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Planning of experimentation to model the pneumatic conveying capability of dry ash

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Abstract:
Dry ash pneumatic conveying is becoming more demanding in various fly ash generating and as well as utilizing industries. Dry ash thus produced generally micro sized fine particles mainly comprising of aluminum silicates, possesses both ceramic and pozzolanic properties. A large number of technologies have been developed for gainful utilization and safe management of Dry ash under the concerted efforts made by Fly Ash Mission/Fly Ash Unit under Ministry of Science & Technology, Government of India since 1994. As a result, fly ash earlier considered to be "hazardous industrial waste" material, has now acquired the status of useful and saleable commodity. Due to recent development in hardware and software required for such system which requires minimum air for conveying in turn power, with reduced pressure and velocity, reduced pipe line configuration and wear rate which increased work place environmental friendly and due to increased workplace safety, this added advantages of Dry ash pneumatic conveying mostly used in power generating unit, cement manufacturing, ready mix concrete manufacturing, EPC Fly ash panel. Till date majority of dry ash producers are using hydraulic conveying systems due to non-availability of efficient and reliable pneumatic system for collection of dry fly ash. Attempts are being made to find practical uses for the dry ash on large scale & also to avoid ground & water contamination, land & water resource constraint, it necessary to avoid the disposal of ash in wet slurry form into ash bund.

The solution of this problem lies in developing improved model for a pneumatic conveying system which uses ecofriendly, energy efficient system which protects the potential dry ash properties for utilization on large scale. It is primary need for reliable design of a pneumatic conveying system, this paper reports the planning of classical plan experimentation and model the conveying capability of dry ash conveying system to generate the design data from experimentation.

KEYWORDS: Conveying capability, Loading ratio, Experimental modeling, ESP- Electrostatic Precipitator

Introduction Dry ash are produced around the world every year from the combustion of pulverized coal in thermal power stations, CEA New Delhi 2017 [1] In the report it was shown that the total no of thermal power in 18 states were of 155 and the generation of fly ash was in these stated during the year 2016-2017 was 169.2533 million tons. The table below will give the summary of fly ash generation and utilization during year 2016-2017.

Table No.1

Description		Year 2016-17
• Nos. of Thermal Power Stations from which data was received	:	155
• Installed capacity (MW)	:	157377.00
• Coal consumed (Million tons)	:	509.46
• Fly Ash Generation (Million tons)	:	169.25
• Fly Ash Utilization (Million tons)	:	107.10
• Percentage Utilization	:	63.28
• Percentage Average Ash Content (%)	:	33.22

Till date majority of ash producers are using hydraulic conveying systems due to non-availability of efficient dry ash pneumatic conveying system. Dry ash largely used in building material sector [2]. Attempts are being made to find practical uses for the dry ash on large scale & also to avoid ground & water contamination, land & water resource constraint, it necessary to avoid the disposal of ash in wet slurry form into ash bund.

The solution of this problem lies in developing a pneumatic conveying system for Dry ash with maximum throughput, which uses ecofriendly, energy efficient system which protects the potential dry ash properties for utilization on large scale in various industries. In the past investigations have been carried out for dry ash pneumatic system for industrial application [3].

Nomenclature:

D Bore of pipe

L Length of conveying line

P_1 Supply pressure

ρ_b Dry ash bulk density

V_p Permeability

M_a Mass flow rate of air

M_s Mass flow rate of ash

Ø or LR Loading ratio

PLANNING OF EXPERIMENTATION

The steps involved in the planning of experimentation [4] under the classical plan of experimentation to enhance conveying capability of dry ash pneumatic conveying are discussed below: -

a) Identification of various physical quantities affecting the modelling of the system.

b) Dimensional Analysis to reduce the variables.

c) Deciding the test envelops Test points and Test sequence.

d) Selection of measuring instruments.

e) Calibration of measuring instruments.

f) Test data checking and rejection.

g) Data analysis and formulation of the model.

Referring theories of engineering experimentation by Hilbert Schenck Jr. [4] it was decided to use classical plan of experimentation, data was collected for dense phase pneumatic conveying system for dry ash to develop model and to correlate dependent π term with independent variables of the system.

Identification of variables (Dependent and Independent) [5]:

Any physical quantity which undergoes change is termed as variable. Variable which can be varied independent of other variable is known as independent variable, whereas any parameter which changer due to change in some other variable or variables is known as dependent variable.

1) Dependent Variable:

Dry ash mass flow rate (m_s) (T/hr): dry ash conveying capacity of a pneumatic conveying system is of primary concern, that is is dry ash flow rate. Values of same were calculated from experimentally and the formulated model.

Air mass flow rate (m_a) (kg/s) the conveying air required, that is mass flow rate of air is of primary concern for efficient system, Values of same were calculated from experimentally and the formulated model. Therefore, dependent variables can be represented by a single dimensional term loading ratio (Ø).

Loading ratio (Ø) = (m_s) / 3.6 **(m_a)** (3.6 is the conversion factor as mass of flow rate of ash is in tons per hour and air is in kg per second)

2) Independent variables

The various independent variables related to pneumatic conveying system are the independent variables are categorized as follows: -

I) Fluid related variables

a) Bulk Density(ρ_b)

II) Flow related variables

a) Permeability (V_p)
b) Supply Pressure (P_1)

III) Geometry related variables

a) Bore of pipe(D)
b) Length of pipe(L)
c) Mean particle size(µ)

4.5 Measurement of variables

The dependent variables;

Loading ratio (Ø): As per the model formulation and experimental values of mass flow rates air by measuring velocity of air from vent box pipe and mass flow rate of dry ash at receiving silo by unloading in bulkers and further weighment on 100-ton weighbridge.

I) Independent variables are;

Fluid related variables

a) Bulk Density(ρ_b): As per test report of Samples received from GEO systems Labs Nagpur

Flow related variables

a) Supply Pressure (P1): Analog Pre- calibrated burden tube pressure gauge
b) Permeability (V_p): As per test report of Samples received from GEO systems Labs Nagpur

Geometry related variables

c) Bore of pipe(D): constant.
d) Length of pipe(L): constant.

e) Size of Particle (μ_p): As per test report of Samples received from GEO systems Labs Nagpur

Dimensional analysis:

Buckingham π –theorem is used to perform dimensional analysis. The following procedure was adopted to determine the dimensionless parameters, that is π terms; (1) list the corresponding parameters; (2) apply the M, L, T, system; (3) list the dimensions of all the parameters; form the π terms.

Table 2. List of variables, notation and their dimensions [5].

Sr. No.	Variables	Symbols	Units	M.L.T.
1	Conveying Pipe Diameter	D	m	$M^0 L^1 T^0$
2	Particle size	μ_p	m	$M^1 L^{-3} T^0$
3	Bulk density of dry ash	ρ_b	kg/m^3	$M^0 L^{-3} T^0$
4	Conveying Length	L	m	$M^0 L^1 T^0$
5	Pressure at inlet	P_1	N/m^2	$M^1 L^{-1} T^{-2}$
6	Permeability	Vp	m/s	$M^0 L^1 T^{-1}$
7	Loading Ratio	Ø	-	$M^0 L^0 T^0$

Planning of experimentation to model conveying capability of dry ash pneumatic conveying
List of Pi terms:

Table 3. List of Pi Terms

Sr. No.	Pi Term
1	$\pi_1 = \frac{L}{D}$ Conveying Diameter
2	$\pi_2 = \frac{\mu_p}{D}$ Particle size
3	$\pi_3 = \frac{P_1}{\rho\, V_p{}^2}$ Inlet Pressure
4	$\pi_4 = Ø$ Loading Ratio

The Loading ratio, Ø is given by:

$$Ø = f\left(\frac{L}{D}, \frac{\mu_p}{D}, \frac{\Delta P}{\rho_b V_p^2}\right)$$

Out of our 4 Pi-terms, fourth is dependent term (i.e. Output), while 1-3 are independent terms.

Table 4. Test envelops, test point for independent and dependent variables

Group	Definition	Test Envelope	Test Point	Test Sequence
π_1	Geometry	Constant	Constant	Constant
π_2	Particle Size	0.000125 to 0.000225	0.000125, 0.000175, 0.000225	Random
π_3	Pressure	$2.38X10^{12}$ - 2.58 $X10^{20}$	$2.5763X10^{12}$, $3.2734X10^{16}$, 2.57X 10^{20}	Random

Main Experimental Setup

The experimental setup is established and tests are conducted at Koradi Thermal Power Station on spare conveying line. Experimental data are tested on dimensional analysis model for Dry ash pneumatic conveying. The Dry ash from various ESP hoppers were collected & tested separately for mean particle size, bulk density and permeability [13]. Experiments were carried out on three samples for various test points and test envelope on pneumatic conveying test pipeline having diameter 0.2 and length around 300 m.

General Arrangement of Main Test Set Up [5]

The Dry Ash pneumatic conveying test setup consists primarily of a dry ash supply hopper/Silo, Dry Ash feeding vessel that is a blow tank, conveying pipelines, receiving silo/discharge hopper with arrangement of air separation that is vent box with bag filter arrangement and some instrumentation. A schematic layout of the Dry Ash pneumatic conveying test rig is shown in Figure.

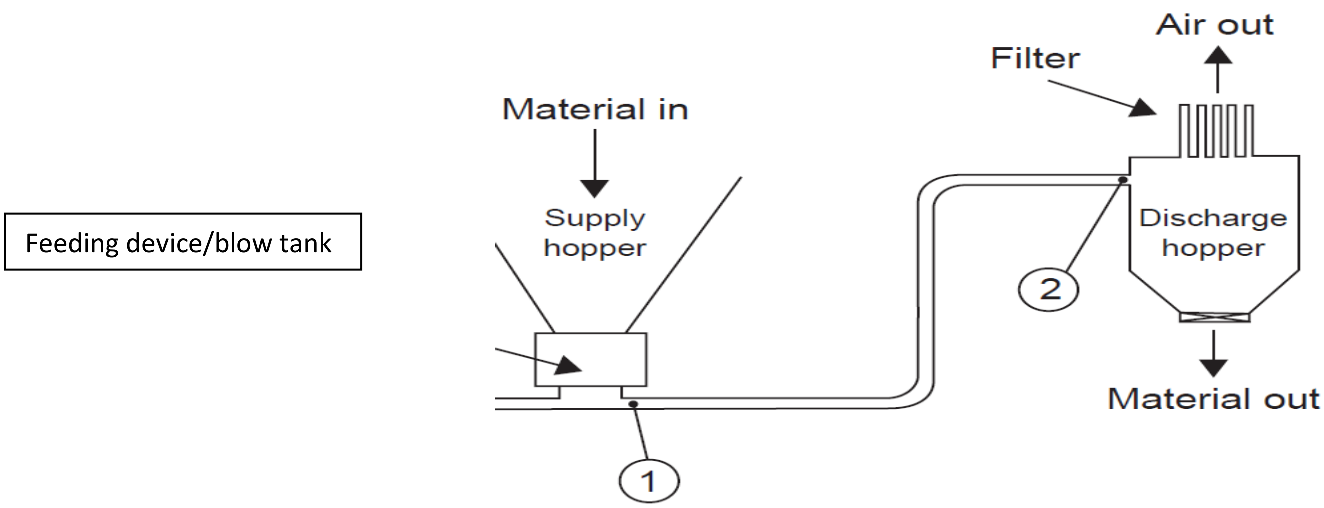

Fig.1 Test setup reference point for dry ash pneumatic conveying system.

Supply hoppers Dry ash from particular ESP supply hoppers were pneumatically conveyed to receiving silo/discharge hopper.

Material Feeders-Blow Tank (airlock vessel) The Principle requirement of a feeder is that it should be capable of feeding at the desired rate (i.e. at Dry ash collection rate) from supply hopper at one pressure in power plant which is below atmospheric in ESP Hopper, to conveying line at another pressure which is at higher pressure in positive pressure conveying.

Conveying Pipeline consists of a mild steel pipeline of 300 m length and bore 0.20 m, fitted with flanges. The main section of the pipeline is constructed horizontally. 8 m and 12 m vertical lift is required to send material from horizontal section to overhead. The pipeline consists of 5 bends with back pressure valve. Effect of bends is very less as compared to the total length of the pipeline and is assumed to be negligible.

Receiving Silo, A 1100 MT Silo is used as a receiving silo. The conveyed dry ash can be measured on weighbridge by unloading from silo in bulkers as well as if required in jumbo bag of capacity of 1 ton. A bag filter on vent line of 200 mm bore pipe is installed on top of the silo to separate the air from the dry ash. Out of total 05 numbers of ash delivery openings, one spare opening was used for installing specially designed delivery spout for dry ash loading to bulkers for dry ash flow rate measurement.

Air Supply and Control

In the Koradi Power Plant Supply of air is taken from stand by conveying compressor, Atlas Copco electric-powered Model GA-308, 3.1 m^3/ min. Various filters and separators are installed in series with these compressors to ensure a dry and oil free air supply to a temporary control station with pressure regulating valve which reduces receiver pressure to required level of around 2.5 to 1.5 kg/cm^2

Air Flow Fine Control Air from control station is further extended to air supply line of bore 0.75m just before conveying pipeline through an orifice plate. However, air mass flow-rate control is achieved with combination of a pressure regulator and standard orifice that maintains a fairly constant upstream pressure.

Experimental Instrumentation and Techniques The instrumentation and techniques are designed to measure directly the following parameters during the experiments on Dry Ash pneumatic conveying;

a) Mass flow rate of dry ash (m_s), bulkers were used to collect dry ash during test which further measured on 80MTweighbridge for measuring mass flow rate of dry ash.
b) Mass flow rate of air (m_a), the velocity of air was measured from silo vent pipe by hand held Anemometer which is further multiplied by ρ of air (1.2kg/m^3) and cross section area of vent pipe 0.0314m^2.
c) Supply air pressure at inlet of the system (P_1) is measured by bourdon tube pressure gauge of range 0-5 kg/cm^2.

Test Procedures

After all the instruments are calibrated [14] and installed.

System Check To ensure the healthiness of experimental set-up for smoothness and correctness, a system check is necessary.

Trial: The trial is carried out on the Dry Ash conveying test set-up. The capacity of Dry Ash pneumatic conveying is governed by the loading ratio i.e. mass flow rate of ash to mass flow rate of air. To maximize the conveying capability, air pressure is gradually reduced by varying the operating pressure from 2.5 to 1.5 Kg/cm^2 & hence mass flow-rate of air.

If the mass flow-rate of air is on higher side, the flow either goes to unstable zone or changes to dilute-phase. Consequently, if a selected mass flow-rate of air is less than the desired value, it will start gradual accumulation of ash inside the conveying line & will ultimately lead to line blockage due to deposition of ash which can be observed on air supply line pressure gauge mounted. The test program is as follows:

(i) The first test with the maximum mass flow-rate of air attained at air pressure of 2.5 kg/cm^2 and last at 1.5 kg/cm^2. The dry ash sample will be conveyed in this range (i.e. between the maximum and minimum mass flow-rate of air) & required parameters will be observed during the test. In order to obtain relationships between the various parameters and Dry Ash pneumatic conveying characteristics, the test will be taken for each Dry Ash sample divided into three groups (ESP-123, ESP-456, ESP-789) according to their bulk density or particle size.

To ensure good accuracy results, each test is repeated at least two times so as to avoid any erroneous reading or judgement error.

Actual images of experimental set-up

Figure 2 Actual experimental setup

Trial experimentation was performed at Koradi to define the safe and optimum conveying conditions, Dry ash pneumatic conveying characteristics are obtained by installing various standard orifices in air supply line which were used for creating differential pressure for measuring of mass flow rate of air so as to control accordingly to pressure required for conveying dry ash considering losses for particular pipe line configuration. Various sizes of orifice are installed at conveying fluid inlet at ash pick-up point to get optimum value of conveying fluid to achieve maximum loading ratio so as to achieve maximum throughput of ash. By varying conveying parameters using required design orifice will provide better accuracy and approximation to obtain better results.

Modification in experimental setup

After trial experimentation, the modifications were carried out in the experimental setup. Since it was found that in the standard orifices used were of single large hole type. However, during experimental trials with standard orifices, difficulties were experienced in measuring air flow by orifice due to constant pressure hunting on downstream orifice. The experimentation with modified multiple hole type orifice [14] is purposely used for getting the steady state uniform air flow & to ensure desired conveying conditions at the pickup point of ash in conveying line. Further, standard straight pipe length ideally required for test conditions was practically not possible due plant layout & space constraint. In general, the ESP design in thermal power plant is of very compact nature consisting of 06 pass, 09 rows & total 108 hoppers per unit & numerous ash piping for ash collection,

Thus, to establish & ensure steady state condition & desired air parameters with even distribution at pick-up points standard orifice plate were replaced by the specially modified gas distribution orifices with multiple small holes.

This unique, innovative designed gas distribution orifice plate has provided unprecedented performance on air flow optimization during trials.

Gas distribution orifice major advantages are

1 Number of small holes equal to one large hole which distributes gas uniformly due to comparably less swirling effect on upstream side and downstream side.

2 Steady state flow condition of air achieved as it requires a straight pipe run of only two diameters upstream and downstream, with standard orifice it was not achieved due to space constraints

3 Orifices with no of small holes, this small hole can partially have blocked as per requirement of system for fine controls with single type.

4 It requires a straight pipe run of only two diameters upstream and downstream, providing significant reduction in piping requirement which reduced system cost also enhanced measurement accuracy.in short length of pipe.

Tested orifices were installed at conveying air inlet to get minimun value of conveying air to achieve maximum loading ratio so as to achieve maximum throughput of ash. The number of holes used can be varied and controlled by blocking some hole. Gas distribution orifice provided better accuracy and approximation and better results are obtained.

Previously, the mass flow rate of air was decided to measure by creating the differential pressure across the orifice just before the ash pick up point in air supply line. However, it was observed that the differential pressure was showing frequent line pressure hunting in downstream pressure of orifice due to complex phenomenon in mixed mode. Hence, it was decided to measure the mass flow rate of air by hand held anemometer at discharge outlet i.e. at air vent line of ash Silo.

To define the safe and optimum conveying conditions, straight-pipeline pneumatic conveying characteristics will be obtained through such small but such unique innovative approach. This method of online experimentation is aimed to address the partial filling of pipe's cross section by the dune of dry ash which requires high volume conveying air or sometimes chocking of section due to large Dry ash plug formation, in between conveying length which increase system downtime. Experimentation on similar pipeline configuration appears to be a better method as it does not require scaling.

Fig. 3a Silo mounting, Target box Vent box with bag filters arrangement.

Fig. 3b Silo mounting, Target box Vent box with bag filters arrangement.

Observation table: To record the values of various parameters an observation table was prepared to record the various experimental parameters. The observation table is prepared in Microsoft excel.

Steady state dry ash conveying data
Dry ash sample-E-123

Sr. No.	ρb	μp	P1	P3	del P	Vair	Ma	Ms	LR
	Kg/m3	μm	kg/cm2	kg/cm^3	kg/cm3	m/s	kg/s	tonns/hr	
1	750	45	2.5	0.99	1.51	4.082315	0.1539	47	84.83142
2	750	45	2.4	0.99	1.41	3.766658	0.142	46.5	90.96244

3	750	45	2.3	0.99	1.31	3.724217	0.1404	46.3	91.60336

Table 5 Sample observation table

Properties of Test Samples were evaluated, and calculations were performed as procedure explained in the next chapter. The detailed procedure calculations of conveying parameters is explained in the next chapter of experimentation and analysis.

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