INVESTIGATION OF THE FLOW-PARAMETERS OF A MULTIFRACTIONAL STOWING MIXTURE BY MEANS OF RADIOACTIVE ISOTOPES

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1. — Introduction

Radioisotope technique offers exceptionally advantageous possibilities of measuring the flow parameters of hydromixtures. Taking as a basis the use of sealed and unsealed radioactive sources it allows one to determine the mean density of the hydromixture, the spatial distribution of solids, and the flow velocities of the mixture components even at a very high concentration of the transported solid material.

The measurement of the mixture density is here realized in a non-contact system, so it does not affect the structure of the flow. Also the disturbances caused by the tracer injection, when the flow velocities are measured, are negligibly small, as the injection is always made at a sufficient distance from the measuring section of the pipeline. Because of the high detection sensitivity of the tracer, the amount of it to be injected into the investigated stream is fairly small. This fact reflects advantageously on the conditions of safe work with radioisotopes, with regard to the rigorous requirements of the radiological safety regulations.

Thus, our research group, consisting of the scientific workers of two co-operating institutes: the Institute of Nuclear Techniques at the Academy of Mining and Metallurgy in Cracow, and the Institute of Nuclear Physics in Cracow, has adopted this technique to large scale measurements in a colliery, on the actual pipe-line of the hydraulic stowing installation [1], [2], [3]. The aim of these investigations was to establish the realationships between the mean density of the stowing mixture and the mean flow velocities of its components, other parameters affecting the flow being constant. Among various kinematic characteristics of the flow of the multifractional solid-liquid mixture this dependence seems to be of essential importance.

2. — Experimental

As was said above, the measurements were carried out on an actual, industrial pipe-line. Radiometric measuring methods were applied for determination of the fractional flow velocities and the mean density of the mixture.

In considering the mixture density one should distinguish the value indicated by the density-gauge mounted directly on the pipe from that ascertained at the outlet of the pipe-line. The former is called the "in-line density" and the latter, the "delivered density". The difference between these two values results from the difference in the flow velocities of the particular components of the mixture.

In our investigations the in-line density was measured by means of a specially developed radiogauge [4], characterized by a relatively small time constant (1 s) and a high accuracy of measurement (better than 1 %). The results of density measurements were recorded by a strip-chart recorder and simultaneously shown to the operating personnel by an additional indicating device, located in

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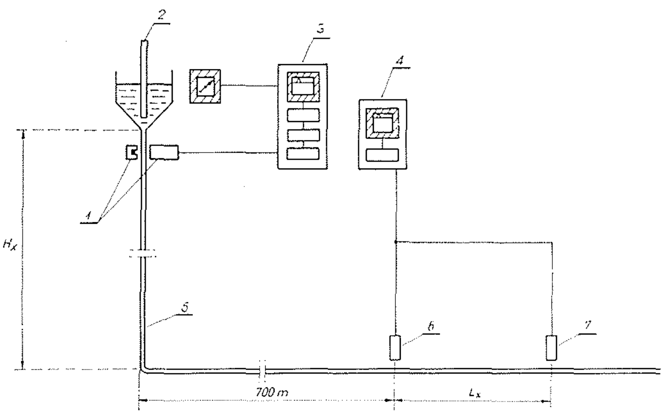
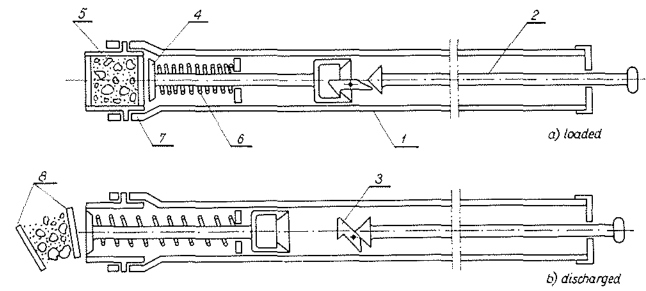


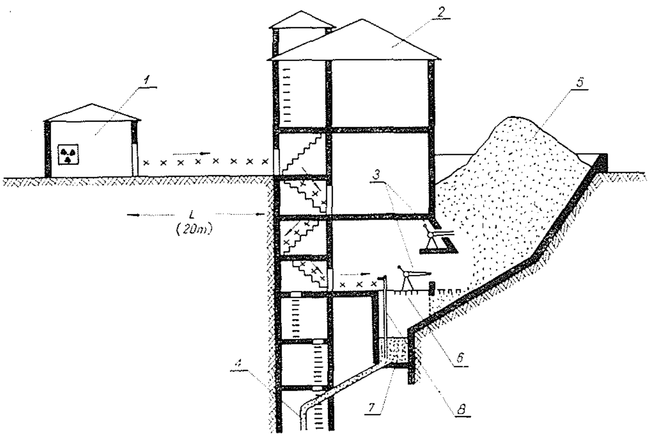
2
3
4
1
H_x
5
6
7
700 m
L_x

1/



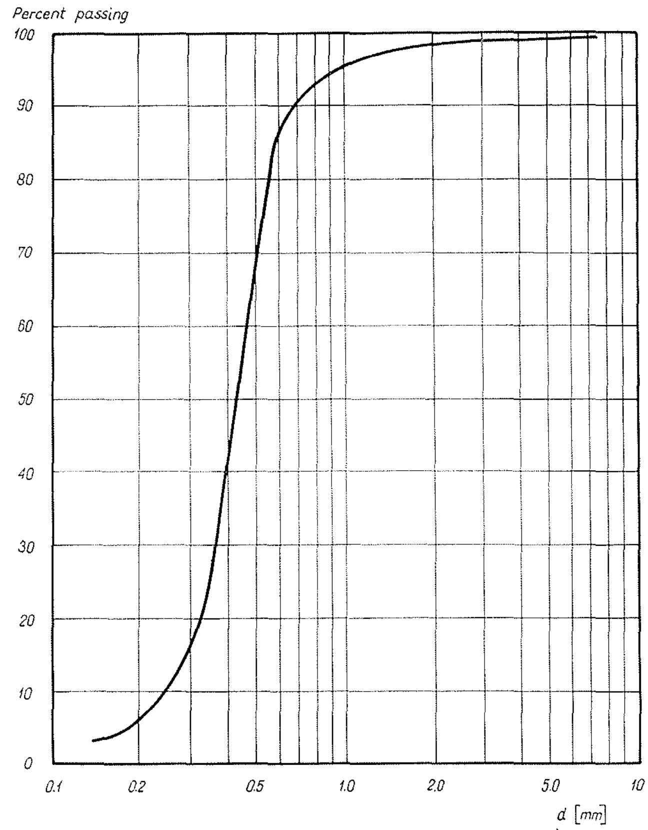
5
4
2
7
6
1
a) loaded
8
3
b) discharged

2/



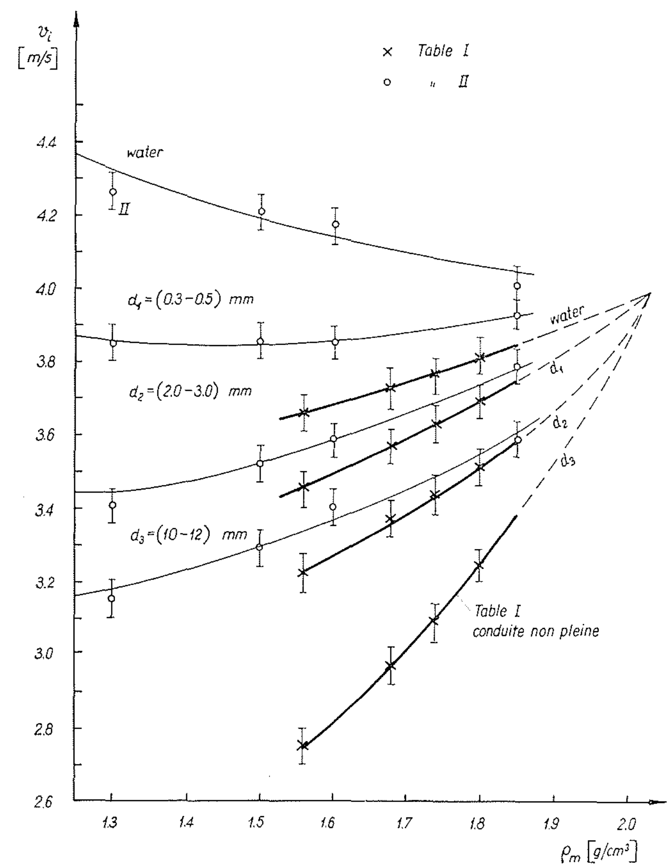
1
2
5
L
(20m)
3
6
4
7
8

3/



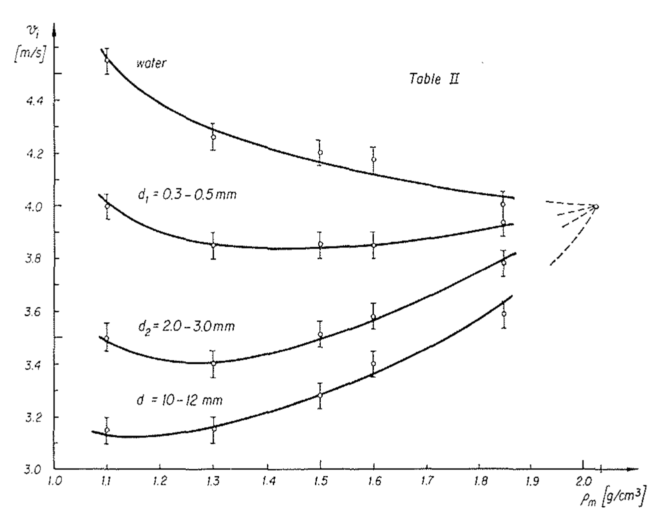
Percent passing
100
90
80
70
60
50
40
30
20
10
0
0.1
0.2
0.5
1.0
2.0
5.0
10
d [mm]

4/



v_i [m/s]
× Table I
○ " II
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
water
II
d_1 = (0.3–0.5) mm
water
d_1
d_2 = (2.0–3.0) mm
d_2
d_3
d_3 = (10–12) mm
Table I
conduite non pleine
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
ρ_m [g/cm³]

5/



v_i [m/s]
water
Table II
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
d_1 = 0.3 – 0.5 mm
d_2 = 2.0 – 3.0 mm
d = 10 – 12 mm
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
ρ_m [g/cm³]

6/

1/ Positioning of the measuring devices on the pipe-line.
1. Density gauge head; 2. Throw-in type injector; 3. Density gauge electronic assembly; 4. Electronic assembly of the transit-time recording system; 5. Pipe-line; 6 and 7. Detecting probes.

Position des dispositifs de mesure sur la conduite.
1. Tête de jauge de densité; 2. Injecteur; 3. Equipement électronique de la jauge de densité; 4. Equipement électronique du dispositif d'enregistrement du temps de transit; 5. Conduite; 6 et 7. Sondes.

2/ Construction of the throw-in injector.
1. Casing tube; 2. Pushrod; 3. Click device; 4. Piston; 5. Injection capsule; 6. Spring; 7. Bayonet socket; 8. Rubber corks.

Détails de construction de l'injecteur.
1. Tube; 2. Tige-poussoir; 3. Dispositif à déclic; 4. Piston; 5. Capsule d'injection; 6. Ressort; 7. Douille « bayonnette »; 8. Bouchons en caoutchouc.

3/ Washery building; positioning of the measuring devices and the installation equipment.
1. Hut for charging the injection capsules; 2. Washery building; 3. Water guns; 4. Pipe-line; 5. Sand; 6. Grating; 7. Retention reservoir; 8. Throw-in injector.

La laverie : position des dispositifs de mesure et des diverses parties de l'installation.
1. Cabane où l'on remplit les capsules d'injection; 2. Laverie; 3. Canons à eau; 4. Conduite; 5. Sable; 6. Grillage; 7. Réservoir; 8. Injecteur.

4/ Grain size distribution of sand used in experiments.

Granulométrie du sable employé au cours des essais.

5/ Fractional flow velocities of mixture components vs. mean mixture density for full rate feeding : (○), and partially filled pipe cross-section (×).

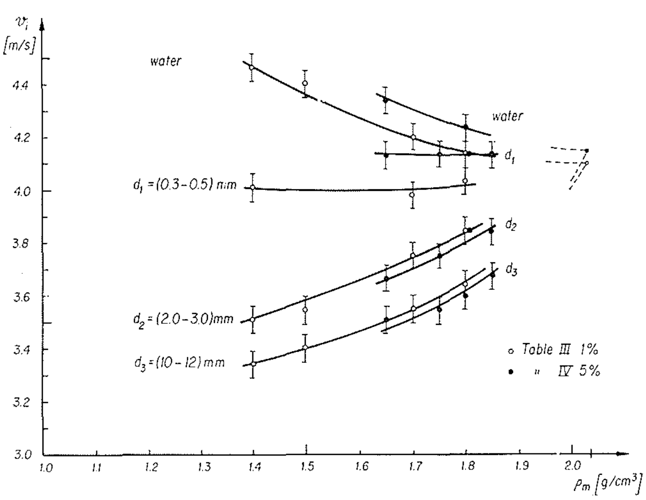
Vitesse d'écoulement (en pour cent) des composantes du mélange en fonction de la densité moyenne du mélange à taux d'alimentation maximal (○) et pour une section de conduite partiellement remplie (×).

6/ The family of curves : $v_i = f(\varrho_m)_{d=\text{const.}}$ for full rate feeding of the stowing mixture.

Famille de courbes : $v_i = f(\varrho_m)_{d=\text{const.}}$ *pour débit d'alimentation maximal du mélange.*

7/ Fractional flow velocities of the mixture components vs. mean mixture density in the presence of the additional stone ($d = 35$ mm) in amounts of 1 % (○) and 5 % (●) respectively.

Vitesse d'écoulement des composantes du mélange (en %) en fonction de la densité moyenne du mélange en présence des cailloux supplémentaires (d = 35 *mm*). *1 % = ○; 5 % = ●.*



7/

the water gun chamber. The measuring head of the density gauge was fastened onto the vertical part of the pipe-line just beyond the sucking zone, as shown in Figure 1. Such a location of the measuring head was imposed by the condition of the smallest possible delay in obtaining the information on the mixture density with respect to its variation at the pipe-line inlet. In this way the fluctuations in pipe-line feeding could be reduced to a negligible value, and the mean density of the mixture maintained on the desired, constant level even during a long period of time.

The measurements of the flow velocities of the chosen mixture components were made using radioactive tracers, by means of the "Pulse Velocity Method" [5]. For this purpose a special measuring set was applied [6]. This consists of the original "Throw-in injector", scintillation detecting probes, and the associated two-channel electronic assembly. In order to avoid the difficulties which may arise in the correct transit-time determination due to the possible overlapping of the activity peaks from different probes, they are recorded in two separate channels; in the first one from both the probes and in the second from one probe only. Owing to the convenience of the injector applied it was possible to introduce into the flowing stream both solid and liquid tracing substances.

Figure 2 shows a simplified sketch of the construction of this injector. It is made of a thick-walled steel tube 30 mm in diameter and 3 m long. The lower part of the casing tube contains a spring-latch and a bayonet socket holding the injection capsule.

The prepared portions of the tracing substances are contained inside the injection capsules and tightly closed by means of rubber corks. They are subsequently fastened in the bayonet socket of the injector, the spring of the latch being strained and protected against accident release. The injection capsules are made of short pieces of brass pipe, to which two small holding pins are welded. Release of the spring latch follows under the pressure of the pushrod which protrudes from the upper part of the casing tube. At this instant the click device is opened and the piston rapidly expresses the content of the capsule, together with both the rubber corks.

The injections were made directly into the pipe-line inlet at the surface in the washery building (Fig. 3). For labelling, three different granulometric fractions of the solid material (quartz sand - Figure 4):

$$d_1 = (0{,}3 - 0{,}5)\ \text{mm}$$

$$d_2 = (2{,}0 - 3{,}0)\ \text{mm}$$

$$\text{and } d_3 = (10 - 12)\ \text{mm}$$

were chosen. All of them, as well as the transporting water, were labelled by the same radioactive element ^{24}Na. The test section length, i.e. the distance between the injection point and the first detector, was long enough (nearly 1 km) to assure a measurable delay in the appearance of particular activity peaks from different tracing substances. Thus, it allowed one to inject simultaneously two or even three labelled components of the mixture. As tracing substances an aqueous solution of activated sodium carbonate $^{24}Na_2CO_3$ and activated sodium containing glass, crushed to the desired particle sizes, were used. The activity of each tracing substance was about 0,5 m Ci.

The detection probes were fastened outside the pipe-wall along the horizontal section of the pipe-line at a distance of 100 m one from the other. In the course of investigations the mean density of the mixture was maintained at as constant a level as possible, this after a few injection runs being changed gradually to another value. In this way experimental data was obtained covering practically the whole range of concentration of solids.

It should be mentioned that, because of the gravitational extorsion of the mixture motion, for a given pipe-line configuration there exists a specific relation between the mean density of the mixture and the flow velocities of its components. However, the average flow velocity of the mixture varies within a narrow range, in spite of a great variation in its mean density. This is due to the fact that the disposable total head and the head-losses depend on approximately the same order of mixture density. For the examined part of the pipe-line installation the average flow velocity of the mixture varied from 3,5 to 4,0 m/s.

3. — Results of measurements

Using the techniques described, four extended series of measurements were carried out. The first of them concerns the case of a mixture flow with a partially filled pipe cross-section. The second series of measurements was performed under the fulfilled conditions of the "full rate feeding" of the installation. This series furnished valuable experimental data for the estimation of universal kinematic flow characteristics of the stowing mixture. The third and fourth series were carried out in similar conditions as the second one, but with simultaneous feeding with broken barren rock of an average size of 30 mm, added to the natural sand in quantities of 1 % and 5 % respectively. All these experimental results are listed in the Tables I, II, III, and IV and presented graphically in Figures 5, 6 and 7.

4. — Discussion

The assembled experimental results make it possible to establish the relationships sought, but they hold their validity strictly within the narrow range of the flow velocity of the stowing mixture. Let us note that the values of the flow velocity of transporting water in each of the measuring runs exceed the terminal value with respect to the first and second granulometric fractions under investigation. This means that these particular fractions of solids were transported in persistent suspension.

Such a kind of flow has been examined by several investigators, but for solid material conveyed pneumatically. In particular, it was ascertained that for large values of the carrier air flow velocity the ratio of flow velocities of the two mixture phases remains constant [7], [8], [9], [10], [11].

Because of the similarity of the aerodynamical and hydrodynamical phenomena there is a temptation to extend the mentioned relationship to hydromixtures flowing with superterminal velocities. It is easy to show that the invariability of the velocity ratio in this region of the mixture motion may result from the assumption of flow resistances retarding the solid particles with respect to the fluid as the square function of the mean flow velocity of the fluid [12]. Following this assumption, then, the kinematic flow characteristics replotted in Figures 8 and 9 become

Table I

Mean mixture density	Mean velocity of mixture	Fraction or phase	Fraction flow velocity	v_i/v_m	$\frac{v_w - v_s}{v_w}$	v_s/v_w
g/cm³	m/s	mm	m/s	—	%	—
1,56	3,55	water	3,66	1,03	—	—
		0,3 — 0,5	3,45	0,97	5,7	0,94
		2,0 — 3,0	3,21	0,90	12,3	0,88
		10 — 12	2,75	0,77	25,0	0,75
1,68	3,66	water	3,74	1,02	—	—
		0,3 — 0,5	3,59	0,98	4,0	0,96
		2,0 — 3,0	3,38	0,92	9,6	0,90
		10 — 12	2,95	0,80	21,0	0,79
1,74	3,70	water	3,76	1,02	—	—
		0,3 — 0,5	3,63	0,98	3,5	0,97
		2,0 — 3,0	3,44	0,93	8,7	0,91
		10 — 12	3,09	0,84	17,8	0,82
1,80	3,75	water	3,82	1,02	—	—
		0,3 — 0,5	3,71	0,99	2,9	0,97
		2,0 — 3,0	3,51	0,94	8,1	0,92
		10 — 12	3,24	0,86	15,2	0,85

Table II

Mean mixture density ρ_m	Mean velocity of mixture v_m	Fraction or phase « i »	Fraction flow velocity v_i	v_i/v_m	v_s/v_w	$\frac{v_w - v_s}{v_w}$
g/cm³	m/s	mm	m/s	—	—	%
1,10	4,51	water	4,55	1,01	—	—
		0,3 — 0,5	4,00	0,89	0,88	12,2
		2,0 — 3,0	3,50	0,78	0,77	23,1
		10 — 12	3,15	0,70	0,69	30,2
1,30	4,19	water	4,26	1,02	—	—
		0,3 — 0,5	3,85	0,92	0,91	9,6
		2,0 — 3,0	3,40	0,81	0,80	20,2
		10 — 12	3,15	0,75	0,74	26,0
1,50	4,09	water	4,20	1,03	—	—
		0,3 — 0,5	3,85	0,94	0,92	8,3
		2,0 — 3,0	3,51	0,86	0,84	16,5
		10 — 12	3,28	0,80	0,78	21,9
1,60	4,05	water	4,17	1,03	—	—
		0,3 — 0,5	3,85	0,95	0,92	6,7
		2,0 — 3,0	3,58	0,88	0,86	14,2
		10 — 12	3,40	0,84	0,82	18,5
1,85	3,95	water	4,00	1,01	—	—
		0,3 — 0,5	3,90	0,99	0,98	1,8
		2,0 — 3,0	3,78	0,96	0,95	5,5
		10 — 12	3,58	0,91	0,90	10,5

Added broken stone concentration 1 %

Table III

Mean mixture density	Mean velocity of mixture	Fraction or phase	Fraction flow velocity	v_i/v_m	$\frac{v_w - v_s}{v_w}$	v_s/v_w
g/cm³	m/s	mm	m/s	—	%	—
1,40	4,33	water	4,46	1,03	—	—
		0,3 — 0,5	4,01	0,93	10,1	0,90
		2,0 — 3,0	3,51	0,81	21,3	0,79
		10 — 12	3,34	0,77	25,1	0,75
1,50	4,25	water	4,36	1,03	—	—
		0,3 — 0,5	3,98	0,94	8,7	0,91
		2,0 — 3,0	3,58	0,84	17,9	0,82
		10 — 12	3,40	0,80	22,0	0,78
1,70	4,11	water	4,20	1,02	—	—
		0,3 — 0,5	3,98	0,97	5,2	0,95
		2,0 — 3,0	3,74	0,91	10,9	0,89
		10 — 12	3,55	0,86	15,5	0,84
1,80	4,09	water	4,16	1,02	—	—
		0,3 — 0,5	4,00	0,98	3,8	0,96
		2,0 — 3,0	3,83	0,94	7,9	0,92
		10 — 12	3,63	0,89	12,7	0,87

Added broken stone concentration 5 % **Table IV**

MEAN MIXTURE DENSITY	MEAN VELOCITY OF MIXTURE	FRACTION OR PHASE	FRACTION FLOW VELOCITY	v_i/v_m	$\frac{v_w - v_s}{v_w}$	v_s/v_w
g/cm³	m/s	mm	m/s	—	%	—
1,65	4,25	water	4,34	1,02	—	—
		0,3 — 0,5	4,13	0,97	4,8	0,95
		2,0 — 3,0	3,66	0,86	15,7	0,84
		10 — 12	3,50	0,825	19,1	0,80
1,75	4,20	water	4,26	1,014	—	—
		0,3 — 0,5	4,13	0,983	3,0	0,97
		2,0 — 3,0	3,74	0,89	12,2	0,88
		10 — 12	3,54	0,84	16,9	0,83
1,80	4,18	water	4,23	1,01	—	—
		0,3 — 0,5	4,13	0,99	2,4	0,98
		2,0 — 3,0	3,80	0,91	10,2	0,90
		10 — 12	3,60	0,86	14,9	0,85
1,85	4,17	water	4,20	1,01	—	—
		0,3 — 0,5	4,13	0,99	1,7	0,98
		2,0 — 3,0	3,85	0,923	8,3	0,92
		10 — 12	3,67	0,88	12,6	0,87

universal in the sense that they are valid for the flow velocities greatly exceeding the terminal value.

The kinematic characteristics presented describe the dependence between the reduced fractional flow velocities v_i/v_m and the mean mixture density ρ_m. As is seen from Figures 8 and 9, the course of the characteristics of solid particles transported in suspension may be approximated by the corresponding straight lines, while those of the liquid phase water have an almost parabolic shape. Similar results were obtained by the research group of the Central Institute of Mining (Katowice, Poland) which carried out complex measurements of stowing mixture flow using exclusively the conventional hydraulic measuring methods [13]. The similarity, however, concerns only the general course of characteristics, which cannot be reduced to one universal form (Figure 10).

The specific course of kinematic characteristics creates a certain possibility of estimating the empirical formula determining the relative slip velocity of solids as the function of the mean mixture density. Let us, then, write the equation of the straight line approaching the kinematic characteristic of the solid phase:

$$v_s/v_m - 1 = \alpha (\rho_m - \rho_{max})$$

The kinematic characteristic of the carrier water, as was said before, may be approximated by a parabola.

It takes the form:

$$v_w/v_m - 1 = \xi (\rho_m - \rho_w) - \varphi (\rho_m - \rho_w)^2$$

In both these equations the following notation is used: ρ_m — mean mixture density, ρ_{max} — maximum density of the mixture, ρ_s — density of solid material, ρ_w — density of transporting water, v_m — mean flow velocity of the mixture, v_s — flow velocity of solids, v_w — flow velocity of water, α, ξ and ρ are the empirical coefficients of proportionality.

The solution of this set of equations leads to the expression for the relative slip velocity in a general form:

$$\frac{v_w - v_s}{v_w} = F(\rho_m)$$

This maintains its validity only with respect to the kind of mixture and the pipe parameters strictly corresponding to those under investigation and no further generalizations are possible.

5. — Conclusions

Measurements performed on a natural-size stowing pipeline installation suffer from the limitations imposed by the gravitational extorsion of the mixture flow. For this reason it was impossible to check the validity of the assumption of a constant velocity ratio in a wide range of superterminal flow velocities. This is a question which needs further, detailed verification, to be carried out on a laboratory, experimental installation.

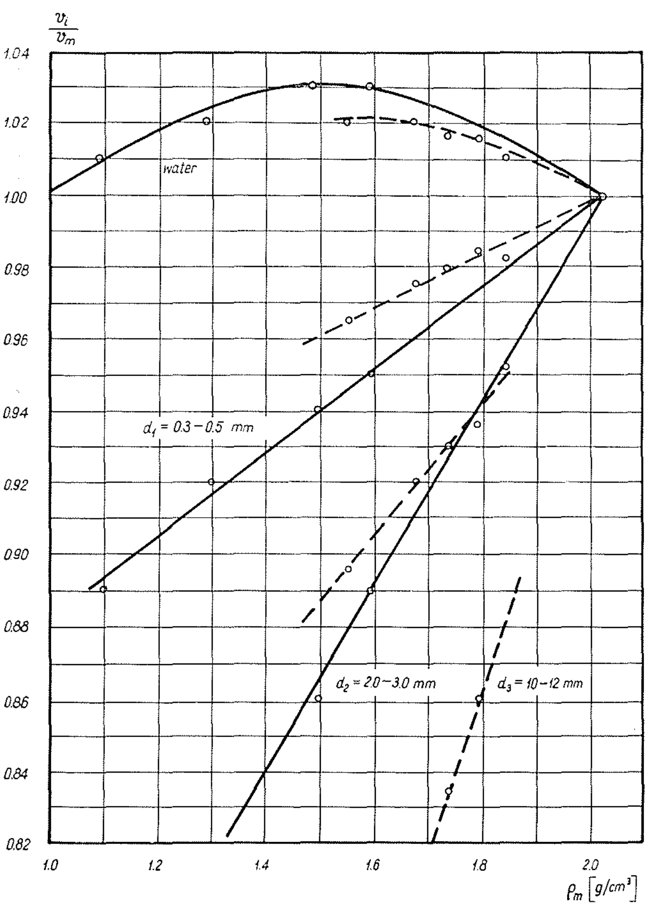
Nevertheless, the results obtained allowed the data given by other authors to be verified [14], [15], and the values of velocity ratios for hydraulic and pneumatic conveying of solid grains of the same size to be compared. In accordance with the theoretical prediction it was proved that the velocity ratio for solids transported hydraulically is much higher than that in the case of pneumatic transport. For the granulometric fraction of sand

$$d_1 = (0{,}3 - 0{,}5)\ \text{mm}$$

the values of the velocity ratio vary, depending on the concentration of solid material, in the range (0,5 — 0,6) and (0,88 — 0,98) for pneumatic and hydraulic transport respectively.

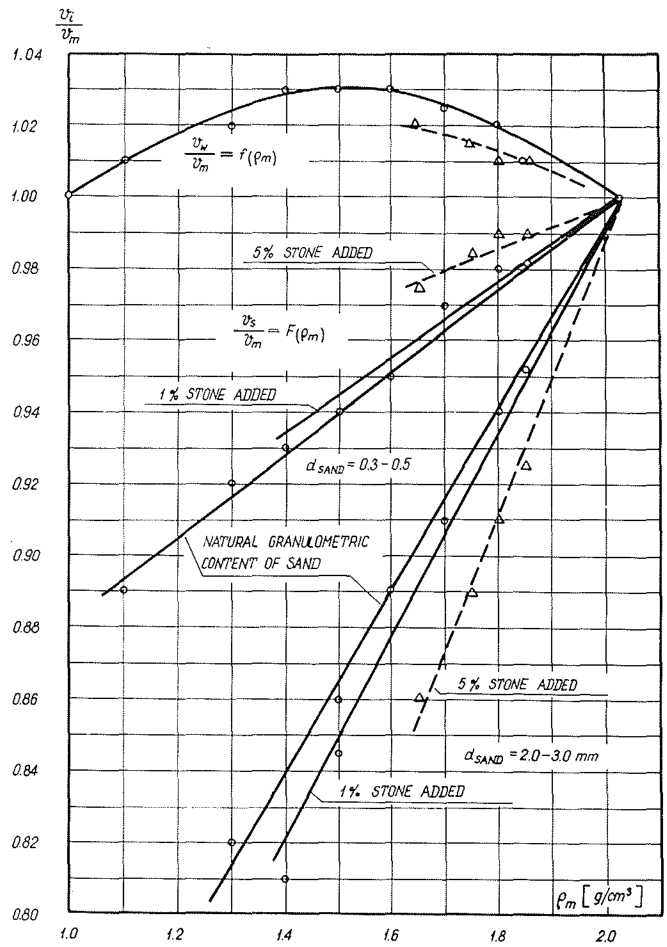
On the basis of the assembled experimental data some conclusions of practical importance have also been drawn. One of them deals with the problem of the accuracy of measurement of the flowing stowing mixture. From the technical point of view, the density of flowing media desired for control of the process is the "delivered" one. Thus, using the measuring devices sensitive to the "in-line" density it is of essential interest to know how far it differs from that obtained at the outlet of the conduit. This difference may be considered as an additional error of the density measurement, and because of its origin it may be called the kinematic error [16].

For the multifractional stowing mixture containing i different fractions of sand of different percentage k_i flowing



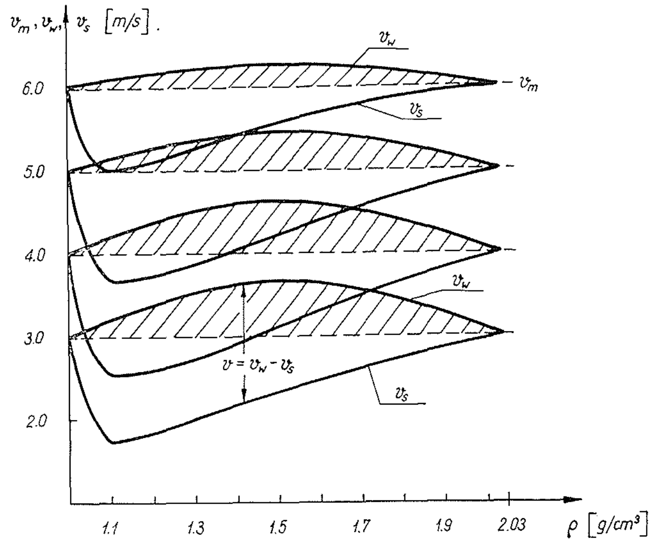
8/ Kinematic flow-characteristic of the stowing mixture for full rate feeding (continuous line) and for partially filled pipe (broken line).

Caractéristique cinématique de l'écoulement du mélange à débit maximal (trait continu) et pour une section de conduite partiellement remplie (pointillés).



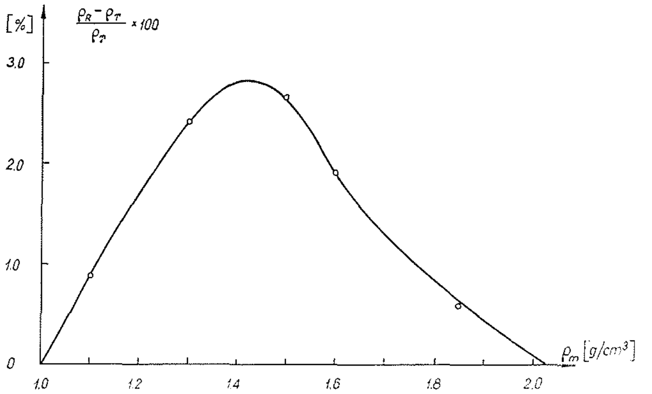
9/ Kinematic flow-characteristic of the stowing mixture containing the additional stone.

Caractéristique cinématique d'écoulement du mélange en présence des cailloux supplémentaires.



10/ The dependence of the flow velocities of solids, liquids, and the mixture on the mean mixture density, according to the results obtained by Lisowski et al. [13].

Vitesse d'écoulement du solide, du liquide et du mélange en fonction de la densité moyenne du mélange (d'après les résultats obtenus par Lisowski et al. [13]).



11/ The kinematic error of the delivered density determination as a function of the in-line density.

Erreur cinématique de la densité mesurée en fonction de la densité dans la conduite.

with different velocities v_i the relative kinematic error of the delivered density determination takes the form:

$$\delta(\rho_{(kin)}) = \frac{(\sum k_i a_i - 1)\ (\rho_s \rho_r - \rho_s \rho_w - \rho_r \rho_w - \rho_r^2)}{\sum k_i a_i \rho_s (\rho_r - \rho_w) - \rho_w (\rho_s - \rho_r)}$$

where: $a_i = v_{si}/v_m$ — the particular velocity ratio, and ρ_r — the in-line density of the mixture. The velocity ratios, as shown before, depend on the mean mixture density but are invariant with respect to the mean flow velocity, if the latter exceeds the terminal level. Due to this peculiarity, the density gauge may be calibrated directly in terms of the delivered density if only the grain size distribution of the sand is kept constant and the super-terminal flow velocities are assured. One can also apply density gauges successfully without any changes in the graduation, correcting the indicated values according to the diagram of the kinematic error. Such a diagram for the stowing mixture is shown as an example in Figure 11.

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