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Hydraulická potrubní doprava

Hydraulic pipeline transport

Summary

The contribution deals with the flow behaviours of slurries containing colloidal, clay, and dust particles and simultaneously, sometimes also coarse-grained particles. A brief review of freight pipeline history is also part of the contribution. The slurry flow behaviour changes from Newtonian to non-Newtonian depending on the solid phase concentration and composition, especially on the content of colloidal particles. The slurry flow behaviours in the laminar, transitional, and turbulent regimes were experimentally investigated in horizontal straight pipes with respect to the particle size distribution, volumetric concentration, and slurry velocity.

The re-circulation pipe loop, with hydraulically smooth stainless steel pipes of inner diameters D = 17.5, 26.8, and 36 mm, was used. As model slurries, water mixtures of kaolin, fly and bottom ash produced during the process of desulphurisation in a fluidic-type combustion chamber, sand slurries, and kaolin-sand slurries were used. Kaolin was added to the sand-water slurry to create a non-Newtonian carrier liquid. To compare the effects of Newtonian and non-Newtonian carriers, a chemical agent with a peptising effect was used to reduce the internal attractive forces between kaolin particles and to change the slurry flow behaviour. The effects of time and intensity of shearing, and drag reducing additives were also studied.

Kaolin slurry has a time-independent, yield pseudo-plastic response for volume concentrations higher than about 3%. In contrast, fluidic fly ash water mixture is time-dependent and its shearing results in a substantial reduction of the hydraulic gradient in the laminar region and a marked decrease in the laminar/turbulent transition velocity value. A similar effect can be attained by addition of coarser bottom ash or drag reducing agents.

The flow patterns are fundamentally different for the laminar and turbulent regimes. The transition from laminar to turbulent regime results in an abrupt increase in the flow resistance. The transition from laminar to turbulent flow is very important for the safe and efficient design and operation of dense slurry pipelining. The optimum operational condition is slightly above the laminar/turbulent transition point, where flow conditions and energy consumption should be often very attractive from operational and economic points of view.

The pipeline transport is reliable and progressive technology for conveying a large quantity of bulk materials. The understanding of slurry flow behaviour and the control of the slurry physical-chemical behaviour, of an inner structure (particle size distribution) and time and intensity of shearing makes possible to optimise the energy and water consumption, to improve quality, safety and economy of the slurry transport and processing.

Souhrn

Přednáška se zabývá tokovým chováním suspenzí obsahujících koloidní, jílovité a prachové částice nebo hrubé částice. Přináší i stručný přehled historie a vývoje potrubní doravy hromadných substrátů. Chování suspenzí se mění od newtonského do nenewtonského v závislosti na koncentraci a zrnitostním složení pevné fáze, zejména na obsahu koloidních částic. Tokové chování jemnozrnných vysoce koncentrovaných a písčitých suspenzí bylo zkoumáno experimentálně v potrubní trase s horizontálním hydraulicky hladkým nerezovým potrubím o vnitřním průměru D = 17.5, 26.8 a 36 mm. Zkoumány byly vodní suspenze s kaolinem, úletovým a ložovým popílkem z fluidních kotlů s procesem odsiřování, pískem a pískem s přídavkem kaolinu. Kaolin byl přidáván do písčitých suspenzí za účelem vytvořit nenewtonskou nosnou kapalinu. Pro srovnání vlivu newtonské a nenewtonské nosné kapaliny bylo použito peptisační činidlo,. Dále byl zkoumán vliv doby a intenzity smykového namáhání a vliv tření snižujících aditiv pro časově závislé popílkové suspenze.

Kaolinové suspenze vykazují časově nezávislé nenewtonské chování, odpovídající pseudo-plastické kapalině s počátečním napětím pro objemové koncentrace vyšší než cca 3%. Přídavek peptizačního činidla působí změnu fyzikálně-chemického prostředí v suspenzi a umožňuje dosáhnout výrazného snížení zdánlivé viskozity a počátečního napětí. Hydrosměsi s obsahem fluidního úletového popílku jsou časově závislé a následkem smykového namáhání dochází k výraznému poklesu třecích ztrát v laminárním režimu proudění a zároveň ke snížení rychlosti přechodu do turbulentního režimu. Obdobný je i účinek přídavku hrubších částic ložového popela nebo přídavku aditiv snižujících tření.

Tokové chování jemnozrnných koncentrovaných suspenzí se výrazně liší v laminární a turbulentní oblasti. Při přechodu z laminárního do turbulentního proudění dochází k náhlému zvýšení třecího odporu. Určení přechodného režimu proudění je velmi důležité pro bezpečný a efektivní návrh i provoz potrubní dopravy. Optimální provozní podmínky jsou dány rychlostí proudění těsně nad přechodem do turbulentního režimu, kde charakter proudění a energetická spotřeba mohou být velmi výhodné z hlediska provozní spolehlivosti a ekonomiky.

Provedený výzkum prokázal, že potrubní doprava je spolehlivá a progresivní technologie pro dopravu hromadných materiálů. Poznání komplexního tokového chování suspenzí a možností řídit jejich fyzikálně-chemické chování, vnitřní strukturu (včetně zrnitostního rozdělení) a intenzitu i dobu jejich smykového namáhání umožňuje optimalizovat spotřebu energie i vody, zlepšit kvalitu, bezpečnost a ekonomii dopravy, manipulace a zpracování přepravovaného materiálu.

Klíčová slova: hydraulická potrubní doprava, experimentální výzkum, vliv zrnitostního rozdělení, laminární proudění, turbulentní proudění, přechodné proudění, kaolinové suspenze, písčité suspenze, suspenze s fluidními popílky, účinek smykové namáhání, snižování tření, kontejnerová potrubní doprava.

Keywords: Hydraulic pipeline transport, experimental investigation, effect of particle size distribution, laminar flow, turbulent flow, laminar/turbulent transition, kaolin slurry, sand slurry, fluidic ash slurry, effect of shearing, drag reduction, capsule pipeline transport.

Contents:

1. INTRODUCTION

In recent times there has been significant growth in the importance of transport. With the development of the economy, demand for improved quality, capacity, and safety in the operation of transport processes has grown. In many situations, the conventional transport modes – railway, truck, and river barges – are not suitable to satisfy new requirements in terms of transport capacity, safety, and cost. Also economic efficiency in transporting large quantities of bulk material over long distances is very important for utilisation of far-off sources. This is the reason why more and more attention is focussed on non-conventional modes of transport which make it possible to increase the efficiency and capacity of transport and reduce air pollution, noise, and the number of accidents, often reducing energy consumption and manpower at the same time. Especially in great urban agglomerations it could sometimes be useful to use freight pipeline transport, which could easily be situated underground, making minimal demands on land occupation in city centres and can serve in energy supply, the transport of building and other bulk materials and waste handling.

A freight pipeline is defined as a pipeline whose main purpose is to convey bulk materials which are in a solid form. Solid form implies that freight is in the solid state, but it may be powdered, granulated, sintered, manufactured, packed, and so on. Bulk implies an impressively large, heavy, or numerous materials such as coal, sand, gravel, phosphates, grain, mineral oils, gases, and so on. Freight pipeline is a transportation system where loads are moved totally enclosed by the pipe and where motive power is applied via a moving fluid – liquid or gas which is employed to entrap, fluidise, and convey the cargo through the pipeline. The freight is in a bulk form and is usually mixed with carrier fluid [41].

The energy of the liquid carrier keeps the solid materials suspended in the liquid stream and conveys them in the direction of liquid flow or pushes them along the pipe bottom in the form of a moving bed. The most important parameters for the safe and economic operation of a slurry pipeline are operational velocity and pressure drop. The operational velocity, which together with solids concentration and pipe diameter determines the pipeline transport capacity, must be higher than the threshold or so called deposition-limit velocity, the velocity at which particles drop out from the carrier liquid and a stationary bed starts to develop at bottom of the pipe the pipe. This situation should be avoided, since it could result in a pipe blockage. Pressure drop, which determines the energy consumption and technology of pumping, is produced by internal friction in the conveyed slurry and friction between the pipe and the slurry. The pressure drop depends on flow velocity, solids concentration, density, shape, and size distribution of the conveyed solid material, the size and roughness of the pipe, and also the mutual particle-liquid, particle-particle, and particle-pipe interactions.

Pipeline transport has been one of the progressive technologies for conveying large quantities of bulk materials in power engineering, mining and ore treatment, and transport of minerals and raw materials, including the handling of wastes. Compared with use of belt, rail, truck, or other mechanical means of transport, hydraulic transport can bring several advantages. It is dust-free, easily surmounts ground obstacles, demands substantially less space, often needs lower investment and operational costs, makes possible full mechanisation and automation, and provides low dependence on the technological discipline and skilfulness of the operating staff [30].

This contribution presents the results of experimental investigation of several fine-grained slurries, heterogeneous slurry, and fine-grained slurries containing coarse-grained particles. It is focussed on the effects of particle size distribution and concentration on the relationship of the hydraulic gradient versus the slurry's average velocity, and the slurry flow behaviour in the laminar, transitional and turbulent regimes.

The flow pattern of fine-grained not organic slurry depends strongly on solids concentration. If the solids content increases, the slurry flow behaviour changes from a Newtonian to a non-Newtonian one, which can be generally described by the yield pseudo-plastic model.

Most knowledge on dense slurry flow behaviour has been concerned with the slurries consisting of either coarse-grained particles with settling tendencies or fine-grained particles creating homogeneous, often non-Newtonian slurry. The flow behaviour of the slurry containing both coarser and very fine particles has not been sufficiently clarified until now. According to the nature of slurry, several types of predictive models exist which can describe the slurry flow behaviour.

For dense homogeneous and pseudo-homogeneous slurries with non-Newtonian behaviour well known rheological models should be used. For heterogeneous slurries many empirical correlations exist. Understanding the mechanisms of the heterogeneous slurry flow makes it possible to adopt the more complex models with physical backgrounds. The two-layer model may be used for description of the fully or partially stratified flow patterns and prediction of the threshold (deposition-limit) velocity, pressure drop due to friction, thickness and translational velocity of the sliding-bed, and also the value of the mean slip between the solid and liquid phases [12].

When the slurry contains both fine and coarser particles in a highly dispersed form and the quantity of the dispersed phase or the particle size increases, heterogeneity becomes more important and the slurry becomes complex homo-heterogeneous. This flow regime is more complicated than either homogeneous or heterogeneous flow since some kinds of conveyed solids behave heterogeneously in a homogenous carrier.

The presence of fine solid particles in a Newtonian liquid evokes a complex rheological behaviour of the slurry. The slurry flow behaviour changes depending on the solid phase concentration and composition, especially on the contents of colloidal and coarse-grained particles and the slurry's physical-chemical environment.

The paper deals with the effect of slurry composition and volumetric concentration on the flow behaviour of slurries containing colloidal, clay, dust, and also coarse-grained particles. The flow behaviour of slurries was experimentally investigated with respect to the effects of solid concentration, size distribution and slurry velocity.

The slurries can change their behaviour from Newtonian to non-Newtonian according to the solid phase concentration and composition, contents of colloidal particles, particle interactions and internal physical-chemical environment [33].

The flow behaviour of coarse-grained slurries also containing fine-grained particles is also discussed in this paper. The effects of fine and coarse particles on different behaviours of slurry containing fly ash only and fly ash/bottom ash in different proportions can be illustrated [32]. Due to the addition of bottom ash the total content of very fine particles in the slurry decreases and consequently the flow behaviour changes markedly.

2. HISTORY OF FREIGHT PIPELINING

The history of pipeline transport goes back to ancient times: the Chinese conveyed natural gas through bamboo tubes around 400 B.C. and the Romans used lead pipes for water supply and sewage disposal. However, the first commercial pipeline conveying natural gas was built in 1825 and the first pipeline conveying crude oil in 1863. We can distinguish three different generations of pipelining. The generations can be distinguished according to the carrier medium: hydraulic pipelining if the carrier medium is liquid, mostly water, and pneumatic pipelining if the carrier medium is gas, mostly air.

The first generation of pipelining includes the movement of gas and fluids in pipelines. The flow pattern is as simple as the flow of natural gas or water, and as complex as the flow of two or more immiscible liquids. The science and technology of this method of pipelining is advanced.

The second generation of pipelining may be regarded as suspension flow or solid-liquid and solid-gas pipelining. A slurry pipeline may be defined as a two-phase flow pipeline, which transports a solid material dispersed in a liquid vehicle. The solid material in a particulate form is incorporated into the fluid stream and conveyed through the pipe. The energy of the fluid stream keeps the solids suspended in the fluid. Second generation pipelining is also fairly well understood. Several empirical and semi-empirical methods have been developed to describe the individual flow pattern, which depends on the properties of the materials transported.

Slurry pipelining was firstly used in commercial practice for conveying gold-bearing sand in California in about 1850. Later, coal slurry was pumped in England, and in 1884 hydraulic transport was used for hydraulic backfill in Pennsylvania. In 1891, W.C. Andrews obtained a U.S. patent for coal slurry pumping, and at the Chicago World Fair of 1893 a model coal slurry pipeline was exhibited. Later, short (about hundreds of metres) pipeline installations for dredging, hydraulic mining, and backfill were constructed. However, the first intermediate length installation (diameter 203 mm, length 544 m) was built in 1914 in London to transport coal from barges on the Thames River to the Hammersmith power station. During the 1920s a 1.5 km long pipeline was constructed at Mt. Carmel, Pennsylvania, for transport of anthracite sludge containing 40 to 60% solids. During the 1940s pipelining was used for transport of a variety of solids over long distances and during the 1950s the second generation of pipelining become an attractive alternative to others modes of transportation, particularly for transport of large quantities of bulk materials over remote or difficult-to-traverse terrain. More than twenty pipelines were installed to transport clay, coal, borax, sand and gravel, limestone, phosphate, and different ores and metal concentrates [41]. Second generation pipelining is used for technological or longitudinal transport of loose materials, ores, minerals, building and mining materials, communal, industrial, agricultural and energetic wastes, and also food and chemical industry products and raw materials. However, several limitations exist in slurry pipelining. The carrier medium energy is required to maintain the solids in suspension, and this becomes particularly important when the density is high or the particle diameter is large. Solid commodities could be damaged through direct contact with the carrier liquid or pipeline. Considerable difficulty may be associated with the separation of solids and liquid.

Some advantages can be found in using air as a carrier medium. George Medhurst invented the use of compressed air as a new method of conveying letters and goods by pipe as early as 1810. But more recently, in 1886, F. Sturtevant developed a pneumatic pipeline system for light materials such as wood shavings, sawdust and waste paper, which were not abrasive and could pass through the blades of a fan. Between 1888 and 1892, Frederic Eliot Duckham built a successful floating plant for unloading grain from ships into land silos in England. By 1914, 60% of all imported grain in England and the Continent was handled by a pneumatic pipeline. Later on, the development of the rotary positive-pressure blowers, invented by P. H.

and F. M. Roots in 1859, allowed transportation of heavier materials. In 1919 the Fuller-Kinyon pump made it possible to move more materials over longer distances and to use the pneumatic pipeline for stowing or back-filling. Commercial pneumatic installations around the world are very numerous. Most existing pneumatic pipelines transport only fine powders and light and granular materials over short distances. However, there are a few installations transporting large size commodities (wood chips, plant foliage, whole fish or chickens up to 2 kg in weight, rocks up to 75 mm in diameter, and metal plates and parts) [21]. The limitations on transport length or size and weight of transported commodities are due more to economic factors than to technological problems; a pneumatic pipeline of any desired length may be constructed but the cost of transport may be high. The longest second generation pneumatic conveyance was the Grand Coulee Dam project, where cement powder (120 m^3/h) was transported about 2.3 km by high-pressure blow tanks, developed by F. L. Smidth & Co. Inc., in the 1930´s.

The third generation of pipelining is based on a method of transportation in which the transported commodities are incorporated into a fluid stream as a segment of the stream, not as dispersed particulate material. Long trains of solid bodies of relatively large dimensions are carried within a pipe by a flowing fluid. The solids may be in the form of cylinders or spheres with diameters approaching the diameter of the pipe. This could be achieved for instance by encapsulation of transported granular or liquid material in rigid or semi-rigid protective containers or by casting the solid material in spherical or cylindrical forms referred to as capsules. In this manner the material might be transported through pipes under similar economical conditions as conventional pipelining [3, 24]. The fluid may be either a liquid or a gas, resulting in hydraulic or pneumatic capsule pipelines.

Hydraulic capsule pipelining includes the transport of commodities in the form of large capsules (whose size is related to the pipe diameter) suspended and conveyed by a liquid, usually water, through the pipeline. The idea of transporting solids as bodies incorporated into solid containers conveyed by a liquid through a pipeline originated during the Second World War. Jeffrey Pyke suggested using this mode of transport for the supply of war materials from Burma to China, since it was much easier to build a pipeline than a railway or road in the mountainous, tropical conditions. Unfortunately due to lack of no experience with this mode of transport, it was not realised. About 15 years later, in the late 1950s, the idea of capsule pipelining emerged again in Alberta, Canada, and simultaneously this idea was employed for vertical transport of coal and iron ore from mines in Ukraine. The advantages of capsule pipelining, compared with slurry transport are the high concentration of transported material, the possibility of common transport of more commodities, the protection of transported material from mechanical and chemical degradation, lower wear on the pipeline, lower power consumption, easier separation of transported material and carrier liquid, and less carrier liquid pollution.

Hydraulic capsule pipelining is still a waiting commercial realisation. Except for pilot plant studies conducted in Canada and the former Soviet Union, no commercial scale hydro-capsule exists. In March 1965, a trial of the concept began with the loading of a capsule weighing 257 kg into a 0.50 m diameter crude oil trunk line at Edmonton, Canada, for a 183 km trip to Hardisty. The capsule (diameter 0.41 m, length 1.29 m) moved without difficulty through the pipeline during the 56 h journey across hilly countryside [9]. In 1986, synthetic asphalt sealed in polyethylene capsules was transported through an oil pipeline from Kirishi to Leningrad. So-called coal-log pipelining is also in the pilot plant stage. With this technology, coal is compacted under high pressure in cylindrical moulds to form solid cylinders called coal logs, which are then injected into the pipe and conveyed by liquid to the destination [10]. ′

If air is used as a carrier medium, the system is called ***pneumatic capsule pipelining***. Since air is a thousand times lighter than water, transporting heavy cargos in pneumatic capsules requires the use of wheeled capsules. Pneumatic capsule pipelining is a very old transport mode, almost as old as the railway. The concept was first mentioned by George Medhurst in 1810 and in 1824 John Vallance patented and built the first experimental pneumatic capsule pipeline, a 50 m long wooden tube, 2.5 m in diameter, with a wheeled carriage about 7.5 m long running on rails within the tube [17]. In 1827 Josiah Latimer Clark developed postal and telegraphs dispatch tubes with a non-wheeled capsule moving inside a pipe 75 mm in diameter. In 1853 and 1858 larger pneumatic mail dispatch systems were built in London (200 m long, 13 mm in diameter, and 1225 m long, and 57 mm in diameter, respectively), which were the beginning of pneumatic mail in the world. The total length of pneumatic mail pipeline was about 470 km in France in 1966 and about 125 km in Berlin (Germany) in 1899, while the British Postal Department operated nearly 1000 km of pipelines.

Besides pneumatic mail, the wheeled capsule pipeline system exists. The system has two places of origin. Early in the 1970s Professor Carstan of Georgia Institute of Technology, Atlanta, USA designed a technology called Tubexpress to move solid cargo through a pipeline. The pilot plant facility operated an installation about 420 m long installation with capsules 2.1 m long. The Russians also developed pneumo-capsule pipelines. In the spring of 1971 the first industrial pneumo-capsule pipeline of diameter 180 mm was constructed in Moscow for transport of products manufactured at the plant Start from the workshop to storage. In November 1971 a system called “LILO – 1” near Tbilisi, Georgia was put into operation to transport gravel over a distance 2.1 km. Each train consisted of six capsules conveying 15 tons of sand and gravel at speeds of 30 km/h. The LILO system was followed by the construction of several further installations which were successfully used for the transport of raw materials, ores, wastes and building materials. In 1972 the Japanese signed a licensing agreement with Tubexpress and later also bought the LILO system, and brought pneumatic capsule pipelining to contemporary commercial exploitation. Sumitomo Metal Industries has carried out the design and construction of several pneumatic capsule pipelines used in the mining and building (construction of highway, tunnelling) industries and waste handling [5, 6, 7].

3. FLOW REGIMES

Slurry can be classified in several ways related to the conveyed product according to its physical nature, type of flow – homogeneous, pseudo-homogeneous, heterogeneous, or complex homo-heterogeneous – or carrier medium. The carrier medium could be a Newtonian liquid, non-Newtonian liquid, or so-called heavy medium. To transport heavy and/or coarse settling particles, especially if high concentrations of the particles are required, a heavy medium is produced by adding fine particles to a carrier liquid. For example, silica sand transported at 20% concentration in a base slurry containing 5% of fine clay resulted in an excess head loss about one third of that expected for the sand alone.

Of course, laminar, transitional and turbulent flow regime should be also distinguished. For heterogeneous and complex homo-heterogeneous types of slurry, only turbulent flow is interesting, since in a laminar regime, sedimentation of coarse-grained particles can lead to flow with bottom sediments and even pipe blockage. According to the nature of the slurry, several types of predictive models exist which can describe the complex slurry behaviour. We distinguish models for homogeneous and pseudo-homogeneous slurries, settling or heterogeneous slurries, and complex homo-heterogeneous slurries.

Based on the conveyed material, we distinguish ***slurry with colloidal particles***, which behaves as a non-Newtonian liquid even at very low concentrations (e.g. kaolin slurry for volume concentrations over 3%). Slurries with dust particles less than 63 μm are called ***homogeneous or non-settling slurries*** and behave as homogeneous liquids. The particles are uniformly distributed within the pipe and the difference between the particle velocity and the fluid velocity is negligible. Velocity and concentration profiles are nearly symmetrical. ***Pseudo-homogeneous slurries*** contain fine and also coarser particles with significant settling velocities. The solids are present in a finely divided, highly dispersed form, nearly uniformly suspended in the carrier medium. If the solids concentration is not extremely high, some segregation is evident in the horizontal flow, that is, the flow is not axially symmetric. As the quantity of the dispersed phase increases or the particle size increases, heterogeneity becomes more important and slurry becomes ***complex homo-heterogeneous***. This flow regime is more complicated than either homogeneous or heterogeneous flow since some of the solids behave heterogeneously in a homogenous carrier. It is necessary to determine what proportion of the flowing stream to treat as homogeneous and what proportion to treat as heterogeneous. It should be mentioned that the classification into settling and non-settling slurry reflects only extremes in the continuous spectrum of the slurry behaviour.

However, if the medium particle diameter is greater than 63-100 μm and the concentration of very fine particles is low, the flow pattern is heterogeneous. ***Heterogeneous flow*** may be defined as flow with asymmetrical concentration and velocity distribution and a Coulombic friction contribution to the friction losses. For the slurry flow Coulombic friction is slightly velocity-dependent. In addition, the inertial effects of the particles must be taken into account since it usually outweighs the viscous effect of the slurry flow. Heterogeneous slurry differs from complex homo-heterogeneous slurry due to the small effect of fine particles on slurry flow behaviour. In contrast in non-settling slurries the deposition critical velocity is a very important parameter for heterogeneous slurries. In the homogeneous flow three flow patterns exist: laminar, transitional and turbulent. Although laminar heterogeneous flow does occur, the majority of heterogeneous slurry flows are turbulent. During a laminar regime, deposition of particles often occurs and the flow pattern becomes completely different since the slurry concentration, solids composition and flow cross-section change. In the design of heterogeneous slurry pipelining, deposition critical velocity is of the same importance as the relationship between friction losses and flow velocity.

3.1 Homogeneous slurry rheology

In modern pipelining, the use of dense slurries is preferred, for instance, coal-water fuel for power plants or common transport and deposition of ash, slag and energetic gypsum as self-compacting and self-sealing materials for hydraulic back-filling, re-cultivation, or simply dumping. The technological processes of transport and storage, treatment, or final deposition of such slurries require advance knowledge of their rheological behaviours for proper design to achieve economical and safe operation.

3.1.1 Laminar flow regime

Newton's law generally describes the laminar flow of Newtonian fluids

$$\tau = \mu(-du/dr), \qquad (1)$$

where τ, μ, u, and r are the shear stress, dynamic viscosity, local velocity of liquid and cylindrical co-ordinate, respectively.

The flow behaviour of non-Newtonian slurries in the laminar regime can in general be modelled as the yield pseudo-plastic fluid, that is by the Bulkley-Herschel rheological model

$$\tau = \tau_y + K(-du/dr)^n, \qquad (2\text{ a})$$

where τ_y, K and n are the yield stress, fluid consistency, and flow behaviour index, respectively. The Bingham or power-law fluid models are special cases of it [2]:

$$\tau = \tau_B + K_B(-du/dr), \qquad (2\text{ b})$$

$$\tau = K(-du/dr)^n. \qquad (2\text{ c})$$

The analytical solution of a laminar flow in a circular tube can be obtained by substituting shear stress from Eq. (2) into the equation describing a laminar flow in a circular tube. Solving this equation it is easy to obtain a velocity distribution. Due to the yield stress a core part of the flow given by a region, where $0 < r < r_p$, is moving as a plug with uniform velocity:

$$u_p = \left(\frac{1}{K}\right)^{\frac{1}{n}} \frac{n}{2(n+1)} \frac{D}{\tau_w} \left(\tau_w - \tau_y\right)^{\frac{n+1}{n}} \qquad (3)$$

and the radius of the plug is given by $r = R\,\tau_y/\tau_w$. After integration of the velocity distribution profile the mean velocity V can be calculated as

$$V = \left(\frac{1}{K}\right)^{\frac{1}{n}} \frac{D}{2\tau_w^{\,3}} \left(\tau_w - \tau_y\right)^{\frac{n+1}{n}} \left[\frac{\left(\tau_w - \tau_y\right)^2}{1+3n} + \frac{2\tau_Y\left(\tau_w - \tau_y\right)}{1+2n} + \frac{\tau_Y^{\,2}}{1+n}\right]. \qquad (4)$$

In these equations K is fluid consistency, n is the flow behaviour index, τ_y is yield shear stress, τ_w is wall shear stress, and $D = 2R$ is the pipe diameter. Equation (3) may be rewritten for the friction factor

$$f = \frac{64}{\mathrm{Re}_0} \frac{3n+1}{4n} (1-\xi)^{1/n-1} \left\{1 - \frac{\xi}{1+2n}\left[1 + \frac{2n\xi}{1+n}(1+n\xi)\right]\right\}^{-1} \qquad (5)$$

where $\xi = \tau_y/\tau_w$, and the Reynolds number is given as

$$\mathrm{Re}_0 = \frac{\rho V D (1-\xi)^{1/n}}{\tau_w^{\,1-1/n} K^{1/n}} \qquad (6)$$

The rheological parameters τ_y, K, and n control the rheogram of the slurry and have to be determined experimentally using some kind of Couette viscometers or pipeline loops, where a laminar flow regime can be achieved

[25]. The Equation (2) can be directly used to obtain rheological parameters from viscometer data, but in the case of a pipeline loop the proper parameters have to be estimated by fitting the measured values of τ_w and V (in a laminar regime) using Eq. (4).

3.1.2 Turbulent flow regime

For the turbulent regime of non-Newtonian fluids several models have been suggested, for sample Metzner & Reed, Torrance, Ryan & Johnson, Hanks, Wilson & Thomas, or Slatter. Thomas and Wilson [23] developed a new analysis for the turbulent flow of non-Newtonian slurries based on enhanced micro-scale viscosity effects (with small time and length scales for the dissipative micro-eddies). The model predicts the thickening of the viscous sub-layer by a factor referred to as area ratio, α, and of throughput velocity and thus promotes a drag reduction [40]. They suggest for the slurry mean velocity V_m

$$V_m = V_N + V_*\left[11.6(\alpha - 1) - 2.5\ln\alpha - \Omega\right], \qquad (7)$$

where V_* is the friction velocity and V_N represents the mean velocity for an equivalent Newtonian flow, based on a secant viscosity from the rheogram, that is flow with the same τ_w as a Newtonian fluid with the same viscosity corresponding to the non-Newtonian value at $\tau = \tau_w$. The term Ω represents the effect of possible blunting of the velocity profile in the logarithmic or core regions of the flow, caused by the yield stress

$$\Omega = -2{,}5\ln(1-\xi) - 2{,}5\xi(1+0{,}5\xi), \quad \xi = \tau_y / \tau_w . \qquad (8)$$

The area ratio α for the yield pseudo-plastic model is defined as the ratio of the integrals beneath the non-Newtonian and assumed Newtonian rheograms, under identical shear stress conditions. The area ratio α is given as $\alpha = 2(1+\xi n)/(1+n)$ [26].

Slatter [18] proposed a model for turbulent flow regime. By analogy with the Newtonian approach he defined the roughness Reynolds number Re_r for yield pseudo-plastic slurry

$$Re_r = 8\,\rho\,V_*^2 / [\,\tau_y + K\,(8\,V_* / d_p)^n\,], \qquad (9)$$

where $d_p \sim d_{85}$ was found to be a good representation of the turbulent roughness effect of the solid particles in the slurry and ρ is slurry density. The mean velocity can be obtained by integration over the pipe cross-section

$$V_m / V_* = \kappa^{-1}\ln(R / d_p) + B - 3.75\,, \qquad (10)$$

where Karman´s constant $\kappa = 0.40$ and coefficient $B = B_R = 8.5$ for the fully developed rough wall turbulent flow ($Re_r > 3.32$) or $B = B_s = 2.5\ln Re_r + 5.5$ for the smooth wall turbulent flow ($Re_r < 3.32$).

3.2 Heterogeneous slurry

With the construction of large industrial pipelines in the 1950s demand for reliable models capable of predicting slurry flow behaviour grew. Many empirical correlations exist for heterogeneous slurries which can be used successfully after calibration [2, 8].

The empirical model developed by Durand in the early 1950s for the horizontal flow and monodisperse particle size distribution [1] in the Laboratoire Dauphinois d´Hydraukique, also called the Durand model, was constructed using dimensional analysis. An empirical relationship between the dimensionless groups of quantities was expected to be of major importance for a description of the slurry flow in a pipe. Based on the experimental results for slurries with volume delivered concentrations up to 22%, the following relationship was proposed for the slurry hydraulic gradient i_s if the heterogeneous slurry is characterised by flow of particles of mean diameter d in a pipe of diameter D:

$$\varphi = (i_s - i_o) / i_o . c_v = K \left[Fr / \sqrt{Fr_w \left(\rho_p / \rho_o - 1 \right)} \right]^{-\alpha} \quad , \qquad (11)$$

where i is the carrier liquid hydraulic gradient, c_v is the slurry concentration, $Fr = V_s^2 / gD$ and $Fr_w = w_{50}^2 / gD$ are the slurry and mean particle Froude numbers, ρ_o and ρ_p are water and particle density, respectively, and w_{50} is the fall velocity of a medium particle.

The Durand method provides a simple tool for a wide range of slurry conditions. Its disadvantage is its low accuracy at low and higher velocity ranges and the fact that the model does not reflect different slurry flow patterns, especially fully-stratified and fully suspended flow patterns. Silin and Kobernik [16] found that the model could be used within the range $4 < Fr/Fr_w^{1/2} < 15$. Zandi and Govatos [41] showed that the Durand model is invalid if the saltation mode of solids transport occurs and that the constant K for ratios of $Fr/Fr_w^{1/2}$ less than 10 is different to those for greater than 10.

For this reason, since the mid 1980s attempts have been made to find a general model using a macroscopic approach. A slurry flow mechanism has been described by a set of differential equations for the conservation of mass, momentum and energy in the slurry flow pattern. A microscopic model provides a numerical solution to the equations in the local position of a cross-section and as a result it predicts the concentration and velocity profiles in the pipe cross-section together with the pressure drop over a pipeline length section [15]. Unfortunately, the experimental technique is not able to provide enough information on the slurry flow mechanism at a microscopic level and the model remains only theoretical. A compromise between the microscopic and empirical approaches is macroscopic modelling, which applies the conservation equations to a large control volume of slurry. It could be a pipe cross-sectional area with approximately uniform concentration of solids in a unit length of a pipe. In the chosen volume the conservation equations are formulated using averaged quantities over the control volume. Wilson [38] developed the so-called two-layer model. The model considers a fully stratified flow in which all particles are concentrated in the lower portion of the pipe (concentration in the layer near the bottom approaches the loose-packed value) and the Coulombic contribution to particle-wall friction is dominant. The RSC two-layer model [14] is based upon force balance for the horizontal layers:

upper layer $-dP/d_z = \left(\tau_1 S_1 + \tau_{12} S_{12}\right)/A_1$, (12)

lower layer $-dP/d_z = \left(\tau_2 S_2 + \tau_{12} S_{12} + F_2\right)/A_2$, (13)

where τ_1, τ_2 and τ_{12} are kinematic stresses, S_i is the responsible partial perimeter, A_i is the responsible cross-sectional area, and F_2 is Coulombic force. The model satisfies the material balance constraints on total flow and the solids transport rate for V_i as bulk velocity in the respective layer or total in situ solids concentration C_i is related to the partial concentrations by

$AV=A_1V_1+A_2V_2$ and $C_vAV=C_1A_1V_1+C_2A_2V_2$ or $C_vA=C_1A_1+C_2A_2$ (14-16)

All the above mentioned quantities including the Reynolds number friction factor and Coulombic friction are defined for each layer as well as the interfacial friction factor f_{12} and the flow parameters can be determined.

3.3 Laminar/turbulent transition

The transition from laminar to turbulent flow (L/T transition) is important for the safe and efficient design and operation of slurry pipelining. The optimum operational conditions are slightly above the L/T transition region, where flow conditions and energy consumption should be often very attractive from operational and economic points of view.

Similarly to Newtonian fluids, the laminar/turbulent transition can be defined using the Reynolds principle. The generally accepted value of the Reynolds number at the lower bound of the L/T transition is $Re = 2100$ [2]. In order to use the standard Newtonian theory Wilson [39] defined an apparent or secant viscosity $\mu' = \tau_w \left(-du/dr\right)_w^{-1}$, which is not a constant for the given slurry, pipe diameter and flow rate. It must be evaluated at each given value of wall shear stress τ_w, where the subscript w indicates values on the pipe wall. Wilson recommended calculating the Reynolds number of the L/T transition as

$$\mathrm{Re}_{Newt} = \rho V_m D/\mu', \quad (17)$$

where ρ and D are the liquid density and inner pipe diameter, respectively.

Metzner & Reed also developed a non-Newtonian generalised Reynolds number for the pipe flow data correlation and similarly Torrance defined *Re* for pseudo-plastic or yield pseudo-plastic fluid

$$\mathrm{Re}_{Tr} = 8\rho V^2 K^{-1} (8V / D)^{-n} . \qquad (18)$$

However, all the above mentioned Reynolds numbers ignore the fact that at under laminar flow conditions a plug flow pattern can exist due to the presence of the yield stress. The facts that plug affects the flow stability in a sheared annulus was taken into account by Slatter [18, 20]. Slatter rejected the plug-flow region as a non-fluid behaviour and regarded the plug as a solid boundary. Only the flow of the sheared fluid in the annulus was considered, and for the mean velocity in the annulus V_{ann} the Reynolds number was defined as

$$\mathrm{Re}_3 = \frac{8\rho V_{ann}^2}{\tau_y + K\left[8V_{ann} / D\left(1 - \tau_y / \tau_w\right)\right]^n} . \qquad (19)$$

To compare different prediction criteria for the L/T transition, a practical approach introduced by Shook and Roco [15] seems to be the most useful. Based on the empirically confirmed fact, they establish as a critical point the intersection of the theoretical lines for the laminar and turbulent flows on a graph of wall shear stress over mean velocity.

4. EXPERIMENTAL MATERIAL AND EQUIPMENT

4.1 Experimental installation

The effect of slurry composition, particle size distribution and volumetric concentration c_v on the flow parameters of kaolin slurry, sand and sand-kaolin slurries and fluidic fly and fly-bottom ash slurries was studied. The slurries were tested using an experimental re-circulation pipeline loop in which the test section consisted of smooth stainless steel pipes of inner diameters D of 17.5, 26.8, or 36 mm (see Fig. 1).

The slurry was forced by an EPS-125-6-60 screw pump or booster centrifugal pump WARMAN 3/2 C–AH from an agitated open storage tank to the transport pipe. A phase advancer was used to achieve the different slurry flow rates [26]. The loop with a screw pump can operate in the laminar as well as the turbulent regime up to an average slurry velocity V_s of about 5 m/s, or with the WARMAN pump up to 7.5 m/s. The measurement section was equipped with three pressure taps connected to Hottinger-Baldvin PD-1 differential pressure transducers (measuring range up to 0.1 MPa, carrier frequency 5 kHz) monitored by computer.

The slurry flow rate and concentration were measured by an electromagnetic flow meter KROHNE-PROFILUX IFM 5080 K A and a mass flow meter KROHNE-CORIMASS-800 G+. The loop also allowed the direct measurement of mass flow rate and of slurry density [31]. The temperature of the slurry was maintained at about 18°C by the heat exchanger. Attention was paid principally to the effects of the slurry's average velocity, concentration, and composition and the effects of time and intensity of shearing on the relationship i_s / V_s of the pressure gradient versus the average slurry velocity.

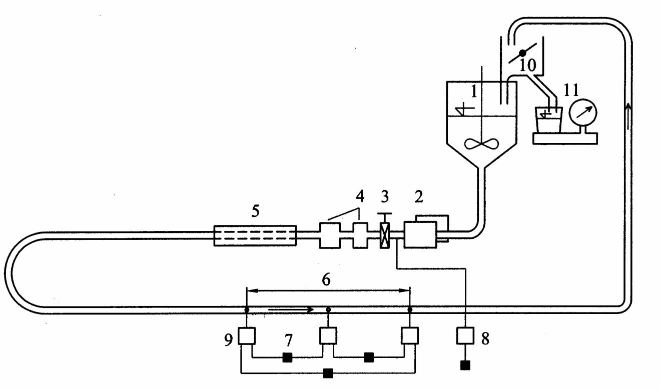

Figure 1 Layout of the experimental pipeline loop (1-slurry tank, 2-pumps, 3-control valve, 4-flow meters, 5-heat exchanger, 6-test section, 7-differential pressure transducers, 8-absolute pressure transducer, 9-pressure taps with sedimentation vessels, 10-flow divider, 11-density and discharge measurement)

4.2 Materials used

Highly concentrated kaolin slurries without and with the peptising agent, that is kaolin-water slurry and kaolin-water-sodium carbonate slurry, with volumetric concentrations varying from c_v = 3 to 35% were tested for the laminar, transitional and turbulent regimes. Several kinds of sand-water mixtures (concentrations from c_v = 6 to 48 %) and also fluidic fly and fly/bottom ash-water mixtures with concentrations varying from c_v = 18 to 31 % were measured.

Table 1 shows the particle size distribution of the kaolin from Horni Briza (d_{50} = 2.8 μm, ρ_p = 2546 kg/m^3). Three kinds of sand of uniform size distribution, for example the fine, medium, and coarse mono-dispersed quartz sands from Provodin (see Table 2), their mixtures (mass proportions 1:2:1 and 1:1:1 of fine, medium and coarse sand) and two natural poly-disperse sands (Zavada sand and Nova Ves sand; density of all sands ρ_p = 2650 kg/m^3), were used. Water as well as kaolin slurries of low and medium concentrations were used as the carrier liquids for the sand slurries. Total volumetric concentration c_v of the investigated sand slurries ranged from 6 to 48 % [28].

Table 1 Particle Size Distribution and Density of the Kaolin (Horni Briza)

d [μm]	< 1	1-2	2-4	4-6	6-10	10-20	20-30	d_{max} [μm]
(%)	28	12	22	21	11	6	0	20

Table 2 Particle size distribution of the measured sands

Sand	Provodin			Nova Ves	Zavada
	fine	medium	coarse		
mean diameter d_{50} [mm]	0.20	0.70	1.40	0.69	0.32
clay and dust [%]	0.02	0.03	0.04	0.2	3.0
$d = 0.063 - 0.25$ mm [%]	95.98	2.77	0.06	10.0	32.0
$d = 0.25 - 1.00$ mm [%]	4.0	96.3	3.9	54.8	63.0
$d = 1.00 - 2.00$ mm [%]	0	0.9	95.0	17.0	1.4
$d > 2$ mm [%]	0	0	1.0	18.0	0.6

To compare the effects of Newtonian and non-Newtonian carrier on the slurry flow behaviour, a chemical agent with a sodium carbonate was used to change the physical-chemical environment of the slurry and to depress the attractive inter-particle forces, which evoke the non-Newtonian behaviour of the slurry. Due to the peptising agent the slurry flow behaviour changes from non-Newtonian to nearly Newtonian [34, 37]. For the ash-water mixture, the fly ashes from Trinec and from Porici and their mixtures with bottom ashes were used. The basic physical parameters are listed in Table 3. Parameters d, d_{50}, d_{max}, and ρ_p are the particle diameter, mean particle diameter, maximal particle diameter, and density of particle, respectively.

Table 3 Physical parameters of fluidic ash

Material		Trinec		Porici	
		fly ash	bottom ash	fly ash	bottom ash
ρ_p	kg/m^3	2 603	2 646	2718	2716
d_{50}	mm	0.014	0.300	0.008	0.450
d_{max}	mm	0.30	12	1.50	20
d< 1 μm	%	4		13	
d<10 μm	%	36		57	
d<63 μm	%	95	4	96	4

The fly ash from Porici differs considerably from the fly ash from Trinec; it is substantially finer and its mean diameter is only half of that of Trinec fly ash. A significant difference was also found in the contents of colloidal particles and particles less than 10 µm. The bottom ash from Porici is significantly coarser compared with the bottom ash from Trinec; its mean diameter is about 50% greater than that of the Trinec fly ash. The volumetric concentration of the studied slurries ranges from 22% to 30% for the Trinec fly ash and from 18% to 23% for the Porici fly ash. The fly/bottom ash slurries reach slightly higher maximum concentrations, of 26% and 31%, respectively, due to the above mentioned different size distribution.

The maximum concentrations of both fly ashes differ in relation to their particle size distributions. The higher the content of colloidal particles and the smaller the mean diameter, the greater the slurry's tendency to coagulate. The colloidal particles create voluminous aggregates, where a great deal of water is fixed and the maximum slurry concentration is lower. It will be shown that shearing of the slurry or the presence of coarse-grained particles helps to destroy the aggregates and a higher concentration of the ash slurry can be achieved.

5. RESULTS AND DISCUSSION

5.1 Kaolin slurry

The kaolin slurries were measured in the laminar, transition and turbulent regimes, and attention was paid to the relationship i_s / V_s of the hydraulic gradient i_s over the mean slurry velocity. The kaolin suspension was determined to be the time-independent, yield pseudo-plastic slurry. Fig. 2 documents the effect of slurry concentration on the relationship i_s/V_s for the kaolin slurry and a yield pseudo-plastic behaviour of measured slurries at concentrations higher than 3%.

With increasing slurry velocity, the hydraulic gradient approaches the curve of water alone in the laminar region. Near the L/T transition point, the hydraulic gradient i_s could reach values even less than that reached by the clear water flow i_o [40]. However, in the transition zone the hydraulic gradient increases sharply and a marked instability is characteristic for this region. The increase in the hydraulic gradient i_s becomes higher than that of water alone i_o in the turbulent region.

Sensitivity analysis was used to find proper values of the flow behaviour index n of laminar and turbulent flow models since it strongly depends on the data evaluation. The best fitting value n for turbulent data depends on concentration [25]. Both Wilson's and Slater's turbulent models approximate the turbulent slurry flow well if the value of n is correctly predeterminate from turbulent experimental data. Dependencies of the most suitable values of rheological parameters *n*, *K*, and τ_y on volumetric concentration c_v were evaluated and the results are illustrated in Fig. 3.

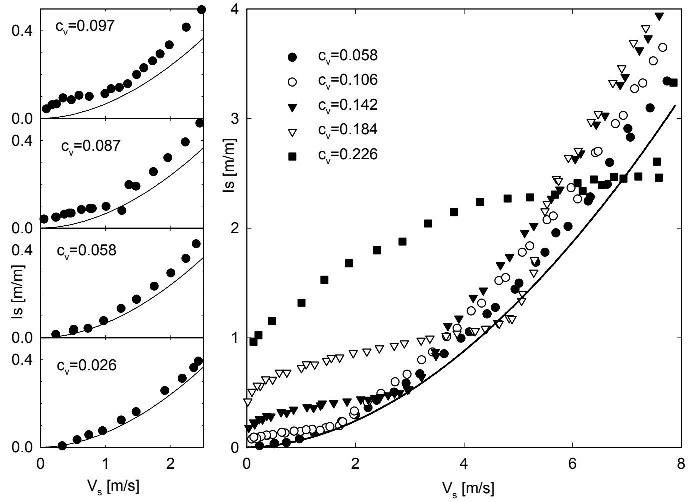

Figure 2 Effect of slurry concentration c_v. Kaolin slurry (*D* = 17.5 mm)

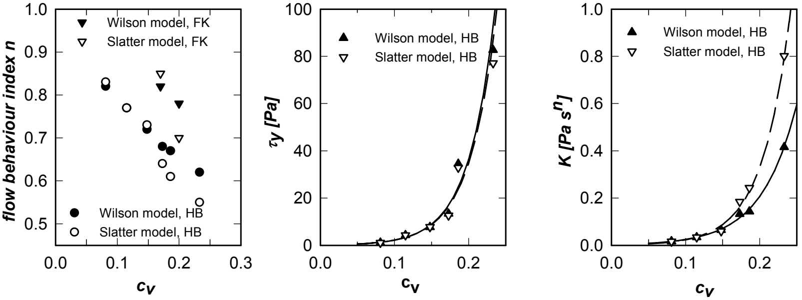

Figure 3 The effect of concentration c_v on the flow behaviour index *n*, yield shear stress τ_y and fluid consistency *K* (HB – kaolin Horni Briza, FK – fluidic fly ash Trinec)

5.2 Sand slurry

The effect of particle size distribution on the hydraulic gradient ratio i_s/i_w versus the average slurry velocity V_s relationship of sand slurries is illustrated in Fig. 4. The coarse sand slurry reaches a higher hydraulic gradient i_s than the fine sand slurry, and the difference decreases with growing velocity. The slurries consisting of both sand mixtures (mass proportion 1:2:1 or 1:1:1 of fine, medium and coarse sand) and natural Zavada sand reach nearly the same values of the gradient ratio i_s/i_w, which are very close to those of the fine sand for the slurry velocity $V_s > 4$ m/s. For $V_s < 4$ m/s the medium sand slurry reaches values of the gradient ratio i_s/i_w that are higher than those of the fine sand and both sand mixtures, and similar to that of the coarse sand. For $4 < V_s < 6$ m/s the medium sand gradient ratio i_s/i_w is surprisingly less even than that of the fine sand, while for the slurry velocity $V_s > 6$ m/s the fine sand gradient ratio i_s/i_w again increases and approaches the values of the sand mixtures and even of the coarse sand.

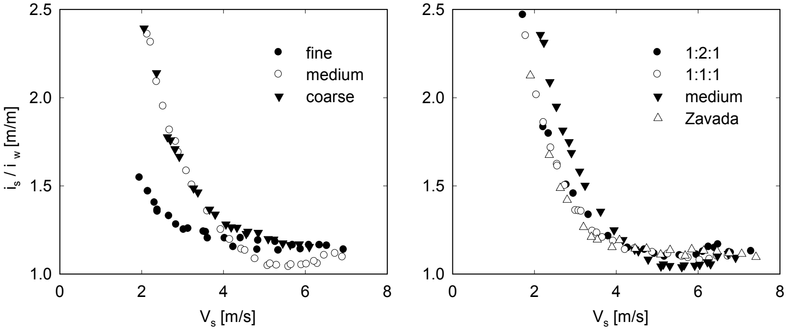

Figure 4 Hydraulic gradient ratio i_s/i_w versus slurry velocity V_s for sand slurries ($D = 6.8$ mm, $c_v = 23$ %)

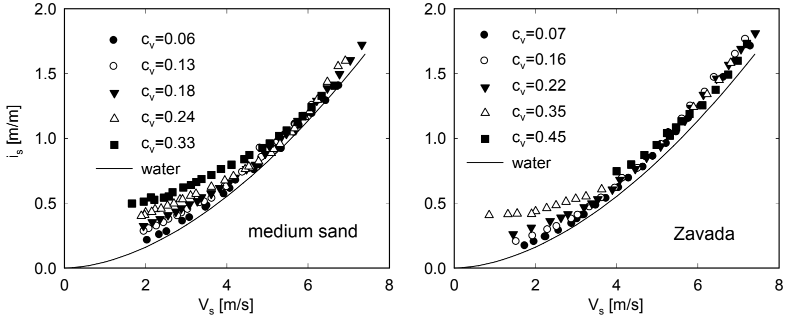

Figure 5 Hydraulic gradient i_s versus slurry velocity V_s for sand slurries ($D = 26.8$ mm)

Polydisperse sand slurries (sand mixture 1:1:1 or 1:2:1, Zavada sand) can reach even lower values of the pressure gradient i_s at the higher slurry concentration and velocity than the less concentrated slurry. This tendency, which can be explained by the L/T transition of more concentrated slurry at the higher velocity V_{TR}, is illustrated in Fig. 5.

The sand-water mixtures of low and medium concentrations can be described by, for exampl, the Durand model. A modified Durand method was used for the experimental data processing and scale-up. The Durand function (see Eq. (11)) can be rearranged as

$$\varphi = K\left[Fr_w\left(\rho_p / \rho_o - 1\right)\right]^{\alpha/2}.Fr^{-\alpha} = B.Fr^{-\alpha}\,, \tag{20}$$

and the material parameters B and α can be determined from the experimental data processing [8]. Eq. (20) can be represented by a linear relationship in a log-log plot of the Durand function φ versus slurry Froude number Fr (see Fig. 6). It is obvious that the method gives acceptable results for $Fr < 60$, that is for the slurry velocity $V_s < 4$ m/s. The great scattering of experimental data shows that the method is unsuitable for the higher velocity range, where the slurry flow behaviour differs from the behaviour expected in the Durand model [28]. The material parameters evaluated for the measured sand slurries in a velocity range $V_s < 4$ m/s are given in Table 4.

Table 4 Material parameters of sand slurries

Sand	B	α	Sand	B	α
fine	35.8	0.90	mixture 1:1:1, 1:2:1	80.4	1.06
medium	159.8	1.18	Nova Ves	82.9	1.10
coarse	88.4	0.98	Zavada	83.5	1.09

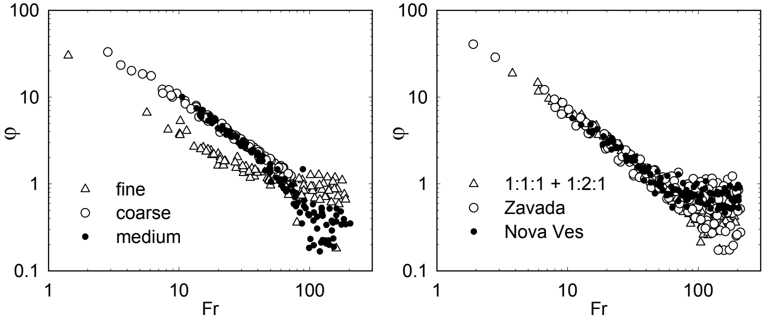

Figure 6 Plot of Durand function φ versus slurry Froude number Fr

5.3 Sand-kaolin slurry

To describe the effects of Newtonian and non-Newtonian carrier slurries consisting of sand conveyed in water, natural and peptised kaolin slurries were measured [34]. The relationship i_s/V_s for the slurry of total concentration $c_v \approx 34\%$ is illustrated in Fig. 7. When sand is conveyed in the kaolin slurry with concentration $c_{v,K}$ = 13%, the slurry exhibits a non-Newtonian behaviour. For the higher velocity range the hydraulic gradient i_s increases markedly compared to the water only or sand-water slurry.

When the carrier kaolin slurry is peptised (to avoid non-Newtonian behaviour of the slurry), i_s in the laminar region becomes markedly lower [27]. However, for the slurry velocity $V_s > 3$ m/s the peptised medium sand-kaolin slurry ($c_{v,S}$ = 21%, $c_{v,K}$ = 13%) reaches a higher hydraulic gradient i_s than the medium sand slurry ($c_{v,S}$ = 33%), which is practically the same as the untreated sand-kaolin slurry. This confirms that the favourable effect of the slurry peptisation in transitional and turbulent regions can vanish. The same trend was observed for the coarse sand. The addition of a small amount of kaolin (concentration of kaolin about $c_{v,K}$ = 3%) favourably affects the flow behaviour of the sand-kaolin slurry.

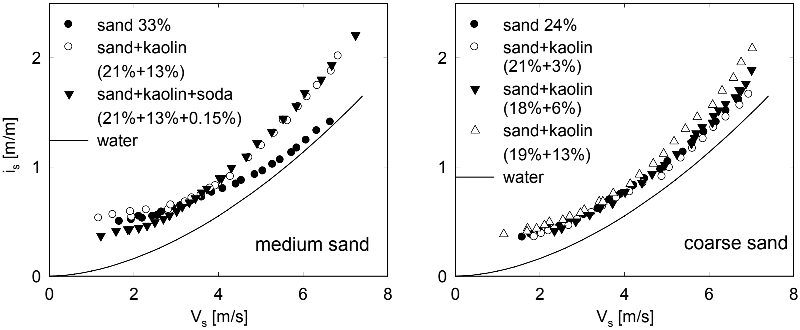

Figure 7 Effect of carrier liquid rheological properties on i_s /V_s relationship for sand slurries (D = 26.8 mm)

5.4 Fly ash slurry

In contrast to the kaolin or sand slurries the fluidic ash-water mixtures are time-dependent, yield pseudo-plastic slurries [26, 31]. The hydraulic gradient trends in laminar and turbulent regimes are similar, but the hydraulic gradient does not reach values close to the water value for the L/T transition point. The effects of the slurry concentration c_v, average slurry velocity V_s and shearing on hydraulic gradient i_s are shown in Fig. 8. For the gradually increasing slurry velocity V_s several intervals of the relationship i_s /V_s can be distinguished. For low velocity ranges of the “fresh” slurry ($V_s < 1$ m/s), the hydraulic gradient i_s increases with growing slurry velocity V_s similarly to the time-independent non-Newtonian slurry. For the fully developed laminar flow the relative increment of hydraulic gradient i_s becomes lower in comparison with the time-independent non-Newtonian slurry. The shearing effect is more evident for the concentrated slurries where an even “plateau” on the i_s/V_s diagram can be observed.

The effect of a different course of shearing is also illustrated in Fig. 8. The “fresh” Porici fly ash slurry (c_v = 22.5%) was pumped for a short time at a slurry velocity V_s < 1 m/s. Afterwards V_s was increased and kept for 2 minutes at the value V_s = 3.75 m/s. Then V_s was decreased to a value close to zero and then gradually increased up to V_s =3.5 m/s. Compared to the slurry with concentration c_v = 23.4 % pumped in a laminar regime with velocity V_s = 1.0 m/s for a period of 4 hours, it was found that high intensity (turbulent) shearing for a short time has a similar effect as shearing for a long time in a fully developed laminar regime. During the period of 4 hours the velocity increase from V_s = 1.0 m/s up to V_s = 1.25 m/s and the hydraulic gradient decreases from i_s = 0.50 to i_s = 0.26 m/m. After about 2.5 hours the slurry becomes stabilised and further laminar shearing has no effect on the slurry flow behaviour (see Fig. 9).

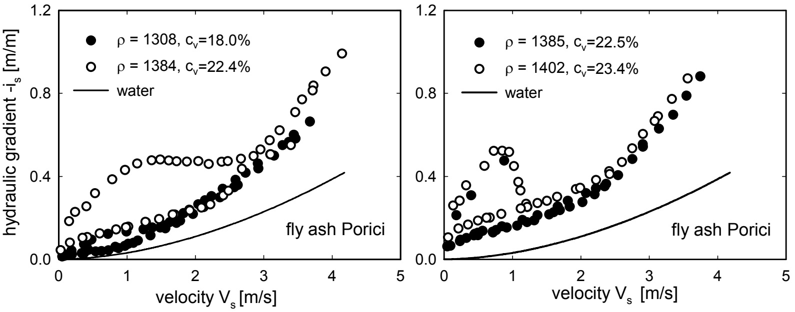

Figure 8 Effect of slurry concentration c_v and slurry velocity V_s on pressure gradient i_s (D = 36 mm)

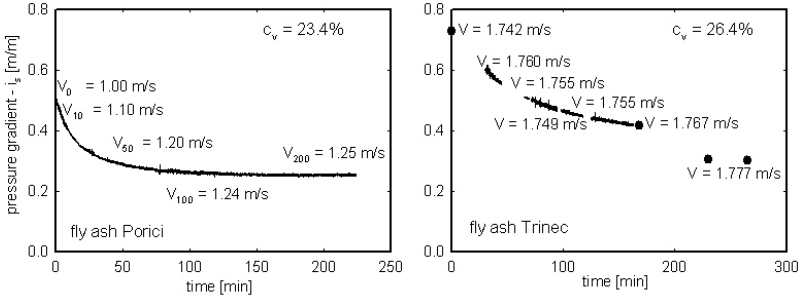

Figure 9 Effect of shearing on fly ash slurry
(Porici, D = 36 mm; Trinec, D = 26.8 mm)

The Trinec fly ash slurry (c_v = 26,4%) was pumped for 3 hours in the laminar regime at a velocity of about $V_s \approx 1.75$ m/s. The effect of shearing was found to be similar to that of the Porici slurry. The effect of shearing is higher for higher slurry concentrations, and the hydraulic gradient decreases markedly with the time of pumping during the initial period of flow.

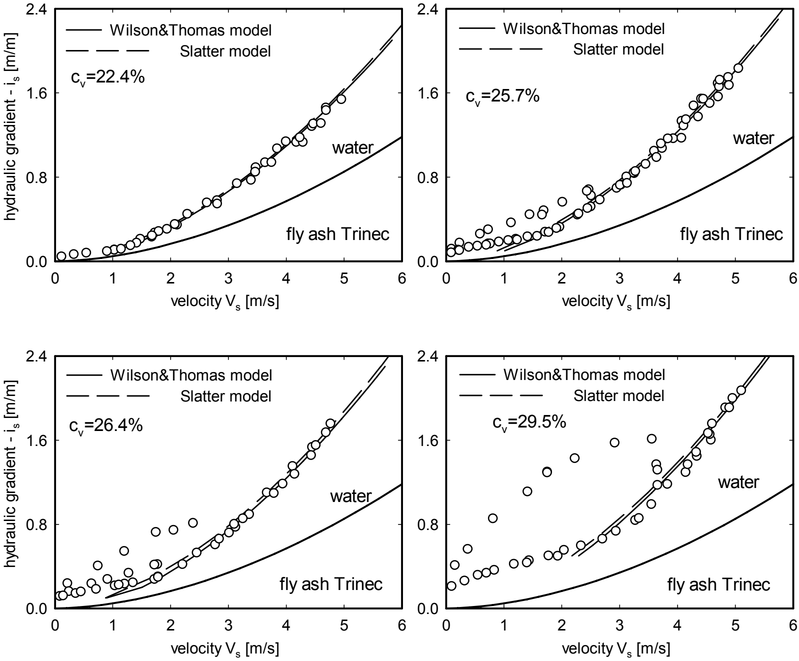

Figure 10 Approximation of hydraulic gradient i_s by turbulent models

Table 5 Trinec fly ash slurry rheological parameters

Slurry concentration	Rheological parameters determined from					
	stabilised slurry turbulent data			stabilised slurry laminar data		
c_v [%]	τ_y	K	n	τ_y	K	n
22.4	2.135	0.0252	0.90	2.14	0.025	0.90
25.7	4.337	0.0451	0.88	3.071	0.1728	0.68
26.4	5.616	0.0420	0.89	5.536	0.0466	0.87
29.5	9.774	0.1324	0.81	11.520	0.0427	0.96

The dependences of the pressure gradient i_s on the slurry concentration c_v, slurry velocity V_s and shearing for the ash slurry from Trinec are illustrated in Fig. 10. Four different concentrations of the fly ash slurry were measured in the laminar, intermediate and turbulent regimes. Laminar flow of the ash slurry can be described well by the Bulkley-Herschel model. For the turbulent region, two models, namely Wilson-Thomas [40] and Slatter [19], were used. Both models represent the experimental data well; however, they are very sensitive to the values of rheological parameters, especially the flow behaviour index n. The rheological parameters should be evaluated from turbulent experimental data (see Tab. 5).

5.5 Fly/bottom ash slurry

To describe the effects of fine and coarse particles contents the slurry consisting of the fly ash and the bottom ash was measured [31]. The addition of bottom ash causes a decrease in the hydraulic gradient i_s and a higher solids concentration c_v can be reached. The "fresh" Porici slurry with bottom ash reaches a markedly lower hydraulic gradient i_s in the laminar region; for example, for the slurry velocity V_s = 1.5 m/s more than twice (see Fig. 11). The effect of coarse particles in stabilised slurries is significantly smaller. In the turbulent region both slurries reach nearly the same value of the hydraulic gradient i_s, however only the fly ash slurry reached the L/T transition for a markedly higher velocity than the fly/bottom ash one. For the "fresh" fly ash slurry $V_{TR} \approx 3.4$ m/s, and for the "fresh" fly/bottom ash slurry, $V_{TR} \approx 2.1$ m/s, while in the stabilised slurry the transition point is reached at substantially lower velocities, $V_{TR} \approx 2.4$ m/s and $V_{TR} \approx 1.6$ m/s, respectively. A similar favourable effect of a bottom ash was found for the Trinec ash slurry, too.

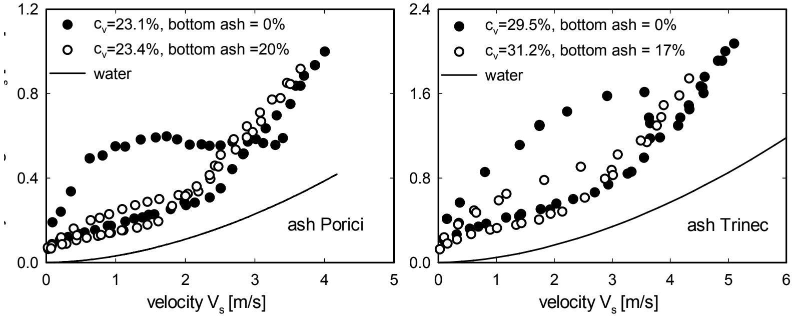

Figure 11 Effect of bottom ash (Porici, D = 36 mm , Trinec, D = 26.8 mm)

The effects of variable proportions of bottom ash and slurry concentration are shown in Fig. 12. For the slurry with 10% bottom ash, the radical change in the course of the i_s/V_s relationship appears near the velocity value V_s = 1.4 m/s, where the sudden reduction of the hydraulic gradient i_s can be observed. Due to the shearing effect, the hydraulic gradient decreases slightly with increasing flow velocity and for the velocity value $V_s \approx 2.3$ m/s it reaches a minimum. Then it gradually increases again with the increasing velocity up to the L/T transition point. In the intermediate or turbulent region the hydraulic gradient increases steeply again.

When the bottom ash proportion grows to 30% the maximum reduction in the hydraulic gradient is more than 50% for the “fresh” slurry and only 25% for the stabilised slurry at $V_s = 1.35$ m/s. For the slurry with 30% bottom ash the sudden reduction in the hydraulic gradient is missing, but the hydraulic gradient i_s reaches significantly lower values in the laminar region. For the “fresh” slurry with 20% bottom ash and total concentration $c_v = 23.4$ or 26.1%, the plateau effect was observed for the higher values of the total concentration only. The hydraulic gradient i_s is nearly constant for the concentration $c_v = 26.1\%$ in the velocity range $V_s \approx 1.0$ m/s to $V_s \approx 3.0$ m/s. For stabilised slurry this effect is missing.

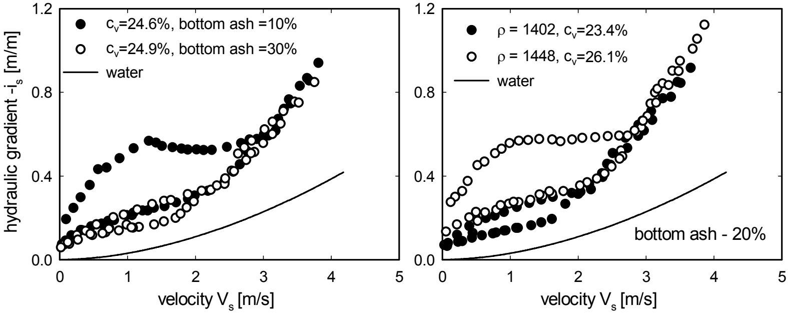

Figure 12 Effect of slurry concentration c_v and slurry velocity V_s on pressure gradient i_s (Porici fly/bottom ash, D = 36 mm)

Similarly, as shown in Figs. 11 and 12 the difference between the hydraulic gradients of the slurries with different proportions of bottom ash is negligible in the turbulent region, but the slurry with higher contents of bottom ash reached the L/T transition at a markedly lower velocity. Consequently, it is possible to use lower operational velocities for the slurry with bottom ash, which brings a significant reduction in pressure losses. The effect of the duration of shearing is greater for the slurry with a higher content of very fine particles and a lower proportion of bottom ash. Intensive shearing or addition of coarse particles depresses the effect of attractive inter-particle forces and results in the destruction of the aggregates. The favourable effect of the addition of bottom ash or shearing is significantly lower in the intermediate and turbulent region.

5.6 Slurry drag reduction

The flow behaviour of highly concentrated slurries with colloidal particles is strongly affected by physical-chemical forces and by the mutual particle-particle and particle-liquid interactions. The presence of the fine solid particles, especially colloidal particles, in a Newtonian liquid evokes the complex rheological behaviour of the slurry due to many physical and chemical factors acting on both liquid and solid components.

Hydrodynamic interactions caused by shear-induced translational and rotational motions of the particles result in particle collisions and the formation of temporary multiples during the slurry flow. This leads to an increase in the rate of viscous energy dissipation and hence the bulk viscosity of the slurry. Non-hydrodynamic inter-particle interactions evoke the non-Newtonian behaviour of the slurry. They originate from the random Brownian motion of particles and colloidal forces due to van der Waals attractive forces and electrostatic repulsive forces. In highly concentrated fine-grained slurries both types of interactions exist and their relative influences on the rheology are a function of the physical and electrochemical characteristics of the particles, the carrier liquid and type of the flow (Nguyen and Boger [13]; Vlasak et al. [35, 36]).

After mixing solid particles with water, attractive and repulsive forces between the fine, especially colloidal particles, initiate the processes of coagulation and peptisation, respectively. If the attractive forces acting in the slurry prevail, the coagulation and sedimentation are initiated. However, a simultaneous existence of the repulsive forces makes it possible to stabilise the slurry and keeps the individual particles separated. The effect of the electrostatic repulsive forces on the stabilisation process could quite well explain a mechanism of fine-grained slurries liquefying (Satava [22]).

The coagulation process in the slurry gives rise to voluminous particle aggregates, where a great deal of water is fixed. During the slurry flow a great deal of energy is consumed by deformation of aggregates. To start the process of peptisation, that is, to break the aggregates, it is necessary to modify the physical-chemical environment or to introduce a high level of shearing to suppress the inter-particle attractive forces and to produce sufficient repulsive forces between the particles. This results in the destruction of the aggregates; the water originally fixed in the aggregates is liberated and the slurry is liquefied. To prove the occurrence of this process, kaolin slurry with and without the peptising agent and fly ash slurry with and without bottom ash were measured in an experimental pipeline loop. It was demonstrated that a high intensity of turbulent or even a long duration of laminar shearing or the addition of a chemical agent or coarse particles could result in significant decrease in the apparent viscosity and yield stress.

5.6.1 Peptised kaolin slurry

The kaolin from the workstation Horni Briza (see Table 1) and a sodium carbonate as a peptising agent were used. This can supply the slurry with Na^+ cations for compensation of the surface charge. The behaviour of the system is determined by a mutual effect of the attractive and repulsive forces between the solid particles which results from the physical and chemical properties of both phases. By addition of the appropriate chemical agent into the slurry the repulsive forces between particles prevail and the viscosity and yield stress decrease. The effect depends on the chemical (peptising) agent and its concentration.

The investigation confirms that the addition of a chemical agent can serve to reduce the yield stress and viscosity of different slurries by orders of magnitude and can help to attain a higher solids concentration together with lower energy consumption by the pipeline transport. A similar principle, for example a change of the chemical environment of the transported slurry, can also be used for other fine-grained dense hydro-mixtures as described for instance by Horsley and Snow [4] for different mine tailings, by Nguyen and Boger [13] for bauxite residue, and by Vlasak et al [33] for fluidic ash-water mixtures.

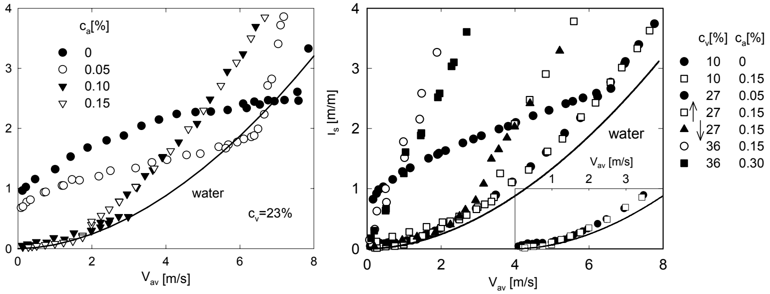

Figure 13 Effect of slurry concentration c_v and peptising agent/kaolin mass ratio c_a on the hydraulic gradient i_s of kaolin slurry (D = 17.5 mm)

As Fig. 13 shows, the flow behaviours of natural and peptised kaolin slurry in the laminar region are considerably different [35, 36, 37]. The efficiency of a peptising agent depends on the slurry and peptising agent concentrations and flow regime. The agent's efficiency increases with its concentration and it is greater at lower flow velocities. Practically no difference between peptised and untreated slurry can be found in transient and turbulent regimes. It was found that peptisation results in a significant decrease in the yield stress. The effect of peptisation becomes essential for higher values of slurry concentration ($c_v \approx 25\%$) and peptising agent/kaolin mass ratio; it is strongly positive in a laminar regime and a substantial decrease in the hydraulic gradient of about 30% was observed.

The peptising agent affects the velocity value V_{TR} corresponding to the beginning of the L/T transition. For the slurry concentration c_v = 23% and peptising agent/kaolin mass ratio c_a = 0.05% the value of V_{TR} decreases from about 7.8 to 6.3 m/s and simultaneously the slurry hydraulic gradient i_s drops by about 30%. In the transition and turbulent regions, the hydraulic gradient i_s of the peptised slurry again increases sharply.

For higher peptising agent/kaolin mass ratio (e.g. c_a = 0.10 or 0.15%), the peptised slurry shows only slightly non-Newtonian behaviour. The L/T transition point occurs at slurry velocity V_{TR} = 3.0 m/s for c_a = 0.10% and at V_{TR} = 2.0 m/s for c_a = 0.15%. For very high slurry concentrations (about c_v = 36%), peptisation suppresses yield stress and the hydraulic gradient/velocity relationship can be approximated by a very steep linear dependence. Unfortunately, it is impossible to compare the flow behaviours of peptised and untreated slurry since without the addition of the peptising agent, slurry of such concentrations does not flow in the pipe.

5.6.2 Drag reduction of fluidic ash slurry

Similarly to the kaolin slurry, the flow behaviour of the ash-water mixture could be controlled by a change in the physical-chemical environment which affects the attractive and repulsive forces between the solid particles and between particles and carrier liquid [32, 35, 36]. The effects of two different kinds of chemical agents were studied for fly ash-water mixture with Porici 2004fly ash. Both chemical agents significantly affect the rheological quality and flow behaviour of fly ash slurry and help to attain higher solid concentrations and/or lower pressure drops during the slurry flow in a pipe. With increases in the concentration of the chemical agent the apparent viscosity decreases. The effect of the addition of a drag reducing agent was studied from the flow out process of the slurry from a cylindrical ring with a diameter/height ratio = 36:29. The ring was put on a glass desk filled with slurry and then lifted up, and the slurry spontaneously flew out and created a circular “cake”. The cake’s final diameter D_c is relevant to the apparent viscosity of the mixture (see Table 6).

The different effects of the two agents are evident. The effectiveness of agent B increases very quickly with increases in the agent content c_a, because $c_a \approx 0.08\%$ reaches a maximum and then decreases again. This means that the re-coagulation process starts and the slurry is very sensitive to the agent contents. Agent A is not so sensitive to its concentration; however the increase in its effectiveness decreases significantly after the mass content reaches more than about c_a = 0.4%. The advantage of agent A is the absence of the re-coagulation process.

Table 6 Effect of drag reducing agents (Porici fly ash)

Drag reducing agent	c_a [‰]	D_c [mm]	Drag reducing agent	c_a [‰]	D_c [[mm]
A	0	74	**B**	0	60
	0.8	80		0.15	72
	1.6	81		0.30	77
	2.0	90		0.60	82
	4.0	95		1.20	81
	8.0	97		2.40	74
	12.0	97		6.00	65
Slurry density : 1 440 kg/m^3			Slurry density : 1 474 kg/m^3		

The Porici 2006 ash-water mixtures with and without the drag reducing agents were also tested in the experimental pipeline loop to demonstrate the effects of drag reducing additives on ash-water mixture flow behaviour in the pipe flow under laminar and turbulent conditions (see Fig. 14). The investigation conducted confirms that the addition of a drag reducing agent can serve to reduce the yield stress and viscosity of ash-water mixture and can help to achieve lower energy consumption in pipeline transportation.

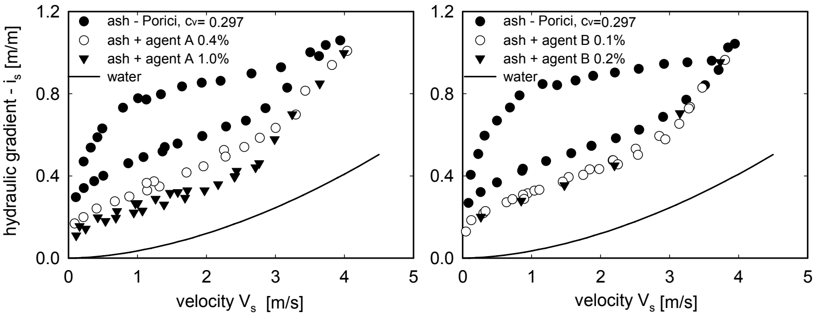

Fig. 14 Effect of drag reducing additives on the flow behaviour of fly ash slurry (D = 36 mm).

6. CONCLUSIONS

The flow behaviour of highly concentrated fine-grained slurries (e.g. kaolin or fly ash slurries) can be approximated by the Bulkley-Herschel model in the laminar region and by the Wilson or Slatter models in the turbulent region. The accuracy of both turbulent models is strongly influenced by the rheological parameters, especially the flow behaviour index n, which should be determined from the experimental turbulent flow data using sensitivity analysis.

The Durand model can be used to scale up the frictional pressure drops of the sand slurries at medium velocities, supposing the material parameters are determined experimentally. For fully stratified heterogeneous slurry, the two-layer model should be used. The coarse sand slurry reaches a higher hydraulic gradient than the fine sand slurry, and the difference decreases with increases in velocity. The polydisperse sand slurries reach nearly the same values of hydraulic gradient as the fine sand slurry. The sand slurry exhibits some attributes of non-Newtonian behaviour at a slurry volumetric concentration $c_v > 20\%$.

Highly concentrated sand-kaolin slurries also show non-Newtonian behaviour. When the carrier kaolin slurry is peptised, the hydraulic gradient in the laminar region becomes markedly lower, and the favourable effect vanishes in the transitional and turbulent regions. The addition of small amounts of kaolin favourably affects the flow behaviour of the sand-kaolin slurry.

The study revealed a time-dependent yield pseudo-plastic behaviour of the fluidic fly and fly/bottom ash slurries and the possibility of substantial reductions in the flow resistance throught mechanical treatment or arrangement of the particle size distribution. The higher the content of colloidal or very fine particles, the greater the tendency of the slurry to coagulate. An intensive turbulent or long duration of laminar shearing or addition of bottom ash evokes significant changes in the flow behaviour of fluidic ash slurries. The hydraulic gradient decreases markedly, the L/T transition is reached at lower flow velocities, and the higher ash slurry concentration can also be reached.

The behaviour of the fine grained slurries is controlled by a mutual effect of the attractive and the repulsive forces between the solid particles caused by the physical and chemical properties of both phases. The addition of the drag reducing agent results in substantial reductions in pressure drops. With increasing concentration of the drag reducing agent, the apparent viscosity and yield stress gradually decrease; the latter even vanishes. Activated slurries reach the laminar/turbulent transition at significantly lower flow velocities than the untreated slurry. The effect of the agent decreases with increasing coarse particle content and increases with slurry concentration and content of colloidal particles.

The present investigation revealed that pipeline transport is a reliable and progressive technology for conveying large quantities of bulk materials. It can bring several advantages compared to mechanical transport. It is dust free, demands substantially less space, makes full mechanisation and automation possible, requires a minimum of operating staff, and helps reduce energy consumption and negative impacts on the environment.

Understanding complex slurry flow behaviour, and control of the slurry's physical-chemical behaviour, its inner structure (particle size distribution), and time and intensity of shearing acting on the slurry makes it possible to optimise energy requirements and water consumption, to improve the quality, safety, and economic efficiency of transporting and/or processing such slurry.

Based on long experience the following trends in pipeline transport can be recommended: dense slurry rheology, slurry laminar/turbulent transition and turbulent flow, liquefaction of the slurry containing colloidal particles through changes in the slurry's physical-chemical behaviour, hydraulic capsule pipeline transport, and pumping technology.

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Curriculum Vitae

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1964-	Institute of Hydrodynamics of CSAS (from 1993 of AS CR)
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