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OPERATION OF GRAVITATIONAL HYDROTRANSPORT PIPELINE SYSTEMS IN COAL MINES

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Nowadays hydraulic backfill in Polish coal mines is almost completely abandoned, however, the pipelines are frequently used for transport of finely grained slurries for filling of cavings and other purposes. In the past, so-called full feed conditions have been introduced to achieve optimal operational parameters of the hydraulic backfill transport systems in terms of efficiency, transport distance, and pipe wear. Modern plants for preparation of fine-grained mixtures, mostly fly ash – water slurries operate with much smaller efficiency than traditional backfill plants, also the rheological parameters are different from hydraulic backfill. In the paper, these differences will be discussed together with the consequences of limited feeding, which results in three-phase flow in the pipeline. Also, fly ash – water slurries have another influence on pipe wall wear and roughness. From the other side the mine personnel do not care properly about the right operation of pipelines because, unlike the backfill, auxiliary work such as filling of cavings is not vital for the extraction process. Among others, the influence of changes of pipe roughness, the formation of solid sediment layer on pipe walls, and flow with reduced velocity will be analysed in terms of the range of transport, risk of pipeline blockage, and concentration of fill mixtures.

KEYWORDS: fill slurries, flow conditions, gravitational hydrotransport, pipe wear, filling of cavings.

1. INTRODUCTION

Fine-grained fill mixtures are used in large volumes in coal mines in Poland for different purposes, to which in first place belongs filling of cavings in a longwall mining system with free fall of roof rocks. Another frequently used application of filling of voids in present mining works is the liquidation of underground mine workings and shafts, construction of isolation plugs, and waste disposal. In contrary to well-known backfill operations, current ways of application of fine-grained mixtures are not targeted on roof support, so they are intentionally named “fill” instead of “backfill” operations, as it can be found in works of Palarski et. al. (2012) or Strozik (2018).

In the aim to utilize old backfill infrastructure, which is still present at most of the Polish coal mines (at least at the older ones) and to avoid unnecessary expenses in areas of secondary importance, the hydraulic backfill pipelines of typical diameters 0.150 m and 0.185 m designed for flow rates 300 – 700 m^3/h, are used for delivery of slurries with flow rates between 80 m^3/h and 200 m^3/h, most often around 100 m^3/h.

While in the past the basic backfilling material was sand, now it is fly ash with binding properties. Another distinct difference is the flushing of the pipelines after the flow cycle. In hydraulic backfill made from sand, special attention has been offered to correct flushing

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of pipes, because any mistake during starting and stopping of the flow led easily to the clogging of the pipeline. Nowadays, the flushing procedure is often shortened or even omitted in the aim to avoid the introduction of excessive water, for which there is no place and whose presence worsens significantly the prospective physical properties of the fill material created after solidification of a fine-grained slurry.

Problems outlined above also affect the operation of hydraulic transport systems, the lifetime of pipes, the accuracy of predicted flow parameters, and other issues, which must be addressed from the point of view of hydraulic transport of grained materials.

2. FLOW CONDITIONS IN DIFFERENT PIPELINE GEOMETRIES

Geometrical analysis of gravitational pipelines can be found i.e. in the work of Palarski, 1982. The idealized model of an underground mine hydraulic transport pipeline shown in Figure 1. It consists only of two pipe segments: a vertical part (mine shaft) and an underground horizontal part representing the way from the shaft bottom to the place of mining operations. If the transport potential of such a pipeline is fully utilized (maximum density of the mixture for the given geometrical conditions), then the vertical part of the pipeline will be completely filled with the mixture. If the density of the mixture is lower and if the intensity of production of the mixture is lower than required, the apparent level of the mixture will occur at a certain height in the shaft. In the initial part of the vertical pipeline a free fall of the mixture will occur, while near the height of the apparent level of the mixture there will be intense turbulences leading to accelerated erosion of the pipeline in this zone, however, in further part of the pipeline favorable flow conditions will occur, it means flow in full cross-section of the pipeline, and lack of negative pressures and cavitation.

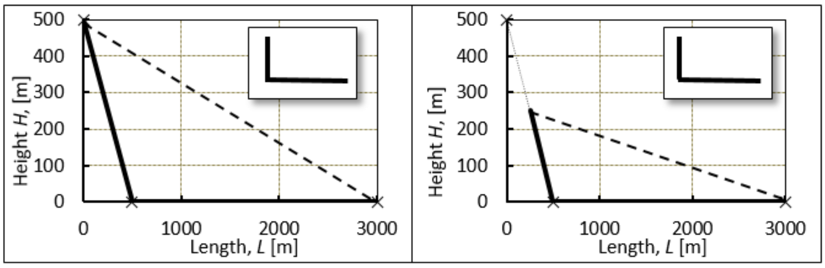

Figure 1. "L" shape hydraulic transport pipeline in an underground mine – full feed (left) and partial feed (right), correct flow conditions regardless of the height of apparent mixture level in shaft

Closer to reality, however, a still beneficial example of a pipeline layout is shown in Figure 2. In this example, the total height difference of the pipeline is distributed over the pipeline length, which creates a more favorable pressure distribution compared to the situation shown in Figure 1, where the pressure in the area of the shaft bottom may reach values easily exceeding the strength of the pipes (typically 6.4 MPa or 10.0 MPa). The partial feed of the cascade type pipeline may results in a very long distance of free fall and not fully developed hydraulic flow zones, however, in the final part of the pipeline, the flow conditions may be still favorable with positive pressure values at the whole length of fully developed flow.

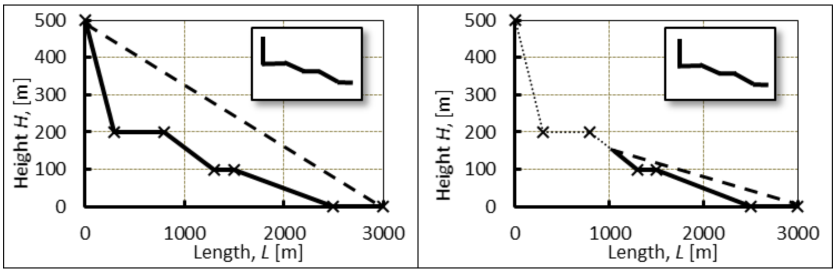

Figure 2. Cascade pipeline in an underground mine – full feed (left) and partial feed (right), correct flow conditions regardless of the height of apparent mixture level in shaft

The layout of mine workings often creates also unfavourable flow conditions as it is shown in Figure 3. The profile of the pipeline is still cascade type, but two (or even more) evident stages may be distinguished on the pipeline route. As a result of the lowering of the apparent height of the mixture level a negative pressure zone may reveal, which results in air suction into the mixture, three-phase flow, cavitation, intense erosion of pipes, shortening of their lifetime, and even pipeline failures during the flow of a mixture It should be borne in mind that the details of the pipeline's geometric layout are constantly changing due to the movement of the mining works. Thus, even well-configured pipeline and mixture composition may not prevent the formation of unfavorable flow conditions.

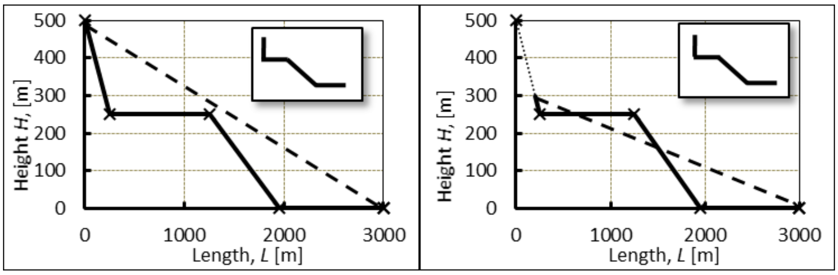

Figure 3. Cascade pipeline in an underground mine – incorrect flow conditions as a result of lowered apparent mixture level during the flow (on the right)

On the basis of numerous case studies, the authors stated that an easily accessible way to avoid the above-mentioned unfavorable situations is to maintain as much as possible the full mixture feed to the pipeline and the high apparent level of the mixture in the shaft. The problem has been discussed in the work of Plewa, Strozik, and Popczyk (2019) on the basis of laboratory measurements carried out by Strozik (2018). Mentioned works have been focused on optimization the mixture's density, however, considerations regarding the geometrical course of the pipeline provide additional reasons for optimizing the conditions of operation of the gravity transport installations.

3. INFLUENCE OF PIPE WALL ROUGHNESS ON FLOW CONDITIONS AND MIXTURES SELECTION

In the industrial conditions of the hydrotransport installation operations, the impact of the pipeline roughness is frequently underestimated. In many cases, in fact, neither the accuracy of the calculation nor the conditions of the flow of the mixtures (lack of fully developed turbulent flow) do not require a closer interest in the issue of wall pipeline roughness.

Hydraulic transport of fly ash – water mixtures exhibiting binding properties, in particular with a high concentration of solids, requires careful flushing of the pipeline. This process is often neglected due to a lack of care or space for excessive water discharge. Also flow with stationary sediment may be the factor influencing the pipe wall coating built-up. As a result of the cyclic transporting of solidifying mixtures, gradually, growing layers of solidified material can deposit on the pipe walls. Due to the resistance of solidified sediment to water, subsequent flow cycles may not wear out the pipe wall surface, but instead, further built-up of pipe wall cover may occur. This process, on the one hand, leads to the reduction of the active cross-section of the pipe, and on the other hand, it causes the flow of the mixture to take place on surfaces of a much greater roughness.

Accordingly, to research result of Bradley et al. (1977) in a rough estimation, absolute roughness of a pipe wall may increase even up to 150 times, from 0.02 mm (new steel surface), up to 10.0 mm (heavily exploited rough concrete wall – surface of solidified fly ash – water mixture has a similar texture as concrete).

The roughness of pipes in mine gravitational transport systems can be significantly differentiated depending on the type of pipes used for the pipeline assembly, their technical condition, and the degree of wear. Moreover, pipe roughness can increase along with the time of pipeline's lifetime due to corrosion, wear, and – in case of mixtures which exhibit binding properties – the build-up of a coating formed from solidified layers of fly ash – waters mixture. Although roughness of new steel pipes is less than 0.1 mm, used and slightly corroded pipes may exhibit absolute roughness of about 0.4 to 1.0 mm.

During a flow of fly ash – water mixture in laminar mode or in turbulent mode with laminar sub-layer, what is a case by low values of Reynolds number as observed in mine pipelines, a thin stationary film of a mixture covers pipe walls and may be able to solidify if there is no or incorrect rinsing of the pipeline after the cycle of transport. As the fill materials after solidification often do not undergo deterioration in the presence of water, subsequent mixture flow cycles may lead to the build-up of rough and durable coating of the pipe walls (mostly at the bottom).

Absolute roughness of such a surface is similar as in the case of concrete and its average roughness is about 3 mm. Old, highly eroded, and pipes with severe wall coating built-up may exhibit roughness even of 10 mm

On the basis of an analysis of rheological properties of the fly ash – water mixtures presented by Plewa et al. (2019), a demonstration of the influence of pipe wall roughness has been presented in Figure 4. The graph illustrates the relation between the type of mixture – described by its density, absolute roughness, and range of transport, calculated for flow in pipeline of constant diameter 0.1 m with the flow rate 100 m^3/h. As can be seen, the transport distance may be reduced even by five times, from almost 5000 m down to

1000 m, considering the change of pipe condition from hydraulically smooth to absolute roughness of 10 mm. The Colebrook-White formula has been adopted, accordingly to the work of Keady (1998).

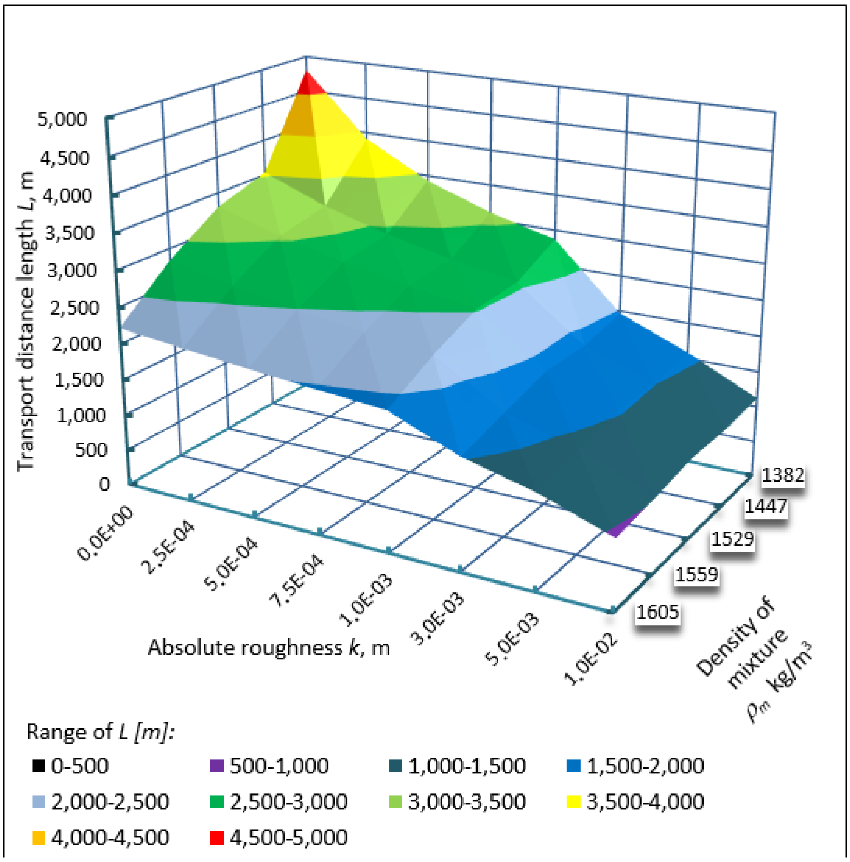

Figure 4. Influence of pipe wall absolute roughness on transport distance length for a mixture of densities from 1382 kg/m^3 to 1605 kg/m^3, pipe diameter 0.1 m, flow rate 100 m^3/h

It may be important to practice that the roughness influences the flow parameters of low-density mixtures rather than the low-concentration ones to a much greater extent (compare $L(k)$ relation for the mixture of density 1382 kg/m^3 and 1605 kg/m^3 in Figure 4). It is a consequence of differences in flow regime of particular mixtures, demonstrated by varying Reynolds number values, which, even by constant flow velocity, vary depending on density and rheological parameters (Bingham viscosity and yield point).

The strong dependence of the transport range on roughness combined with the possibility of rapid formation of a rough sediment layer on poorly rinsed pipes can lead to serious disturbances in the transport of mixtures to more distant places of applications.

Figure 5 presents an example of the distribution of the maximum density of the mixture, which can be effectively delivered to individual walls in the course of their operation. The height difference between the mixture preparation plant on the ground surface and the longwall panel was varying from 690 to 750 m, and pipeline length from 2280 m to 4580 m. A pipeline made from UHMW polyethylene of 0.1 m diameter has been proposed. Considering the hydraulically smooth pipeline (Figure 5 left), the maximal permissible density of mixture varied from 1447 kg/m^3 to 1605 kg/m^3 in relation to the current position of mining works, and the mixture of density 1559 kg/m^3 would be used to the greatest extent. After the introduction of roughness (ε= 1.0 mm), the range of maximal permissible fill mixture density decreased to 1382-1559 kg/m^3 and the densest mixture would be used only in a small extent (Figure 5 right). Detailed analysis of this case study can be found in the work of Strozik (2018).

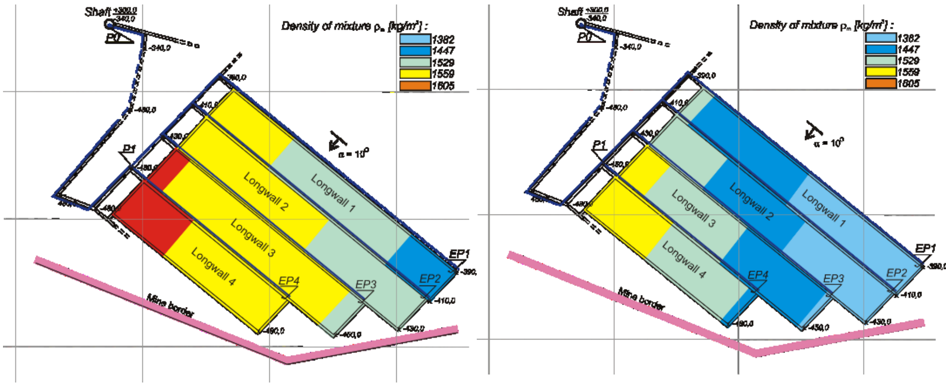

Figure 5. Filling of cavings in a group of longwalls – distribution of maximal density of fill mixture calculated for hydraulically smooth (left) and rough pipeline (ε= 1,0 mm) (right).

4. PROBLEMS OF NON-RUNOFF PIPELINES SECTIONS

In addition to the considerations in Chapter 2, one more unfavorable arrangement of the transport pipeline will be presented on the basis of the geometry of the pipeline for transport of fill mixtures to longwalls presented in Figure 5. An outlet of the pipeline at the end of longwall 1 (point EP1) is placed 90 m above the deepest part of the pipeline. As a result, there exists a large, over 2 km long non-runoff zone in the pipeline (Figure 6). The stagnation zone contains in the considered case a volume of 250 m^3 of water (if the pipeline is correctly cleaned after mixture flow), which has to be downloaded in order to avoid maintaining static pressure in the pipeline, whose value over the predominant length of the section is 0.9 MPa.

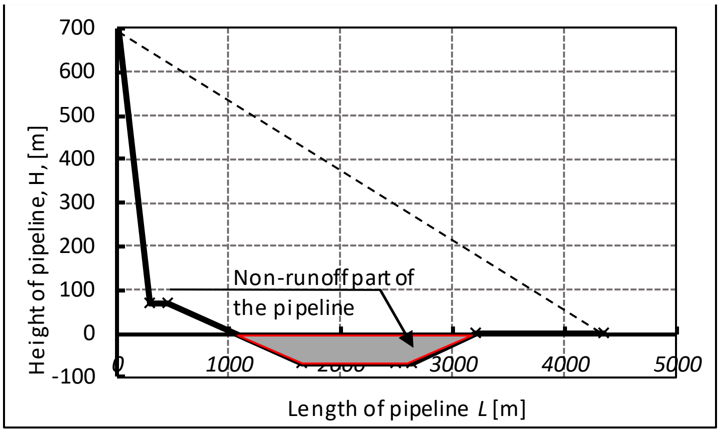

Figure 6. Hydraulic profile of the pipeline for delivery of fill mixture to longwall 1 presented in Figure 5

Presence of stagnation (non-runoff) zones in pipelines favours sedimentation of the mixture and formation of a layer of solidified fill material. Also flow of mixtures in inclined pipelines creates an opportunity for sedimentation of solid particles, especially of larger grain-size. After each flow cycle such a pipeline has to be rinsed and then the water discharged, however, this action may be difficult to introduce in the system of mine workings, located far from the places of current mining operations. By the way, it can be added that during the application of the hydraulic backfill (made from sand mainly, rarely coarse waste rock), the discharge of excess water was not a problem, because the drainage systems of coal mines were adapted to collect and pump onto the surface large amounts of water.

5. CONCLUSION

Due to the inability to effectively control the flow of mixtures in gravitational installations, the parameters of the mixtures for filling of underground voids are often underestimated. As a result, both the efficiency of mining technologies used is reduced and the flow conditions in the transport pipeline are getting worse. The latter relates to the operation of the pipelines with lowered apparent mixture level, which can lead to the creation of negative pressure zones and other flow disturbances in the pipeline, such as cavitation or increased pipe wear.

Regarding the influence of pipeline roughness on flow parameters, it was concluded that the roughness can have a serious impact on the limitation of the transport range (increase in flow resistance). This is particularly important in the situation when irregular and improperly conducted transport of solidifying mixtures can result in the short time to the formation of a coating on the pipeline walls, whose absolute roughness by orders of magnitude exceeds the roughness or new steel pipes (is similar to a concrete wall).

Good utilization of the potential of the pipeline's geometric layout and proper consideration of the roughness allows for the precise selection of the best parameters (compositions) of mixtures for filling underground cavities, under the condition that their rheological properties are known.

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