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Effect of Additive on the Performance Characteristics of Centrifugal and Progressive Cavity Slurry Pumps with High Concentration Fly Ash Slurries

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ABSTRACT

Slurry pumps that are used in the hydraulic transportation of fly ash slurries through pipes in thermal power plants can be broadly classified into two main categories namely positive displacement and centrifugal pumps. The two types of pumps differ considerably in construction as well as in operating principle compared to the conventional pumps. The present study reports the effect of additive on the performance characteristics of centrifugal and progressive cavity screw pumps with fly ash slurries at high concentrations (above $C_w \approx 50\%$ by weight). Mixture of sodium carbonate and Henko detergent (5:1) at a concentration of 0.2% by weight has been used as an additive. For each type of pump, the effect of additive on the performance characteristics has been experimentally evaluated at rated speed with fly ash slurries in the concentration range of 50 to 70% by weight. The pump total head, overall efficiency and pump input power as a function of flow rate have been measured. The results obtained from the centrifugal slurry pump performance show that at rated speed, the performance of the pump improves with the addition of drag reducing additive. In the case of progressive cavity screw pump, pump performance characteristics and behavior were completely different as compared to the centrifugal slurry pump. At rated speed, the performance of screw pump deteriorates with the addition of drag reducing soap solution.

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1. Introduction

The pump is the heart of any hydraulic transportation system as it determines both the efficiency and reliability of the system. Today a wide range of slurry pumps are available and most commonly used pumps are broadly classified into two main categories namely positive displacement and centrifugal types. Progressive cavity screw pumps are of the positive displacement type that transfers fluid through a sequence of small, fixed shape cavities as a helix shaped rotor is rotated. Centrifugal pumps consist of a casing and an impeller mounted on a rotating shaft. Further, both types of pumps

differ considerably in construction as compared to the conventional pumps when they are designed for solid-liquid mixtures. Thus, for proper design and selection of a slurry pump, extensive data is required for accurate estimation of the deviation in the pump performance due to slurry flow at high concentrations.

The performance of centrifugal slurry pumps is dependent on various parameters such as particle size, solid concentration and specific gravity of solids etc., and its performance deteriorates with increase in the values of these parameters (Fairbank, 1942; Vocaldo et al., 1974; Gahlot et al., 1992; Kazim et al., 1994; Gandhi et al., 2001). The investigators also observed that the addition of fine particles in the slurry of coarser material leads to reduction in the additional losses that occur in the pumps due to the presence of solids.

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Fig. 1. Schematic Diagram of the Experimental Setup used for Centrifugal Slurry Pump Performance.

The performance curves for screw pumps are totally different from centrifugal pumps (Frei and Huber, 2005; Chandel, 2010). For screw pumps; the characteristics were different compared to the centrifugal pump. The overall efficiency of the screw pump was positively influenced by the viscosity; higher viscosity meaning an increased value of the overall efficiency. The addition of additives in a small amount improves the performance of slurry pump (Chand et al., 1985; Gasljevic and Matthys, 1992; Satoshi et al., 2006). Pump head and efficiency improved with the use of polymer and surfactant additives. Little is known on the quantitative improvement of slurry pump performance when additives are used. Most studies have been on water pumps and only a few studies have been conducted on the improvement of slurry pump performance.

Hydraulic transportation of solid materials in the form of slurry through pipelines is one of the widely used methods for conveying

bulk quantities of materials. Slurry pipelines are widely used for the bulk transportation of materials such as coal, mineral ores, and sand, both over short and long distances at concentrations varying over a wide range. The pump is the key element in any slurry transportation system for short to medium distances and, hence, in the present paper, effect of additive on the performance characteristics of two different types of slurry pumps, namely centrifugal and progressive cavity screw pumps have been investigated with fly ash slurries at high concentration. Measurements have been made in the operating range of the pumps for a wide range of solid concentration (50 to 70% by weight). The total head, overall efficiency, and pump input power as a function of the flow rate have been measured. Based on these measurements, an attempt has been made to establish the effect of additive on the performance of these slurry pumps.

Fig. 2. Schematic Diagram of the Experimental Setup used for Progressive Cavity Screw Pump Performance.

Table 1

Physical properties of fly ash (Source: TPS, BADARPUR)

(a) Specific Gravity of Fly Ash (Unsieved) = 1.992												
(b) Particle Size Distribution (% finer by weight)												
Size (μm)	300	200	100	75.4	64.0	49.76	40.94	36.10	23.58	17.24	12.57	9.10 4.25
% Finer	100	97.2	90.1	85.8	69.8	63.10	60.44	55.12	42.66	28.44	16.0	8.33 4.23
Weighted Mean Diameter, $d_{wm} = 49 \mu\text{m}$, $d_{50} = 25 \mu\text{m}$												
(c) Settling characteristics of the Suspension (Initial Concentration $C_w = 30.0\%$ by weight)												
Time (minutes)	0	1/4	1/2	1	1.5	2	5	10	20	40	80	1440
% Settled Concentration	30.0	30.61	31.0	31.25	31.91	32.0	33.30	35.0	40.60	50.85	58.0	58.0
(d) pH value (un-sieved sample)												
% C_w , (by weight)	50	60	65	70								
pH	7.15	7.12	7.12	7.12								

Table 2

Rheological properties of fly ash slurries (Chandel, 2010)

% C_w (by weight)	Temp. ($^{\circ}\text{C}$)	Yield Stress τ_y (Pa)	Slurry Viscosity η_p ($\times 10^{-3}$) (Pa-s)	Water Viscosity η_w ($\times 10^{-3}$) (Pa-s)	Relative slurry Viscosity η_r	Remarks
0	25	—	—	0.891	1.0	Newtonian
50	25	0.044	3.73	0.891	4.18	non-Newtonian
60	25	0.360	14.50	0.891	16.27	non-Newtonian
65	25	1.36	53.40	0.891	60.00	non-Newtonian
68	25	1.712	172.10	0.891	193.15	non-Newtonian
70	25	1.945	245.30	0.891	275.30	non-Newtonian

2. Experimental Set-up

2.1. Experimental Set-up for Centrifugal Slurry Pump

The schematic diagram of the experimental set-up used for performance evaluation of a 50-mm “50K WILFLEY” (Make: Hindustan Dorr Oliver Limited, India) centrifugal slurry pump is shown in Figure 1. The slurry is prepared in the 2.73-m³ hopper-shaped mixing tank, which is provided with suitable stirring arrangement for keeping the slurry well mixed. The slurry is drawn from the mixing tank into 53-mm diameter pipe loop by the slurry pump with a Ni-hard impeller and casing and returned back to mixing tank. The pilot plant consists of a closed circuit Mild Steel pipe test loop of 7.0-m length. The pump is driven by an induction motor of 22 kW, 415 V, 40 Amp (Type: ILA 2174-4, Make: M/s Siemens Limited, India). The capacity of the pump is sufficient to cover the entire range of head and discharge needed for simulating the conditions in the prototype pipeline. The flow rate in the loop can be varied over a wide range by suitably operating the plug valves provided in the pipeline. The operation of the closed pipe loop also helps in keeping the slurry well mixed in the mixing tank.

The impeller for centrifugal slurry pump was of closed type having five vanes. The impeller and casing were made of Ni-hard material. The suction and delivery flange sizes are 100 mm and 50 mm respectively. The rated speed of the motor was 1450 rpm.

2.2. Experimental Set-up for Progressive Cavity Screw Pump

Figure 2 shows the schematic diagram of the experimental setup to evaluate the performance of a “Roto Flow” (Make: Roto Pumps Limited, Noida, India) progressive cavity screw pump. The test set-up consists of a 50-m closed circuit Mild Steel pipe test loop. The set-up comprises of a 42-mm diameter [40 mm NB] pipeline, connected to a mixing tank forming a closed re-circulating pipe test loop. The slurry is prepared in the hopper-shaped mixing tank, which is provided with suitable stirring arrangement for keeping the slurry well mixed. The storage capacity of the hopper ensures the continuity of operation and the overall system availability for continuous operation of the pilot plant. The slurry is pumped from the mixing tank into 42-mm diameter pipe loop by a screw pump and that pump is driven by an induction motor of 10 kW, 415 V (Type: 72P-0132M4, Make: M/s Power Build Limited, India). The

Table 3

Rheological properties of fly ash slurry with additive

% C_w (by weight)	Temp. ($^{\circ}\text{C}$)	Yield Stress τ_y (Pa)	Slurry Viscosity η_p ($\times 10^{-3}$) (Pa-s)	Water Viscosity η_w ($\times 10^{-3}$) (Pa-s)	Relative Slurry Viscosity η_r	Remarks
0	25	—	—	0.891	1.0	Newtonian
50	25	0.035	1.92	0.891	2.16	non-Newtonian
60	25	0.28	7.75	0.891	8.70	non-Newtonian
65	25	0.99	35.90	0.891	40.30	non-Newtonian
68	25	1.04	110.0	0.891	123.50	non-Newtonian
70	25	1.20	150.20	0.891	168.60	non-Newtonian

(a) Head – Capacity Characteristics

(b) Power – Capacity Characteristics

(c) Efficiency – Capacity Characteristics

(a) Head – Capacity Characteristics

(a) Power – Capacity Characteristics

(c) Efficiency – Capacity Characteristics

Fig. 4. Comparison of Performance of the Centrifugal Pump for Fly Ash Slurry with and without Additive at $C_w = 65\%$ by Weight.

Fig. 3. Performance Characteristics of Centrifugal Pump with Fly Ash Slurry in the Presence of Additive.

Table 4

Performance characteristics of centrifugal slurry pump

S No.	Solid Concentration (% by wt)	Without Additive			With Additive		
		Head (m)	Input Power (kW)	Efficiency (%)	Head (m)	Input Power (kW)	Efficiency (%)
1	60	14.40	6.30	36.0	15.40	5.80	40.9
2	65	13.90	6.80	33.1	14.90	6.30	37.3
3	68	13.50	7.60	30.0	14.50	6.80	35.0
4	70	13.10	8.40	26.0	14.30	7.30	30.5

flow rate in the loop can be varied over a wide range by suitably operating the plug valves provided in the pipe loop.

2.3. Instrumentation

To measure the flow rate for both pumps, a pre-calibrated electro-magnetic flow meter (Make: ABB Limited, India) is installed in the vertical pipe section of the loop. Measurement uncertainty for the discharge flow rate was $\pm 2\%$. Both test loops are provided with an efflux sampler fitted with a plug valve in the vertical pipe section near the discharge end for collection of the slurry sample to monitor the solid concentration. The average efflux concentration is evaluated using the measured correlation between the slurry specific gravity and the solid concentration. The absolute error in the measurement of solid concentration is less than $\pm 1\%$. In the case of centrifugal slurry pump, pressure taps are provided in the suction and delivery lines of the pump to measure the total head developed by the pump. In the case of screw pump, pressure tap is provided only in the delivery line of the pump to measure the discharge head developed by the pump. The suction head was measured using a U-tube mercury manometer for centrifugal pump using separation chambers. The U-tube manometer was inclined at 30° angle to the horizontal to have higher sensitivity. This arrangement resulted in a minimum of 0.5 mm of mercury column for suction measurement. Since the mixing tank is directly connected to the progressive cavity pump through the hopper, the suction head was taken as the height of the slurry level in the mixing tank above the centerline of the pump. The delivery head was measured using a Bourdan tube-type pressure gauge for both the pumps. The pressure gauges have an accuracy of $\pm 1\%$ and were calibrated using a dead weight pressure gauge tester at regular intervals during experimentation. Separation chambers with water as the intermediate fluid were used to prevent the choking of the connecting tubes used in head measurement.

The pump speeds were measured using an optical digital electromagnet tachometer (Digital Tacho -DT 2001A, Make: M/s Electronic Automation Pvt. Ltd., Bangalore, India). The resolution of the device was 1 rpm. Arrangements were also made to measure the input power of the motors which are coupled with centrifugal and progressive cavity screw pumps, using two wattmeter method with an estimated uncertainty of $\pm 1\%$. The input voltage to the motor was controlled by a 3-phase voltage regulator. At any setting, the input voltage, current and line frequency were also measured for both the motors. The measuring instruments used for measurement of the electric supply were of AE make and were calibrated periodically during experimentation. The pump input power was calculated from the measured values of the input power to the motor and knowledge of its efficiency. Before starting the test runs, the motor efficiency was determined by performing no load and locked rotor tests as per relevant Indian Standards (IS:

4889-1967, 1968; IS: 11346-1985, 1985). All measurements were made in accordance with the requirements specified in relevant pump test codes (IS: 4029-1967, 1969; IS: 5120-1977, 1990).

3. Properties of Fly Ash Used

Fresh fly ash samples from the electrostatic precipitator hoppers of a thermal power plant were used for the present study. For determining the physical properties of the solids, representative sample was collected using standard cone and quarter method. The physical properties of fly ash are given in Table 1. Specific gravity is an important design parameter as it determines the settling characteristics of the slurry. The 1.992 specific gravity of the solid was determined using Standard Pyknometer Method. The particle distribution has been obtained by two methods namely, sieve analysis and hydrometer analysis. For the coarser particles, sieve analysis was used to determine the particle size distribution. Standard Hydrometer analysis was used to determine the distribution of finer particles (below $75 \mu\text{m}$). The maximum size in the fly ash sample is $300 \mu\text{m}$ and 85% by weight is below $75 \mu\text{m}$. The weighted mean size (d_{wm}) and the d_{50} of the fly ash particles are $49 \mu\text{m}$ and $25 \mu\text{m}$ respectively. The static settled concentration is also a very important parameter as it determines the maximum solid concentration which can be achieved by gravitational settling. The maximum static settled concentration of the fly ash slurry is 58% by weight. The measured values of pH at various concentrations lie in the range of 7.15 to 7.12, indicating that the suspensions are non-reactive at all concentrations. A Weissenberg Rheogoniometer (Model: R 18 by M/s. Sangmo Control Ltd. U. K.) with concentric cylinder platens was used for obtaining the rheological characteristics of the fly ash slurries at various concentrations. The experimental data of shear stress (τ) and shear rate ($\dot{\gamma}$), in the range of 20 to 120 sec^{-1} , for fly ash slurries having concentration in the range of 50 to 70% (by weight) were analyzed for identifying the rheological model. The variation of the shear stress with shear rate for all concentrations showed that all the data points have a linear dependence of the type:

$$\tau = \tau_y + \eta_p \dot{\gamma} \quad (1)$$

The straight-line equation is fitted for each set of data using the method of least squares. The values of τ_y are non-zero for all sets of data, implying that fly ash slurry over the range investigated shows a non-Newtonian behavior and can be represented as a Bingham Plastic fluid (Equation 1) where τ_y is the yield stress and η_p the Bingham plastic viscosity. The rheological properties of fly ash slurries with and without additive at different concentrations are tabulated in Tables 2 and 3. Relative Bingham viscosity (η_r) of the slurry is obtained by dividing the Bingham viscosity (η_p) by the viscosity of the water (η_w) at test temperature:

(a) Head – Capacity Characteristics

(b) Power – Capacity Characteristics

(c) Efficiency – Capacity Characteristics

Fig. 5. Performance Characteristics of Progressive Cavity Screw Pump with Fly Ash Slurry in the Presence of Additive.

$$\eta_r = \frac{\eta_p}{\eta_w} \quad (2)$$

From the results, it is observed that mixture of sodium carbonate and Henko detergent as additive significantly reduces both viscosity and yield stress of fly ash slurry. This effect can be attributed to the reduction of surface tension and inter-particulate forces between the fine particles due to the presence of the additive (Chandel et al., 2009).

4. Experimental Procedure and Range of Parameters Studied

The performance of the pumps was determined with clear water before, as well as periodically during actual experiments so as to establish the possible effects of erosion of different pump components. After evaluating the performance characteristics of the pumps with water, the above procedure was repeated to evaluate the performance of the pumps with the solid materials at preselected solid concentrations. Care was taken to ensure that solids were properly mixed.

The performance of centrifugal slurry pump was evaluated at the rated speed of 1450 rpm with clear water and fly ash slurries with additive for various concentrations (60.3%, 65.2%, 67.9%, 70.2% (by weight)). The performance of progressive cavity screw pump was evaluated at the rated speed of 125 rpm with clear water and slurries of fly ash. Experiments were conducted with fly ash slurries at four concentrations (50.2%, 60.1%, 65.3%, 70% (by weight)) with additive. During each test run, two efflux samples were collected to monitor the concentration and further analyzed for particle size distribution in order to establish the extent of attrition of solid particles during the tests.

5. Results and Discussion

5.1. Performance Characteristics of Centrifugal Slurry Pump

The performance characteristics of the centrifugal pump with water and fly ash slurries at various concentrations with additive are given in Figure 3(a–c). The nature of variation is similar to that observed without additive which has been reported in our earlier publication (Chandel, 2010; Chandel et al. 2011). In order to highlight the effect of additive, the pump characteristics with and without additive have been compared in Figure 4(a–c) and at a solid concentration of 65% (by weight) (Table 4). It is observed from the figure that both head and efficiency of the pump increase with the addition of additive (Figures 4a and 4c) whereas the pump input power decreases (Figure 4b). As noted above, the addition of soap solution (mixture of sodium carbonate and Henko detergent) to the fly ash slurry changes its rheological properties (both viscosity and yield stress) considerably. The experimental data shows that addition of small quantity of additive in fly ash slurry results in a substantial decrease in the losses in the pump and thereby its efficiency increases.

5.2. Performance Characteristics of Progressive Cavity Screw Pump

The performance characteristics of the screw pump with clear water as well as with fly ash slurries with additive are shown in Figure 5(a–c). As pump is a positive displacement type, it does not have shut off head and the variation of head and efficiency with discharge show similar trend that was observed with fly ash

Table 5Performance characteristics of progressive cavity screw pump (at 12.5 m³/hr)

S No.	Solid Concentration (% by wt)	Without Additive			With Additive		
		Head (m)	Input Power (kW)	Efficiency (%)	Head (m)	Input Power (kW)	Efficiency (%)
1	50	25.7	3.5	35.0	21.1	3.2	32.1
2	60	30.1	4.0	38.0	27.6	3.8	34.8
3	65	36.0	4.60	40.0	32.0	4.50	36.7
4	70	40.2	5.1	42.8	33.8	4.8	38.9

slurries without additive (Chandel, 2010; Chandel et al., 2011). Figure 5 (b) shows the variation of the pump input power with the discharge rate. The pump input power at a given solid concentration decreases with flow rate. Figure 5 (c) depicts the variation of efficiency with discharge rate, showing that the efficiency at any given discharge increases with increasing concentration. A comparison of pump parameters for fly ash slurry with and without additive at designed flow rate as well as at other flow rates shows that the pump head decreases with the addition of soap solution (Table 5). For a designed flow rate (12.5 m³/hr), the head developed by the pump with additive is 34 m, whereas for without additive it is 41 m at 70% solid concentration. The maximum efficiency of the pump at 70% solid concentration is 52% for fly ash slurry, whereas for fly ash slurry with additive it is reduced to 47%. Hence, it is seen that the efficiency increases with increase in concentration for a given flow rate but, comparatively, efficiency values are lower for fly ash slurry with additive. This is due to the addition of soap solution to the fly ash slurry reducing the viscosity of the fly ash slurry. The performance of screw pump improves with the increase in the viscosity of the slurry. This can be explained by the fact that the screw pump has a small clearance between the screw and the casing. These clearances result in leakage (known as slip) from the pump outlet cavity to the pump inlet cavity (Chandel, 2010; Chandel et al., 2011). Thus, slip is the loss of capacity from the higher pressure area through the internal clearance and is a function of fluid viscosity, pump outlet pressure

and fluid characteristics. Slip is calculated as the difference between the theoretical volumetric displacement of the screw pump and the actual flow rate. As the viscosity increases, slip decreases (Figure 6). Thus, the performance of the pump also deteriorates as viscosity of the slurry decreases. As the viscosity increases, slip flow decreases and, therefore, the values of slip with fly ash slurry without additive are lower (Chandel et al., 2011) as compared to fly ash slurry with additive. Data points for both types of fly ash slurries (with and without additive) fall on a single curve, thereby showing that percentage slip is mainly dependent on slurry viscosity and not on other parameters. For fly ash slurry with additive, slip increases with increase in head but decreases with increase in solid concentration (Figure 7). For water, the maximum slip is around 57%, whereas for $C_w = 50\%$, it reduces to 50%. This trend becomes more pronounced at higher concentration and at 70% solid concentration, the maximum slip is reduced to 16%. Percentage slip increases for fly ash slurry with additive as compared to fly ash slurry without additive. For fly ash slurry at $C_w = 50\%$, the maximum percent slip is around 40% (Chandel, 2010), whereas for fly ash slurry with additive at same concentration, it increases to 50% due to the reduction in the viscosity of the slurry.

6. Conclusions

The effect of drag reducing additive on the characteristics of two different types of slurry pumps namely centrifugal and progressive

Fig. 6. Variation of Slip with Viscosity for Fly Ash Slurry at H = 30 m with and without Additive (Progressive Cavity Screw Pump).

Fig. 7. Variation of Slip with Head for Fly Ash Slurry with Additive (Progressive Cavity Screw Pump).

cavity pumps with fly ash slurries have been investigated and following broad conclusions are drawn:

- (i) The head and efficiency of the centrifugal slurry pump decrease with increase in solid concentration and slurry viscosity whereas pump input power increases with increased solid concentration.
- (ii) The addition of drag reducing additive improves the performance of the centrifugal slurry pump in terms of head and efficiency.
- (iii) For screw pump, the head and efficiency increase with increase in solid concentration and slurry viscosity whereas pump input power decreases with flow rate at a given solid concentration. The performance of screw pump deteriorates with the addition of drag-reducing additive.

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