Synergising mixture DoE with CFD for ash-slurry optimisation

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Abstract: Present research work describes the issues associated with slurry transportation systems in thermal power plants. It not only explores the importance of such ash handling systems but also embarks upon a step-by-step procedure to optimise slurry contents, without ignoring flow process parameters like velocity and pipe diameter to ensure least possible drop in the flow pressure, along the length of pipe. After analysing the research gaps, a strategic methodology based on the philosophies of mixture design of experiments (DoE) and computational flow dynamics (CFD) was suggested. Experiments were designed and performed in a balanced orthogonal matrix, before simulating through CFD. A deviation of mere 8% (approximately) was found in the end results, and hence an average drop in pressure from 3176 to 1252 KPa was unleashed, in the first attempt itself. The rheological properties (like pH value or settling properties) of slurry were assumed to be in required ranges and their relative impacts on critical flow metrics of slurry transportation system were not studied. The present study used an integrated approach to study the flow and further proved its authenticity by implementing it in an Indian thermal power plant successfully.

Keywords: bottom ash; CFD; cox-plot; fluent; fly ash; gambit; Minitab; mixture DoE; overlaid contour plot; slurry.

Paper Type: A Case Study.

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1 Introduction

Ash is a major by-product of thermal power plants all over the world. It is an outcome of burning of pulverised coal and is divided into two main categories: fly ash and bottom ash (Usui, Li and Suzuki, 2001). The fly ash particles are too fine that they can be transported from the combustion chamber by exhaust gases themselves (refer Figure 1). They exist in powder form and basically constitute the non-combustible mineral matter in coal (Jaglan, Khanduja and Kaushik, 2013). Fly ash differs from bottom ash in physical, mineralogical and chemical perspectives (Boylu, Dinc¸er and Atesok, 2003). Bottom ash is a coarse, granular and incombustible product obtained at the bottom of furnace (see Figure 2). Generally, mixture of solids with liquids is known as slurry (Sarkhi and Solemani, 2004). The physical characteristics of slurry are dependent on many factors such as particle size distribution, solid concentration in the liquid phase, turbulence level, temperature, conduit size and viscosity of the carrier (Harmadi, Machmudah and Winardi, 2002). Actually, slurry is a mixture of solid particles and fluids held in suspension. Water is the most commonly used fluid. The speed of slurry flow should be sufficiently high to maintain the particles in the state of suspension. Slurry transportation through pipeline provides best way to transport ash (Ibrahim, 2005). It causes minimum pollution and is less noisy (Patnaree and Narasingha, 2012). So, this article emphasises more on optimisation of slurry content as well as pipeline dimensions, to improve overall effectiveness and efficiency of transportation.

Figure 1 Fly ash (see online version for colours)

Figure 2 Bottom ash (see online version for colours)

Different types of pipes such as pipes made from carbon steel, cast iron and galvanised iron pipes are being used for transportation of slurry from one point to another. In the present work, carbon steel pipe has been used to transfer slurry from boiler section of plant to the dumping site (Zengjie et al., 2011). Such slurry pipelines have been used to transport solid materials mixed with water for shorter or longer distances. In fact, these pipelines are widely used in many industrial applications for brisk material handling (Verma, Singh and Seshadri, 2006). The slurry is blended with some compound known as ‘surfactant’ that lowers the surface tension (or interfacial tension) between two liquid particles or between the liquid and solid particles. Detergents, wetting agents, emulsifiers, foaming agents and dispersants can be used as surfactants (Aktas and Woodburn, 2000). For ash slurry, Triton X-100 has been used to reduce interfacial tension in slurry flow. It is realised that slurry system fails mainly due to choking problem in regular operating conditions and this can be avoided substantially by reducing the pressure drop of slurry along the length of pipe. So the pressure drop along the length of pipe becomes the critical metric, which must be monitored and checked while deciding the slurry composition, flow velocity, pipe diameter and so on.

Experiments at different compositions of fly ash, bottom ash, additive and water are designed through 'Mixture Design of Experiment' technique. Even runs at various settings of flow velocity and pipe diameters have also been carried out. Computational fluid dynamic (CFD) software is used to perform flow analysis for assessing slurry pressure drop inside the pipeline. Initially, the geometry of actual pipe is generated as per its dimensions by using 'Gambit' design tool. Then, the mesh generation of pipe geometry is created that subdivides it into minute control volumes. Meshing is a way to define and break up the whole pipeline into small elements (Goh, 1988). Now each control volume has corresponding values for its flow-dependent variables like velocity and pressure. During pre-processing, boundary conditions are formulated (Mukhtar, Singh and Seshadri, 1994). The simulation is performed at steady-state and the obtained results are visualised post-processing. In the present scenario, a straight pipe is generated to study pressure drop per 100 metre length. Modelling of the pipe is developed in Gambit Software (version 2.2.30), and the next simulation of fluid flow through pipeline is carried out in 'Fluent' software.

Before executing all the designed runs, some extra runs at various compositions have been simulated and validated with actual experimental findings. Now, once simulation is fine-tuned, the CFD software is utilised for systematic accomplishment of all designed runs. Mixture DoE will do the necessary analysis of CFD findings as far as impact of slurry contents, flow velocity and pipe diameter on pressure drop are concerned. This article provides an optimisation approach that not only determines the optimised slurry composition but also provides suitable values of process variables like flow velocity and pipe diameter at which pressure drop would be minimum or within the permissible limits. The two-sample hypothesis testing is applied to verify the solution provided by Minitab calculations. About 30 runs have been conducted at optimised settings and are fed to statistical software for assessing actual accomplishments.

2 Literature review

Huge attention has been paid to the topic of easy and safe transportation of slurry since 1996. With time, people have earmarked the hazardous aspects of handling fly and bottom ash. The majority of scholars believe in transporting the ashes and coal dusts by making suitable aqua-based slurry. They found it to be the fastest and environmental-friendly method to tackle the menace of this fine-grained ash, which may cause fatal diseases like tuberculosis, kidney stones and sever stomach syndromes. Some authors put pressure on nontangible way to transport ash from furnace region. It has been surveyed that the condition in developing nations is even worst and need immediate attention, as ash handling is done manually because of availability of cheaper labour (Sushil, 1990). A wide literature review on slurry transportation system has been conducted to realise the 'status quo' of existing slurry pipeline facilities. An effort has been made to put the philosophies and innovative ways to improve performance metrics of slurry transportation method in a chronological order, as explained in the table below.

Table 1 Scrutiny of existing work

References	*Work illustrations*
Logos and Nguyen (1996)	The results obtained in this study indicated that, with a careful control of the particle size distribution, it was possible to prepare optimum coal-water slurry which had a low viscosity and high solid loadings.
Aktas and Woodburn (2000)	This article found that coal and water slurry viscosity was influenced significantly by surfactant loading, the particle size distribution and the solid content of coal in water.
Usui, Li and Suzuki (2001)	The work represented a feasibility study of fly ash hydraulic transportation system with minimum viscosity from a coal-fired power station to a controlled deposit site which was carried out to predict the maximum packing volume fraction with non-spherical particles.
Harmadi, Machmudah and Winardi (2002)	This work studied experimentally the effects of particle size distribution of pulverised coal to rheology and stability of coal-water mixture (CWM). Particle size distribution affected the maximum coal solid concentration achieved in CWM suspension. The results showed that maximum solid concentration increased with decrease of particle size.
Boylu, Dinc¸er and Atesok (2003)	In this work, three main methods for reducing the frictional pressure loss were discussed. The first method reduced the degree of flotation of the particles in the slurry by using suitable chemical additives and thereby reduced the slurry viscosity. The second method used boundary liquid such as water, oil and polymer solutions, which were injected at comparatively small flow rates into the pipe downstream adjacent to the pipe wall. The third method involved gas injection into the pipe downstream (from the pump to form a slug flow pattern) which resulted in substantial frictional pressure loss reductions for a non-Newtonian slurry.
Sarkhi and Solemani (2004)	This work measured the impact of addition of the drag-reducing polymers (DRP) to two-phase flow patterns in a horizontal 0.0254-m pipe. The characteristics of two-phase flow with and without DRP were described. It was noted that the interfacial shear stress decreased sharply by adding DRP and the flow pattern map was changed. Pressure reduction occurred in almost all flow pattern configurations.
Ibrahim (2005)	This study explained the new empirical equations for head loss ‘h’ due to friction undergone by water flowing in a pipeline. The calculation of the parameters of the proposed models had been done through nonlinear multivariable regression. Maximum relative errors of each model were less than 2%. Therefore, these simple equations could offer vital advantage in optimisation study.
Verma, Singh and Seshadri (2006)	Discussed the rheological behaviour of fly ash slurry with and without additives for different particle size distributions and concentrations of the solid-liquid mixture. Sodium hexa-metaphosphate was used at 0.1% concentration (by weight) as additive and the pressure drop in a straight pipeline of 75 mm diameter was also calculated by using the rheological data.

Table 1 Scrutiny of existing work (continued)

References	*Work illustrations*
Ahmed, Ching and Shoukri (2007)	Investigated the effects of coal characteristics on the properties of coal-water slurry by using 16 different samples of Chinese coal (from lignite to anthracite). From the investigation author concluded that the carbon content and grindability index of coal showed a positive correlation with the slurry ability. The experiments performed revealed that the rheological behaviour of CWS could be positively correlated with ash content.
Ekambara et al. (2008)	Described the internal phase distribution of concurrent air-water bubbly flow (in a 50.3-mm horizontal pipeline) modelled through CFD. The liquid and gas volumetric superficial velocities varied from 3.8 to 5.1 m/s and 0.2 to 1.0 m/s, respectively.
Naik, Mishra and Karanam (2009)	Defined the design of pipeline to deliver fluid at the required head and flow rate in a cost-effective manner. This study presented a computer-aided optimisation technique for determination of optimum pipe diameter for a number of idealised turbulent flows.
Chandel, Singh, and Seshadri (2010)	Carried out a rheological study for mixture of fly ash and bottom ash slurry. The dependence of relative pressure drop on flow velocity at various concentrations was also analysed. Furthermore, by using the rheological data, pressure drop had been predicted for a straight pipeline of 42 mm diameter at higher concentrations. Experimental results obtained from a pilot test loop were compared with the predicted results. The comparison showed a very good agreement between these data. Specific energy consumption for the transportation of coal ash slurry was calculated at fixed velocities and its dependence in solid concentration was quantitatively analysed.
Naik, Mishra and Karanam (2011)	Observed the flow characteristics of fly ash slurry at 40% concentration with and without additives after collecting six samples of fly ash from different power stations from South India. They concluded that in this way it was possible to design pipelines and pumping systems for transporting ash slurries at high concentrations.
Chandel (2011)	Investigated the slurry flow in a vertical pipe for pressure drop predictions. An axisymmetric model was considered to obtain a steady, incompressible solution of solid-liquid flow in a vertical pipe. Finite volume methodology had been adopted. The Eulerian Multiphase Model in FLUENT 6.1 R was adopted for this work. Mixture *k*-€ turbulence model was used for modelling the turbulence.
Zengjie et al. (2011)	Highlighted the effect of ash content and particle size gradation on rheological properties. Author selected two coal samples with corresponding different grinding times and particle sizes. The researcher measured the concentration, viscosity, fluidity and stability of each coal water slurry sample. From the investigations, it was concluded that the ash content in Australian coal was 21.72% higher than the ash content measured in Chinese coal.
Patnaree et al. (2012)	This work examined the impact of particle size distribution and packing characteristics on the rheological behaviour and solid loading of coal-water slurry (CWS). The coal samples with six particle size ranges (i.e., < 38 µm, 38–63 µm, 63–75 µm, 75–90 µm, 90–180 µm and 180–250 µm) were used and three different packing characteristics were chosen for the experiments (i.e., mono-modal, bi-modal and multi-modal). The results showed that the coarse-to-fine ratio had an effect on the rheology of CWS.

Table 1 Scrutiny of existing work (continued)

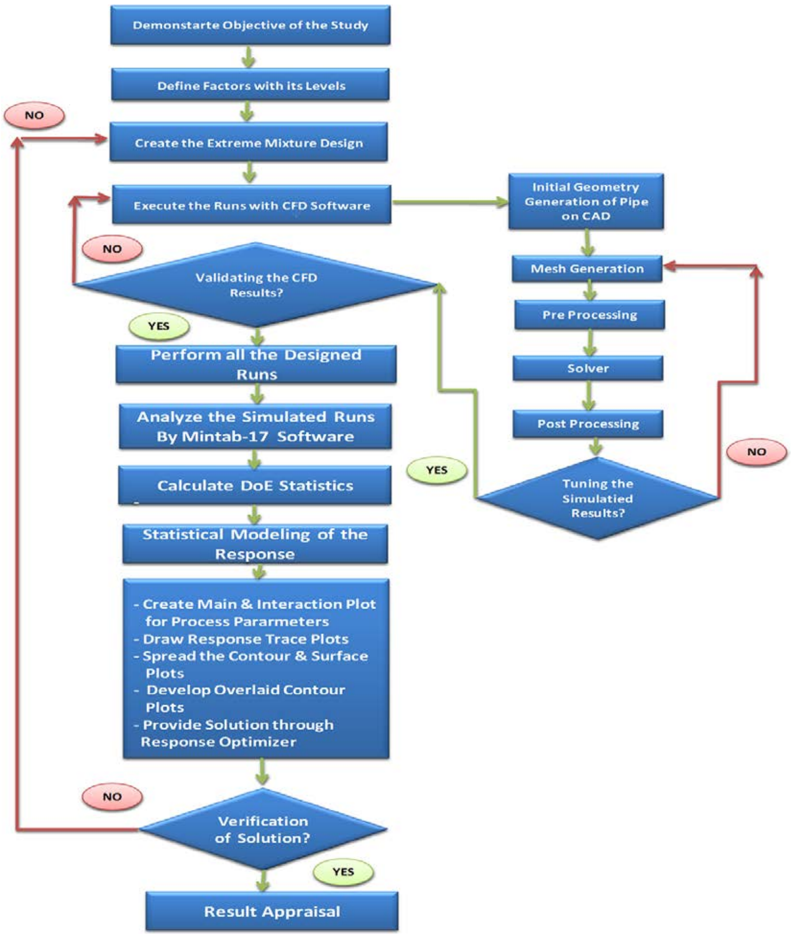
References	*Work illustrations*
Kaushal et al. (2012)	Conducted a numerical simulation of pipeline slurry flow of mono-dispersed fine particles at high concentration by using Mixture and Eulerian two-phase models. Both models were an integral part of the software package FLUENT. It was concluded that the lateral variation of solid concentration in the pipe cross-section was more dominant at higher concentrations and flow velocities.
Desamala et al. (2013)	Investigated the transition boundaries of different flow patterns for moderately viscous oil-water two-phase flow through a horizontal pipeline with internal diameter and length of 0.025 m and 7.16 m, respectively. Geometry and meshing of the present problem was drawn by using GAMBIT, and ANSYS FLUENT was used for simulation. A total of 47,037 quadrilateral elements were chosen for the geometry of horizontal pipeline.
Nicolici, Prisecaru and Dupleac (2013)	Used CFD for simulation of two-phase flow in pipe-bends, which were also subjected to erosion due to liquid or solid particles. The main objective was to obtain the impact characteristics of the particles upon the bend, outer wall velocity, angle and frequency of impact. The influences of some parameters (i.e., particle dimension, particle density, carrier fluid viscosity etc.) were investigated.

Generally, investigators concentrated more on rheological properties of coal, dust, ash and so on to reduce the pressure drop of slurry along the pipeline. However, this has not given a major breakthrough. Mainly, work has been done on the study of slurry flow through pipeline with small diameter and shorter length. The composition of slurry is less focused as far as pressure drop is in picture. Very few scholars have made efforts in this scheme and used the conventional one-factor-at-a-time (OFAT) technique. It is rare to find the work which could optimise contents of slurry by designed and balanced experimental runs, specifically by using Mixture DoE technique. Many authors used simulating software like CFD to save time and energy, but it is hard to see synergy of Mixture DoE with CFD to bring necessary optimisation of slurry composition by taking care of process variables (e.g., flow velocity and pipe diameter) simultaneously.

3 Proposed methodology

The present investigation provides an economical slurry flow by minimum use of costly additives and precious water. The rheological properties of slurry are assumed to be favourable and within ranges. The proposed methodology is a unique experimental way to blend various contents of slurry in such a fashion that it ensures minimum possible pressure drop per 100 meter of pipe length. It also elaborates the variation of response at different levels of pipe diameter and flow velocity. It envisages a step-wise approach to use sophisticated Mixture DoE technique for effective slurry optimality (refer Figure 3 for details). Moreover, it is a fact that CFD simulation eases the actual experimentation at various designed conditions appreciably.

Figure 3 A comprehensive approach for slurry optimisation (see online version for colours)



CFD is a branch of fluid mechanics that uses numerical methods and algorithms to analyse and solve problems that involve fluid or slurry flows (Malik, Aggarwal and Dua, 2014). Nowadays it has become an indispensable tool in the design, development, evaluation and refinement of new industrial equipment and flow processes. The use of CFD reduces the development cost of experiments and cuts the time of execution.

4 Case findings

An experimental study was conducted in an Indian thermal power plant as per the guidelines of mentioned in the methodology. Initially, the objective was to create an appropriate composition of slurry constituents with relevant values of process parameters, which ensured inherent least pressure drop in slurry flow. After brainstorming with the concerned people, factors (or constituents) had been interpreted at their corresponding lower and upper levels (Raisinghani et al., 2005). Two process parameters, namely velocity of slurry flow and diameter of pipe, were shortlisted for studying their respective impact on pressure drop. One linear constraint (regarding bottom ash and fly ash content) was implicated, while designing orthogonal matrix of runs through Mixture DoE.

Table 2 Factors with respective levels

Factors	*A*	*B*	*C*	*D*	*P1*	*P2*
Levels	Bottom ash	Fly ash	Additive	Water	Velocity	Pipe diameter
Lower	4%	6%	1.50%	40%	25 m/s	350 mm
Upper	40%	50%	3%	70%	40 m/s	450 mm

Linear constraint; A + B ≤ 55%

'Minitab-17 Release' software was utilised to generate designed runs by considering principle of multi factor at a time (MFAT) of Mixture DoE. Runs were designed in such a way that the total percentage of constituents in each run remained constant (i.e., 100%), which varied with the different factors in between their respective levels, along with imposed constraint (Antony, Yao and Ghosh, 2003). Initially, 10 runs were executed in actual environment and their respective pressure drop was calculated with suitable pressure gauges. Now, the same experimental runs were repeated by using CFD as simulating software. After a few minor adjustments, the results of CFD simulation emerged with only less than 4% error (which was less than the permissible limit of 10%). Hence, CFD had successfully simulated the real-world experiments along with its environmental and process constraints. After proper validation, all the experimental runs were simulated on CFD at various flow process settings and carried out in the lab itself. About 100 runs had been designed with DoE (refer Annexure 1 for details). These runs at respective experimental settings were performed through CFD simulations. The standardised procedure to organise these runs is described in Table 3.

Table 3 Simulation of experimental runs with CFD (see online version for colours)

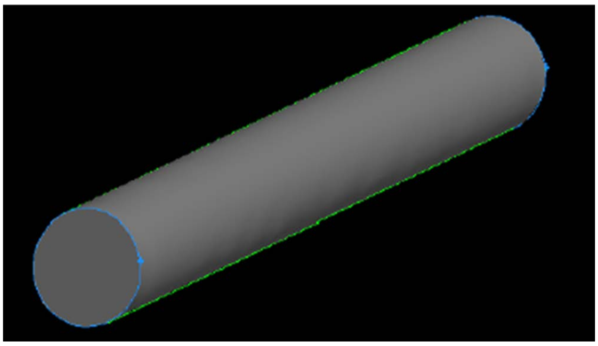
Geometry generation The three-dimensional modelling of a straight pipe was developed in Gambit software version 2.2.30. The geometry was created from the real dimensions and specifications of actual pipe length as shown in the second column of the table.	

Table 3 Simulation of experimental runs with CFD (see online version for colours) (continued)

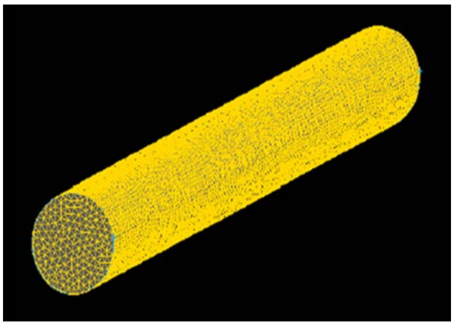
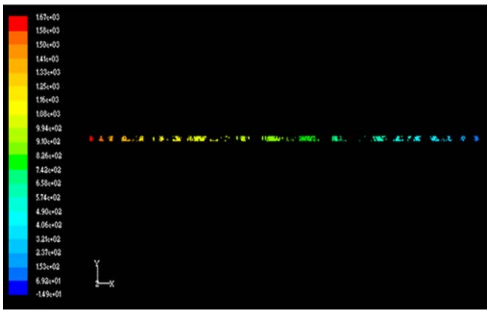
Mesh generation It was the process of subdividing a region (to be modelled) into a set of small control volumes (Joshi and Singh, 2013). In general, a finite element model was defined by a mesh network, which was made up of elements and nodes. Nodes represented points at which features such as displacements were calculated. It was important to check the quality of mesh because parameter such as skewness affected the accuracy of the CFD simulation (Desamala et al., 2013). Each element had a value of skewness between 0 and 1. The smaller values of equi-angle skew and equi-size skew were more acceptable.	
Boundary conditions The first step in pre-processing was setting up the boundary conditions. Boundary condition will be different for each type of problem. Physically, meaning of boundary condition is to specify the input and output conditions (Nicolici, Prisecaru and Dupleac, 2013). In the present study, velocity was given at the inlet and pressure at the exit of slurry transportation pipeline. Multiphase flow is a flow in which more than one fluid is present. In general, the fluids consist of different chemical species, e.g., solid-water. Two-phase flow of water and coal ash was given as input parameter to simulate the computational fluid dynamic problems (Kaushal et al., 2012). These conditions specify the flow and thermal variables on the boundaries of a physical model. Boundary conditions are therefore a critical component of simulation, and it is important that these are specified logically (Chandel, 2011). It is also important to verify that all of the elements in mesh have positive area/volume ratio; otherwise the simulation in solver is not possible. Basic assumptions on which the simulation was done were as follows (Naik, Mishra and Karanam, 2011): • Steady-state condition • Incompressible fluid flow • Constant fluid properties	The conditions that were applied for numerical simulation of the slurry transportation line were given below: • Velocity inlet was applied on the inlet face of pipeline. Pressure outlet was applied on the outlet face of delivery pipeline. • Slurry was added in material list by giving soot conditions density and molar mass. Bottom ash density and molar mass were taken as 2250 kg/m3 and 36.281 g/mol, respectively. In this case, if fly ash density was taken as 1950 kg/m3 then its corresponding molar mass was 28.12 g/mol. • Bottom ash's specified diameter was taken as 162 micron and for fly ash it was 57 micron. Simulations were done according to designed run conditions provided by Mixture DoE matrix. • 4% turbulence intensity and turbulence viscosity ratio of 10 was taken for inlet conditions. The 4% backflow turbulence intensity and backflow turbulence viscosity ratio of 10 was taken for outlet condition.

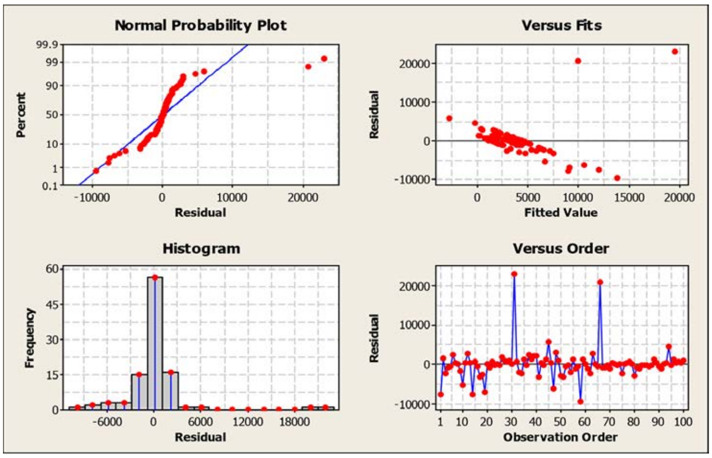
Table 3 Simulation of experimental runs with CFD (see online version for colours) (continued)

Solver The simulation was started and the equations were solved iteratively on a steady-state (Löhner and Camelli, 2005). There were mainly three methods for solver: • Finite volume method (FVM) • Finite element method (FEM) • Finite difference method (FDM) In the finite volume method, governing equations were in the integral form. In this method, the solution domain was subdivided into a finite number of continuous control volumes (Ekambara et al., 2008). After this conservation equation was applied to each control volume. Computational node was located at the cancroids of each control volume. Advantage of this method was that it could be applied to any types of grids.	In finite element method, governing equations were multiplied by a weight function before they were integrated for the entire domain. The finite element method formulation requires special care to ensure a conservative solution (Ahmed, Ching and Shoukri, 2007). This method is more stable than the finite volume method. Finite difference method used the governing equations in differential form. In this method solution domain was subdivided into grids. This method replaced the partial derivatives by approximations in terms of node values of the functions (Fan, Lampinen and Levy, 2006). One algebraic equation per grid node was presented. Linear algebraic equation system was used in this method. Finite difference could be applied to structural grids (Tralli and Gaudenzi, 2006).
Post-processor Post-processor is used for the analysis and visualisation of the obtained results. It displays the domain geometry and grid (Logos and Nguyen, 1996). Vectors and contour plots are used to visualise the results. The figure in the second column shows that when the concentration of bottom ash is increased in slurry then pressure in the pipe is also increased. The pressure will increase, when the velocity of slurry in straight pipe increases. It can be observed that pressure loss difference at high velocities is considerably more than the pressure loss difference at low velocities.	

Three-dimensional meshing with double-precision (3-ddp) solver was extremely useful when dealing with very sensitive analyses like aerodynamic drag prediction and multiphase flow systems. Meshing was an important factor to obtain better results. The standard K-€ model was selected for pipeline flow simulation. This model gave very useful results for turbulent flow. The convergence criterion in the simulation was 10^{-3}. The second-order scheme with limiters is one of the most popular numerical scheme due to its accuracy and stability. In CFD, simple algorithm was utilised in the numerical procedure to solve the Navier Stoke's equation, and, hence, it was extensively applied by many researchers to solve different kinds of fluid flow and heat transfer problems. All the designed runs were simulated as per the above procedure, and a proportionate value of slurry 'Pressure Drop' along the length of pipe was estimated (see Annexure 1 for details).

Generated runs with response values (pressure drop) were fed into Minitab-17 software for necessary evaluation and analysis. Primarily, data testing was conducted by residual plot to verify the error in predicted regression model of Mixture DoE (look at Figure 4). The normal probability plot ensured that the error was randomly distributed, but scatter plot identified some of the downward trends. This could be ignored because the numbers of runs of response (pressure drop) were more than 30 (sample size was sufficiently large). So it faded away somehow as a chance of systematic error (Narasimhan, 2005).

Figure 4 Residual analysis of response (see online version for colours)



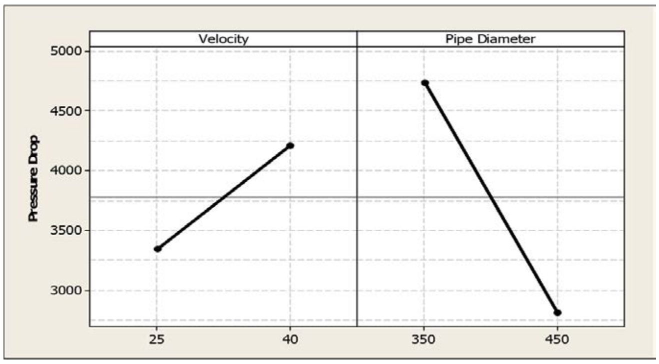
The third graph displayed an almost bell-shaped frequency distribution plot, and the last graph highlighted an arbitrary residue plot around the mean. It implied that the error (or residue) in predicted pressure drop was independent of run occurrence order. Minitab correlated and regressed an equation of pressure drop in terms of slurry contents (i.e., bottom ash, fly ash, additive and water) along with its two-way, three-way interactions and main parameters (i.e., flow velocity and pipe diameter) as quoted below.

$$\begin{aligned}\text{Pressure Drop} = {} & -9197\ \text{Bottom Ash} - 10918\ \text{Fly Ash} + 6008 \\ & \text{Additive} + 22605\ \text{Water} + 142848\ (\text{Bottom} \\ & \text{ash} \times \text{Water}) + 27694\ (\text{Water} \times \text{Velocity}) + \\ & 1362719\ (\text{Additive} \times \text{Water} \times (-)\ \text{Velocity}) - \\ & 119\ (1/\text{Additive} \times \text{Velocity}) + 133896 \\ & \text{Bottom Ash} \times \text{Water} \times (-)2 \times \text{Pipe Diameter} \\ & - 730580\ (\text{Additive} \times \text{Water} \times (-)2 \times \text{Pipe Diameter})\end{aligned}$$

The magnitude of coefficients for different factors and factor interactions directly reflected the impact of each on pressure drop. Higher weight signified the higher influence of corresponding factor on the response (Singh and Khanduja, 2011a). From the above model, it was obvious that in the present case, water had more effect on pressure drop than fly ash and bottom ash. The sign (positive or negative) of coefficient revealed whether the factor or its interaction was directly or inversely proportional to pressure drop.

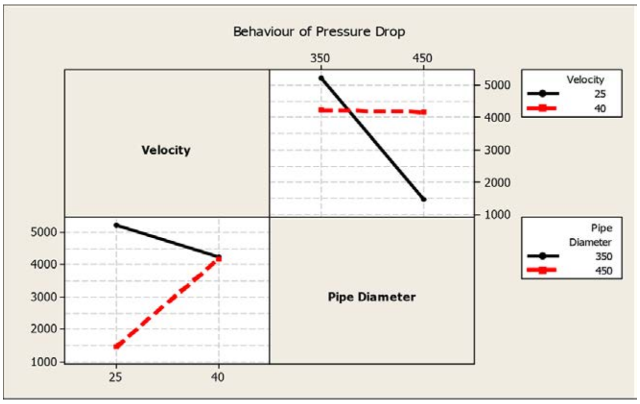
The main effect plot of process parameters highlighted the independent repercussions on pressure drop when each factor varied in between its lower and upper levels (see Figure 5). It pin-pointed the regular rise of pressure drop with variation in velocity from 25 m/s to 40 m/s, whereas response decreased when pipe diameter increased from 350 to 450 mm.

Figure 5 Main effect plot for pressure drop (see online version for colours)



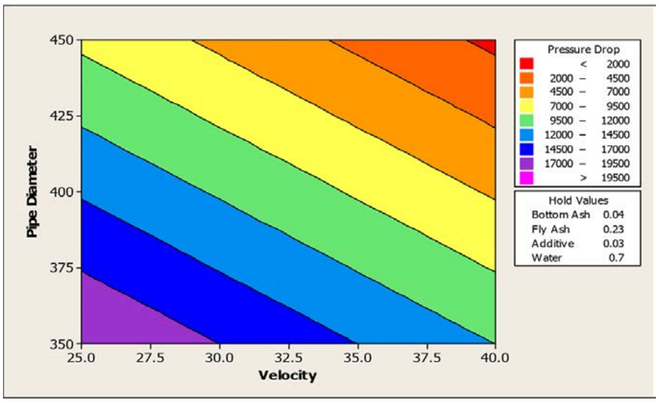
Similarly, behaviour of pressure drop with simultaneous variations in flow velocity and pipe diameter had been drawn through interaction plot for the process parameters (refer Figure 6). While varying the factors concurrently (within their level ranges), the crossed lines revealed the significance of the given interaction, as far as pressure drop was concerned.

Figure 6 Interaction plot of process parameters (see online version for colours)



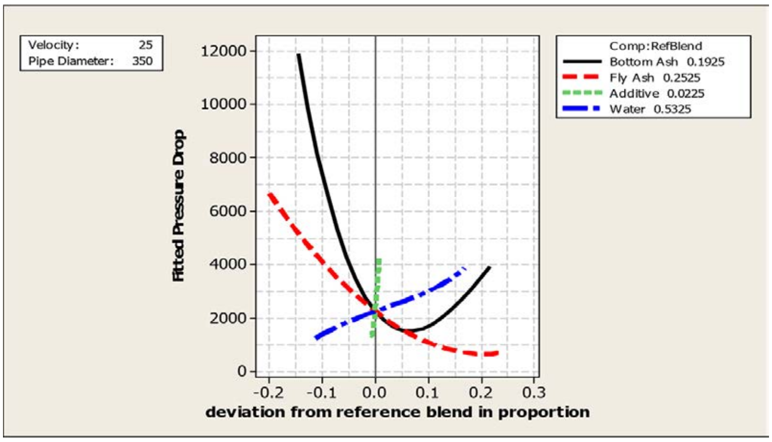
For a deeper insight, a surface plot had been sketched (see Figure 7). Flow velocity was taken on X-axis and corresponding pipe diameter on Y-axis. The whole region of the XY plane was divided suitably into differently coloured sections. Each section earmarked the region of specific pressure drop range. The relative holding values of slurry composition was clearly indicated on the side margin. For example, purple colour reflected the region of pressure drop (more than 19500) which was lying relatively closer to the boundaries of pipe diameter from 350 to 375 mm and velocity variation from 25 to 30 m/s, respectively.

Figure 7 Surface plot for process parameters (see online version for colours)



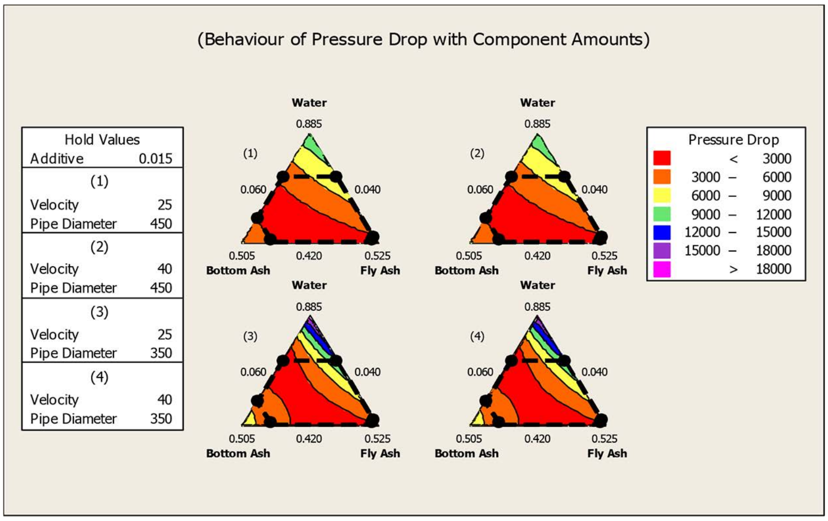
In compliance with the proposed approach, a response trace plot (also called a component effects plot) had been delineated. It showed how each component (or a mixture constituent) affected the response, relative to a reference blend. If the design contained process (or amount) variables then they must be held at a fixed level (look at Figure 8). In the present manifestation, reference blend was presumed and detailed at the margin of Cox plot as below. This ratio of mixture was assumed as a zero setting. Now if we increase or decrease the proportion of any component then pressure drop will vary accordingly and this is being represented here by different coloured lines. For example, if we increased the bottom ash from reference blend (0.1925) then respective pressure drop dipped up to 1400 kPa, but it suddenly started rising till 4000 kPa (follow the black curve). Similarly, if water level raised from the reference blend value (i.e., 0.5325 or 53.25%) then the pressure drop reached up to 3800 kPa. Upon further escalating the additive from 0.0225 (or 2.25%), it showed the pressure drop till 4200 kPa. The two shortlisted process parameters were maintained at lower levels.

Figure 8 Cox response trace plot (see online version for colours)



According to the proposed methodology, mixture contour plots had been laid down using a variety of holding combinations of process parameters by taking a reasonable additive value of 0.015 (or 1.5%). The response variable was related to the three mixture components based on a model equation (refer Figure 9). Those points which had the same response were connected to produce contour lines of constant responses. If you changed the holding levels (or values) then response surface would change as well and sometimes deviate drastically.

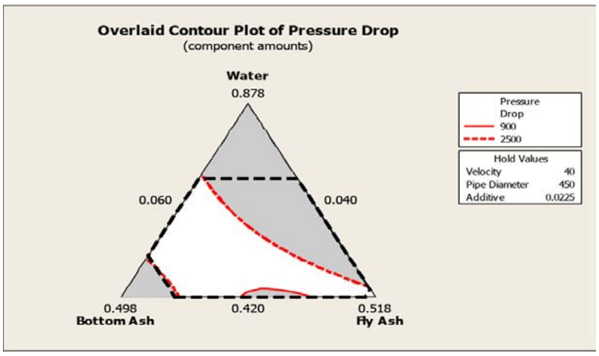
Figure 9 Multiple-mixture contour plot for pressure drop (see online version for colours)

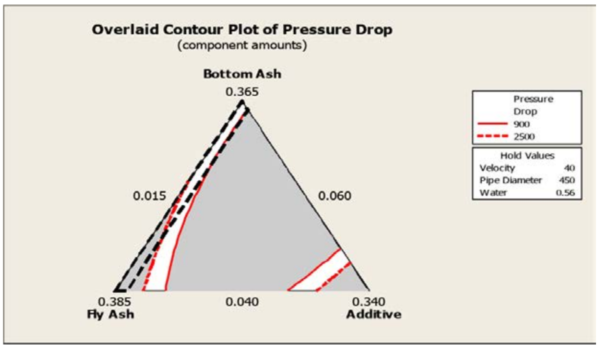


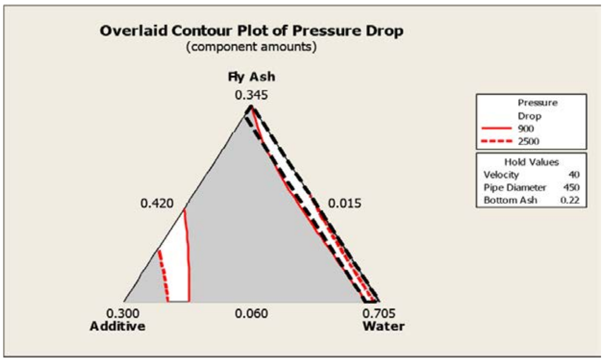
Water, bottom ash and fly ash were the three major constituents in thermal power plant's slurry. The additive percentage was worked out from the Cox plot, and a value of 1.5% was found sufficient. Now, for lower- and upper-level combinations of flow velocity and pipe diameter, four contour plots had been analysed that elaborated the pressure drop variations comprehensively. Each plot was a combination of set of regions related to specific pressure drop zones like brown zone, which reflected the pressure drop zone from 3000 to 6000 kPa, or the red zone, which represented the pressure drop less than 3000 kPa.

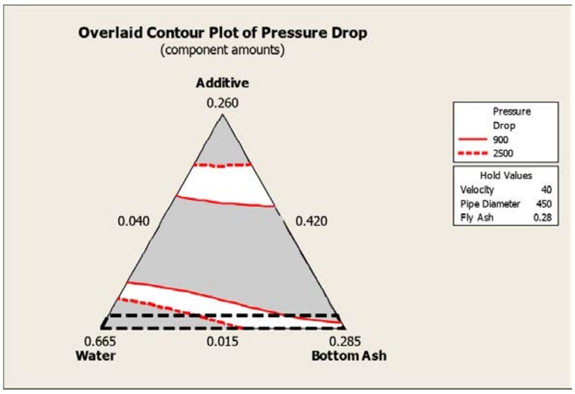
After studying the main and interaction plot, the velocity was fixed to 40 m/s, and corresponding pipe diameter was shortlisted as 450 mm, to bring some breakthrough in pressure drop. To materialise the favourable region of response, an overlaid contour plot was sketched out (see Table 4). Each set of contour lines defined the boundaries of acceptable response range which one could impose. As we wanted to reduce the pressure drop, we tried to highlight the region corresponding to pressure drop between 900 to 2500 kPa only. The solid line was the lower bound, and the dotted line represented the upper bound in each contour plot drawn respective to various holding values of factors. It focused on the optimised values of factors to a great extent. The white region was the desired one, which entitled response in its required range. The coordinates of three factors that enclosed this white region could easily be back-tracked. Minitab software draw the plots individually by holding additive at 2.25%, water at 56%, bottom ash at 22% and fly ash at 28%, sequentially.

Table 4 Overlaid contour plots (see online version for colours)



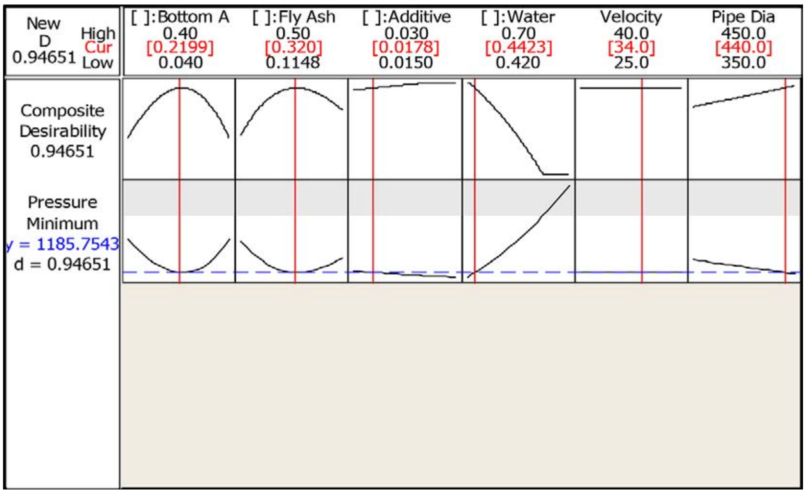






At last, the response optimiser tool of Minitab software was used to predict specific values of slurry components and process parameters at which pressure drop would be least (refer Figure 10). The optimisation plot showed how the factors affected the predicted responses and allowed us to modify the factor settings interactively. Each column of the graph was set to correspond to a factor and the row was dedicated to a response variable. Each cell of the graph showed how the corresponding response variable or composite desirability changed as a function of one of the concerned factor while other factors remained fixed (Singh and Khanduja, 2011b). The numbers displayed in the top row displayed the high and low factor settings in the experimental design, and the readings specified by the red colour were the solutions provided by response optimiser. The first column showed a combined overall desirability of 94.6% to obtain pressure drop of about 1185.7 kPa (whereas slurry contains 21.99% bottom ash, 32% fly ash, 1.78% additive and water content at 44.23%). The flow velocity should be approximately 34 m/s and pipe diameter must be near 440 mm. The vertical red lines on the graph represented the current factor settings chosen as a solution to slurry optimisation problem. The horizontal blue lines represented the corresponding response values (Parody and Autin, 2013). The grey regions indicated the factor settings where the corresponding response (pressure drop) has zero desirability.

Figure 10 Response optimiser (see online version for colours)



In order to verify the pressure drop achieved from synergy of CFD and Mixture DoE, real-world experimental runs (at least 30 in numbers) had been performed at optimised slurry composition and process parameter values. After that, a two-sample *t*-test was executed on pressure drop data (as shown in Table 5) to check and monitor the actual response value achieved at predicted solution. It also compared the pressure drop at optimised settings appropriately with regular drop in pressure at general settings. The optimised settings (OS) of factor was the specific solution provided by Mini Tab, whereas general settings (GS) of factors were the random values varying in between the respective lower and upper levels of factors.

Table 5 Pressure drop data at general settings and optimised settings of factors

Pressure drop (GS)	*Pressure drop (OS)*
4243.8	1345.2
4243.8	1278.9
2912.3	1195.2
1426.8	1352.1
1084.4	1225.4
1425.1	1255.1
4243.8	1320.4
4243.8	1133.7
1185.2	1335.2
4243.8	1159.2
4243.8	1332.4
4243.8	1145.2
4125.3	1175.5
2103.6	1201.5
3488.4	1188.2
4243.8	1195.4
2489.3	1301.5
2995.5	1234.7
3808.6	1255.9
1424.8	1204.2
4243.8	1191.4
4113.4	1298.1
2674.7	1325.1
4243.8	1301.2
4243.8	1288.4
1502.5	1280.4
4243.8	1199.4
3597.5	1208.4
2987.3	1301.4
994.2	1339.3

The required hypothesis was formulated. 'Null hypothesis' favoured no variation in mean pressure drop, whereas 'alternate hypothesis' supported the major variation in pressure drop at respective general and optimised settings. The data procured during the experimentation had been fed to Minitab software for conceiving the two-sample *t*-test and the relevant statistics are illustrated in Figure 11.

Figure 11 Statistics of two-sample *t*-test

Two-sample *t*-test: pressure drop (GS) vs. pressure drop (OS)

Two-sample *t*-test for pressure drop at general settings and pressure drop at optimised settings

Mean, SD, SE, Mean

Pressure drop (GS) 30 3176 1221 223

Pressure drop (OS) 301252.3 66.1 12

Difference = mu (pressure drop (GS)) – mu (pressure drop (OS))

Estimate for difference: 1923

95% CI for difference: (1467, 2380)

T-test of difference = 0 (vs not =): T-Value = 8.61

***P*-value = 0.000,** *df* = 29

As the '*p* value' came out to be 0.000, which was less than the barrier value of 0.05, the alternate hypothesis had been accepted. Hence, the statistically significant difference between the means of pressure drop at general settings and optimised settings was found to have the 95% confidence intervals. To verify the results of *t*-test graphically, appropriate individual value plot and box plot should be drawn (Singh and Sodhi, 2014). The first graph was the individual value plot, pinpointing all the pressure drop points independently at general and optimised settings (see Figure 12). The pressure drop mean line showed a negative slope towards optimised settings, which means substantial reduction in mean pressure drop (i.e., from 3175.5 to 1252.2) had been achieved.

Figure 12 Individual and box plot (see online version for colours)

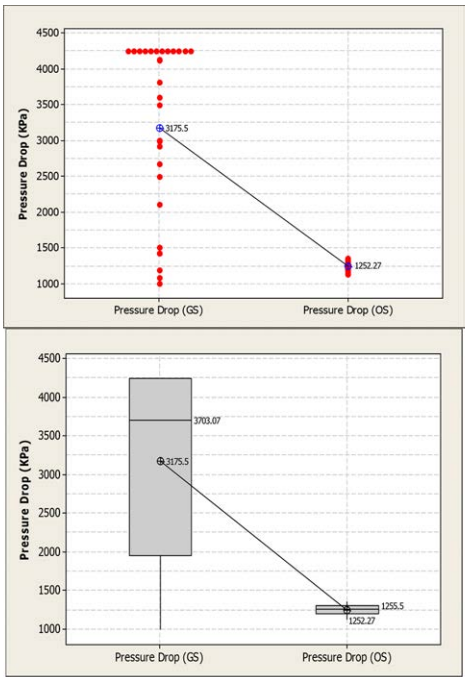
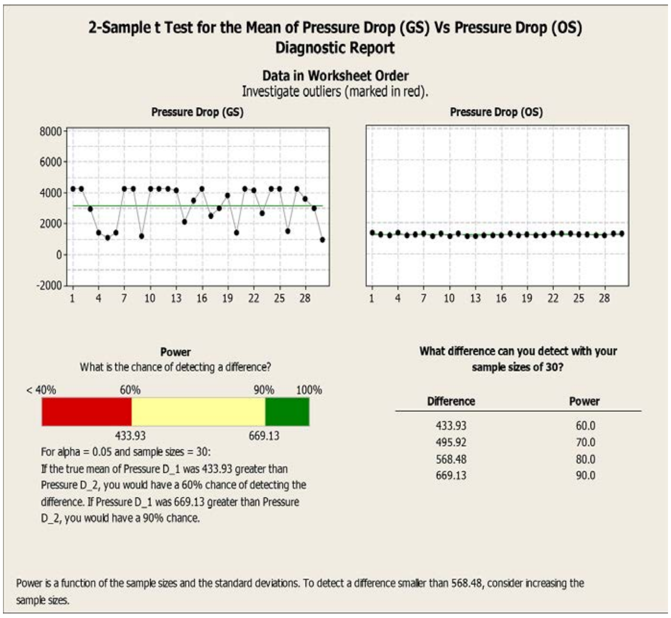


Figure 13 Comparison of Pressure drop at GS & OS (see online version for colours)



2-Sample t Test for the Mean of Pressure Drop (GS) Vs Pressure Drop (OS)
Diagnostic Report

Data in Worksheet Order
Investigate outliers (marked in red).

For alpha = 0.05 and sample sizes = 30:
If the true mean of Pressure D_1 was 433.93 greater than Pressure D_2, you would have a 60% chance of detecting the difference. If Pressure D_1 was 669.13 greater than Pressure D_2, you would have a 90% chance.

What difference can you detect with your sample sizes of 30?

Difference	Power
433.93	60.0
495.92	70.0
568.48	80.0
669.13	90.0

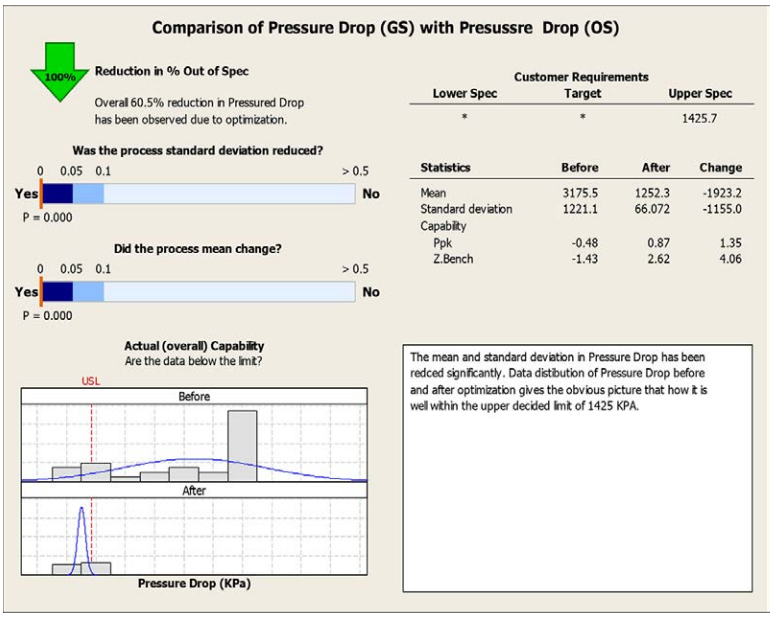
Power is a function of the sample sizes and the standard deviations. To detect a difference smaller than 568.48, consider increasing the sample sizes.

The software predicted an average pressure drop of 1185.7 kPa, but in actual terms we obtained a drop of 1252.2 kPa. This difference might have occurred due to some noise and uncontrolled elements in actual working conditions. The second graph was the box plot, which demonstrated the non-ignorable gap between mean and median of pressure drop data in general settings than those in optimised settings. This reflected an uncertain or volatile behaviour of slurry flow process in general setting of factors.

A diagnostic report was provided by the software to visualise the pressure drop at general and optimised settings effectively. The control graphs explained in particular the deviation and dissimilitude among pressure drop data at general and optimised settings. The mean pressure drop line at general settings was lying quite higher than the corresponding mean pressure drop line at optimised settings. Hence, this was supporting our findings. Moreover, this report also depicted 60% probability of getting difference of 433.9 kPa in between pressure drop at GS and OS, respectively. Similarly, it also predicted in advance how the chance of getting the difference increases (from 60 to 90%) with relative rise in difference of pressure drop (from 433.9 to 669.1 kPa) as far as GS and OS are concerned.

Finally, a summary report encapsulated the whole findings and illustrated the substantial decrease in mean and standard deviation of pressure drop at GS and OS statistically (refer Figure 14). Normal distribution curves before and after optimisations were self-explaining the achievements along with the hike of 1.35 in flow process performance index (Ppk). The decrease in standard deviation (–1155.0) further inculcated more consistency and repeatability in slurry flow process among longer pipes.

Figure 14 Summary report (see online version for colours)



Overall 60.5% reduction in Pressured Drop has been observed due to optimization.

Customer Requirements		
Lower Spec	Target	Upper Spec
*	*	1425.7

Statistics	Before	After	Change
Mean	3175.5	1252.3	-1923.2
Standard deviation	1221.1	66.072	-1155.0
Capability			
Ppk	-0.48	0.87	1.35
Z.Bench	-1.43	2.62	4.06

The mean and standard deviation in Pressure Drop has been redced significantly. Data distibution of Pressure Drop before and after optimization gives the obvious picture that how it is well within the upper decided limit of 1425 KPA.

More than 95% of pressure drop data (at optimised settings) was falling behind the upper limit of 1425 kPa, and this proved the efficacy of the proposed approach. An overall reduction of 60.5% in pressure drop had been attained through this comprehensive methodology, which used the application of Mixture DoE and CFD principles, strategically.

5 Conclusion

The problem of ash handling is mounting day by day in thermal power plants, specifically in developing nations. The literature review stresses the flushing of bottom and fly ash through mixture of water and additives, since it is emerging as a most economical and green way to accomplish this difficult job. Pressure drop along the length of pipe has now emerged as a critical performance metric, which can cause choking or even death for personnel involved in such transportation systems. The rheological properties of ash-slurry ensures smooth flow but only up to some extent. In the above study, we assumed controlled ranges of rheological properties of slurry, but it still needs a lot of improvement and input to decrease the pressure drop sufficiently. This work emphasises the optimisation of slurry composition and flow process parameters to tackle this erratic problem of severe pressure drop along the pipe lengths. The methodology proposed in this article has been devised by taking care of the fact that shear stress within the slurry increases with rise in concentration of bottom and fly ash along with various combinations of flow velocities and pipe diameters. This integrated approach will involve the advantages of Mixture DoE and CFD, simultaneously. The designed experiments are better than hit-and-trial runs and have the capability to utilise the effect of multiple factors at a time. Further runs are simulated with CFD, which trims the effort, energy and time remarkably. The results have been analysed through Minitab statistical software to deduce logical inferences. The optimised solution provided by tab is further verified by conducting some pilot runs. A two-sample *t*-test has been applied and the test predicted reduction in pressure drop from 3176 to 1252 kPa, with 95% confidence level. Approximately 60% cutback in pressure drop has been effectuated in a single attempt, which is quite remarkable and opens new doors for its scope in future. Thermal plant engineers and practitioners can use this exhaustive approach to bring breakthroughs in their already-installed ash-slurry transportation systems or can also design a new system. CFD application gives freedom to simulate runs with different compositions of various contents along with different process parameters. Like in some plants, only bottom ash is flushed out by slurry transportation system because of having independent fly ash arresters with corresponding disposal system. Any number of constituents with feasible levels of presence can be simulated through CFD. Flow process parameters like pipe material, viscosity, discharge and impact of different additives can also be studied efficiently through this noteworthy methodology.

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Annexure 1

Designed experiments of slurry

Runs	*Bottom ash*	*Fly ash*	*Additive*	*Water*	*Velocity*	*Pipe diameter*	*Pressure drop (kPa)*
1	0.04	0.23	0.03	0.70	40	350	4243.8
2	0.05	0.50	0.02	0.44	25	350	4243.8
3	0.23	0.06	0.02	0.70	40	450	2912.3
4	0.04	0.50	0.02	0.45	25	450	1426.8
5	0.21	0.16	0.02	0.62	25	450	1084.4
6	0.30	0.16	0.02	0.53	25	350	4243.8
7	0.30	0.20	0.03	0.48	25	350	2845.9
8	0.40	0.15	0.03	0.42	25	450	1477.1
9	0.40	0.06	0.02	0.53	40	350	4243.8
10	0.04	0.25	0.02	0.70	25	450	1193.2
11	0.04	0.50	0.03	0.43	25	450	1425.1
12	0.21	0.06	0.03	0.70	40	350	4243.8
13	0.40	0.06	0.02	0.53	25	350	4243.8
14	0.04	0.23	0.03	0.70	25	450	1185.2
15	0.05	0.50	0.02	0.44	40	350	4243.8
16	0.12	0.38	0.02	0.49	40	350	4243.8
17	0.12	0.24	0.03	0.62	25	350	4243.8
18	0.12	0.38	0.03	0.48	40	450	297.5
19	0.21	0.06	0.03	0.70	25	350	2103.6
20	0.19	0.25	0.02	0.54	40	450	3196.7
21	0.05	0.50	0.02	0.44	25	450	1211.8
22	0.04	0.50	0.03	0.43	40	450	3482.6
23	0.04	0.50	0.02	0.45	40	450	3105.0
24	0.12	0.24	0.03	0.62	40	450	3196.2
25	0.30	0.16	0.02	0.53	40	350	4243.8

Designed experiments of slurry (continued)

Runs	*Bottom ash*	*Fly ash*	*Additive*	*Water*	*Velocity*	*Pipe diameter*	*Pressure drop (kPa)*
26	0.30	0.16	0.03	0.52	40	450	3488.4
27	0.30	0.16	0.03	0.52	25	350	4243.8
28	0.12	0.38	0.02	0.49	25	350	2489.3
29	0.40	0.06	0.03	0.51	40	450	2995.5
30	0.40	0.06	0.02	0.53	40	450	3808.6
31	0.04	0.23	0.03	0.70	25	350	42473.8
32	0.05	0.50	0.03	0.42	25	450	1424.8
33	0.40	0.15	0.03	0.42	40	350	4243.8
34	0.12	0.25	0.02	0.62	25	450	1018.0
35	0.20	0.16	0.03	0.62	40	450	2674.7
36	0.12	0.38	0.03	0.48	40	350	4243.8
37	0.30	0.20	0.02	0.49	25	350	4243.8
38	0.30	0.20	0.03	0.48	25	450	1502.5
39	0.12	0.38	0.02	0.49	25	350	4243.8
40	0.19	0.25	0.02	0.54	25	350	4243.8
41	0.21	0.06	0.03	0.70	25	450	1446.5
42	0.05	0.50	0.02	0.44	40	450	3132.7
43	0.12	0.25	0.02	0.62	25	350	4243.8
44	0.30	0.20	0.02	0.49	25	450	1450.5
45	0.21	0.06	0.03	0.70	40	450	2926.5
46	0.05	0.50	0.03	0.42	40	450	2973.0
47	0.04	0.25	0.02	0.70	25	350	4243.8
48	0.30	0.16	0.02	0.53	25	450	3214.7
49	0.30	0.20	0.02	0.49	40	450	3597.5
50	0.12	0.25	0.02	0.62	40	450	2987.3
51	0.12	0.24	0.03	0.62	25	450	994.2
52	0.20	0.16	0.03	0.62	25	350	4243.8
53	0.21	0.16	0.02	0.62	40	350	4243.8
54	0.40	0.06	0.03	0.51	25	350	4243.8
55	0.21	0.16	0.02	0.62	25	350	2961.5
56	0.21	0.16	0.02	0.62	40	450	2977.3
57	0.12	0.38	0.03	0.48	40	350	4243.8
58	0.04	0.25	0.02	0.70	40	350	4243.8
59	0.23	0.06	0.02	0.70	40	350	4243.8
60	0.12	0.38	0.03	0.48	25	450	1238.8
61	0.12	0.38	0.02	0.49	40	450	2777.1
62	0.12	0.24	0.03	0.62	40	350	4243.8
63	0.30	0.16	0.03	0.52	25	450	3317.5

Designed experiments of slurry (continued)

Runs	*Bottom ash*	*Fly ash*	*Additive*	*Water*	*Velocity*	*Pipe diameter*	*Pressure drop (kPa)*
64	0.12	0.38	0.02	0.49	25	450	1221.6
65	0.40	0.15	0.02	0.44	40	350	4243.8
66	0.04	0.25	0.02	0.70	40	450	30557.1
67	0.04	0.50	0.03	0.43	40	350	4243.8
68	0.12	0.38	0.02	0.49	40	450	2777.1
69	0.19	0.25	0.02	0.54	40	350	4243.8
70	0.20	0.16	0.03	0.62	25	450	1301.8
71	0.12	0.38	0.03	0.48	25	350	3149.8
72	0.40	0.15	0.02	0.44	25	350	4243.8
73	0.04	0.50	0.02	0.45	25	350	3092.4
74	0.12	0.38	0.02	0.49	25	450	1221.6
75	0.40	0.06	0.03	0.51	40	350	4243.8
76	0.30	0.20	0.02	0.49	40	350	4243.8
77	0.20	0.16	0.03	0.62	40	350	4243.8
78	0.19	0.25	0.02	0.54	25	450	1447.8
79	0.04	0.50	0.02	0.45	40	350	4243.8
80	0.12	0.25	0.02	0.62	40	350	4243.8
81	0.23	0.06	0.02	0.70	25	450	1091.5
82	0.40	0.15	0.03	0.42	25	350	3144.3
83	0.12	0.38	0.02	0.49	40	350	4243.8
84	0.40	0.06	0.02	0.53	25	450	1382.1
85	0.30	0.16	0.03	0.52	40	350	4243.8
86	0.40	0.06	0.03	0.51	25	450	1293.1
87	0.30	0.20	0.03	0.48	40	350	4243.8
88	0.30	0.20	0.03	0.48	40	450	3308.8
89	0.12	0.38	0.03	0.48	25	450	1238.8
90	0.04	0.50	0.03	0.43	25	350	2900.4
91	0.40	0.15	0.02	0.44	25	450	1486.6
92	0.30	0.16	0.02	0.53	40	450	3066.6
93	0.12	0.38	0.03	0.48	25	350	3149.8
94	0.23	0.06	0.02	0.70	25	350	4243.8
95	0.05	0.50	0.03	0.42	40	350	4243.8
96	0.04	0.23	0.03	0.70	40	450	2622.3
97	0.12	0.38	0.03	0.48	40	450	3344.5
98	0.40	0.15	0.02	0.44	40	450	3943.0
99	0.05	0.50	0.03	0.42	25	350	3164.3
100	0.40	0.15	0.03	0.42	40	450	4296.2