of Power Engineering, Katowice by employees of the Department of Water Engineering and Hydrotransport, Agricultural University, Wrocław, who also designed the test installation project in this laboratory.

The measurements for the mixture of brine and ash labeled D were conducted in the laboratory of the Institute of Mining Technology of Silesian Technical University in Gliwice in pipelines with a diameter of 80 and 100 mm.

Grain size distribution of the investigated ashes is presented in Figure 3. The density of four test ashes changes from $\rho_m = 2010\ \mathrm{kg/m^3}$ (ash C) to $\rho_m = 2150\ \mathrm{kg/m^3}$ (ash D).

Fig.3. Grain size distribution of ashes



CHARACTERISTICS OF MIXTURE FLOW IN PIPELINES

The ash mixture flow in a pipeline is described by the following global and local characteristics:

- hydraulic gradient in the function of mixture velocity and mixture density (concentration),

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- limit deposit velocity in the function of mixture density,
- limit concentration at which non-Newtonian properties occur,
- mixture density distribution in the pipeline vertical axis in the function of mixture flow velocity and mixture density.

The knowledge of hydraulic gradients in the function of flow velocity and mixture density allows for the selection of optimal transportation conditions. From an economic point of view, hydraulic ash transport aims to minimize water quantity in the mixture. Less water means lower energy consumption that is necessary to pump out mine water filtered off from hydraulic backfill or to pump return water from ash storage areas. Reducing the water quantity in the mixture generally leads to the occurrence of non-Newtonian properties. Thus, in order to establish the desired resistance values, it is necessary to be acquainted with the hydraulic gradient value in Newtonian and non-Newtonian flow zone.

The knowledge of limit deposit velocity is significant from the operational point of view of hydraulic transport installation. The flow velocity of ash-water mixture, lower than limit velocity, causes the formation of a stationary deposit layer in the bottom of the pipeline. In this case, not all the pipeline cross-section will be used for mixture transport and the pipeline may be regarded as ‘overmeasured’, that is to say that the costs were higher than necessary, by installing a pipeline whose diameter was to large.

The knowledge of mixture density distribution in pipeline vertical axis is useful for the evaluation of pipeline-wall wear.

HYDRAULIC GRADIENT

A good indicator for comparing the energy loss values for the flow of various mixtures are given by $I_m = f(v_m)$, in which the hydraulic gradient is presented in meters of mixture column (m m.c.). Curves of this kind for pseudo-homogeneous mixtures overlap with those given for liquid constituting the mixture base, $I = f(v)$, and the hydraulic gradient value can be calculated from the O’Brien and Folsom [2] formula

$$I_m = I_L \frac{\rho_m}{\rho_L}$$

where
I_m – hydraulic gradient for mixture flow, I_L – hydraulic gradient for liquid flow, ρ_m – mixture density, and ρ_L – liquid density.

An example of such mixtures is ash A, for which the hydraulic gradient values are presented in Figure 4. In this figure hydraulic gradient is presented in meters of water column (m H_2O), in meters of mixture column (m m.c.), and also in meters of mixture column (m m.c.) in logarithmic coordinates. It is clearly visible that measurement points are placed around curve $I = f(v)$ for water except points for the mixture flow with the volume concentration 0.40 in pipeline with a diameter of 207 mm. In the case of this mixture, non-Newtonian fluid properties occurred, which caused a repeated increase of the hydraulic gradient. The Bingham model (Figure 4) best approximates the measurement points in the laminar zone of this mixture flow.

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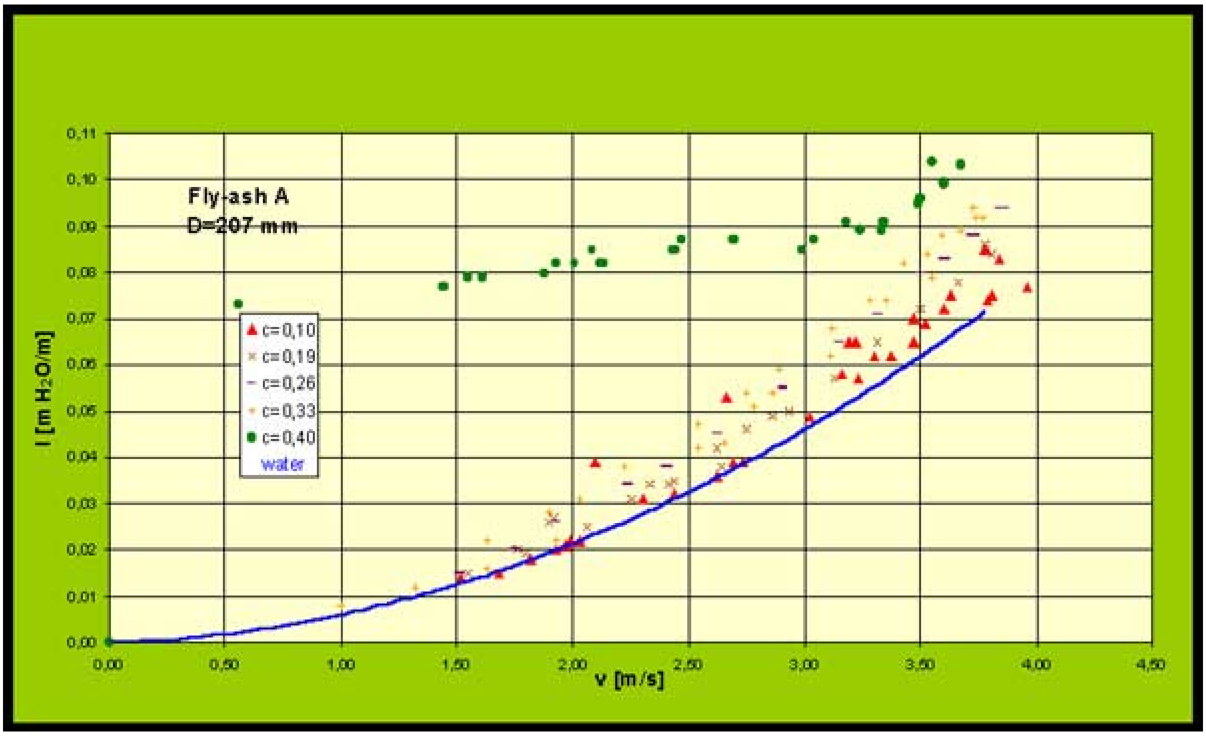
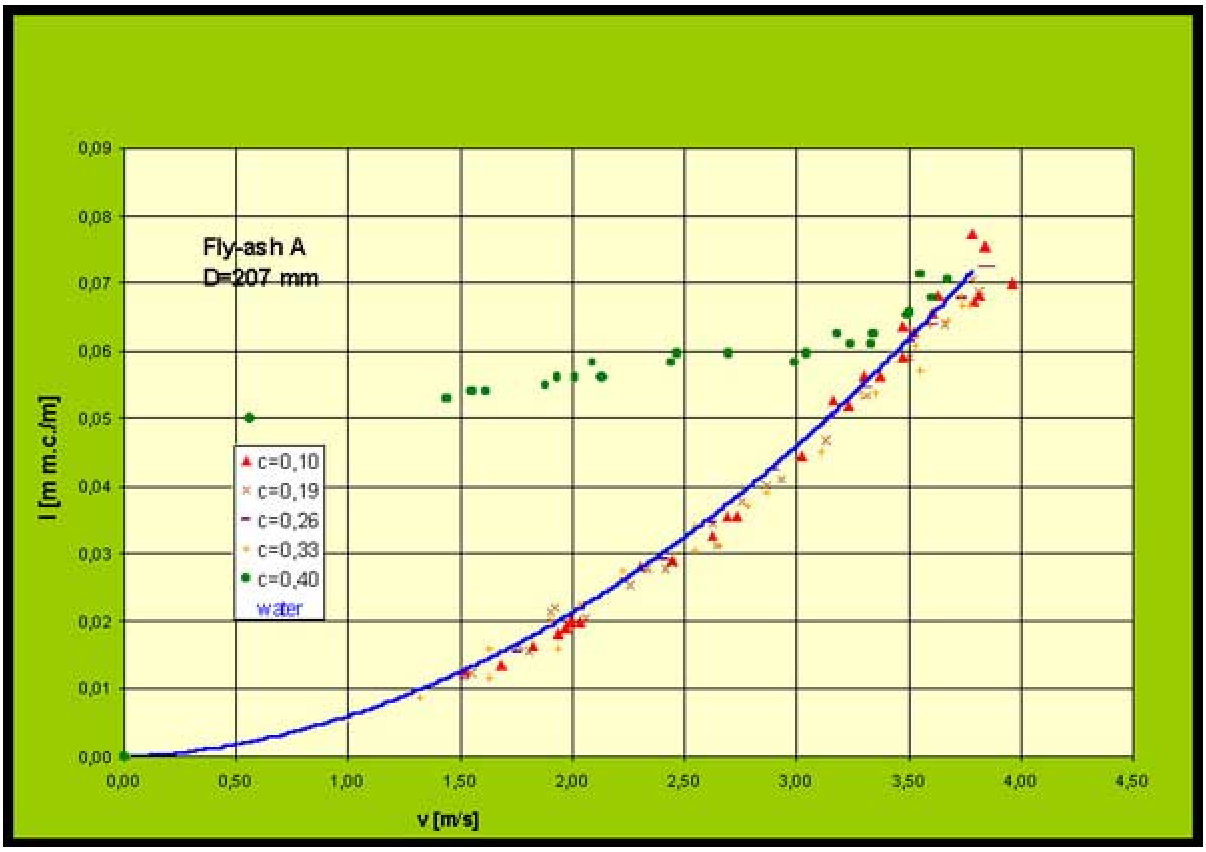
Fig. 4. Relationship between hydraulic gradient and velocity for ash A mixture (a-hydraulic gradient in meters of water column, b-hydraulic gradient in meters of mixture column, c-hydraulic gradient in meters of mixture column in logarithmic coordinates, d-flow in laminar zone approximated by Bingham model)

a



b



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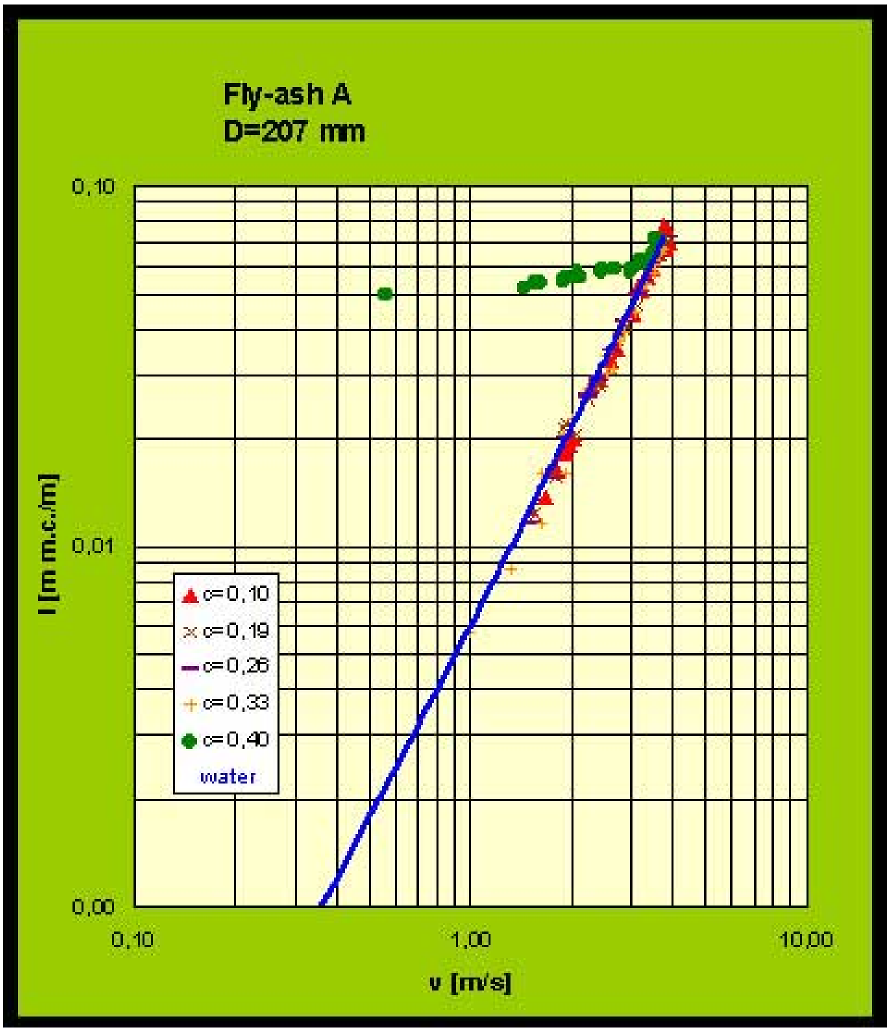
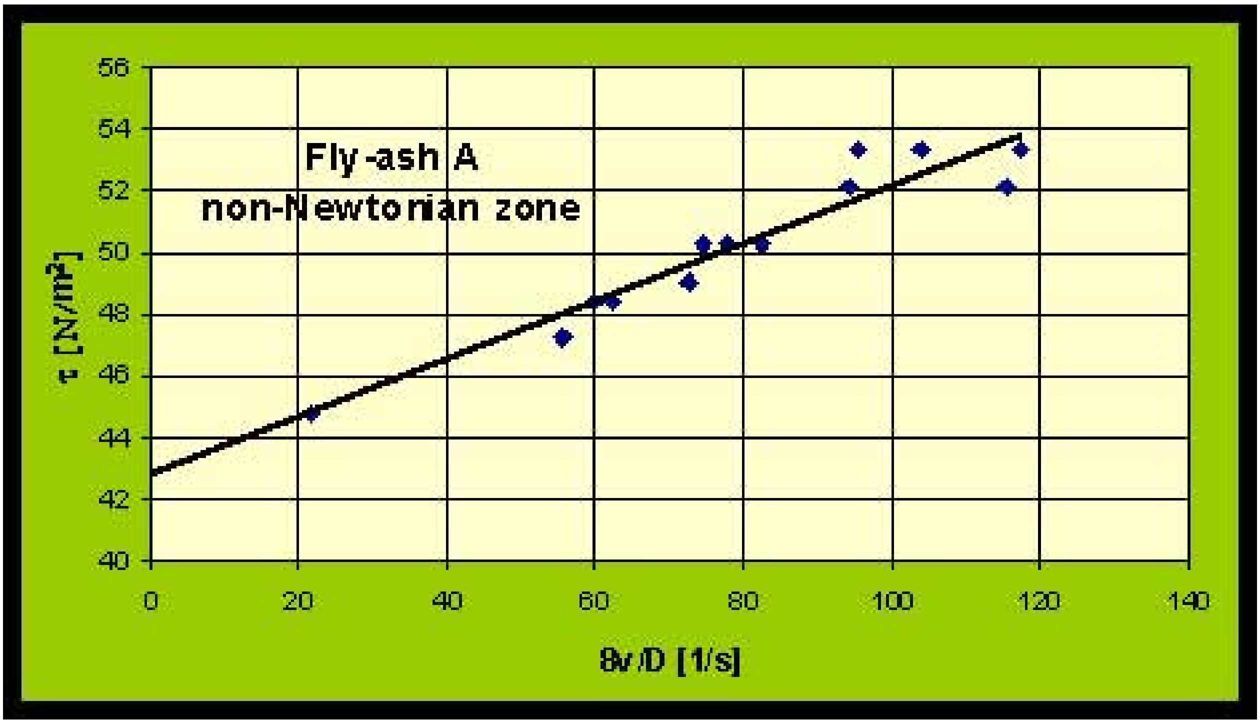
c


Fly-ash A
D=207 mm
0,10
0,01
0,00
I [m m.c./m]
0,10
1,00
10,00
v [m/s]
▲ c=0,10
× c=0,19
– c=0,26
+ c=0,33
● c=0,40
water

d


Fly-ash A
non-Newtonian zone
56
54
52
50
48
46
44
42
40
τ [N/m²]
0
20
40
60
80
100
120
140
8v/D [1/s]

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Non-Newtonian properties also occurred for the mixture flow of ash B and C, with volume concentrations higher than 0.4.

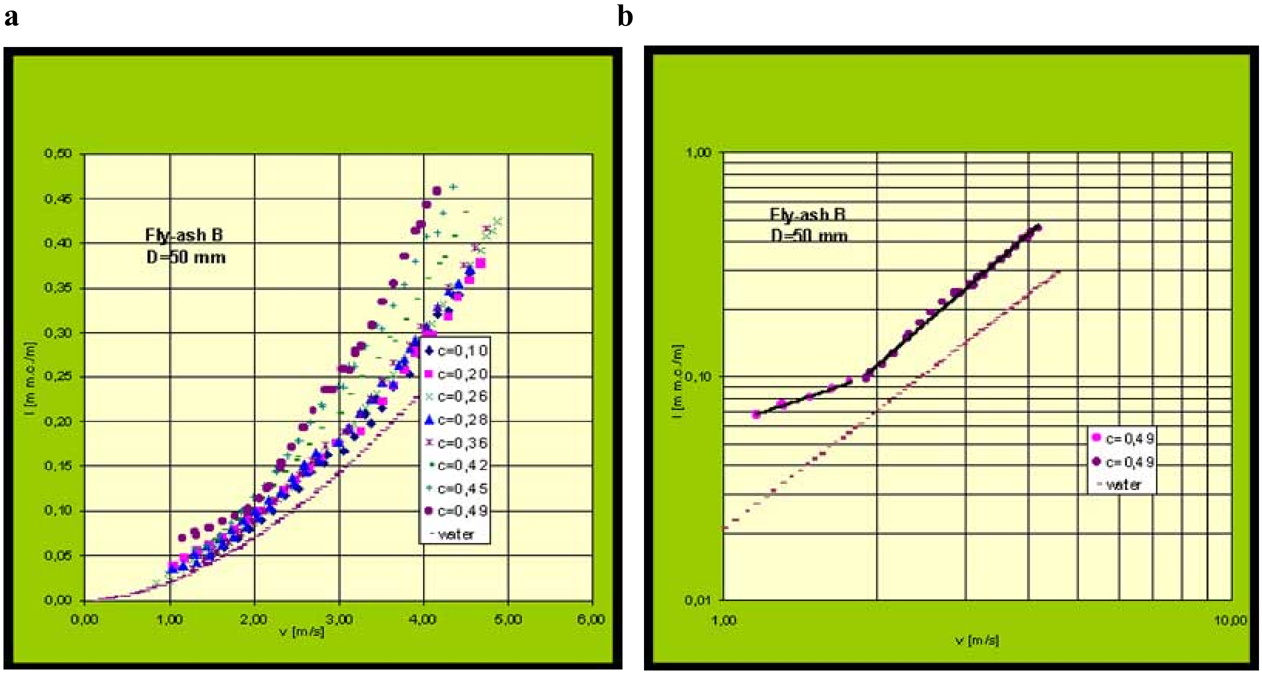
The mixture of water and ash B with a volume concentration of 0.49 in a pipeline with a diameter of 50 mm, is shown in Figure 5 by measurement points placed along a straight line for velocities lower than $v_m \approx 1.80$ m/s.

A similar situation is presented in Figures 5a and 5b for mixture of water and ash C, with a concentration of 0.46 in a pipeline with a diameter of 36 mm.

A slightly different form of the function $I_m=f(v_m)$ was achieved during the examination of brine and ash D, which are presented in Figure 5 [1]. The brine had the density of $\rho_L=1222$ kg/m^3 and viscosity of $\mu_L=4.98$ MPa s. The curves representing the hydraulic gradient dependence on the mixture velocity do not converge with the water curve at the point of velocity decrease, as it occurs for the remaining examined mixtures. But the hydraulic gradient increases to a certain extent together with the velocity decrease. Such forms of the curve $I_m=f(v_m)$ is characteristic of heterogeneous mixtures. The curve shapes for A, B, and C ash mixtures are characteristic for pseudo-homogeneous mixtures.

The experimental results indicate that the hydraulic gradient may increase more than it did from the mixture density growth, as shown by ash A. The hydraulic gradient increase is variable and different for particular mixtures. Due to the fact that it is a function of concentration and flow velocity as illustrated in diagrams in Figure 5. On this basis, one can state that it is not possible to describe the hydraulic gradient with one equation $I_m=f(v_m)$ for all the examined ash mixtures. Thus, the only way to specify in detail the energy losses for the ash mixture flow is an experiment.

Fig. 5. Relationship between hydraulic gradient and velocity
5a and 5b - ash B and water mixture (a - Cartesian coordinates, b - logarithmic coordinates),
5c and 5d - ash C and water mixture (c - Cartesian coordinates, d - logarithmic coordinates),
5e - ash D and brine mixture)



a

b

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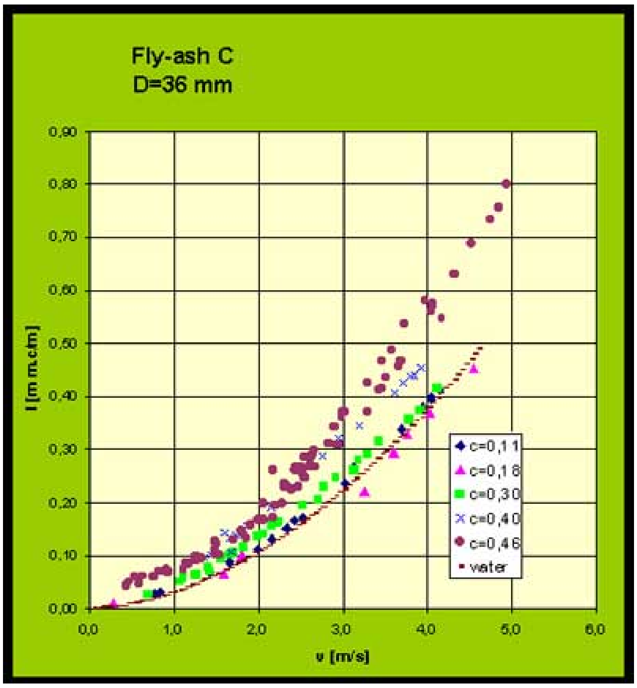
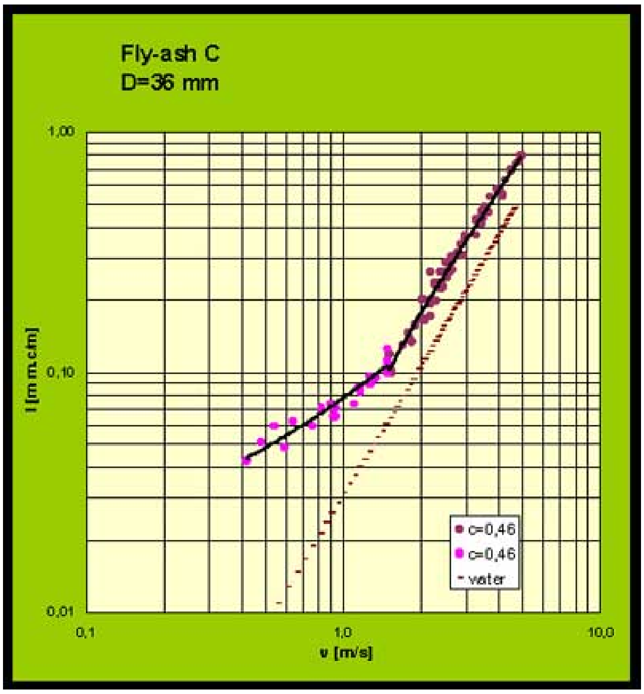
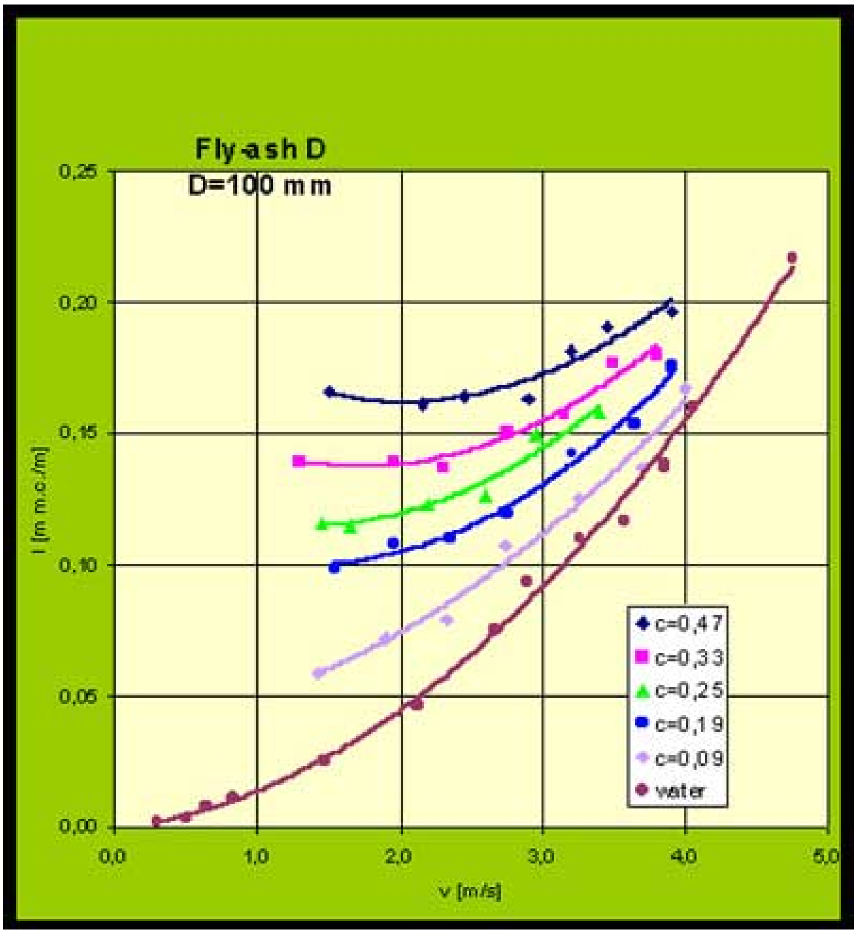
c


Fly-ash C
D=36 mm
0,90
0,80
0,70
0,60
0,50
0,40
0,30
0,20
0,10
0,00
I [m m.c/m]
0,0
1,0
2,0
3,0
4,0
5,0
6,0
v [m/s]
c=0,11
c=0,16
c=0,30
c=0,40
c=0,46
water

d


Fly-ash C
D=36 mm
1,00
0,10
0,01
I [m m.c/m]
0,1
1,0
10,0
v [m/s]
c=0,46
c=0,46
water

e


Fly-ash D
D=100 mm
0,25
0,20
0,15
0,10
0,05
0,00
I [m m.c./m]
0,0
1,0
2,0
3,0
4,0
5,0
v [m/s]
c=0,47
c=0,33
c=0,25
c=0,19
c=0,09
water

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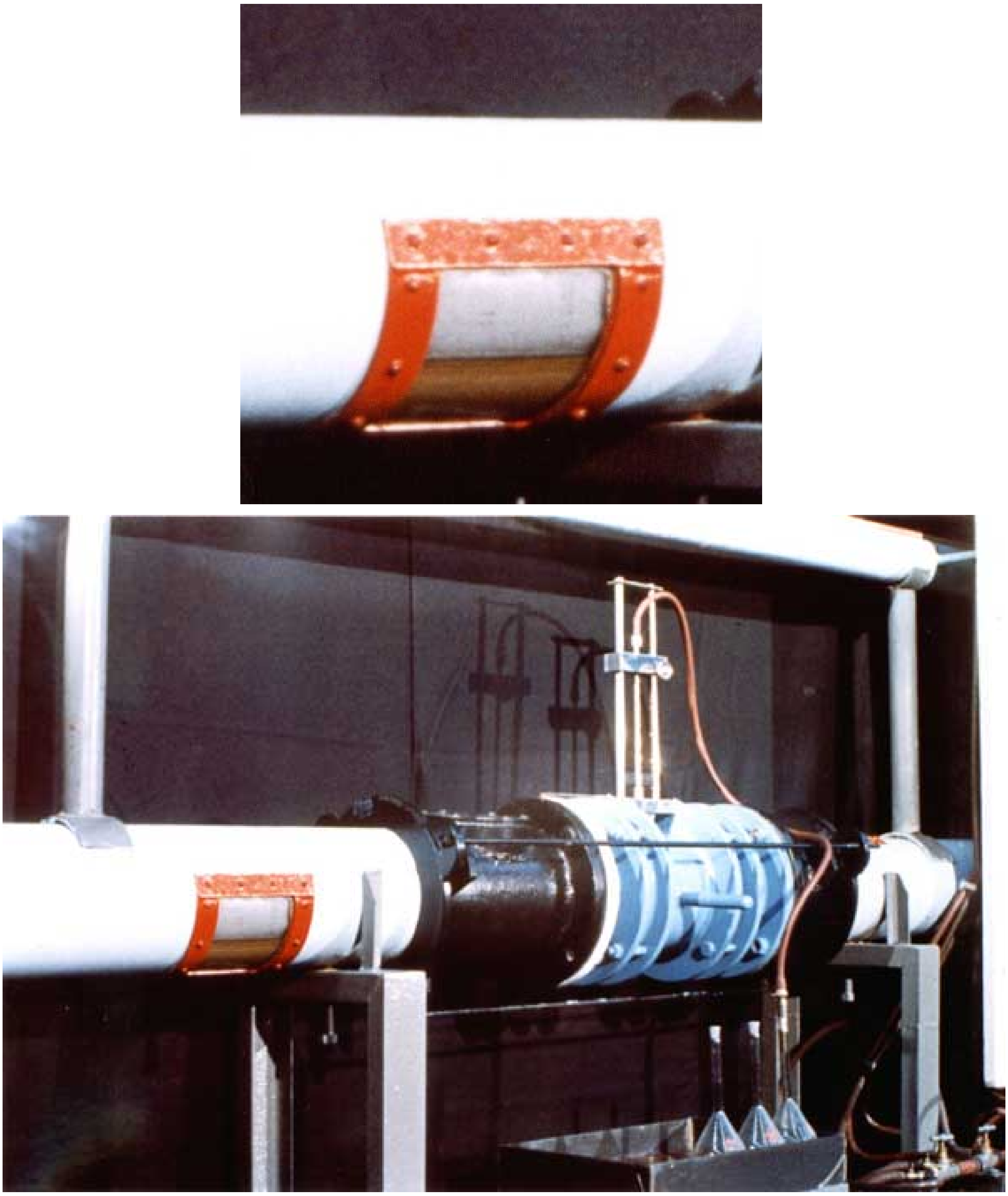
LIMIT DEPOSIT VELOCITY

From the point of view of engineering practice, limit deposit velocity is one of the more important characteristics of mixture flow in a pipeline.

Limit deposit velocity is a velocity at which grains fall out of the mixture stream and form a stationary layer at the bottom of the pipeline. Limit deposit velocity was established on the basis of the mixture behavior observations in the pipeline through a transparent window comprising the lower half of the pipeline (Figure 6).

Fig. 6. View of transparent widow for a determination of limit deposit velocity in pipeline



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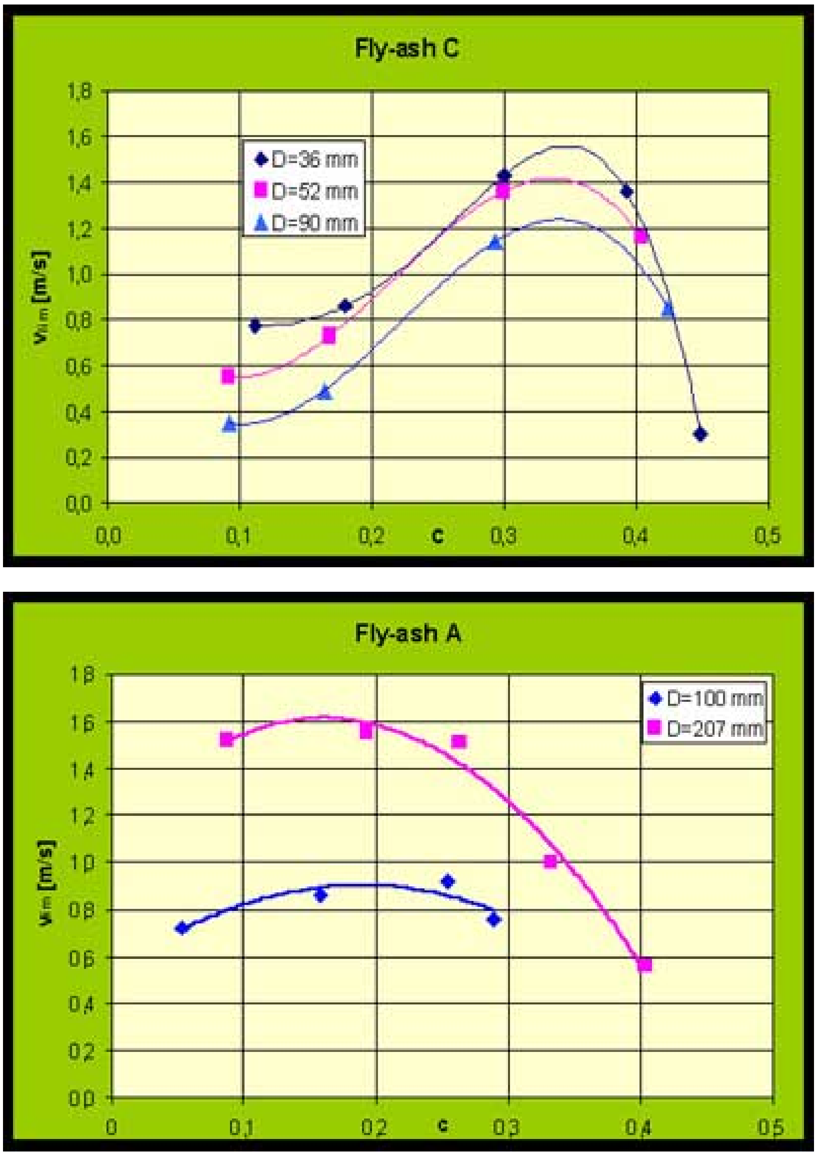
This velocity, according to the current formulas for various mixtures, depends on the pipeline diameter, graining, and mixture density. In case of ash, the issue is more complex, as it is shown in experimental results.

For mixture of water and ash A, the limit deposit velocity, in pipelines with a diameter of 100 and 207 mm, to a concentration of 0.30, is initially constant (v_{lim}~1.5 m/s for D=207 mm and v_{lim}~0.85 m/s for D=100 mm). During subsequent concentration growth the limit deposit velocity decreases (Figure 7).

Fig. 7. Limit deposit velocity vs volume concentration of ash slurry (upper - for fly-ash C, down - for fly-ash A)



For mixture of water and ash C, with a pipeline diameter of 36, 52, and 90 mm, the limit deposit velocity increases to a concentration of 0.35 and then decreases, as it is demonstrated in Figure 7.

Comparing the measurement results for ash-water mixtures, A and C, one can see an entirely different influence of pipeline diameter. For ash A, the limit deposit velocity, at the same value of mixture density, grows together with the pipeline diameter, quite the opposite of ash

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C. The decrease of limit deposit velocity together with the pipeline diameter can be found rarely in literature. This situation was not foreseen in the analysis of the phenomenon conducted by Parzonka, Kenchington and Charles [3], and in the review of the formulas carried out by Wiedenroth [8] and Sobota [6].

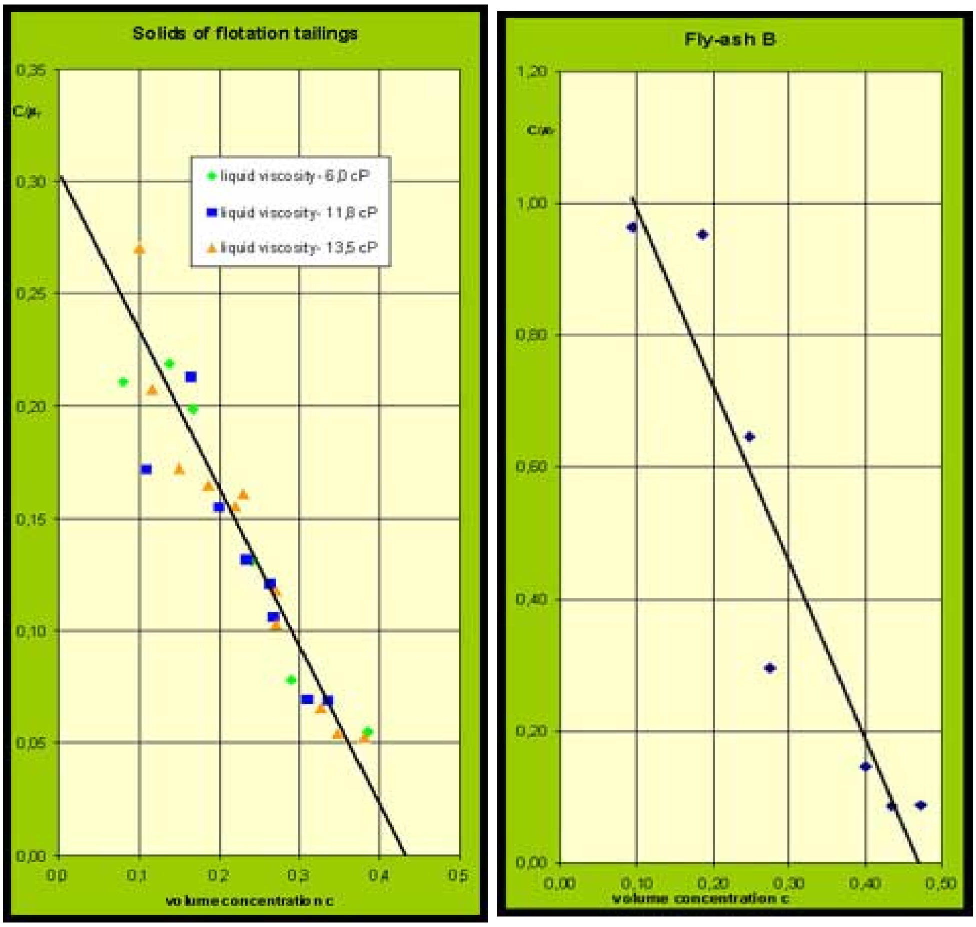
The occurring differences in the dependence character $v_{lim}=f(c)$ presumably lie in the physical and mechanical qualities of both examined ashes, and especially in the chemical properties.

The presented results of experimental research on limit deposit velocity reveal that in the case of ash-water mixtures the base for specifying the limit deposit velocity should be the measurements in pilot installations because of the diversified physical, mechanical, and chemical properties of ashes.

LIMIT CONCENTRATION

The knowledge of the limit concentration c_{lim}, at which non-Newtonian properties occur, is an important issue when considering the hydraulic gradient value concerning mixture flow. The method suggested by Ting and Lauebbers was used to estimate the limit concentration value [7]. According to this method, non-Newtonian properties will occur in the mixture when the viscosity relation of relative μ_r to volume concentration in the function of volume concentration proceeds towards zero. This method was earlier used for estimating the limit concentration for the mixtures of post-flotation waste material of copper ore [5]. It is illustrated by diagram in Figure 8.

Fig. 8. Estimation of limit concentration by Ting and Lauebbers method (left - for copper ore tailings [7], right - for fly-ash B and water mixture)



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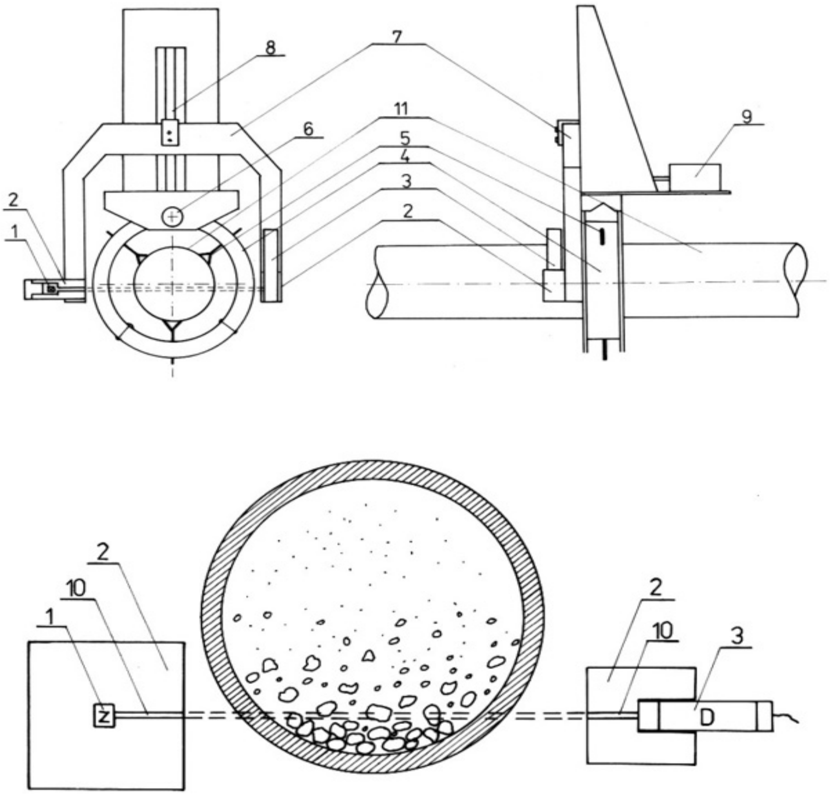
The diagram of the function mentioned earlier for ash B, is presented in Figure 8. It is clear that the non-Newtonian properties for mixture of water and ash B will occur when the volume concentration is equal to 0.47. These results confirm the experimental research of these mixtures' flow in pipelines. The results of the hydraulic gradient measurements for ash B flow in pipeline with a diameter of 50 mm, is presented in Figure 5, and indicates that the mixture, with a concentration 0.49 has non-Newtonian properties, and the mixture with a concentration of 0.45 has the properties of Newtonian fluid. It testifies to the correctness of the estimated limit concentration for this ash mixture calculated by Ting and Lauebbers' method, which amounts to c_{lim}~0.47.

On the basis of these experimental results it can be agreed that the method suggested by Ting and Laubbers can be used for the value estimation of the limit concentration c_{lim} of the non-Newtonian property occurrence of fluid-particulate solid mixtures.

DENSITY PROFILE IN VERTICAL AXIS

The density profile in the vertical axis of the pipeline (called the density profile further on) is the parameter characterizing the density distribution in the pipeline cross-section. This is the relationship between the mean cross-section density of the hydromixture along a given horizontal chord and its relative distance from bottom y/D, expressed by the ratio of this distance y to the pipeline diameter D. The profile was determined by means of the radiometric scanning method. This method, presented in detail in papers [4,6], consists in the narrow beam gammascopy, along chosen chords of the pipeline cross-section respectively. Applying the law of the gamma radiation absorption in the matter, it is possible to determine a time-averaged density of the hydromixture along a given chord. For a set of measurements conducted for a system of horizontal chords, a density profile along the vertical axis of the pipeline can be determined (Figure 9).

Fig. 9. Measurement of density profile in vertical axis by scanning radiometric method
a - schema (1-radioactive source, 2-source container lead, 3-scintillation counter, 4-clamping ring, 5-adjusting screw, 6-clamping screw, 7-support, 8-driving screw, 9-driving motor, 10-collimator, 11-pipeline)



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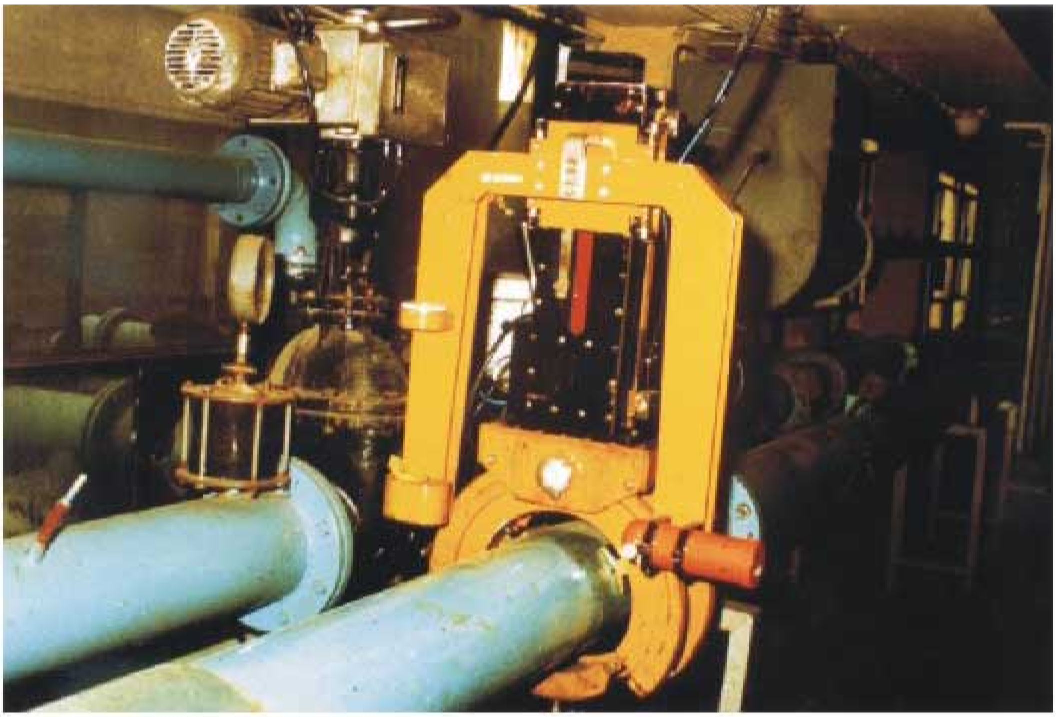
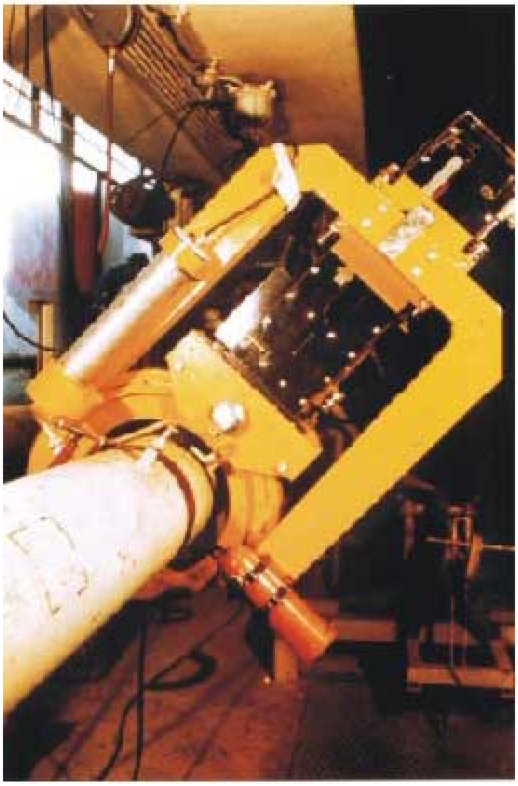
b - view





The results of the measurements of density profiles in a pipeline with a diameter of 207 mm, are presented in Figure 10. The mixture profiles of the particular mean density were measured for several velocities; yet, only density profiles for limit velocity and the maximum measured velocity were presented in the pictures in order to increase the picture clarity. The profiles for intermediate velocities are to be found in the area specified by values presented in the

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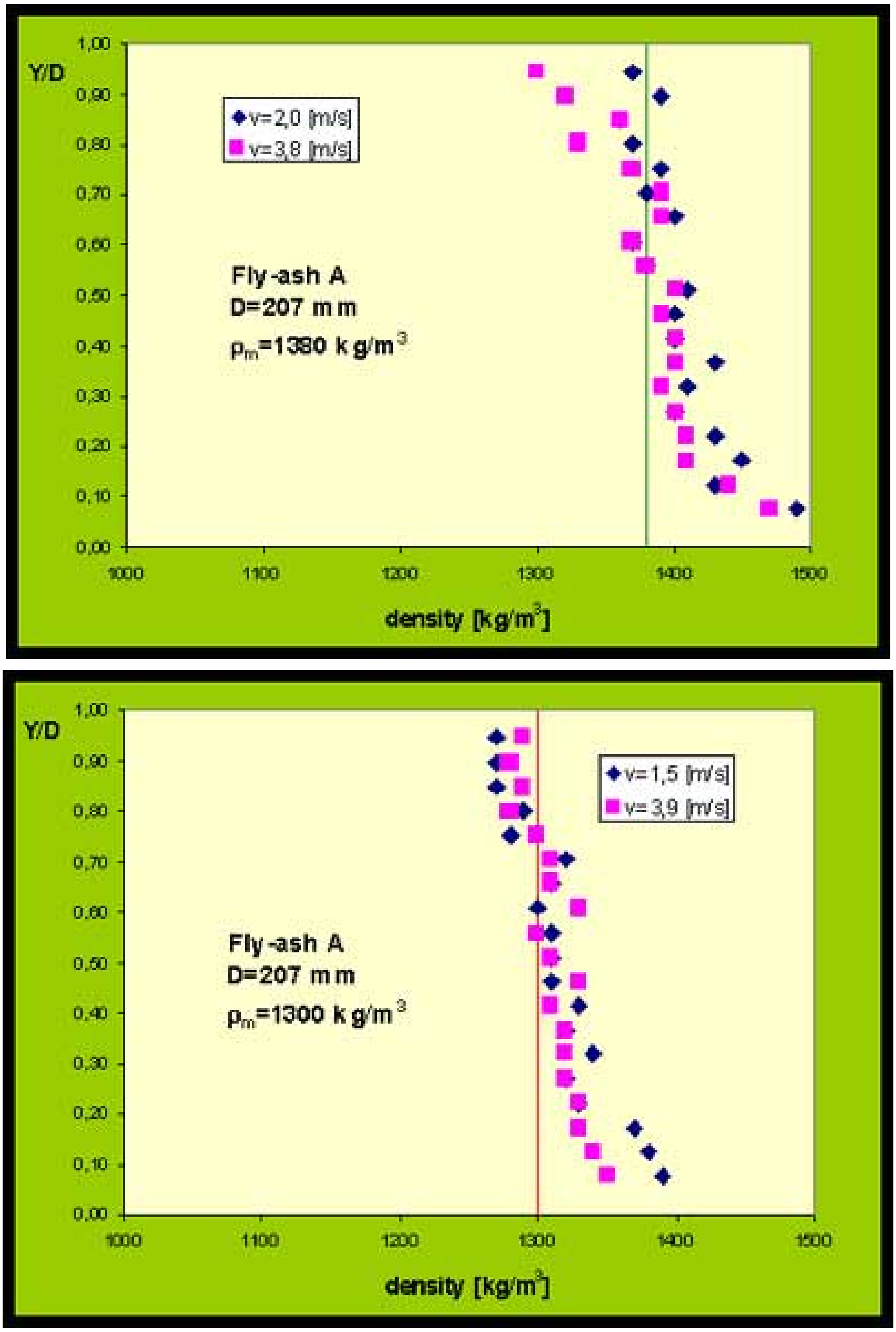
diagrams. These results lead to the conclusion that ash-water mixtures behave like pseudo-homogeneous fluids. Only for lower average densities, does the density profile for velocities close to the limit velocity demonstrate a slight deviation from the profile characteristic of a homogeneous fluid. This deviation disappears, however, at an insignificant flow increase, at which the density profiles reveal a tendency to isotropicity.

Fig.10. Density distribution of ash-water mixture in vertical axis in a pipeline of D=207 mm



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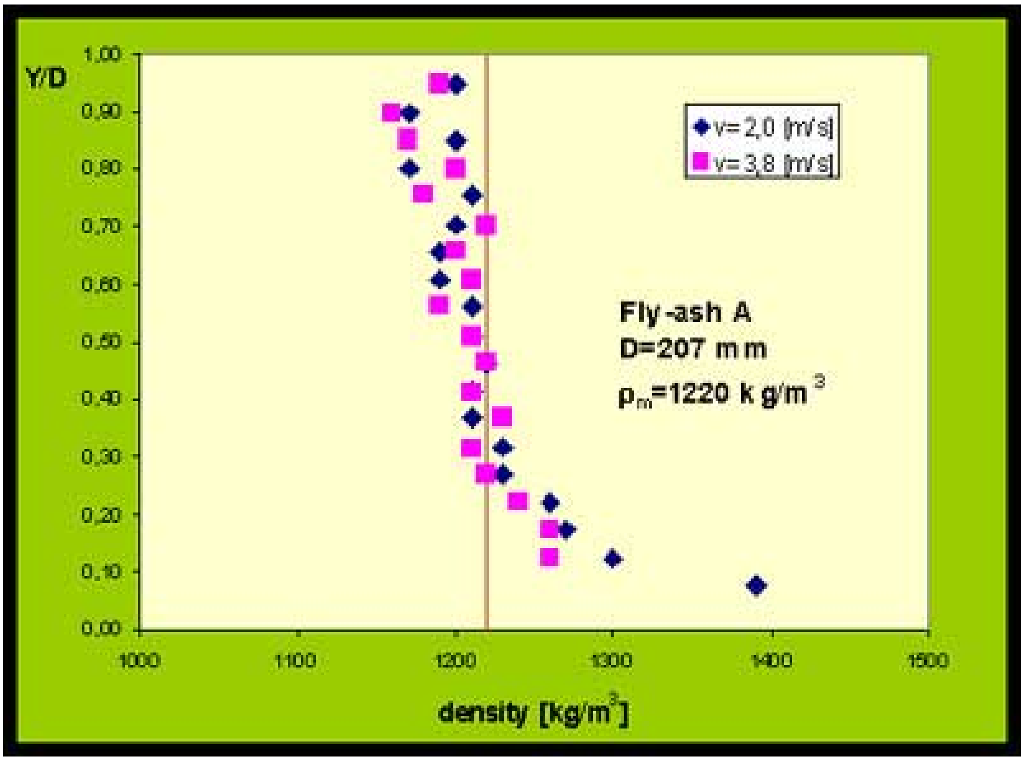

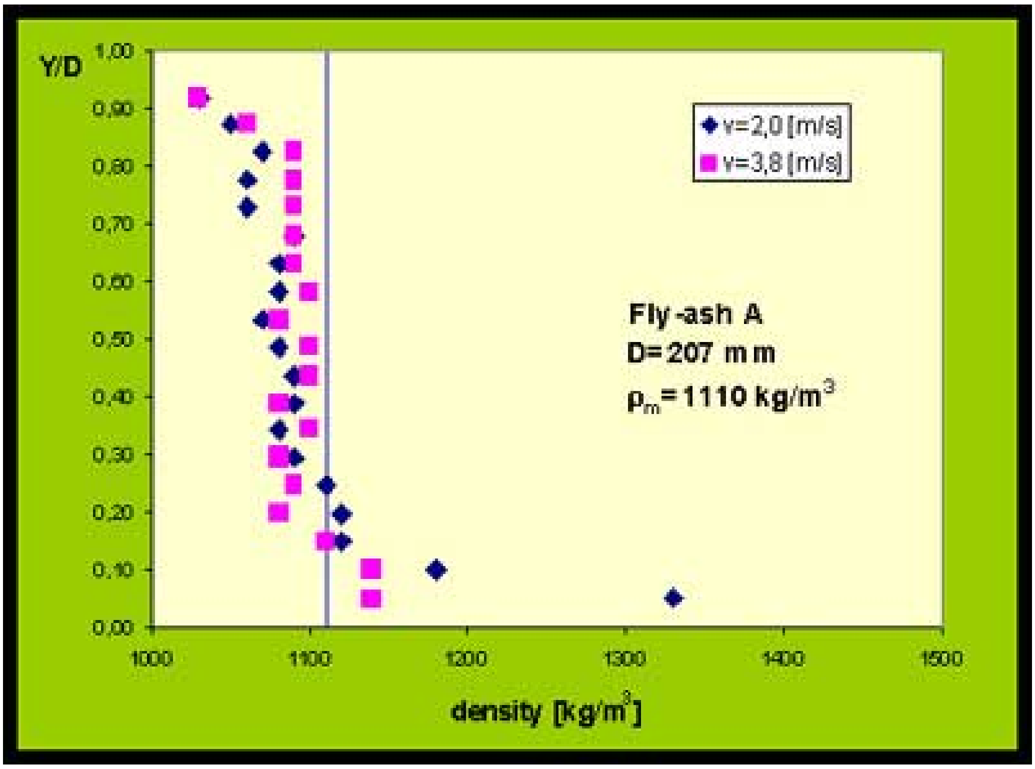

PUMPING ENGINE CHARACTERISTIC

The scope of the research on C ash-water mixture flow also comprised the characteristic calculation of operation. Calculating the characteristic consists in specifying the dependence of $H = f(Q)$, $N = f(Q)$, and $\eta = f(Q)$, where H – value of pump lifting, N – effective power, and η – efficiency coefficient of pumping set.

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The subject of research was a pumping engine consisting of a centrifugal pump and an electrical engine were N = 11.0 kW, n = 2900 rotation/min, and $cos\Phi$ = 0.89. The centrifugal pump used had a closed structure rotor with a diameter of 160 mm and relieving blades that reduced the longitudinal forces and decreased the pressure under the stuffing box that was sealed with grease. The diameter of the sucking pipe was 65 mm while the force pipe was 50 mm in diameter.

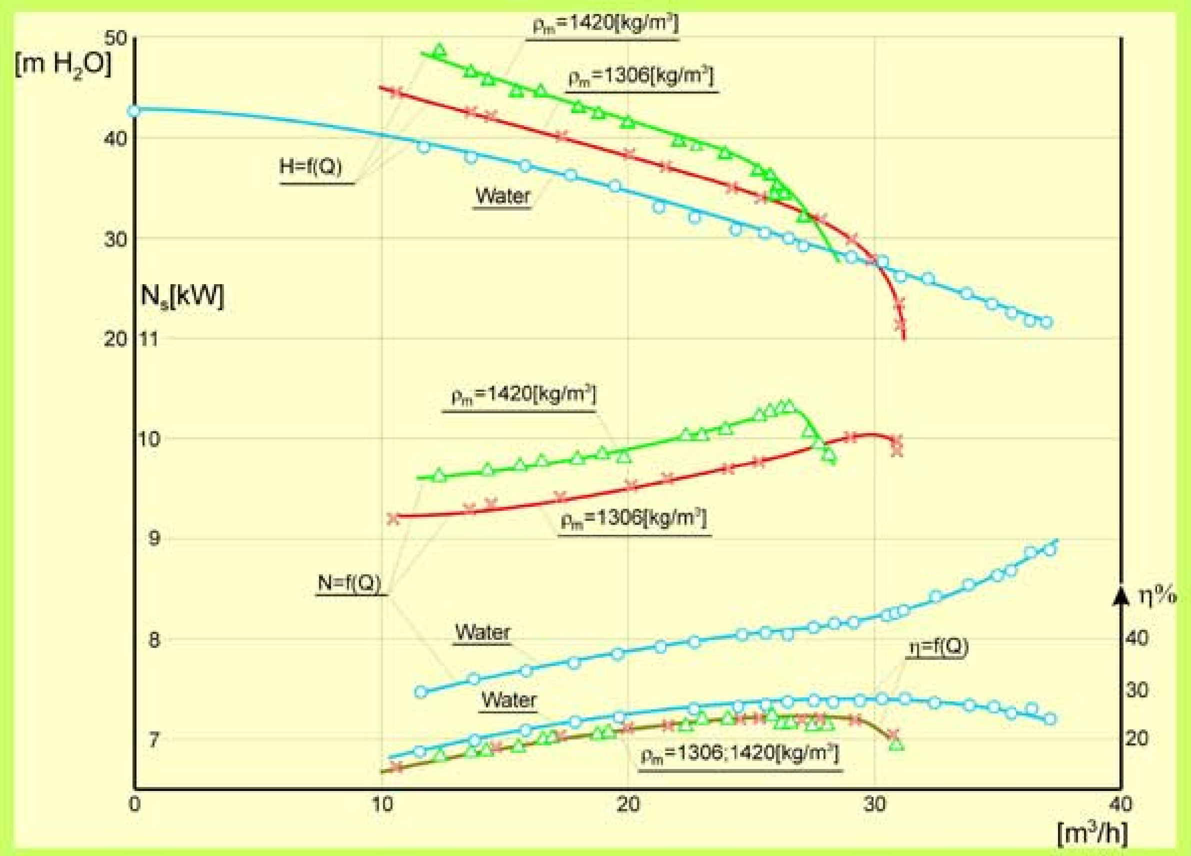
The pump characteristics were calculated on the basis of flow rate (*Q)* measurements, pressure on pumping and sucking, rotational dyke speed, and power on dyke. The pump examinations were carried out according to generally accepted rules:

- the reading of related physical quantities was conducted simultaneously,
- the reading was performed after specifying the motion conditions.

The results from the investigation are presented in Figure 11 in the form of characteristics for two mixtures of the highest densities ρ_m =1306 kg/m^3 and ρ_m = 1420 kg/m^3.

For water flow**,** the power characteristic is unoverloadable, which corresponds with a stable and steep flow characteristic. With mixture flows these characteristics change considerably, which results from the occurrence of cavitation. The efficiency coefficient with mixture pumping is lower than with water pumping, but does not depend on mixture density. The specified recounting coefficient of the power characteristic, equal to the power relation at water flow to the power at mixture flow, is for K_N = 1.22 for mixture ρ_m = 1306 kg/m^3 and K_N = 1.27 for ρ_m = 1420 kg/m^3. These conversion factors can be applied to the calculation of power and design pump set efficiency.

Fig. 11. Results of pumping engine characteristic measurement



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CONCLUSIONS

The investigation results show that experimental examinations in pilot or laboratory installations are the basis for specifying the basic flow characteristics of mixtures including ashes. The estimation of limit concentration separating Newtonian and non-Newtonian mixture properties is a significant parameter for engineering practice.

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