The Effect of Permeability on Lignite Fly Ash Pneumatic Conveying System Design

NIKOLA KARLICIC*, ALEKSANDAR JOVOVIC, DEJAN RADIC, MARKO OBRADOVIC, DUSAN TODOROVIC, MIROSLAV STANOJEVIC

University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, 11120 Belgrade 35

The aim of this experimental study was to evaluate the effect of permeability on the mode of flow that lignite fly ash will support in a pneumatic conveying pipeline. This research was initiated by recurring problems with the long distance and high capacity low grade lignite ash pneumatic conveying system at the 1200 MWe thermal power plant, such as clogging, unsteady flow mode, significant increase of velocity due to pressure drop and erosive wear of pipeline. Ash samples were taken during pneumatic conveying system clogging for further analysis. The experiment was limited to measuring parameters that provide data to determine minimum fluidizing velocity and permeability. The results showed very heterogeneous materials of group B by Geldart, what caused specific phenomenon during the experimental fluidization tests. Minimum fluidizing velocity for this kind of material is not authoritative for defining pneumatic conveying system, since extremely heterogeneous materials at this air speed will remain stationary or will convey very slow or with stoppage, and that required velocities are from 10 to 15 times higher than minimum fluidizing velocity. According to the results, this ash is the most suitable for dense phase pneumatic conveying.

Keywords: fly ash; permeability; fluidization; pneumatic conveying; lignite coal; thermal power plant

Millions of tons of fly ash and by-products are generated in coal fired thermal power plants. Global annual production in world is estimated to 600 million tons [1]. In many situations fly ash is discharged utilizing pneumatic conveying systems. When designing or evaluating a pneumatic conveying system, investigating operational problems or upgrading an existing plant to achieve higher capacity, obtaining as much data as possible on conveying characteristics is mandatory [2]. Successful running of a pneumatic conveying system depends completely on the characteristics of the material conveyed, not only between different materials, but may vary from one batch to another [3]. One of the main disadvantages of pneumatic ash disposal systems is heightened clogging and erosion wear of horizontal and especially shaped elements of pneumatic transport pipelines.

The fluid flow through the bed of bulk material has been studied a lot. The efficiency and flow patterns of pneumatic conveying system are defined by multiple factors, such as bulk density, permeability and deaeration factor. These properties are recognized as the most important ones to be measured and analyzed regarding pneumatic conveying systems. One of the distinguishing characteristics in such an operation is permeability factor.

Mills [4] defines permeability as a measure of the ease with which air will pass through a bed of bulk particulate material when a pressure difference is applied. Sanchez et. al [5] state that permeability depends on several material properties: particle size, size distribution and shape and offers extremes. Geldart classified powders into 4 groups by their fluidization parameters [6], and this classification is widely used in all fields of powder technology. It differs from a uniform-sized Geldart D material with a large permeability factor to a cohesive C material with low permeability factor. As Mills [4] stated, there are many examples of pipeline blockage by a material that has a very wide particle size distribution, where a small plug of the material is capable of holding an upstream pressure of 5 bar for a period of a few minutes. Experimental investigations of many common fly ashes [7], [8] showed large differences in their fluidization characteristics, from well-fluidized systems with larger particles to very hard fluidization with fly ashes collected by electrostatic precipitator.

Experimental part

Materials and methods

The research presented in paper was initiated by persistent problems with the long distance and high capacity lignite ash pneumatic conveying system at the 1200 MWe (2 units of 620 MWe) thermal power plant. Low grade lignite coal with high and variable ash content is used as a fuel in this plant [9]. Dominant problems were clogging, unsteady flow mode from dense to dilute, significant increase of velocity caused by the pressure drop what led to high erosive wear of pipeline. Sometimes system can provide sufficient pressure to overcome the increased pressure drop, however more often case is pipeline blockage which couldn't be cleared by increasing pressure. All these problems could eventually lead to plant shut-down [9].

Lignite ash is collected and delivered to the blow tanks from the electrostatic precipitator, the flue gas duct at the steam boiler and from the regenerative air heater of the Ljungström type.

The objective of this study was to investigate the permeability as significant characteristic in defining a pneumatic conveying system. Parameters such as particle size and density, bulk density, chemical composition and minimum fluidizing velocity were also determined in order to have comparative data.

Ash samples

Twelve samples of ash were taken during pneumatic conveying system clogging for further analysis. Four samples were taken from electrostatic precipitator (EF1 – EF4), four samples from the flue gas duct at the steam boiler (KDG1-KDG4) and four samples from the

* email: nkarlicic@mas.bg.ac.rs

Table 1
PHYSICAL AND CHEMICAL CHARACTERISTICS OF ASH SAMPLES

	Unit	EF-1	EF-2	EF-3	EF-4	KDG-1	KDG-2	KDG-3	KDG-4	LUV-1	LUV-2	LUV-3	LUV-4
Poured bulk density, $\rho_{z,0}$	kg m^{-3}	690.6	594.1	672.7	709.1	607.4	569.6	671.9	617.3	617.5	568.5	683	617.8
Density, ρ_s	kg m^{-3}	1680	1500	1700	1620	1660	1630	1650	1710	1590	1600	1770	1730
Porosity, ε_0	-	0.59	0.6	0.6	0.56	0.63	0.65	0.59	0.64	0.61	0.64	0.61	0.64
Average diameter, d	µm	117	160	151	199	256	290	262	187	200	263	213	266
Quartz	%	14.79	10.51	17.74	18.79	22.68	11.97	31.85	33.04	22.92	12.17	30.51	26.71
Amorph. phase	%	57.23	54.94	53.62	70.68	45.58	53.19	59.93	71.67	51.48	53.46	57.23	54.94
Loss on ignition	%	1.6	2.18	1.97	4.31	5.27	1.77	3.59	2.83	1.86	4.36	1.6	2.18
SiO_2	%	56.13	55.88	57.06	57.91	60.31	55.85	64.38	64.02	60.44	56.79	65.5	61.78
Al_2O_3	%	25.63	26.88	25.08	23.73	23.21	25.76	18.57	21.22	22.85	26.31	20.62	21.1
Fe_2O_3	%	5.86	6.18	5.78	6.15	5.36	6.17	4.59	4.66	5.87	6.21	5.27	4.96
CaO	%	5.27	3.91	5.18	4.54	4.12	3.05	3.17	3.49	2.68	2.77	2.66	3.12
MgO	%	2.02	1.96	1.96	1.9	1.69	1.75	1.3	1.5	1.5	1.75	1.44	1.57
P_2O_5	%	0.05	0.05	0.05	0.06	0.05	0.06	0.04	0.05	0.05	0.05	0.04	0.05
SO_3	%	0.36	0.22	0.51	0.29	0.31	0.16	0.2	0.25	0.16	0.15	0.16	0.23
K_2O	%	1.56	1.5	1.35	1.55	1.35	1.49	1.15	1.44	1.32	1.53	1.24	1.33
Na_2O	%	0.128	0.07	0.094	0.174	0.138	0.075	0.231	0.276	0.115	0.072	0.171	0.247
TiO_2	%	0.848	0.797	0.796	0.803	0.775	0.764	0.649	0.793	0.698	0.779	0.661	0.67
Cr_2O_3	%	0.037	0.04	0.041	0.04	0.042	0.037	0.043	0.049	0.039	0.039	0.045	0.045
Mn_2O_3	%	0.076	0.061	0.08	0.088	0.071	0.074	0.062	0.061	0.062	0.066	0.065	0.056
ZnO	%	0.01	0.009	0.009	0.01	0.003	0.005	0.001	0.005	0.004	0.006	0.004	0.002
SrO	%	0.03	0.026	0.029	0.029	0.025	0.022	0.021	0.024	0.019	0.02	0.019	0.021

regenerative air heater of the Ljungstrom type (LUV1-LUV4). Detailed characteristics of each ash sample are given in table 1. Based on plant operating data, lignite coal had lower heating value 5505-7742 kJkg^{-1}, with ash content 15.5-25% and moisture content 46-50%.

Experimental rig

Experiments on determining permeability were carried out in a standard type of experimental fluidization rig. At the bottom of transparent Plexiglas tube there is porous membrane which holds poured material and is air permeable. Below porous membrane, the fluidising air is distributed to the air flow equalization chamber that contains packed bed for better air distribution. Schematic view of the experimental rig is presented in figure 1.

Experimental part

This experiment was limited to measuring parameters (as given in fig. 1) that provide data to analyse dependence Δp/H and w_{mw}, i.e., to determine minimum fluidizing

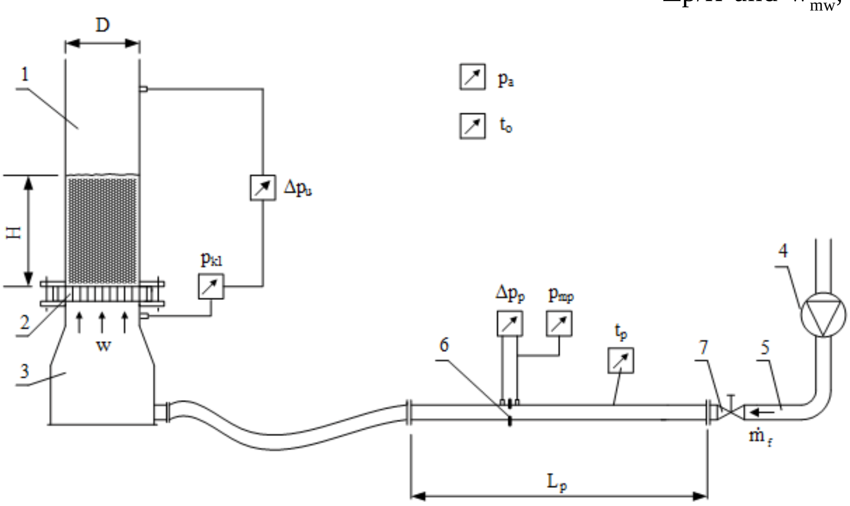

Fig. 1 Schematic view of experimental rig for determination of permeability
1. plexiglas fluidizing column (D = 142 mm, H_C = 1750 mm), 2. porous membrane, 3. air flow equalization chamber, 4. air mover, 5. pipeline for air supply, 6. orifice plate, 7. regulating valve

velocity and permeability. The following parameters were measured in order to determine permeability:

- p_{K1}, overpressure of air below the porous membrane (U-tube with water), mmH_2O,
- Δp_u , pressure drop on the layer of ash (U-tube with water), mmH_2O,
- H , height of the ash in column (meter), cm,
- Δp_p , pressure drop through the orfice (inclined tube manometer with alcohol), mm alc.,
- p_{mp} , overpressure of air in front of orfice plate (U-tube with mercury), mmH_g,
- t_p, air temperature in front of orfice plate (thermometer), °C,
- p_a , atmospheric pressure (barometer), bar,
- t_o , ambient temperature (thermometer), °C.

Prior to starting the experiment, porous membrane characteristics is defined, i.e., the dependence of the pressure drop on the air speed while the column is empty. Ash sample is then poured to the specified height in the fluidizing column on the porous membrane. Air is fed into the column through the pipeline which is connected to a blower, air flow equalization chamber and porous membrane. Experiment is carried out by gradually increasing the air flow into the column, while visually following changes of parameters and phenomenon that occur in the layer of material which migrates to fluidized condition.

Results and discussions

Permeability corresponds to the relationship between air flow rate and the pressure drop for the fixed bed of material. There are many equations for determining pressure drop through the bed of material and the minimum fluidizing velocity [10] and this paper won't discuss them. Probably the best-known work on this subject is by Ergun [11], who proposed equation:

$$\frac{\Delta p_s g}{H} = 150\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu_f w}{d^2} + 1,75\frac{(1-\varepsilon)}{\varepsilon^3}\frac{\rho_f w^2}{d}, \quad (1)$$

This relationship for laminar flow defines the superficial air velocity through bed:

$$w = \frac{C\Delta p_s}{H}, \ \mathrm{ms^{-1}}, \quad (2)$$

where:

-C, permeability factor, $m^3 s\ kg^{-1}$ or $m^4 N^{-1} s^{-1}$,
-Δp_s, pressure drop across the bed, $N\ m^{-2}$,
-H, bed height, m.

Ash samples permeability is determined under flow conditions before reaching minimum fluidizing velocity, according to the formula:

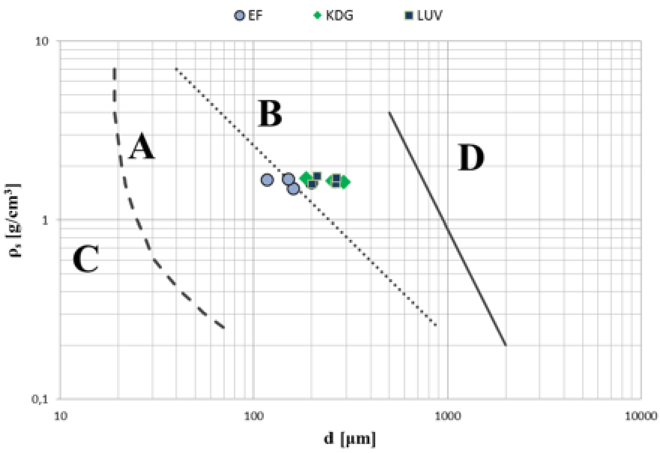

Fig. 2 Geldart classification of ash samples

$$C = \frac{w}{\frac{\Delta p_s}{H_0}}, \ \mathrm{m^2 Pa^{-1} s^{-1}}, \quad (3)$$

where:

- $\frac{\Delta p_s}{H_0}$, $Pa\ m^{-1}$, pressure drop through layer reduced to layer height at constant porosity.

The most of the ash samples belong to materials of group B by Geldart [6] according to their properties as given in figure 2.

Table 2 gives review on results of fluidization parameters for all ash samples calculeted according to (3): initial layer height, minimum fluidization velocity w_{mf}, maximum pressure drop per layer height $(\Delta p/H)_{max}$ at minimum fluidization velocity and permeability C.

During the experimental tests, fluidization has been visually monitored. A several phenomenon has been noticed during air flow, formation of channel-like features through the ash bed, an obvious layering of ash samples, the occurrence of bubbling on the top of bed and uneven fluidization of heterogeneous material. In some samples, the beginning of vertical pneumatic conveying was noticed for the finest particles. While air flowing-through the bed at speed that matches the minimum fluidizing velocity for smaller and lighter particles, these particles will emerge to the top of layer, and this part of material will have all parameters that determine the beginning of fluidization at variable porosity. Bottom part of this ash layer is still in the area of fluidization at constant porosity. The smallest particles are completely fluidized and start to convey, while bigger particles are still stationary and fluidization haven't

Table 2
FLUDIZATION PARAMETERS OF ALL ASH SAMPLES

Sample	Initial layer height, H_0 [cm]	Layer height at the begging of fluidization, H [cm]	Minimum fluidization velocity, w_{mf} [cm s^{-1}]	Maximum pressure drop per layer height $(\Delta p/H)_{max}$ [mmH$_2$O cm^{-1}]	Permeability C [m (Pa s)$^{-1}$]
EF-1	25.3	25.3	1.37	6.29	$6.05\cdot10^{-5}$
EF-2	25	25.0	1.67	4.87	$2.73\cdot10^{-5}$
EF-3	24.2	25.0	1.68	6.35	$2.85\cdot10^{-5}$
EF-4	25	25.5	1.68	6.53	$3.39\cdot10^{-5}$
KDG-1	24.9	26.5	2.91	5.86	$3.83\cdot10^{-5}$
KDG-2	24.9	25.0	2.38	6.89	$2.70\cdot10^{-5}$
KDG-3	25.3	25.4	2.57	7.13	$3.26\cdot10^{-5}$
KDG-4	24.5	24.5	2.17	6.31	$1.28\cdot10^{-5}$
LUV-1	25	25.3	2.37	5.31	$2.89\cdot10^{-5}$
LUV-2	25	25.0	1.94	5.62	$2.97\cdot10^{-5}$
LUV-3	25	25.5	2.91	6.44	$3.38\cdot10^{-5}$
LUV-4	25	26.0	3.22	5.62	$2.76\cdot10^{-5}$

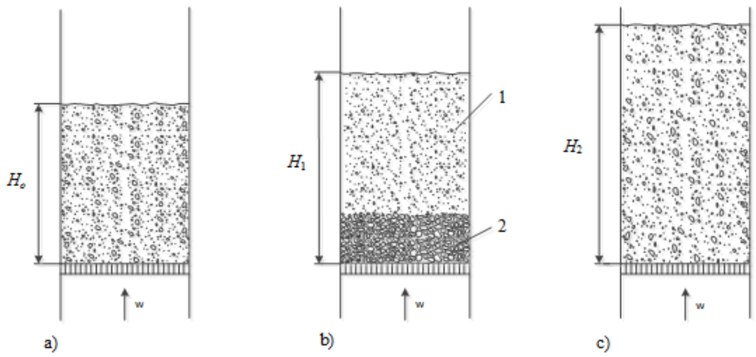

Fig. 3 Heterogeneous material fluidization review
a) layer of material before fluidization;
b) smaller particles of material (1) are fluidized; larger particles of material (2) are stationary;
c) complete fluidization of material

Fig. 4 Partial and complete fluidization of heterogeneous ash material

even begun. These effects are best described in figure 3 and figure 4.

Air temperature insignificantly changed, so the fluidization air flow velocity was inverse proportional to the pressure. The maximum value of pressure drop through the layer of ash was about 280 mmH_2O, which implies difference of 0.7 % of air flow velocity on the bottom and on the top of ash layer, so this velocity was calculated with average value of pressure. Considering this fact, maximum deviation real from average velocity was ± 0.35 %.

It has been found that all ash samples from the observed power plant are very heterogeneous. This implies that all of observed parameters are not unambiguously determined what leads to a specific phenomenon during fluidization, and is significant for pneumatic conveying system selection. All samples has been classified to Geldart B type of material (sand like).

In most test samples there was tendency of forming channel-like features during air flowing-through ash layer at speed around or at minimum fluidizing velocity speed for smaller and lighter or at speed that that matches it. Further velocity increase would cause emerging the finest particles to the top of sample and forming a layer with all parameters that determine the beginning of fluidization at variable porosity, while larger and heavier particles remain stationary. The smallest particles are completely fluidized and start to vertically convey, while bigger particles are still stationary in the area of fluidization at constant porosity. With one sample, a finest part of material started to vertically convey in form of a plug, but collapsed with increase of velocity.

When coping with this kind of material, minimum fluidizing velocity determined in this way is not authoritative for defining pneumatic conveying system, since extremely heterogeneous materials at this air speed will remain stationary or will convey very slow or with stoppage. Minimum fluidizing velocity for samples taken from the electrostatic precipitator (EF) was noticed to be two times less than for the flue gas duct at the steam boiler and regenerative air heater samples. During the experiment, occurence of particles leaving layer of sample material and starting to convey vertically upwards was visually followed. According to measurements this was noticed to happen at velocities 10 to 15 times higher than minimum fluidizing velocity. EF samples had this velocity from 16 to 17 cm/s, and for LUV and KDG was from 20 to 32 cm/s.

Since permeability is defined as a measure of the ease with which air will pass through a bed of bulk particulate material, there are some recomendations [1] for materials having permeability factor $C = 10^{-5} \div 1.2 \cdot 10^{-4}$ $m^2 Pa^{-1} s^{-1}$ can be applied dilute phase mode of conveying (solids loading ratio 15), with high air-flow velocities (>12 m s^{-1}) and high energy consuption. For materials having permeability factor lower than 10^{-5}, dense phase mode of conveying is recomended (solids loading ratio more than 20, and velocities as low as 3 m s^{-1}) [1]. According to experimental test results, this ash is the most suitable for dense phase pneumatic conveying.

Conclusions

The research in this paper was initiated by persistent problems with the long distance and high capacity pneumatic conveying of low grade lignite coal ash at the 1200 MWe thermal power plant: clogging, unsteady flow mode, erosive wear of pipeline, etc. Until now, there has been no reliable method to assess conveyability based only on material distribution size. The aim was to determine aeration properties of ash samples, primarily permeability and to evaluate the effect of permeability on the mode of flow that lignite fly ash would support in a pneumatic conveying pipeline. Experimental test program included twelve samples of ash that were taken during pneumatic conveying system clogging for further analysis. Four samples from electrostatic precipitator, four samples from the flue gas duct at the steam boiler and four samples from the regenerative air heater of the Ljungström type. The experiment was limited to measuring parameters that provide data to determine minimum fluidizing velocity and permeability. All of test samples were very heterogeneous and the most of the ash samples belong to group B of materials of by Geldart. A several specific phenomenon were noticed during the experimental fluidization tests, formation of channel-like features through the bed, layering, the occurrence of bubbling on the top of bed, uneven fluidization of heterogeneous material. Minimum fluidizing velocity for this kind of material was found not to be authoritative for defining pneumatic conveying system, since extremely heterogeneous materials at this air speed will remain stationary or will convey very slow or with stoppage, and that required velocities are from 10 to 15 times higher than minimum fluidizing velocity. Permeability factor C was determined to be lower than 10^{-5} $m^2 Pa^{-1} s^{-1}$. In order to properly define samples and give a conclusion on a fine grained material pneumatic conveying system, physical and chemical properties must be taken into the consideration. According to all results, physical and chemical properties, Geldart classification and permeability this ash is the most suitable for dense phase pneumatic conveying.

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