Journal of Environmental Science and Sustainable Development

Volume 6
Issue 1 *July*

Article 6

7-31-2023

WATER HAMMER ANALYSIS FOR ASH SLURRY DISPOSAL PIPELINES OF A THERMAL POWER SYSTEM

Biprodip Mukherjee
School of Water Resources Engineering, Jadavpur University, Kolkata, 700032, India, biprodip87@gmail.com

Subhasish Das
School of Water Resources Engineering, Jadavpur University, Kolkata, 700032, India, subhasishju@gmail.com

Satyapriya Mandal
School of Water Resources Engineering, Jadavpur University, Kolkata, 700032, India, satyapriya2008sm@gmail.com

Recommended Citation

Mukherjee, Biprodip; Das, Subhasish; and Mandal, Satyapriya (2023). WATER HAMMER ANALYSIS FOR ASH SLURRY DISPOSAL PIPELINES OF A THERMAL POWER SYSTEM. *Journal of Environmental Science and Sustainable Development*, 6(1), 70-85.
Available at: https://doi.org/10.7454/jessd.v6i1.1111

Journal of Environmental Science and Sustainable Development
Volume 6, Issue 1, Page 70-85
ISSN: 2655-6847
Homepage: http://scholarhub.ui.ac.id/jessd

WATER HAMMER ANALYSIS FOR ASH SLURRY DISPOSAL PIPELINES OF A THERMAL POWER SYSTEM

Biprodip Mukherjee[1], Subhasish Das[1]*, Satyapriya Mandal[1]
[1]School of Water Resources Engineering, Jadavpur University, Kolkata 700032, India

*Corresponding author: subhasishju@gmail.com

(Received: 7 October 2021; Accepted: 25 July 2023; Published: 31 July 2023)

Abstract

Coal-ash slurry transportation via pipelines has been accepted as a potential, economical, and dependable mode of two-phase flow of solid-liquid transportation. It is solid-liquid transportation where the ash slurry generally flows through mild steel, and a good amount of pump energy and pressure is required to convey the slurry with a density above 1220 kg/m3. The study is basically on the water hammer analysis of ash slurry conveying pipes. Nevertheless, since the hammer analysis is typically carried out in normal water, the study of ash slurry is compared to the know criteria of potable water. The study aims to understand the flow characteristics of such pipelines. Investigators worldwide have been analyzing the flow experimentally, numerically, and theoretically. HAMMER and WaterGEMS software was used to carry out the hydraulic analysis of such pipelines and to monitor the maximum transient pressure head being developed. The above software was further used to monitor the maximum transient pressure head being developed due to a sudden power failure which caused the stoppage of the regular pump operation. A transient stress analysis was performed on the pipelines where the maximum transient pressure head was detected. For necessary safety measurements of the pipelines, the ultimate transient stresses were computed from the parameters observed in the software results to find whether such pipes are safe. In the same system, the transient head observed due to the slurry hammer was approximately two times the transient head observed in the water flow. The operational pressure incorporates the slurry pipeline pressure at a steady state to surmount friction and static heads. The code requires that the pressure level increase due to surges not exceeding at any time the internal design and implemented pressure of more than 10%.

Keywords: Hydraulic analysis; Slurry flow; Sustainability; Transient analysis; Waterhammer head.

1. Introduction

Thermal power plants (THPPs) produce electric power more than 50% of the world's requirement by burning millions of tons of coal and, at the same time, individually generating large quantities of coal ash. The slurry combines solids (coal ash) and liquids (water and wastewater). Physical characteristics of slurry depend on several factors, such as particle size and particle distribution, the solids concentration in the liquid phase, conduit size, turbulence level, working temperature, and carrier absolute or dynamic viscosity. Slurry pipeline networks are widely used across worldwide to transport coal ash (bottom ash and fly ash) from the THPPs to the ash pools in the THPPs. Many of these slurry pipeline networks in THPPs transport ash slurry at medium or low solid concentrations for either a medium or short distance. These slurry transport networks are very energy efficient and lead to extreme wear of pipelines and necessary water consumption (Oldshue, 2003). In addition, the present improved realization of environmental inequalities and related strong government policies are pressuring the THPPs to adopt environment-friendly slurry transport arrangements.

Therefore, the highly concentrated slurry disposal arrangement has become a favored option for transporting coal ash in THPPs as this arrangement is cost-effective and atmosphere friendly. The concerned slurry that is recognized to be weightier than water and the crack of a slurry pipe can have catastrophic consequences on the slurry pipe network in resisting collective erosive and corrosive effects that can cause accidental loss. Few people also analyzed that the enhanced solid concentration is the reason for the failure of such ash slurry pipelines in THPPs (More et al., 2018). The research was also undertaken in the computational method of ash slurry flow calculation (Rawat et al., 2016; Kumar et al., 2016a). For this cause, concerned engineers and contractors must follow definite codes and standards similar to the tests performed on Newton flows for slurry (Abulnaga, 2002).

The American Society of Mechanical Engineers (ASME B31.11) is mainly considered to be the lone standard definite to slurry pipe networks. The loss of water in pipelines can cause transiency of pressure and simultaneously can produce stresses on the concerned system. Much research has proved the theory of cavitation and losses due to transient effects both numerically and experimentally (Apollonio et al., 2016; Ghodhbani et al., 2019; Hatcher & Vasconcelos, 2017; Kim & Kim, 2019). Studies also assessed ash slurry's stabilization and rheological behavior (Das et al., 2019; Das et al., 2020; Pattanaik et al., 2019; Routray et al., 2022). The critical flow velocity of slurries is an essential parameter in the process of the slurry conveyance system (Sayari et al., 2020). Following the above, the impact of additives on the ash slurry is also useful for slurry flow study (Prasad et al., 2019; Seitshiro et al., 2012; Seitshiro et al., 2013; Seitshiro et al., 2014). In assistance with the above statement, the study of performance characteristics of centrifugal slurry pump handling bottom ash was carried out. The pressure study of slurry pipelines becomes important and depicted in a few pieces of research (Li et al., 2002; Xu et al., 2016; Yang et al., 2019).

Works have been carried out on modeling the hydraulic pipe network transients along with cavitations and gas bubbles applying parallel genetic techniques, which are also kept into consideration while the construction of slurry pipelines (Beltrán et al., 2016; Kou et al., 2016; Zhao et al., 2020a). The comparison between simulation outcomes and the test data signifies that genetic parallel techniques are possible and effective in measuring unknown parameters in slurry line hydraulic transient models associated with cavitation and gas bubble effects (Li et al., 2008). Experimental study of water hammer also works as an effective tool for accessing the fluid flow for various multiphase flows (Lema et al., 2016; Zhao et al., 2016; Zhao et al., 2018; Zhao et al., 2020b). Depending upon particle size and temperature, rheological behavior was an essential aspect of the flow of ash slurry (Singh et al., 2016). Works on designing and modeling a self-dispersing twisted pipe and headloss characteristics of pipe characteristics to mitigate the setting of coal ash also impacted the study (Singh et al., 2018; Singh et al., 2019; Singh et al., 2021).

Over the past years, several researchers have investigated a dense phase of slurry transmission of the solid-liquid mix into flat and upright pipelines and have observed that dense phase slurry flow is possible at significantly low velocities when the overall hydraulic pressure drop is also low. Moreover, for a solid (coal ash) concentration of more than 40% by mass, ash slurry behaves as inconsistent non-settling, and simultaneously the slurry pipeline flow can be kept in a laminar state at a relatively low velocity. Therefore, the slurry pipe network will suffer less erosion wear throughout at low velocity. It was found that up to 50% solids concentration by mass, pumping of slurry (coal ash mixed with water) can be done safely by operating centrifugal pumps (Biswas et al., 2000; Chandel et al., 2009). This slurry is a non-Newtonian fluid (Singh et al., 2017). An experimental study also assesses the slurry pressure drop (Singh et al., 2019). Flow characteristics for multi-particulate bottom ash suspension were measured in some research (Kumar et al., 2016a; Kumar et al., 2016b; Kumar et al., 2017).

This study was taken up to compare the outcome of the transient analysis in the slurry-carrying pipes concerning the water-conveying pipeline. In assistance with the above statement, an ash slurry pipeline in India was considered as a case study. While undergoing the study, it was observed that during any sudden closure of valves or pumps huge mass of slurry gets stuck in the valve apertures and vent pipes in conjunction with high-range vibration, which may lead to the breakage of pipes which is a separate phenomenon that occurs apart from normal water conveying pipelines. Henceforth to understand the problem and to find the remedy, the transient analysis study became much necessary.

2. Methods

2.1 Study area

Hinduja National Power Corporation Limited (HNPCL) was chosen as a case study. The HNPCL is setting up a 1040 MW THPP near Palavalasa village, PedaGantyada Mandal, Visakhapatnam, Andhra Pradesh, India. This power plant is designed to operate on Indian coal. The total daily coal requirement is 17,520 tons per day (TPD) at 100% turbine maximum continuous rating (TMCR). Based on the total daily coal requirement, the total ash generation is 7,884 TPD (bottom ash 1,577 TPD and fly ash 6,307 TPD), considering 50% ash content in coal. Ash disposal system has been designed considering 45% to 50% concentration.

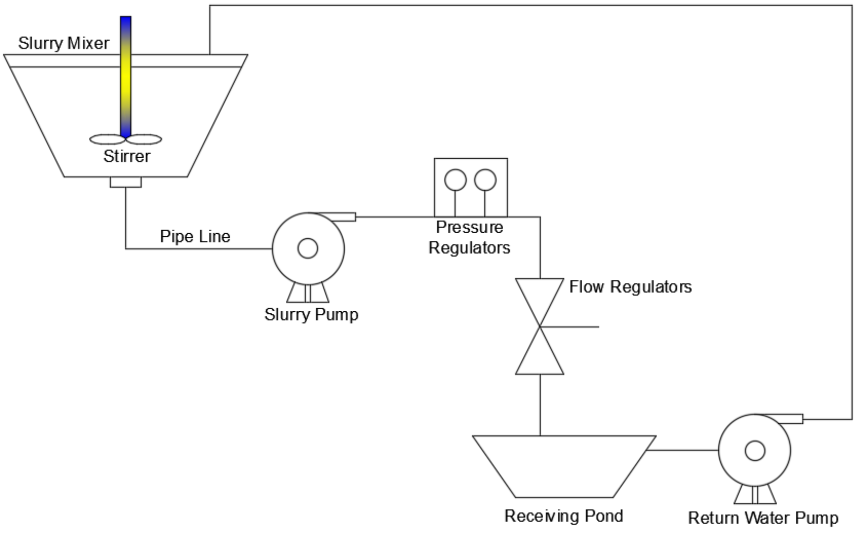

Figure. 1 Typical schematic diagram showing ash slurry transportation arrangement.

As-built, The ash pond can store the ash produced by both units for approximately ten years at a distance of approximately 3.5 km from the ash slurry pump house. At present, it has been decided that both bottom ash and fly ash are being evacuated and stored in the ash pond, and efforts are being made to ensure that fly ash generated from both units is sold to prospective customers as per the Ministry of Environment & Forest (MoEF) norm. Whenever

DOI: https://doi.org/10.7454/jessd.v6i1.1111

the tie-up with prospective customers is not in place, the Fly ash is evacuated to the ash pond through a slurry-based wet fly ash disposal system. The ash from the different collection points, i.e., bottom ash hopper, electrostatic precipitator (ESP), air preheater (APH), and economizer hopper, are collected in the sump of ash mixed slurry. The ash-mixed slurry is pumped by a centrifugal pump to the ash pond through a mild steel pipe, whose diameter is 450 mm throughout the length. The conveying distance is approximately 3.5 km from the pump-house for ash mixed slurry to the ash pond.

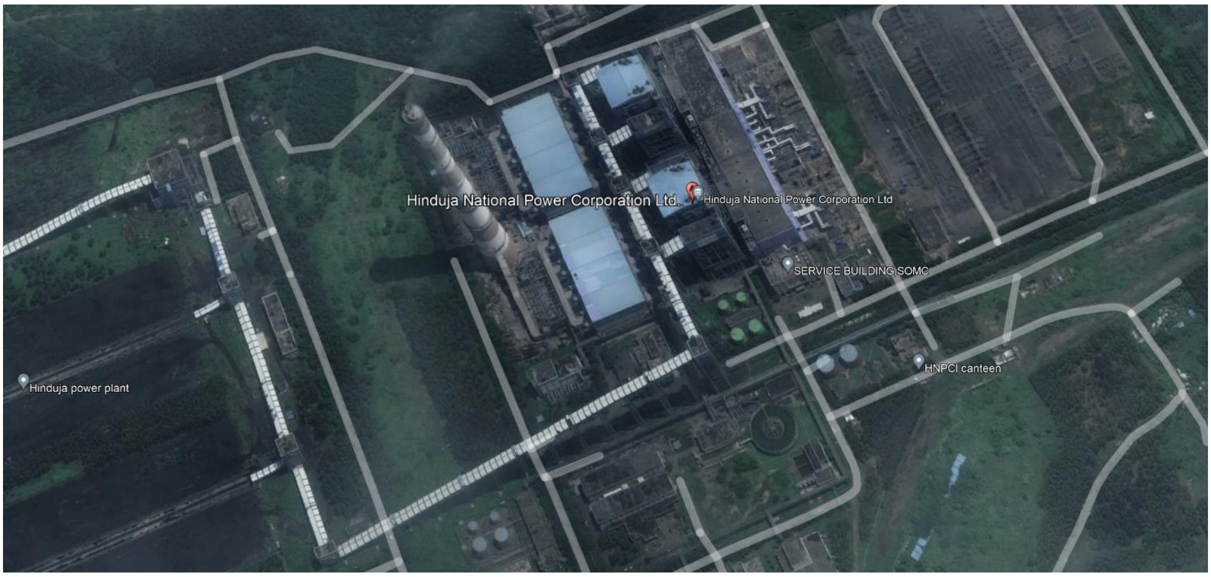

Figure. 2 Satellite view showing an overall plan layout of (2×520) MW thermal power plant

Initially, static lift, such as the level difference between the ash mixed slurry pump-house and the top of the ash pond, is 14.2 m. The first stage of the rising ash pond will occur after three years; finally, the static lift will be 36.2 m. There are two numbers of slurry pipelines, one of which is working and another in standby mode. Each pipeline has two (2) numbers of slurry pumps in series to achieve the final head requirement. Each pump has a slurry carrying capacity of 1195 cum/hr.

2.2 Data analysis

Transient flow or temporary flow of state is defined as the intermediary stage flow, which takes place when a state of flow condition takes place from one stable state to another state of a stable state. While the system operates in its usual ongoing manner, releasing air from the pipeline is prudent, thus preventing or limiting two-phase flow. Some of the hindrances and dangers characterized by the existence of air movement in the pressurized pipeline system are (a) Interference with the flow in pipeline-up to complete stoppage at times, (b) serious head loss-energy loss, (c) slurry water hammer dangers, (d) inaccurate readings in meters and metering valves, (e) inadequate supply of slurry to areas in the system and (f) corrosion and cavitations.

A subsequent methodology was implemented to study the detail of the ash-slurry pipeline networking system. A map of the entire pipeline routing layout relating to ash slurry disposal to ash ponds under HNPCL was studied. Prior to modeling the entire networking system, live data compilation is run. The ash-slurry disposal piping layout of HNPCL was collected from the technical division unit (TDU), Vizag THPP. Rheological test reports on fly ash for the Vizag ash slurry disposal system were collected from the TDU, Vizag THPP. Operation and control philosophy of ash disposal system of Vizag THPP, general arrangement drawing of ash-slurry mixture pump house, ash slurry mixture pump and datasheet of ash slurry mixture pump along with performance curve, valves were collected from TDU, Vizag THPP. Based on the most common data analysis of the ash-slurry disposal networking system and access data was necessarily provided by TDU, operations & maintenance (O&M) division of Vizag THPP. The available layout map (plan and elevation views) of the ash-slurry disposal pipeline system has been drawn and modeled using the Waterhammer simulation software platform.

In the entire layout, the hydraulic part was modeled in the subsequent process. The drawing of the ash-slurry disposal piping layout was converted into Drawing Exchange Format (DXF) from Auto-CAD format. The ash-slurry disposal piping layout drawing was exported into the Waterhammer simulation software to form a background layer. The reservoir (ash slurry sump) was first drawn. Connected pumps and suction lines were drawn, and the associated links, such as slurry carrying pipes and controlling valves, were placed correctly to connect the slurry pumps and the ash slurry reservoir using the applicable toolbar selecting from the drawing window of Waterhammer software. Then the ash pond, including head-works, was drawn. The associated pipes and controlling valves were connected with the upstream, downstream junctions to the slurry pumps. After choosing the reservoirs, magnitudes of elevation were given. Similar data input has also been specified to the side by nodes. The necessary values of pump discharge and mechanical power were given by choosing and fixing the slurry pump locations. The magnitudes of lengths, diameters, and pipe roughness values were given by choosing the pipe options. The magnitudes of valve internal diameter, their type, and operation settings were given by choosing the valve options. Simultaneous minor loss values were entered by choosing the several bends and network valves. The value of maximum elevation was entered by choosing the ash pond location. After model building, the entire slurry networking arrangement and the slurry networking system analysis were performed by several runs, and the subsequent results, such as hydraulic pressure grades, hydraulic gradient lines in requisite junctions and unit head losses, velocities, and flows in pipes were put aside.

A few basic equations are discussed to understand the outputs through the pipe flow simulation software. To balance the energy crossways, two points in a pipeline yield Bernoulli's energy, Equation 1 for stable-state flow as taken help in various practical cases as:

$$\frac{p_1}{\rho g} + z_1 + \frac{v_1^2}{2g} + h_p = \frac{p_2}{\rho g} + z_2 + \frac{v_2^2}{2g} + h_L \tag{1}$$

where p_1, p_2 = pressure at nodes 1 and 2, respectively; v_1, v_2 = velocity at nodes 1 and 2, respectively; Z_1, Z_2 = elevations from datum at nodes 1 and 2, respectively h_p = head gain from the pump, and h_L = combined headloss in the pipeline. According to the Darcy-The Weisbach formula, the combined head loss is given in Equation 2.

$$h_L = f\,\frac{l}{d}\,\frac{v^2}{2g} \tag{2}$$

Transient analysis was carried out, and for this, a pump shutdown was considered. After running the transient analysis, the transient initial and final conditions reports were saved. The magnitude of the maximum unprotected head developed due to the instantaneous shutdown of pumps. Instead, it crosses the safety limit of the pipes concerning the ultimate tensile strength of various pipes material was checked. The Joukowsky head of the pipes, which is the difference between the maximum transient head (in m) developed at the pipes when the pumps were shut down, and the initial head (in m) under normal operating conditions, was also found (Das et al., 2013; Mukherjee et al., 2015).

The water hammer frequently happens when an operating valve is suddenly closed at any end of a pipe system, or there is a sudden power failure, and thus a wave of pressure that does propagate through the pipe system. It may know as a hydraulic shock. The elasticity combined of both the flowing water and the concerned pipe walls is described by the hydraulic pressure wave velocity (a). This relative between the water hammer-head or Joukowsky head (Δh) and the change of water velocity through a pipe (Δv) in a basic form of the applicable Equation for an immediate work stoppage of water velocity is given in Equation 3.

$$\Delta h = \left(\frac{a \Delta v}{g} \right) \tag{3}$$

Where g is the acceleration due to gravity, celerity is frequently applied for differentiating between the velocity of pressurized water and the subsequent pressure wave velocity that depends upon the section-wise pipeline elasticity. The pressure wave propagation velocity through a pipeline restraining water can be significantly decreased even if a negligible quantity of air is present as gas bubbles are dispersed through the water. The pipe material properties which affect the celerity are the modulus of elasticity (E_p) of pipe material, the outer diameter of the pipe (D), and pipe wall thickness (e). The water properties of significant importance are water's bulk modulus of elasticity (EL), the operating density of pseudo-homogeneous flow (ρ_m), and the amount of air entrained in the water. The wave of celerity (a) is defined as follows (Equation 4):

$$a = \left[\left(\frac{E_L}{\rho_m} \right) \Big/ \left\{ 1 + \left(\frac{E_L}{E_p} \right) \left(\frac{D}{e} \right) c_1 \right\} \right]^{1/2} \tag{4}$$

Where c_1 is the pipe support coefficient, the factor c_1 depends on the pipe network support character and Poisson’s ratio (μ). The pipe support coefficient c_1 depends on the following $c_1=1-\mu^2$ when the pipeline is fastened throughout next to the axial movement $c_1=1-\mu/2$ when the pipeline is held up at only one end and permitted to undertake both lateral and longitudinal stresses and strains, $c_1=1$ when the pipe is equipped with functioning expansion joints throughout (Wylie et al., 1993). The speed for wave propagation (Equation 5-6) intended for pseudo-homogeneous type flow as formulated by (Han et al., 1998) was:

$$a_{m1} = \left[\left(\frac{E_L}{\rho_m} \right) \Big/ \left\{ 1 - C_v + \left(\frac{E_L}{E_s} C_v \right) + \left(\frac{E_L D}{E_p e} \right) \right\} \right]^{1/2} \tag{5}$$

$$a_{m2} = \left[\left(\frac{C_v}{\rho_s} + \frac{1 - C_v}{\rho_L} \right) E_L \Big/ \left\{ 1 - C_v + \left(\frac{E_L}{E_s} C_v \right) + \left(\frac{E_L D}{E_p e} \right) \right\} \right]^{1/2} \tag{6}$$

where C_v = solid concentration by volume; ρ_s = density of slurry; ρ_L = density of a liquid, a_{ml} = wave propagation for pseudo-homogeneous flow, and a_{m2} wave propagation for heterogeneous flow.

In order to check the pipe safety at increased flow conditions, the maximum circumferential stress for the pipe material under consideration was computed from the maximum pressure observed during the analysis. By using the factor of safety, which is always according to the user's desire, and accordingly, by finding out the maximum allowable circumferential stress, it can be judged whether the maximum circumferential stress observed in the pipe under consideration is more or less than the maximum allowable circumferential stress.

Equation (7-8) is used to find out the maximum circumferential stress (σ_h) and the maximum allowable circumferential stress of pipe material (σ_{at}) for pipe safety checking in various zones where p_h is the total pressure developed at the pipe, including transient and static pressures.

$$\sigma_h = \frac{p_h D}{2e} \tag{7}$$

$$\sigma_{at} = \frac{\sigma_h}{FOS} \tag{8}$$

The detailed flowchart describing the methodology of the study of the slurry hammer has been reflected in Figure 3.

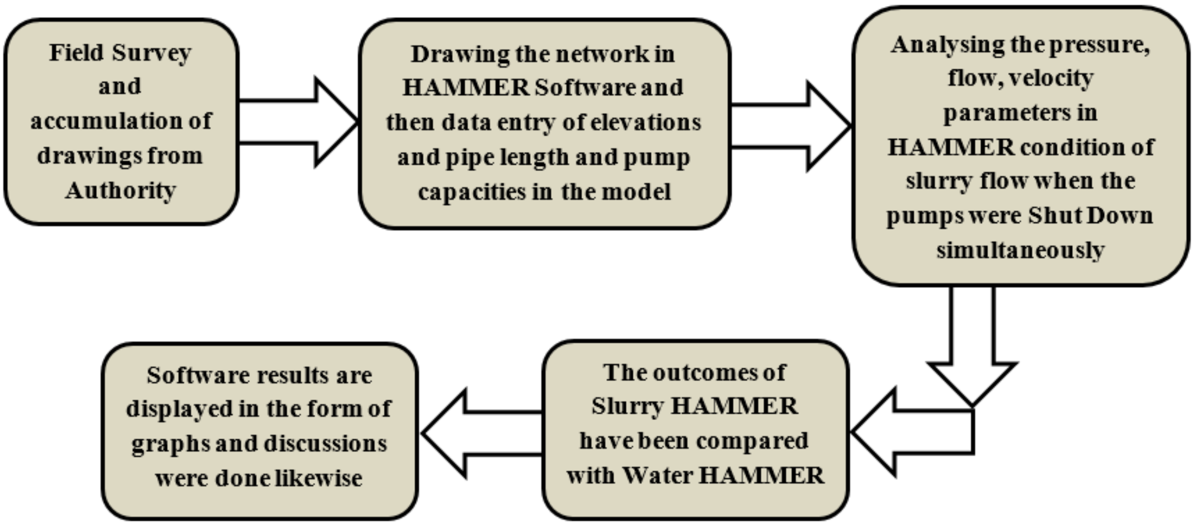

Figure. 3 Flowchart describing the methodology

3. Results and Discussions

In order to carry out a hydraulic analysis of such slurry pipeline, help was taken from WaterGEMS software as developed by Bentley Systems, USA. Moreover, it was found that the hydraulic grade line was the same for the fluid in the same pipeline, either water or slurry.

Understanding the viscosity and density of both fluids differ after that. There is a high chance of changes in the flow phenomenon while regular pump operation but Figure 3 depicts almost the same HGL in both cases. The outcome will later depict in detail the comparative study of the flow phenomenon when the transient condition occurs for both types of fluids.

As shown in Figures 4 (a) and Figure (b), the above results show that there shall be no change in the hydraulic grade line for the fly ash slurry concerning water due to the specific gravity of both being nearby the same. The results also depict that the other parameters, like frictional head loss and pressure developed in the pipeline, are the same. The dynamic principle of fluid motion indicates that an abrupt change in velocity in a sealed conduit will outcome in an immediate pressure variation, known as a "waterhammer." A solid movement with the liquid flow at hyper-concentrated solid particles is known as a slurry waterhammer or a slurry hammer. Due to the subsistence of a proliferation of solids in slurry movement, slurry does not have the identical density and elastic modulus as clear water. The slurry hammers, therefore, behave in a different manner than waterhammer.

Many studies and research have focused on calculating the water hammer pressure phenomenon of single-phase for a pipeline of uniform characteristics. However, less work has addressed calculating slurry water hammer pressure in complex pipelines with slurry flows carrying solid particles, as depicted by Han et al. (1998). Tieli et al. (2014) revealed the characteristics of solid-liquid flow, a continuity equation where the momentum equation of pseudo-homogeneous flow was presented, and a pseudo-homogeneous water hammer model was built based on the characteristic line method. The characteristics of solid-liquid flow viscosity, resistance, and wave velocity were considered in the model. Through the numerical simulation and analysis of the transient process of a long-distance slurry transportation pipeline system, the protective properties of the accumulator were presented and discussed. The result showed that the accumulator works well during a pumping accident, and the accumulator can be an effective protection measure for long-distance slurry transportation pipelines.

However, interestingly, an abrupt change was depicted when both fluids were tested in transient conditions. In order to carry out the transient analysis, help from the software HAMMER, as developed by Bentley Systems, USA, was taken. Solid flow in liquids is usually divided into heterogeneous type flow and pseudo-homogeneous type flow. In pseudo-homogeneous type flow, solid particles are excellent and can be suspended entirely in the liquid. The analysis of slurry transportation in pressure pipelines is essential both from practical and theoretical points of view. Due to the nature of the medium, the number of problems arising in the course of design, operation, measurements, and mathematical modeling is much higher compared to the cases where the flowing liquid is homogeneous, as per the research of Kondura et al. (2017). The distribution of concentrations over the upright line is similar, whereas the solid constituent parts and liquids have equal movement and change rate velocity. In heterogeneous type flows, the solid constituent parts have a relatively lower movement velocity than liquids as coarse constituent parts cannot be sufficiently suspended. Moreover, their bed-loads can be present. The wave propagation speed and the additional pressure of the waterhammer for pseudo-homogeneous type flow and heterogeneous type flow will be conferred separately.

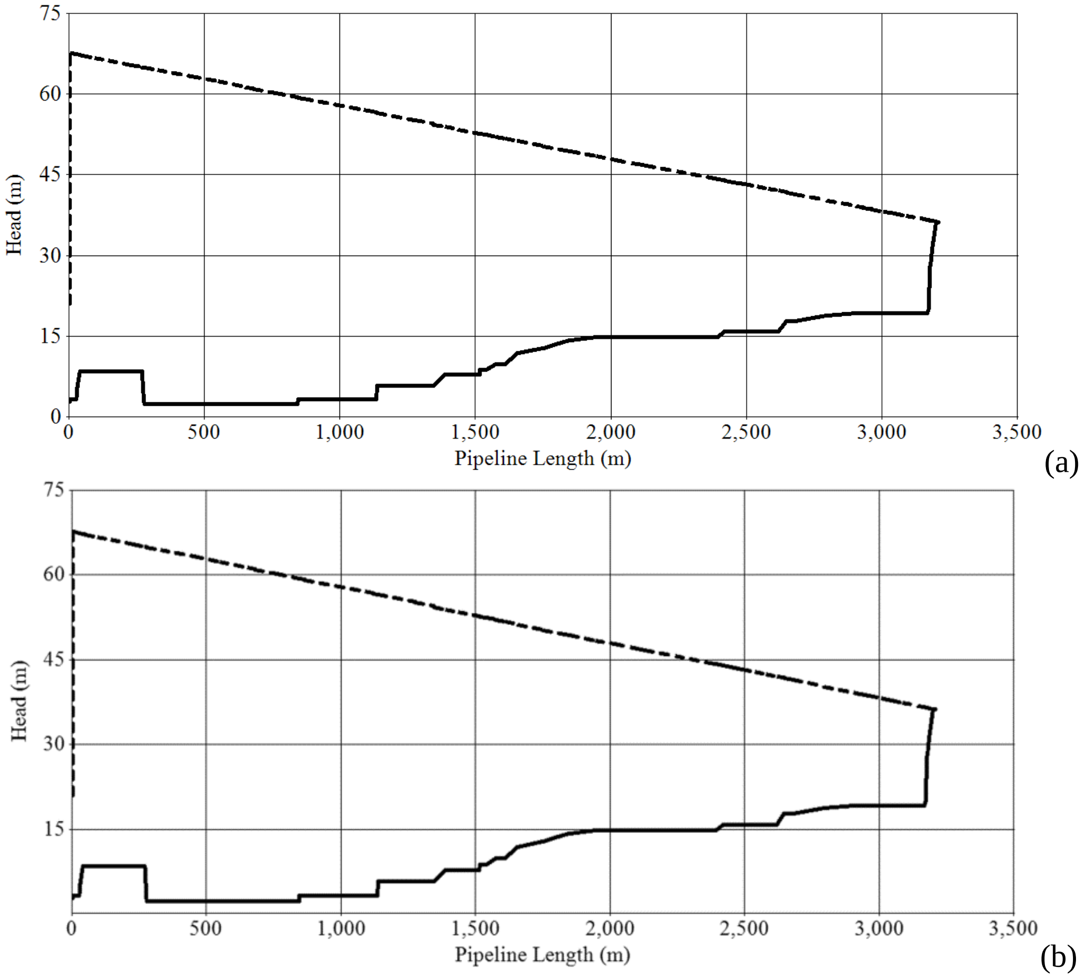

Figure. 4 Comparison of hydraulic grade lines for both (a) slurry (mixture of fly ash and water) and (b) water flow in a steady-state condition

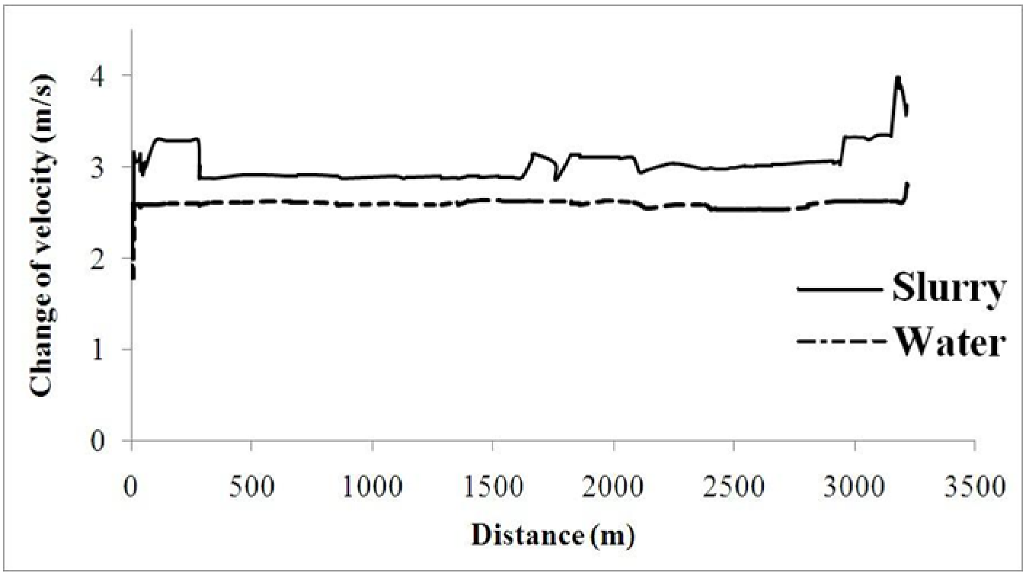

Figure. 5 Overall comparison of change of velocity in both slurry (mixture of fly ash and water) and water flow due to hammer condition

When the pump operation suddenly failed (which is supposed to be the most severe condition), there was a considerable difference between the changes in slurry velocity and water, as depicted in Figure 5. The velocity results were also compared with the works of Lahiri & Ghanta (2010) to validate the velocity results of slurry flow, which depicted the characteristics of the slurry flow only with the help of computational fluid dynamics (CFD). Like the present study, the velocity was asymmetric in the study of slurry flow by CFD. After accessing the velocity profiles with the previous computational dynamics study, the research was further extended by exploring other modeling parameters, as discussed in the later section. From Equation 3, it can be said that the more the fluid velocity change due to the waterhammer condition. This condition shows that the effects are more severe during the transient phenomenon when it occurs for a slurry conveying pipeline concerning the water pipeline. Moreover, to justify the above point, more results from the software suggested that fly ash slurry, though highly viscous fluid, has more severe effects than water when the question comes to a hammer condition.

From Figure 6 (a), it is seen that up to 200 seconds after pump failure, the changes of velocity are much more in slurry flow than in the water flow whose water flow hammer results were revealed in the research of Das et al. (2013) through the first overshoot due to the hammer condition for both the flow is identical. However, the steadiness of the slurry flow is delayed than the water flow. For other parameters like hydraulic grade and pressure, the overshoot is also high for slurry flow concerning water flow. Since the resolution after the hammer shock is 1800 seconds and no surge protection device was used, the oscillatory flow due to the hammer shock doesn’t come to rest, as seen in Figures 6 (b) and 6 (c). In heterogeneous flows, no influence was found in reducing solid viscosity onto predictions of pressure gradient for the range of mixture mean velocity analyzed. Four orders of magnitude decreased solid viscosity, and the mean pressure gradient difference was less than 1.5%. The results of slurry flow pressure, as depicted in Figure 6(c), were compared with pressure outcomes in the CFD analysis by FLUENT software and compared with the numerical studies in the study of Hernandez et al. (2008) and found almost similar. From Equations (7) and (8), the pipe stresses were checked, and the stresses observed due to hammer conditions remain under control, i.e., below 522 m head (ultimate tensile strength of the mild steel pipe material), so no surge protection devices were considered in the network. For lower values of mean slurry velocity, all numerical models' predictions are equal. When mean velocity increases, full multiphase simulation performs better than the algebraic slip-mixture (ASM) model. In addition, kinetic theory slightly improves pressure gradient predictions when the velocity is reduced compared to modeling without kinetic theory. This is due to the estimation of particle interactions. However, a difference in solid concentration distribution is observed when kinetic theory is not employed (Hernandez et al., 2008).

In the slurry-ash mixture pump house, the waterhammer mentioned above analysis was performed, and it has been verified when the flow of the slurry pumps is maximized, probably up to 100% of the rated flow capacity, whether the slurry conveying pipeline system will be in safe hands or not. The previous research studies proved that the maximum hammer-head change observed by increasing the flow capacity is much less, so the highest maximum hammer-head that occurred did not go beyond the ultimate tensile strength of the mild steel pipe material (Das et al., 2013).

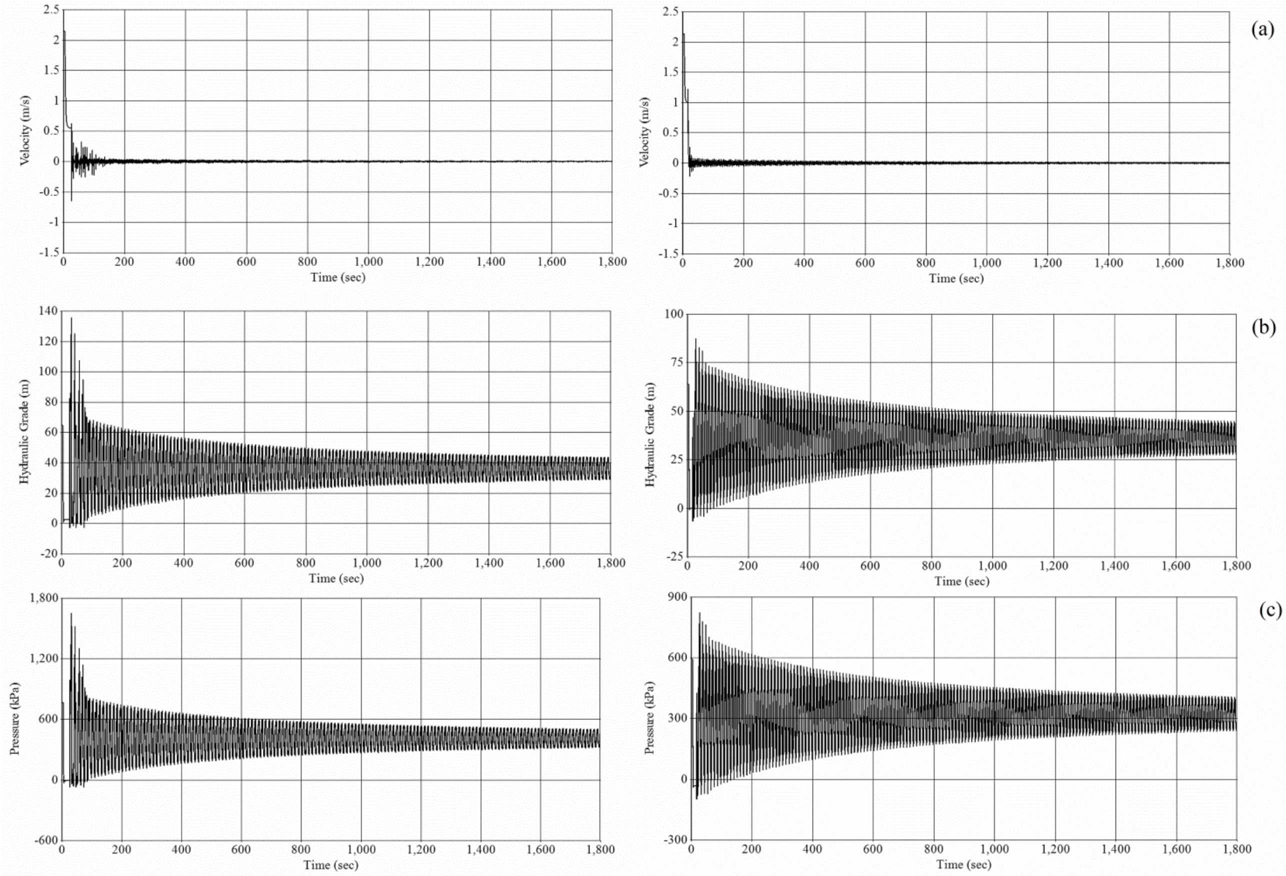

Figure. 6 Comparison of various parameters (a) velocity, (b) hydraulic grade, and (c) pressure for both slurry flow (mixture of fly ash and water) and water flow after hammer condition for a junction in the network where maximum hammer-head occurred

From the study above, it becomes easier for an engineer to design the perfect diameter and proper selection of slurry pumps for the pipes they would use to convey the slurry. As per the research of Cellek & Engin (2016), the performance of centrifugal slurry pump impellers strongly depends upon the complex configuration of the asymmetrical flow field in the axial direction, which is highly unsteady. The flow field, in turn, is considerably affected by the design parameters of the volute casing and impeller geometry. Although many studies have focused on their optimization in water pumps, few studies have been conducted about centrifugal slurry pumps. Improper selection of the diameter of the pipes will lead to more pressure drop and also face a hazardous consequence to hammer conditions. More pressure drop means utilizing more water and more conveyance of slurry, which is wastage in our day where water is scarce. The ASME B31.11 code necessitates an instituted plan for operating and maintaining processes. Such instituted plan should be coded with proper operating and maintaining instructions to operate the slurry pipe networks. It must comprise provisos for controlling external and internal corrosion and wearing newly installed and existing slurry pipelines. Research by Ringas (2007) elaborated that microbiologically induced corrosion (MIC) refers to corrosion caused by various microorganisms. This form of corrosion is not widely recognized in many industries, although it is widespread and causes many corrosion problems in internal and external pipelines. Sulfate-reducing bacteria (SRB) are responsible for the bulk of the corrosion problems caused by MIC. Corrosion caused by SRB is found extensively in water pipelines conveying raw, potable, and wastewater and pipelines conveying slurries.

4. Conclusions

It becomes the ultimate accountability of designing and implementing engineers and the concerned contractors for providing safe procedures for the network system operation and maintenance of the ash water slurry pipelines. The respective codes provide some proper guidelines. The slurry pipeline consists of fly ash and water, so proper use of technology will lead to sustainable water use. It must portray an emergency course of action in case of system malfunctions, accidents, and further hazards. This study has tried to develop a comprehensive slurry flow model using both WaterGEMS and HAMMER software and utilize the model to predict pressure drop and validate the results with the theoretically calculated results.

The above software was further used for checking the maximum hydraulic head developed because of an unexpected power failure which caused the work stoppage of the regular operation of slurry pumps. A stress investigation was carried out simultaneously in the slurry pipes where the maximum waterhammer head was detected and for necessary safety investigation of the concerned slurry conveying pipes. Also, the ultimate stresses were computed from the parameters observed in the software results. These results were evaluated with the usual tensile stresses of the slurry pipe material applied by allowing the suitable safety factor. Since several damaging effects of pipe bursts have been accounted for when the stress and pressure built up by the waterhammer surpass the ultimate pressure and stress of the slurry pipe material utilized, such a study becomes more important. In the same system, the transient head observed due to slurry hammer was approximately two times the transient head observed in the water flow. Interestingly these results opened up a new era in the transient hydraulics study, where it was thought that the transient head developed in the water flow would be much higher than that of the two-phase solid-liquid flow. Such types of indications were analyzed here in this research.

Staffs need training in these emergency procedures. Because pipelines end up in rural or urban areas and can impact the environment, local authorities should be consulted when such a system is established. The plan must provide details of the review process and consider critical changes affecting the most-needed safety and reliability of the slurry piping systems. A mechanism must be in place to monitor and report changes in construction, rail and road crossings, and urban and commercial activity. No one should come with an implant and damage the buried pipe because he/she did not know it existed. The evacuation plan should include procedures for extinguishing and disposing of the pipeline and appropriate cleaning procedures before discharge. The operational pressure incorporates the slurry pipeline pressure at a steady state to surmount friction and static heads. The code requires that the pressure level increase due to surges not exceeding at any time the internal design and implemented pressure of more than 10%.

Acknowledgment

The master’s dissertation work of the third author helped to perform this research.

Author Contribution

Conceptualization, S.D., S.M., and B.M.; Methodology, S.D., B.M., and S.M.; Software, B.M.; Validation, B.M., and S.D.; Formal Analysis, S.M.; Investigation, S.M.; Data Curation, S.M.; Writing – Original Draft Preparation, B.M.; Writing – Review & Editing, S.D.; Visualization, S.D., and B.M.; Supervision, S.D.

References

Abulnaga, B. E. (2002). *Slurry Systems Handbook*. McGraw Hill.

Apollonio, C., Balacco, G., Fontana, N., Giugni, M., Marini, G., & Piccinni, A. (2016). Hydraulic transients caused by air expulsion during rapid filling of undulating pipelines. *Water*, *8*(1), 25. https://doi.org/10.3390/w8010025

Beltrán, J. P., Ceci, P., Miguez, P., & Casali, P. (2016). Construction of slurry pipelines. *Procedia Engineering*, *138*. https://doi.org/10.1016/j.proeng.2016.02.070

Biswas, A., Gandhi, B. K., Singh, S. N., & Seshadri, V. (2000). Characteristics of coal ash and their role in hydraulic design of ash disposal pipelines. *Indian Journal of Engineering and Materials Sciences*, *7*(1).

Chandel, S., Seshadri, V., & Singh, S. N. (2009). Effect of additive on pressure drop and rheological characteristics of fly ash slurry at high concentration. *Particulate Science and Technology*, *27*(3). https://doi.org/10.1080/02726350902922036

Cellek, M.S., & Engin, T., (2016). Parametric investigation of a centrifugal slurry pump while handling clear water. *Journal of Thermal Science and Technology*, *36*(2). 19-28.

Das, D., Pattanaik, S., Parhi, P. K., Mohapatra, R. K., Jyothi, R. K., Lee, J. Y., & Kim, H. I. (2019). Stabilization and rheological behavior of fly ash-water slurry using a natural dispersant in pipeline transportation. *ACS Omega*, *4*(25). https://doi.org/10.1021/acsomega.9b03477

Das, D., Routray, A., Pattanaik, S., Parhi, P. K., Das, B. R., & Das, S. N. (2020). Effect of particle size distribution and selective alcohol additives for preparation of high concentration coal-water slurry. *Micro and Nanosystems*, *12*(2), 102–111. https://doi.org/10.2174/1876402912666191010142942

Das, S., Mukherjee, B., & Mazumdar, A. (2013). Analysis of hammer head at increased flow demand in pipe networks: A case study. *International Review of Mechanical Engineering*, *7*(4).

Ghodhbani, A., Akrout, M., & Haj Taïeb, E. (2019). Coupled approach and calculation of the discrete vapour cavity model. *Journal of Fluids and Structures*, *91*. https://doi.org/10.1016/j.jfluidstructs.2019.102691

Han, W., Dong, Z., & Chai, H. (1998). Water hammer in pipelines with hyperconcentrated slurry flows carrying solid particles. *Science in China Series E: Technological Sciences*, *41*(4), 337–347. https://doi.org/10.1007/BF02917005

Hatcher, T. M., & Vasconcelos, J. G. (2017). Peak pressure surges and pressure damping following sudden air pocket compression. *Journal of Hydraulic Engineering*, *143*(4). https://doi.org/10.1061/(asce)hy.1943-7900.0001251

Hernandez, F. H., Blanco, A.J., & Solorzano, L. R. (2008). CFD modelling of slurry flows in horizontal pipes. *Proceedings of FEDSM2008, 8th Symposium on Applications in computational dynamics,* Aug. 17-20, 2008, Jacksonville, Florida. https://doi.org/10.1115/FEDSM2008-55103

Kim, H., & Kim, S. (2019). Two dimensional cavitation waterhammer model for a reservoir-pipeline-valve system. *Journal of Hydraulic Research*, *57*(3). https://doi.org/10.1080/00221686.2018.1494046

Kodura, A., Stefanek, P., & Weinerowska-Bords, K. (2017). a\An experimental and numerical analysis of water hammer phenomenon in slurries. *Journal of Fluids Engineering-Transactions of the ASME*, 139(12). https://doi.org/10.1115/1.4037678

Kou, Y., Yang, J., & Kou, Z. (2016). A water hammer protection method for mine drainage system based on velocity adjustment of hydraulic control valve. *Shock and Vibration*, *2016*. https://doi.org/10.1155/2016/2346025

Kumar, K., Kumar, S., Gupta, M., & Garg, H. C. (2016a). Effect of addition of bottom ash on the rheological properties of fly ash slurry at varying temperature. *IOP Conference Series: Materials Science and Engineering*, *149*(1). https://doi.org/10.1088/1757-899X/149/1/012044

Kumar, S., Gandhi, B. K., & Mohapatra, S. K. (2016b). Leaching characteristics of bottom ash from thermal power plants. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, *38*(5). https://doi.org/10.1080/15567036.2015.1010051

Kumar, K., Kumar, S., Gupta, M., Garg, H., & Singh, G. (2017). Measurement of flow characteristics for multiparticulate bottom ash-water suspension with additives. *Journal of Residuals Science and Technology*, *14*(1). https://doi.org/10.12783/issn.1544-8053/14/1/2

Lahiri, S. K. & Ghanta, K. C. (2010). Slurry flow modelling by CFD. *Chemical Industry & Chemical Engineering Quarterly AChE*, 16(4), 295-308. https://doi.org/10.2298/CICEQ091030034L

Lema, M., López Peña, F., Buchlin, J. M., Rambaud, P., & Steelant, J. (2016). Analysis of fluid hammer occurrence with phase change and column separation due to fast valve opening by means of flow visualization. *Experimental Thermal and Fluid Science*, *79*. https://doi.org/10.1016/j.expthermflusci.2016.07.008

Li, L., Usui, H., & Suzuki, H. (2002). Study of pipeline transportation of dense fly ash-water slurry. *Coal Preparation*, *22*(2), 65-80. https://doi.org/10.1080/07349340210959

Li, S., Yang, C., & Jiang, D. (2008). Modeling of hydraulic pipeline transients accompanied with cavitation and gas bubbles using parallel genetic algorithms. *Journal of Applied Mechanics, Transactions ASME*, *75*(4). https://doi.org/10.1115/1.2912934

More, S. R., Bhatt, D. V., & Menghani, J. V. (2018). Failure analysis of coal bottom ash slurry pipeline in thermal power plant. *Engineering Failure Analysis*, *90*. https://doi.org/10.1016/j.engfailanal.2018.04.015

Mukherjee, B., Das, S., & Mazumdar, A. (2015). Transient analysis of a pipeline network for drinking purpose in Assam, India. *Journal of the Institution of Public Health Engineers, India*, 14-26.

Oldshue, J. Y. (2003). Fluid mixing. *Encyclopedia of Physical Science and Technology*, 79-104. https://doi.org/10.1016/B0-12-227410-5/00252-0

Pattanaik, S., Parhi, P. K., Das, D., & Samal, A. K. (2019). Acacia concinna: A natural dispersant for stabilization and transportation of fly ash-water slurry. *Journal of the Taiwan Institute of Chemical Engineers*, *99*. https://doi.org/10.1016/j.jtice.2019.03.020

Prasad, V., Mehrotra, S. P., & Thareja, P. (2019). Influence of additives, particle size, and incorporation of coarse particles on the shear rheology of concentrated Indian coal ash slurries. *Asia-Pacific Journal of Chemical Engineering*, *14*(5). https://doi.org/10.1002/apj.2358

Rawat, A., Singh, S. N., & Seshadri, V. (2016). Computational methodology for determination of head loss in both laminar and turbulent regimes for the flow of high concentration coal ash slurries through pipeline. *Particulate Science and Technology*, *34*(3). https://doi.org/10.1080/02726351.2015.1075637

Ringas, C. (2007). Internal corrosion of slurry pipelines caused by microbial corrosion: causes and remedies. *Journal of the Southern African Institute of Mining and Metallurgy*, *107*(6).

Routray, A., Senapati, P. K., Padhy, M., Das, D., & Mohapatra, R. K. (2022). Effect of mixture of a non-ionic and a cationic surfactant for preparation of stabilized high concentration coal water slurry. *International Journal of Coal Preparation and Utilization*, *42*(3). https://doi.org/10.1080/19392699.2019.1674843

Sayari, S., Mahdavi-Meymand, A., & Zounemat-Kermani, M. (2020). Prediction of critical velocity in pipeline flow of slurries using tlbo algorithm: a comprehensive study. *Journal of Pipeline Systems Engineering and Practice*, *11*(2). https://doi.org/10.1061/(ASCE)PS.1949-1204.0000439

Seitshiro, I., Fujii, S., Yokoyama, N., Sato, I., & Sato, H. (2013). The multi-sized slurry flows in horizontal pipes: Innovated models and verification. *International Journal of the Society of Material Engineering for Resources*, *19*(1-2). https://doi.org/10.5188/ijsmer.19.24

Seitshiro, I., Sato, I., & Sato, H. (2012). Verification and application of design model for settling slurry transport in pipes. *International Journal of the Society of Material Engineering for Resources*, *18*(2). https://doi.org/10.5188/ijsmer.18.44

Seitshiro, I. T., Katende, J., & Sato, H. (2014). Slurry pipeline design of multi-sized solids: Application of innovated models. *International Journal of the Society of Material Engineering for Resources*, *20*(2). https://doi.org/10.5188/ijsmer.20.201

Singh, H., Kumar, S., & Mohapatra, S. K. (2018). Influence of solid concentration on rheological characteristics of fly ash-water suspension. *IOP Conference Series: Materials Science and Engineering*, *377*(1). https://doi.org/10.1088/1757-899X/377/1/012134

Singh, H., Kumar, S., & Mohapatra, S. K. (2021). Design and modeling of a self-dispersing twisted pipe to mitigate settling in coal water suspension. *Advanced Powder Technology*, *32*(2). https://doi.org/10.1016/j.apt.2020.12.012

Singh, J. P., Kumar, S., & Mohapatra, S. K. (2019). An experimental study on head loss characteristics of pipe bends for flow of coal–water slurry at high solid concentration. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, *233*(5). https://doi.org/10.1177/0954408919844928

Singh, M. K., Ratha, D., Kumar, S., & Kumar, D. (2016). Influence of particle-size distribution and temperature on rheological behavior of coal slurry. *International Journal of Coal Preparation and Utilization*, *36*(1). https://doi.org/10.1080/19392699.2015.1049265

Singh, M. K., Kumar, S., Ratha, D., & Kaur, H. (2017). Design of slurry transportation pipeline for the flow of muti-particulate coal ash suspension. *International Journal of Hydrogen Energy*, *42*(30). https://doi.org/10.1016/j.ijhydene.2017.04.259

Tieli, W., Jin J., & Gang L. (2014). Research on accumulator for water hammer protection of long-distance slurry transportation pipelines. *ISFMFE - 6th International Symposium on Fluid Machinery and Fluid Engineering, Wuhan*, pp. 1-6. https://doi.org/10.1049/cp.2014.1256

Wylie, E. B., Streeter, V. L., & Suo, L. (1993). *Fluid Transients in Systems*. Prentice Hall.

Xu, W., Yang, B., Yang, S., & Dang, P. (2016). Experimental study on correlativity between rheological parameters and grain grading of coal gauge backfill slurry. *Journal of Central South University (Science and Technology)*, *47*(4). https://doi.org/10.11817/j.issn.1672-7207.2016.04.026

Yang, J., Yang, B., & Yu, M. (2019). Pressure study on pipe transportation associated with cemented coal gangue fly-ash backfill slurry. *Applied Sciences (Switzerland)*, *9*(3). https://doi.org/10.3390/app9030512

Zhao, L., Yang, Y., Lu, Y., Hu, X., & Fan, L. (2016). Cavity water hammer characteristic test on two places. *Advances in Science and Technology of Water Resources*, *36*(1). https://doi.org/10.3880/j.issn.1006-7647.2016.01.006

Zhao, H., Zhou, Z., & Peng, W. (2018). Research on water hammer phenomenon during stop valve closing process based on CFD. *ACM International Conference Proceeding Series*. https://doi.org/10.1145/3305275.3305303

Zhao, L., Yang, Y., Wang, T., Han, W., Wu, R., Wang, P., Wang, Q., & Zhou, L. (2020a). An experimental study on the water hammer with cavity collapse under multiple interruptions. *Water (Switzerland)*, *12*(9). https://doi.org/10.3390/W12092566

Zhao, L., Yang, Y., Wang, T., Zhou, L., Li, Y., & Zhang, M. (2020b). A simulation calculation method of a water hammer with multipoint collapsing. *Energies*, *13*(5). https://doi.org/10.3390/en13051103