

**České vysoké učení technické v Praze, Fakulta stavební**

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**Hydraulická potrubní doprava hrubozrnných směsí – použití v praxi  
a možnosti optimalizace provozu**

**Hydraulic Transport of Settling Slurries in Pipelines – Practical  
Application and Optimization of Pipeline Operation**

## Summary

The paper surveys the most often used applications of the hydraulic transport of solids in the Czech Republic and abroad and discusses main problems associated with a practical use of the hydraulic transport. Possibilities are analyzed of the optimization of a slurry-pipeline operation from the energy and safety points of view. The work describes the state of the art in the research on energy losses in flows of coarse slurries through pipes and surveys some of the author's contributions to this research area.

The hydraulic transport of ash and slag from power plants and heating stations to deposit sites is the most common application of the hydraulic transport in the Czech Republic. In abroad, the largest tonnages of transported solids are associated with the dredging industry. A fast growing application is the transport of tar sands and their tailings. The longest pipelines (hundreds kilometers long) transport the ores from mines in isolated areas to processing plants. Transportation of large quantities of solids over long distances is an energy consuming operation. An optimization of a pipeline operation can diminish operational costs considerably. In practice, the optimization options are often limited to an appropriate choice of flow rates of slurry and solids through a pipeline. An ability to determine (predict) energy losses associated with the pipeline operation at certain flow rates of mixture and solids is an essential condition for a successful optimization of a slurry-pipeline operation. Predictive models for energy losses should be based on a description of the mechanisms governing slurry flow rather than on empirical equations of a limited applicability. A quality of the mechanistic models depends on an ability to describe friction and dispersion mechanisms in a flow of settling slurry. The work indicates that the author's version of a two-layer model combined with the turbulent-diffusion model that implements the hindered-settling effect has a potential to become a successful predictive tool for energy losses in heterogeneous flows in pipelines.

## Souhrn

Přednáška uvádí přehled nejběžnějších aplikací hydraulické dopravy sypanin v České republice a v zahraničí a diskutuje hlavní problémy spojené s praktickým použitím hydraulické dopravy. Analyzovány jsou možnosti optimalizace provozu trubních linek z hlediska energetické náročnosti a bezpečnosti provozu. Práce popisuje současný stav poznání ve výzkumu energetických ztrát při proudění hrubozrnných směsí a shrnuje některé autorovy dosavadní příspěvky do této výzkumné oblasti.

Nejběžnější aplikací hydraulické dopravy v ČR je hydraulické odpopelňování, tedy doprava odpadů ze spalování uhlí v tepelných elektrárnách a teplárnách na složiště. Ve světě jsou největší objemy přepravovaných sypanin spojeny s provozem sacích bagrů, značná množství sypanin jsou v poslední době dopravována také při procesu získávání ropy z pískových podloží. Nejdelší trubní linky (v řádech stovek kilometrů) slouží k přepravě substrátů z rudných dolů nacházejících se v špatně dopravně dostupných oblastech do zpracovatelských kombinátů. Hydraulická doprava velkých objemů sypkých materiálů na velké vzdálenosti je energeticky náročná operace. Optimalizace provozu může značně snížit náklady na provoz trubní linky. V praxi je možnost optimalizace provozu často omezena na správnou volbu průtoku směsi a pevné fáze potrubím. Schopnost kvalitně určit (předpovědět) energetickou ztrátu spojenou s provozem potrubí za určitého průtoku směsi a pevné fáze je základní podmínkou úspěšné optimalizace provozu trubní linky. Předpovědní modely pro energetické ztráty by měly být založeny na popisu řídicích mechanismů proudění směsi potrubím spíše než na empirických rovnicích omezeného rozsahu použití. Kvalita mechanistických modelů je závislá na stupni poznání frikčních a disperzních mechanismů v proudu hrubozrnné směsi. Práce ukazuje, že autorova verze dvouvrstvého modelu s implementovaným modelem turbulentní disperze za uvažování vlivu rušené sedimentace má potenciál být úspěšným předpovědním nástrojem k určení energetické ztráty v heterogenním proudění potrubím.

**Klíčová slova:** proudění směsi, disipace energie, laboratorní experiment, dredging, sací bagr, empirické modelování, dvouvrstvý model

**Keywords:** slurry flow, energy dissipation, laboratory experiment, dredging, empirical modeling, two-layer model

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## **1. HYDRAULIC TRANSPORT IN PRACTICE**

Hydraulic transport is a widely used mean of transportation of solids all over the world. In many practical situations it is considered a cost effective, safe and environmental-friendly tool to transport different sorts of solids to both short and long distances. In some specific application areas (e.g. dredging) there is no realistic alternative to hydraulic transport.

Transportation of solids by pipeline using a liquid vehicle dates back to the early twentieth century. As transportation costs have become a more significant component of total product costs, the use of slurry pipelines has received greater attention. Factors favoring slurry applications include economies of scale (lower unit capital costs and power requirements with larger-diameter pipelines), and very high reliability. In addition, slurry pipeline systems have very low operating costs relative to alternative modes of transportation, low labor requirements, are relatively immune to the effects of escalation, are safe, and have a lower impact on the environment as compared to vehicle traffic.

### **1.1 Major Applications in the Czech Republic**

In the Czech Republic the hydraulic transport has a long standing tradition. One of the oldest documented projects involving hydraulic transport of large volumes of solids was the one financed by the industrial tycoon J.A. Baťa in the mid 1930s. The objective of the land reclamation project was to prepare a ground for a construction site by flushing marshlands in Otrokovice with soil excavated from the Tresný hill nearby. In 1933-1935 more than 3.5 million cubic meters of soil were transported hydraulically through open channels and flumes over a distance of about 2 kilometres [12]. The reclaimed land was used for building houses and industrial plants.

#### 1.1.1 Energy industry - transport of ash and slag

Since the 1970s, the largest volumes of hydraulically transported solids in Czechoslovakia (the Czech Republic respectively) have been associated with power plants producing electrical and thermal energy by burning coal. The biggest population of the coal-fed power plants was built in the Northern Bohemia in the vicinity of coal mines supplying the plants with coal. The burning of relatively low quality coal has produced large quantities of ash and slag that had to be disposed. During the years, millions of tonnes of ash and slag have been transported through pipelines from power plants to disposal sites (Figure 1). During last decade the



quantities of disposed solids have gradually decreased as still more waste solids are recycled, being used e.g. for a production of construction materials. However, masses of solids transported to disposal sites are still considerable.



Figure 1. Slurry pipeline conveying ash and slag from the Tušimice II power plant to a disposal site (source: Hochtief web site).



Figure 2. Disposal site of Litvínov heating plant.

A new trend in waste disposing is a use of waste solids for backfilling of open-pit mine spaces instead of settling at disposal sites. Since recently, waste solids from power plants Tušimice II and Prunéřov are transported to backfill empty spaces of the Nástup Tušimice mine. Additional producers of waste solids from burned coal are heating plants. These are smaller than power plants and thus produce less ash and slag. Figure 2 shows a disposal site of the heating plant Litvínov. Of about 500 000 cubic meters of waste solids are disposed there annually.

### 1.1.2 Other applications

Along ash and slag, other solids are transported in various industries although transported volumes are usually smaller than in the energy industry. Typical transported solids are coal dust in the mining industry, sand, gravel, crushed stone, cement, concrete in civil engineering, ceramic clay, kaolin, etc. in the processing industry. Maintenance of waterways, rivers, ponds and lakes requires removing of sediments in form of silt, sand and gravel by dredging. Different solid-liquid slurries are transported also in chemical and food industry.

## **1.2 Major Applications Abroad**

In some other parts of the world, the hydraulic transport is used much more intensively than in the Czech Republic. Vast tonnages of solids are transported particularly in dredging, oil-sand industry and mining industry.

### 1.2.1 Dredging

The dredging industry is the application that involves the largest quantities of pumped solid-water mixtures. The most important dredging activities are

- the capital dredging – creating waterways and harbors through enlarging and deepening of rivers and access channels,
- the maintenance dredging, i.e. the removal of sediments which have accumulated in the bottom of dredged waterways to ensure the required water depths, another maintenance application is a beach nourishment, i.e. flushing coastal beaches with sand dredged from a sea bottom to which it was eroded from beaches,
- the land reclamation and dredging for construction - dredging is an important way of providing sands and gravels for construction and reclamation projects.





Figure 3. Trailing suction hopper dredger supplying a shore slurry pipeline.

The largest dredging projects now in progress are the reclamation projects in Singapore and in Dubai.

The government of Singapore builds a major oil and chemical platform in Singapore by linking up seven existing islands to one Jurong island. The 550 million m<sup>3</sup> of sand, needed to create the 1460 ha of reclamation, is brought in by large trailing suction hopper dredgers from sand sources in Indonesian and Malaysian waters. The 25 million m<sup>3</sup> of dredged mud and clay is dumped by barges in the new reclamation areas. The dredging work is to be completed in 24 months.

The Palm Islands in Dubai are three large artificial islands, currently being constructed. Each settlement will be in the shape of a palm tree topped with a crescent and will have residential communities and resorts built upon them. It is possible to make these islands due to the wide continental shelf off the Dubai coast and the relatively shallow depth of the Persian Gulf. The islands will be built from 80 million m<sup>3</sup> landmass dredged from the approach channel. It should be mentioned that the massive dredging operations cannot avoid an impact on the environment in the coastal area of the Persian Gulf. The dredging will affect ecosystems such as seagrass beds, lagoons and coral communities and marine life like fish, turtles, and dolphins. Coral reefs and oyster beds are being buried under the weight of sand and rocks, while marine life is staying away.

The World is a system of over 300 artificial islands that forms a map of the continents four kilometres off the coast of Dubai. The configuration measures seven by nine kilometres and is protected by a breakwater 25 kilometres in length, the longest ever constructed. The completion of The World requires 325 million cubic metres of sand to be dredged to construct the islands.

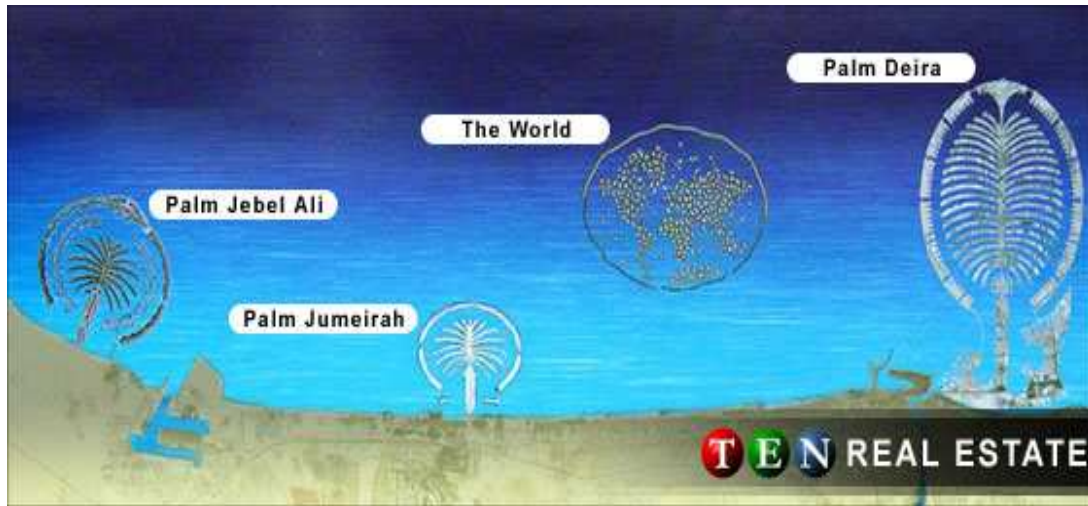


Figure 4. Land reclamation works carried out by dredging companies in Saudi Arabian Emirates (source: website Ten Real Estate).

### 1.2.2 Oil industry

Canada ranks second largest in terms of global proven crude oil reserves (15% of world reserves) after Saudi Arabia. The majority of these reserves are found in Alberta's oil sands – over 174 billion barrels of oil are trapped underground in a complex mixture of sand, water and clay in a form of bitumen, a heavy, carbon rich, and extremely viscous oil.. It takes about two tonnes of oil sand to produce a barrel of oil. Oil sands production of more than 1 million barrels a day (1 barrel = 159 liters) now account for approximately 50 per cent of Canada's total consumption.

Although about 80% of the oil sands in Alberta are buried too deep below the surface for open pit mining, the open pit mining is still the excavation method used. The Athabasca area is the largest and closest to the surface, accounting for the large-scale oil sands development around Fort McMurray.



Figure 4. Processing plant with supplying pipelines handling tar sands and crude oil in Alberta, Canada (source: website Syncrude).

Hot water is used to separate oil from excavated oil sands. Oil sand is mixed with hot water creating slurry. Slurry pipelines are used to condition and transport the oil sand from the mine to the bitumen extraction plant, which can be located many kilometres away. At present, all mined oil sand is transported using a slurry pipeline. The slurry is fed into a separation vessel where it separates into three layers - sand, water and bitumen. The bitumen is then skimmed off the top to be cleaned and processed further. After bitumen is extracted from oil sand the leftover mixture of water, sand, silt and fine clay particles is pumped to the settling basin. There the fast-settling sand particles are used to construct mounds, dikes and other stable deposits. The leftover muddy liquid (called fine tailings), consisting of slow-settling clay particles and water, is processed further.

Oil sand hydrotransport is a much less expensive way to move oil sand than the old method of using long conveyors. It is also a more flexible process and pipelines don't have to run in straight lines or over level ground. The other important benefit is that oil sand can be processed at lower temperatures, thus lowering energy consumption.

### 1.2.3 Mining and processing industry

The numerous solids that have been transported in slurry form include coal, copper, iron, phosphate, lead, zinc, nickel, and bauxite concentrates as well as limestone or tailings. Typically, long distance concentrate slurry transportation systems are used to convey the solids. Many long distance systems are in operation today, transporting slurries over the distances of hundred kilometers. Table 1 surveys the longest operational pipelines currently used.



Figure 5. Slurry pipeline through rugged isolated area in Andes, South America (source: website Pipeline Systems Inc.).

Table 1. The longest operated slurry pipelines [4]

| <b>Location<br/>(year of commission)</b> | <b>Material<br/>transported</b> | <b>Pipe<br/>length<br/>[km]</b> | <b>Pipe<br/>diameter<br/>[m]</b> | <b>Annual<br/>capacity<br/>[Mt/year]</b> |
|--|---------------------------------|---------------------------------|----------------------------------|--|
| USA, Black Mesa<br>(1970)                | coal                            | 439                             | 0.46,<br>0.31                    | 4.5                                      |
| Brazil, Samarco<br>(1977)                | iron ore                        | 396                             | 0.51,<br>0.46                    | 16.5                                     |
| Mexico, La Perla<br>(1983)               | iron ore                        | 382                             | 0.20,<br>0.36                    | 4.0                                      |
| Argentina, Alumbreira<br>(1997)          | copper ore                      | 312                             | 0.15                             | 0.6                                      |
| Australia, Queensland<br>(1999)          | zinc ore                        | 303                             | 0.32                             | 0.15                                     |



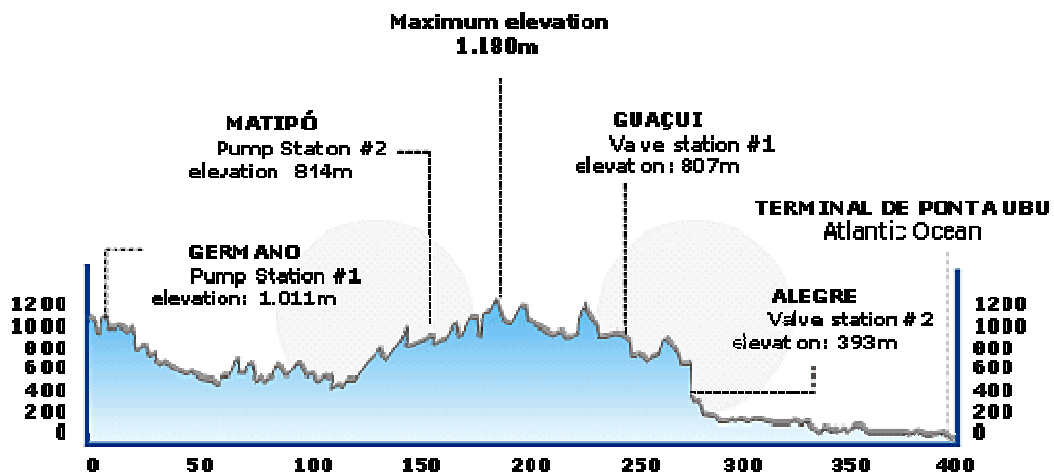


Figure 6. Samarco's Alegria mine and 396-km long iron-ore slurry pipeline in Brasil (source: website Samarco).

## 2. POTENTIAL PROBLEMS ASSOCIATED WITH OPERATION OF PIPELINES TRANSPORTING SETTLING SLURRIES

An operation of a slurry pipeline must be both safe and efficient. During operation flow conditions should be continuously checked and controlled. In case of changing operation conditions (e.g. changes in the properties of transported solids, as is the particle size distribution, in the solids concentration or in the pipeline length), measures must be taken in order to avoid potential problems. Basically, an operational control seeks a

value of the average velocity of slurry that is appropriate to current flow conditions in a pipeline.

From the safety point of view a slurry pipeline must operate at velocity high enough to prevent a blockage of the pipeline by transported solids. If the velocity would be too low, solid particles settled out to the bottom of the pipe, stop their movement and form a stationary bed. In pipelines transporting slurries at high solids concentrations the stationary bed might grow to such a thickness that it occupies a substantial part of a pipe cross section. At locations of local disturbances along the pipeline the settled particles could further accumulate and finally form a stationary plug that blocks the pipeline. A remedy from the blockage is an expensive operation that costs resources, energy and time. Thus, the slurry velocity in a pipeline should not be too low, but it has not to be too high either. Too high average velocity of slurry means an excessive consumption of energy fed to a system by slurry pumps. Moreover, fast flowing slurry and thus fast moving solid particles increase wear of system components with which particles come into contact (pipe wall, valves, pump interiors). A further factor that plays a role in a choice of an optimum velocity of slurry through pipelines is time, namely a period within which a project must be finished.

### **3. OPTIMIZATION OF PIPELINE TRANSPORT SYSTEM**

#### **3.1 Economy Related Parameters of Slurry Flow in Pipe**

As discussed in the previous chapter, a slurry pipeline operation must be safe and efficient. In principle, the measure of efficiency is given by the amount of consumed energy (a major source of costs during an operation) and by time required to carry out a project. These two aspects are quantified using two economy related parameters of slurry flow through a pipe, the specific energy consumption and the solids production.

The production of solids by a system is the flow rate of solids through a pipe and it is defined as a volume or mass of solids transported through a

pipe per unit time period,  $Q_s = \frac{\pi}{4} D^2 \cdot v \cdot C_{vd} \cdot 3600 \left[ \frac{m^3}{hour} \right]$ . In the

equation,  $Q_s$  is the volumetric flow rate of solids, i.e. the production of solids in  $m^3/hour$ ,  $D$  is the pipe diameter in  $m$ ,  $v$  is the mean mixture velocity in  $m/s$ , and  $C_{vd}$  is the volumetric delivered concentration of solids which is dimensionless.



The efficiency of a slurry pipeline is evaluated by means of a parameter called specific energy consumption (SEC). The SEC determines the energy required to move a given quantity of solids over a given distance in a pipeline. It is defined as a ratio between the power consumption per meter of pipe and the (dry) solids throughput in a pipe. Power consumption per meter of a pipe is given by  $I_m \cdot \rho_f \cdot g \cdot Q_m$  and solids throughput (mass flow rate of solids) is  $\rho_s \cdot C_{vd} \cdot Q_m$ . Then  $SEC = \frac{I_m g}{S_s C_{vd}} \left[ \frac{J}{kg \cdot m} \right]$  or  $SEC = 2.7 \frac{I_m}{S_s \cdot C_{vd}} \left[ \frac{kWh}{tonne \cdot km} \right]$ . In the equations,  $I_m$  is the frictional head loss [ $m_{H_2O}/m$  pipe-length],  $g$  is the gravitational acceleration [ $m/s^2$ ], and  $S_s$  is the relative density of solids [-].

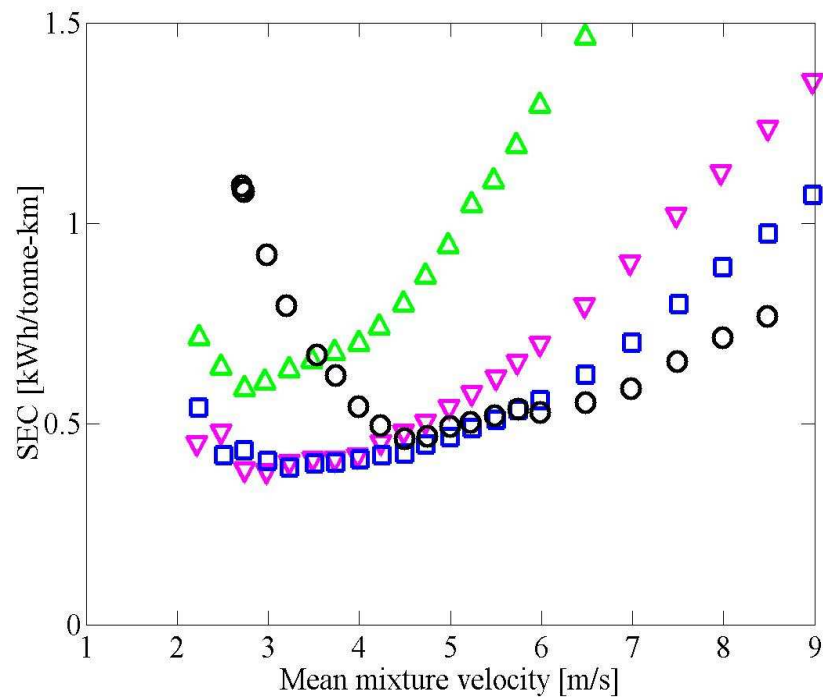


Figure 7. Specific energy consumption in flow of medium-sand slurry through a 150-mm pipe for various mean velocities of slurry and delivered concentrations of solids; ( $\Delta$ ):  $C_{vd} = 0.12$ , ( $\nabla$ ):  $C_{vd} = 0.26$ , ( $\square$ ):  $C_{vd} = 0.34$ , ( $\circ$ ):  $C_{vd} = 0.43$ , [8].

The test results plotted in Fig. 7 indicate that an energy-optimum operation (i.e. an operation at the minimum SEC) can be achieved through the control of both velocity and delivered concentration. For the particular case shown on the Figure 7 (the medium-sand slurry in the

150-mm pipe), the optimum operation from the energy point of view is obtained for flow of medium values of the concentration ( $C_{vd}$  at 2.26 - 0.34) and the velocity ( $v$  at 3.0 – 3.5 m/s).

### 3.2 Possibilities to Optimize Pipe Operation

During a pipeline operation the possibilities to control the flow conditions are rather limited. The only parameters that are subject to tuning are the average velocity of slurry and solids concentration in slurry. As the second parameter can be influenced only under suitable conditions (non-cohesive solids layer to be dredged) and using an equipment that is not always available (jets on a suction head), the only flow parameter left for regulation is the average velocity of slurry in a pipeline. This is controlled through a regulation of drive/pump speed. In principle, velocity can be controlled also by a valve mounted to a pipeline, but this solution is not recommended for slurry pipelines as the valve tends to wear out, can be a source of pipeline blockage or cavitation and also costs extra energy dissipation.

## 4. FRICTIONAL PRESSURE LOSS IN SETTLING SLURRY FLOW

The optimization parameter SEC is strongly dependent on the frictional pressure loss (see discussion on  $I_m$  below). Thus a prediction of conditions for the minimum SEC in a slurry pipeline requires an ability to predict frictional pressure loss with a reasonable accuracy. This chapter discusses methods of the friction-loss determination and prediction.

### 4.1 Pipe Characteristic: I-v curve

Flow resistance is given by the amount of mechanical energy dissipated in a slurry flow when flowing through a pipeline. The mechanical energy balance along a pipeline section - expressed by the Bernoulli equation - shows that energy dissipation in a steady slurry flow is characterized by the pressure difference along a horizontal pipeline section of constant diameter. The resistance is evaluated as the pressure drop  $\Delta P = P_1 - P_2$  (differential pressure over a pipeline section confined at the inlet by the pipeline cross section 1 and at the outlet by the pipeline cross section 2)

[Pa], or the hydraulic gradient  $\frac{\Delta P}{\rho_f g L}$  due to friction, also termed the

frictional head loss ( $I_m$ ) (head that is lost owing to friction is divided by

the length of a pipeline section,  $L$ ), which is dimensionless and expresses the pressure gradient by the ratio of meter liquid column and meter pipeline length.

A relation between the mechanical dissipation due to mixture flow through a pipeline and the mean mixture velocity is expressed in a pipeline-resistance curve. This relates the hydraulic gradient (i.e. pressure head lost due to friction over a unit distance of a pipe) with the mean slurry velocity  $v$  (see Fig. 8).

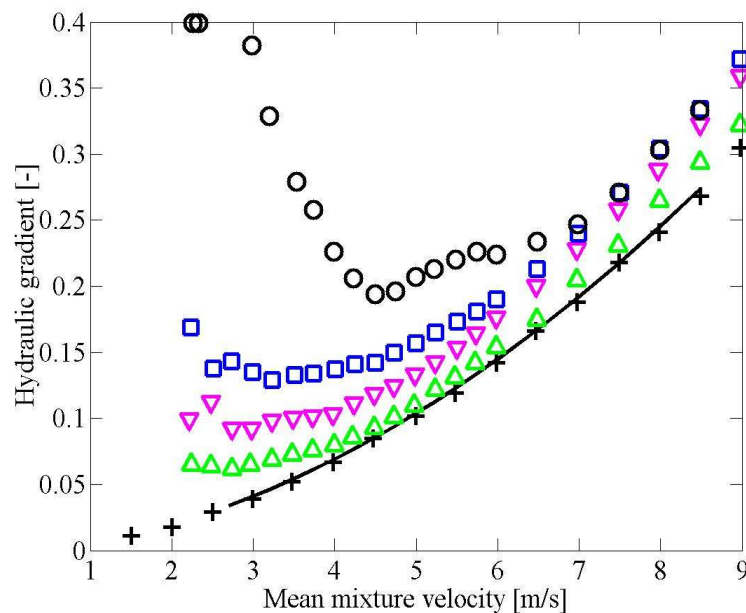


Figure 8. Frictional pressure loss in flow of medium-sand slurry through a 150-mm pipe for various mean velocities of slurry and delivered concentrations of solids; (+): water, ( $\Delta$ ):  $C_{vd} = 0.12$ , ( $\nabla$ ):  $C_{vd} = 0.26$ , ( $\square$ ):  $C_{vd} = 0.34$ , ( $o$ ):  $C_{vd} = 0.43$ .

A shape of the I-v curve is associated with a development of the internal structure of a settling slurry flow in a pipe (Fig. 9). A presence of a granular bed at the bottom of a pipe causes high pipe-wall friction (see I-v curve part left of the minimum point). The bed is a major source of solids friction. It narrows a flow cross section and causes extensive mechanical friction while sliding over a pipe wall.

#### 4.2 Modeling Techniques and Contemporary Trends in Research on Characteristics of Settling-Slurry Pipes

The hydraulic-performance optimization can be successful only if it is based on a sufficient knowledge of a behavior of a slurry flow in a pipeline and if it is carried out using reliable predictive models for

pipeline flow of slurries. In practice, predictive models for the pipeline hydraulic performance are usually based on an empirical approach rather than on a physical description of the slurry-flow mechanisms. This is because settling-slurry flows are rather complex and the present understanding of their mechanisms rather limited.

Empirical correlations can be established on the basis of relatively simple experiments that cover only measurements of integral flow parameters in a pipe [1, 11]. The problem is that the empirical approach is not mechanism-based and thus difficult to generalize. Development and verification of a better slurry-flow model based on a description of flow mechanisms require more sophisticated experiments. Simple tests (covering measurements of the integral flow parameters only) may indicate phenomena occurring in a pipeline flow of a mixture but they cannot identify the mechanisms governing the phenomena. The identification of mixture flow mechanisms requires identification of the internal structure of the mixture flow. The simplest mechanism-based model that handles both friction and dispersion mechanisms in settling-slurry flows is a two-layer model. Its verification and calibration requires experimental data including concentration profiles of tested slurry flows.

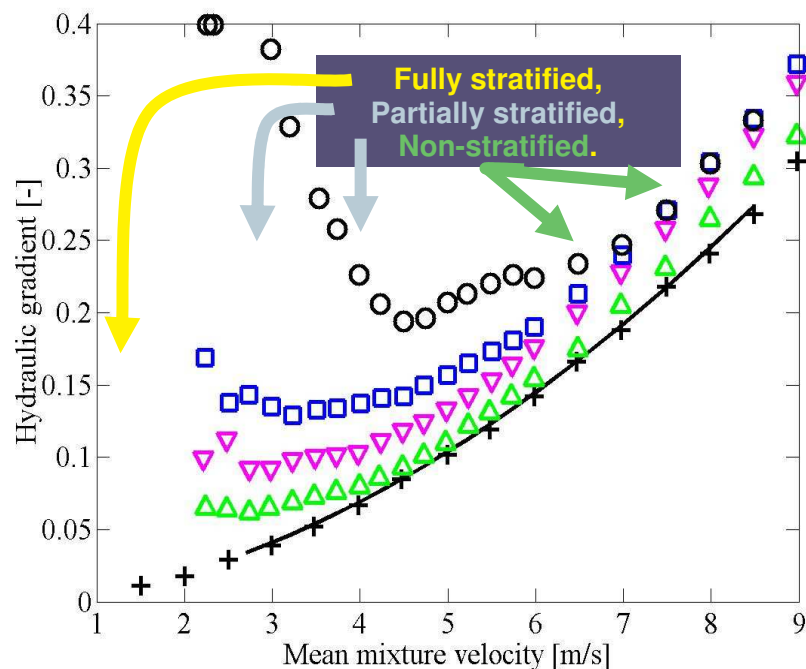


Figure 9. Frictional pressure loss in flow of medium-sand slurry through a 150-mm pipe for various mean velocities of slurry and delivered concentrations of solids; (+): water, ( $\Delta$ ):  $C_{vd} = 0.12$ , ( $\nabla$ ):  $C_{vd} = 0.26$ , ( $\square$ ):  $C_{vd} = 0.34$ , ( $o$ ):  $C_{vd} = 0.43$ .

#### 4.2.1 Current theoretical research

- Macroscopic modeling: a further development of a two-layer model leads to an extension of its applicability to specific flow conditions (inclined pipe, broad particle size distribution, stratified flow with a non-Newtonian carrier) and to a more accurate description of its components (new methods for a description of friction at the top of a granular bed, for an interaction between traveling particles and the boundary layer in the near-wall region of the flow, etc.) [13, 14, 17, 18],
- microscopic modeling: a development of complex models that describe flow mechanisms within two-phase flow in a micro-scale; these models are not yet suitable for practical computations.

#### 4.2.2 Current experimental research

- Measuring techniques: currently no suitable techniques are commercially available to measure the internal structure of high concentrated settling-slurry flows, new methods and techniques are emerging (MRI, etc.),
- testing in unusual conditions: experimental work focuses to flow conditions that were unusual earlier, and are still more common today, as are very high concentrated slurries, unsteady solids flows, flows in large pipe diameters [2, 3, 13, 15].

### **4.3 Author's Contribution to Flow-Friction Research**

The author's research results provide new information over the particle-dispersion mechanisms in settling slurries due to the diffusive action of carrier turbulence and over the friction mechanisms due to particle-boundary contacts (see e.g. [5-10]). The research results contribute to better understanding of mechanisms of solids suspension and friction in flowing slurries. They improve capabilities to model and predict settling-slurry flows in pipelines and help to optimize an operation of slurry pipelines in practice. The example on Fig. 10 shows a comparison of the author's experimental and theoretical results. The measured concentration profiles and the measured accompanying I-v curve are matched by the outputs of the author's two-layer model 2LM with the implemented turbulent-diffusion model (for details see [7, 9]).

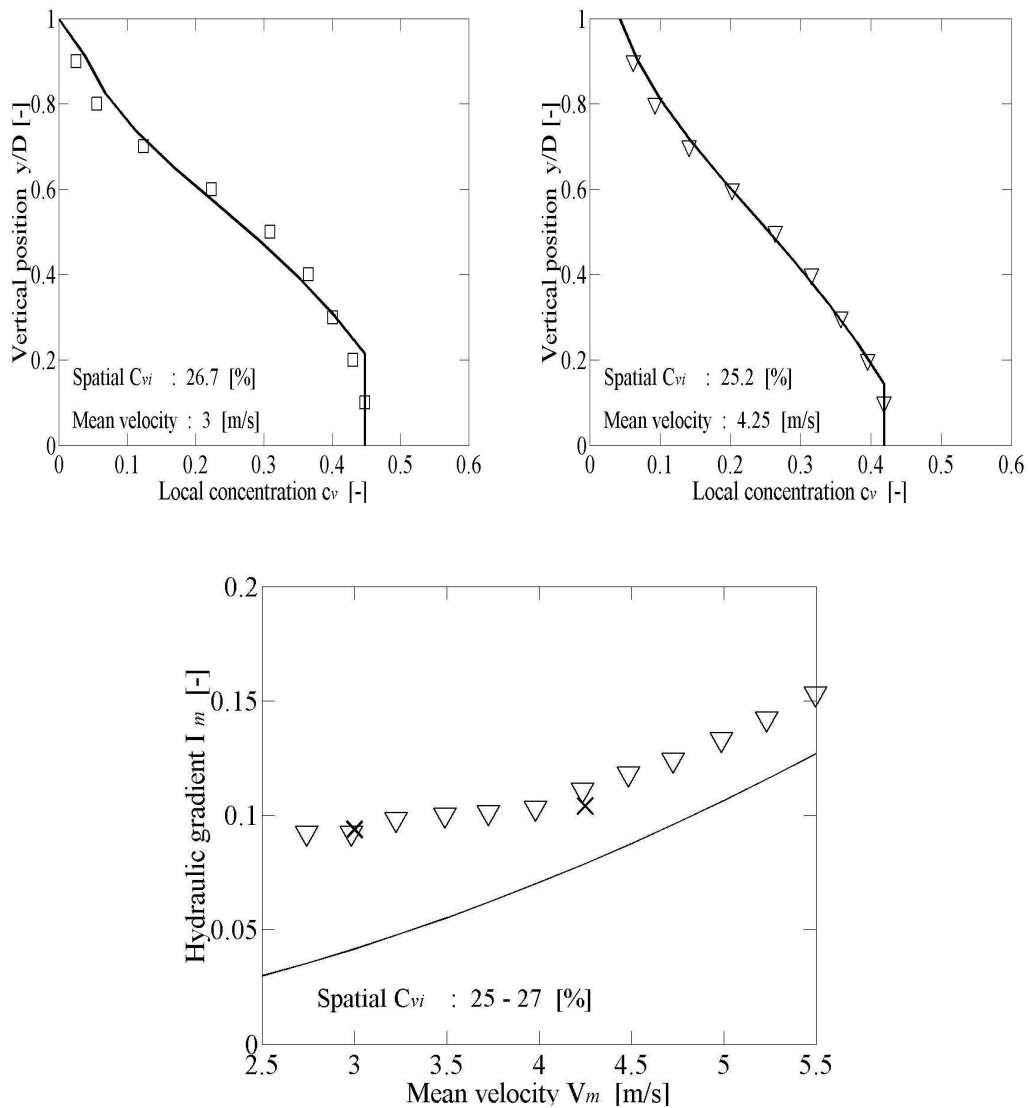


Figure 10. Comparison of measured ( $\nabla, \square$ ) and predicted (-) parameters of flow of medium-sand slurry through a 150-mm pipe, [7].

## 5. CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Conclusions

Major optimization parameters for a slurry-pipeline operation ( $SEC, Q_s$ ) are strongly related to dissipation of mechanical energy in slurry flow in a pipeline. The simplest way of operation optimization is a regulation of mean velocity of slurry and mean delivered concentration of solids in a pipeline.



Dissipation of mechanical energy is associated with an internal structure of settling-slurry flow in a pipe. Mechanical friction between particles and a pipe wall is a major source of energy dissipation in settling-slurry flows.

A successful prediction of frictional pressure losses in slurry pipelines is required for a successful optimization of a slurry-pipeline operation.

In practice still widely used empirical models for a loss prediction should be replaced with mechanism-based models that have a potential of flexibility and gradual improvement by implementing new results in slurry-flow research. The author applied his research results on friction and dispersion mechanisms in settling slurry flows to a mechanism-based prediction model easily applicable for practical solutions with slurry pipelines transporting heterogeneous slurries.

## **5.2 Recommendations**

During the optimization process attention should be paid to

- the identification of the internal structure of the flow (a degree of flow stratification),
- the selection of a suitable prediction model for a pipeline-characteristic curve (I-v curve) for the evaluated pump-pipeline system.

## **REFERENCES**

- [1] Durand, R. (1953). Concentration Measuring Instrument for Hydraulic Transportation Installation. *La Houille Blanche*, Vol. 8, No. 2, pp. 296-297.
- [2] Gillies, R.G. and Shook, C.A. (2000). Modelling high concentration settling slurry flows. *Canadian Journal of Chemical Engineering*, Vol. 78, 709-716.
- [3] Korving, A.C. (2002). High-concentrated fine-sand slurry flow in pipelines: experimental study. *Proc. 15<sup>th</sup> Int. Conf. on Hydrotransport*, Ed.: N. Heywood, Banff (Canada), 3-5 June 2002, 769-776.
- [4] Marrero, T.R. (2004). Freight pipelines: a survey. *Proc. Int. Conference Hydrotransport 16*, BHR Group, edited by N. Heywood, pp. 645-658.

- [5] Matoušek, V. (2005). Research developments in pipeline transport of settling slurries. *Powder Technology*, Vol. 156, No. 1, pp. 43-51, Elsevier (ISSN 032-5910).
- [6] Matoušek, V. (2002). Pressure Drops and Flow Patterns in Sand-Mixture Pipes. *Journal of Experimental Thermal and Fluid Science*, No. 26, pp. 693-702, Elsevier.
- [7] Matoušek, V. (2002). Partially stratified flow with turbulent suspension in a pipe. *Proc. 11th Int. Conference on Transport & Sedimentation of Solid Particles*, Ghent, pp. 391-8.
- [8] Matoušek, V. (2002). The pipeline transport of different sand fractions in dense slurries. *Proc. ASCE Int. Conference Dredging 02*, Orlando (Proceedings on CD).
- [9] Matoušek, V. (2000). Concentration distribution in pipeline flow of sand-water mixtures. *Journal of Hydrology and Hydromechanics*, Vol. 48, No. 3, pp. 180-196 (ISSN 0042/790X).
- [10] Matoušek, V. (1997). Flow Mechanism of Sand-Water Mixtures in Pipelines. Doctoral thesis. Delft University Press, 258 p.
- [11] Newitt, D.M., Richardson, J.F. and Gliddon, B.J. (1961). Hydraulic conveying of solids in vertical pipes. *Trans. Inst. Chem. Engrs*, Vol. 39, 93-100.
- [12] Novák, P. (2005). Splavování kopce Tresného v Otrokovicích. *Stavební listy*. No. 10, pp. 20-21.
- [13] Pugh F.J. and Wilson K.C. (1999). Velocity and concentration distributions in sheet flow above plane beds. *Journal of Hydraulic Engineering*, Vol. 125, No. 2, 117-125.
- [14] Pullum, L., Graham, L.J.W. and Slatter, P. (2004). A non-Newtonian two-layer model and its application to high density hydrotransport. *Proc. 16<sup>th</sup> Int. Conf. Hydrotransport*, BHRG, Cranfield, UK, pp. 579-593.
- [15] Skudarnov, P.V, Lin, C.X. and Ebadian, M.A. (2004). Double-Species Slurry Flow in a Horizontal Pipeline. *Journal of Fluids Engineering ASME*, No. 126, pp. 125-132.

- [16] Wilson, K.C., Addie, G.R., Sellgren, A. and Clift, R. (2006). Slurry Transport Using Centrifugal Pumps. Third Edition, Springer (ISBN-10: 0-387-23262-1).
- [17] Wilson, K.C. and Sellgren, A. (2003). Interaction of particles and near-wall lift in slurry pipelines. Journal of Hydraulic Engineering, Vol. 129, No. 1, 73-76.
- [18] Whitlock, L., Wilson, K.C. and Sellgren, A. (2004). Effect of near-wall lift on frictional characteristics of sand slurries. Proc. 16<sup>th</sup> Int. Conf. on Hydrotransport, Ed.: N. Heywood, Santiago (Chile), 26-28 April 2004, 443-454.

[www.deme.be](http://www.deme.be)

[www.hochtief-vsb.cz](http://www.hochtief-vsb.cz)

[www.iadc.com](http://www.iadc.com)

[www.oilsandsdiscovery.com](http://www.oilsandsdiscovery.com)

[www.pipesys.com](http://www.pipesys.com)

[www.samarco.com](http://www.samarco.com)

[www.syncrude.ca](http://www.syncrude.ca)

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- 1986 MSc (Ing.), Czech Technical University in Prague, Faculty of Civil Engineering
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### **Professional positions:**

- 1986 - 1992 researcher, Institute of Hydrodynamics, Czechoslovak Academy of Sciences
- 1996 - 2005 lecturer, Delft University of Technology, Faculty of Mechanical Engineering
- 2005 - lecturer, Czech Technical University, Faculty of Civil Engineering,  
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### **Fields of interest:**

fluid mechanics, multiphase flow, hydraulic transport of solids, dredging

### **International cooperation:**

- Industry: Dutch and Belgian dredging companies (Boskalis, IHC, Van Oord, DEME, Jan de Nul), GIW Industries (USA), Hyundai Institute for Construction Technology (Korea),
- Research: Delft University of Technology, Delft Hydraulics (the Netherlands), British Research Council (UK), Cape Technikon (South Africa), University Gent Hydraulic Laboratory (Belgium), Hohai University (China), Texas A&M University (USA), University of Saskatoon (Canada), Queen's University (Canada),
- Membership in organizations: Central Dredging Association (Netherlands) and Western Dredging Association (Americas)

### **Research projects:**

- 1996 – 2004 eight international research projects in the field of dredging (for companies Royal Boskalis Westminster, MTI Holland, Stichting Speurwerk Baggertechniek, ODS BV, Wolfard & Wessels, Jan de Nul Dredging etc.),
- 1996 – 2005 a number of TU Delft research projects,
- 2005 - research-centre CIDEAS project,
- 2006 - GACR project No. 103/06/0428.

**Publications:**

More than fifty papers in international technical and scientific journals and conference proceedings, one monograph, one chapter in monograph, eight international research-project reports, a TU Delft textbook.