Abrasive, Erosive and Corrosive Wear in Slurry Pumps – A Review

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Abstract - *This paper gives an overview of the last few decades of research work which have done on the investigation of the mechanism of wear on different parts of the slurry pumps. Slurry pumps have widely used for disposal and transportation of both settling and non-settling slurries in many industries i.e. coal, steel, iron ore, etc. Wear is the main phenomenon which reduces the life of the costly slurry pump components. The main factors which affect the service lives of the parts of slurry pumps are the solid particle size, shape, hardness, concentration, impact angle, rotational speed, hydraulic design of the pump and material selection. Wear strongly depends on rotational speed, particle size and solid concentration. The wear can be occurring due to abrasion, erosion, and corrosion, in which erosion wear is the main wear phenomena. Erosive wear mainly occurs on the impeller and casing of the slurry pumps due to the solid concentration and impact of the solid particles with a high velocity. For improved the performance characteristics of slurry pumps investigators throughout the world continuously research experimentally, numerically and theoretically on it. The use of ceramic reduces the wear rate of the parts of the slurry pump. The wear can also be reduced by the use of ceramic reinforced metal matrix composites in the future due to its high strength with good wear and corrosion resistance properties.*

Key Words: Slurry, Erosion, Wear, Impeller, Pump etc.

1. INTRODUCTION

1.1 Slurry

Slurry is a mixture of any liquid with some solid particles. The physical characteristics of the slurry is depend upon the type, size, shape and quantity of the particles, distribution of the solid particles in liquid, concentration of solid particles in the liquid, size of the conduit, level of turbulence, temperature and absolute viscosity of the carrier [1], [2].

Types of slurry - Slurries are mainly classified into two groups: Non-settling slurry and settling slurry. **Non-settling slurries** entail very fine particles which can form stable homogeneous mixtures exhibiting increased apparent viscosity. These slurries usually have low wearing properties but, when fine solids are present in the slurry in sufficient quantity to cause this change in behaviour away from a normal liquid, they are referred to as being non-Newtonian. **Settling slurries** are formed by coarser particles and tend to form an unstable & heterogeneous mixture and these coarser particles tend to have higher wearing properties as compared to fine particles [2], [3].

1.2 Slurry Pump

The pump which is used to transport settling or non-settling slurries is called slurry pump. It also run on the same principle of operation of clear liquid or gas pumps. But slurry pumps will never reach the same efficiency as a clear liquid pump even if both are pumping water. Slurry pumps are widely used to transport corrosive/abrasive and high concentration slurry in many industries such as Gold, Silver, Iron ore, Tin, Steel, Coal, Titanium, Copper, Mineral sands, Lead and Zinc. Various other industries include Molybdenum, Electric Utilities, Oil Shale, Water and Sewage Utilities, Building areas, Sand and Gravel, Tobacco and Agriculture (hog, poultry, and dairy manure). Slurry pump impellers must have thicker blades than clear liquid pumps to withstand wear and prevent them from breaking from the impact of solids. With this extra thickness, there must be fewer blades, not only to minimize obstruction but also to keep the passageways wide enough to allow the largest solid particles to pass through. Varieties of pumps are available for pumping the slurries i.e. positive displacement and special effect types such as Venturi eductors are used but centrifugal pump is the most common type of slurry pump [2], [4].

1.3 Centrifugal Slurry Pump

The centrifugal slurry pump based on physics principle that increases the pressure of liquid and solid particle mixture through centrifugal force (a rotating impeller) and converts electrical energy into slurry potential and kinetic energy. Centrifugal slurry pumps are a very unique turbo-machine that must be able to handle the flow of high concentrations of solid particles which greatly accelerate wear. The centrifugal slurry pumps need to consider impeller size and design, its ease of maintenance, the type of shaft seal to be used and the choice of the optimum materials. This is needed to withstand wear caused by the abrasive, erosive and often corrosive attack on the materials. Many other important considerations are also required. There is an ever increasing use of centrifugal pumps in applications which require the pumping of liquids containing solids in suspension and liquids other than water. A dredge pump is an example of the first application and an oil pump of the second. Centrifugal slurry pumps are arranged in series to obtain a large pressure head. It is used to handle and disposal the ash produced in power plants [2], [4]–[7].

1.4 Wear

Wear is defined as the progressive volume loss of material from a target surface. It may occur due to corrosion, abrasion or erosion. Wear is a very important consideration in the design and operation of slurry systems, as it affects both the initial capital costs and the life of components. ‘**Abrasive wear**’ is the loss of material by the passage of hard particles over a surface. ‘**Erosive wear**’ is caused by the impact of particles against a solid surface. In some practical situations the film material is formed by chemical attack of either contacting body and while this may provide some lubrication, significant wear is virtually inevitable. This form of wear is known as ‘**corrosive wear**’ and when atmospheric oxygen is the corroding agent, then ‘**oxidative wear**’ is said to occur. Wear on the components of slurry pumps by abrasion & erosion are caused by contact between a particle and solid material. Abrasion and erosion in particular are rapid and severe forms of wear and can result in significant costs if not adequately controlled [8]–[11].

The erosion wear has classified as a solid particle erosion, liquid impingement erosion and cavitation erosion. Solid particle erosion is the loss of material that results from repeated impact of solid particles suspended in the flowing fluid, at any target surface. The slurry erosion is a complex phenomenon and it is not yet fully understood because it is influenced by many factors, which act simultaneously. Erosive wear is a function of particle velocity and is more significant on impeller and volute casing in slurry pumps. The material of impeller and casing is usually high chromium cast iron due to its wear resistance property. The factors responsible for erosive wear are the rotational speed of the pump impeller, hardness of the target material, solid concentration in slurry, solid particle size and angle of impingement. From order-of-magnitude calculations, the erosion mechanism in slurry pumps for mining applications was found to be a scouring type. Impact erosion was found to be unlikely to occur [5], [12], [13]. The one most often quoted for both pump and pipe wear is:

$$\text{Wear} \propto (\text{velocity})^{n}$$

Where index *n* may vary depending on the material and the other factors involved. For pump wear value of *n* appears to be 3, but for pipe wear value of n lying between 0.85 and 4.5. However, in practice it is doubtful if wear will vary with velocity as a simple power law [10].

1.5 Metal Matrix Composite Materials

Metal Matrix Composite (MMC) is the most advanced and flexible engineering material. This is produced by the macroscopic assembly of reinforcement and matrix materials. MMCs have very good combination of mechanical, tribological as well as corrosion resistance properties [14]–[24]. Al MMCs provides good combinations of strength to weight ratio and it has been used for lightweight applications like aerospace, automobiles [25]–[27]. Rolling, forging and extrusion process can be applicable in particulate reinforced Al MMCs, which enhanced its mechanical properties. Particulate reinforced Al MMCs also provides isotropic property in nature [26], [28]. Due to its advantageous properties i.e. wear and corrosion resistance with high specific strength these materials can replace the conventional materials which are used for the various components of slurry pumps.

2. LITERATURE SURVEY

Many researchers have worked on to analyse the phenomena of wear on slurry pumps and also try to overcome this wear. Truscott [29] has reported a literature survey on abrasive wear in hydraulic machinery. This survey considers the factors affecting abrasive wear. According to his survey, wear increases rapidly when the particle hardness exceeds that of the metal surface being abraded. Wear increases generally with grain size, sharpness and solids concentration. The very hard alloys (e.g. tungsten carbide) and surface treatments are extremely resistant. Chemical composition, micro-structure and work-hardening ability all play an important part in wear resistance of metals. Wear increases rapidly with flow velocity, and is often reported as being approx. $\propto (\text{velocity})^3$, or $\propto (\text{pump head})^{3/2}$ from both theoretical considerations and test results. The actual value of the index, for any given conditions, probably depends on at least some, if not all, of the other factors involved in the overall wear process. Head limits quoted are up to about 300 ft/stage for all-metal pumps, and 150 ft/stage for rubber-lined. Good hydraulic design, particularly by avoiding rapid changes in flow direction decreases wear and should be compromised as little as possible by solids handling considerations. Shrouded impellers are generally favored. Rubber lining can give a much-increased life compared to that for metal, provided that the solids are not large or sharp, bonding is good and heads & temperatures relatively low.

Ahmad et al. [30] have reported computation and experimental results of wear in a slurry pump impeller. Tests were carried out on the Simon-Warman pump to obtain wear patterns by painting the pump impeller in four layers of different colours. The thickness of each layer was measured to be of the order of 0.2 mm. The paint exhibited a ‘ductile’ behavior and did not peel off the vanes. For this slurry pump under low solids concentration the regions of maximum wear is on the pressure side of the blade near the leading edge and on the back shroud in the eye of the impeller.

Roco & Addie [31] have investigated erosion wear in slurry pumps and pipes. A complex hydraulic loop system was built in laboratory to systematically test. The average concentration is 18 vol. % of sand 0.2 mm. Two operating flow rates are considered 9▯0 ^{3} m^3/h and 15▯0 ^{3} m^3/h, both at a rotational speed of 275 rpm. At 9▯0 ^{3} m^3/h, the wear is more uniformly distributed along the casing wall and the maximum wear of 0.11 m is reached after 22 months of operation. The same maximum wear is attained in 19 months if the flow rate is increased to 15▯0 ^{3} m^3/h. The location maximum wear is at the casing bottom in both cases.

Madsen [32] has measured the erosion-corrosion synergism with a slurry wear test apparatus. Three types of tests were conducted to determine (1) the total erosive-corrosive wear rate, (2) the wear rate due to erosion only, and (3) the electrochemical corrosion rate. Low alloy steel (type A514), a stainless steel (type 316), and a commercial abrasion-resistant low alloy steel with the trade name REM 500 were used for test. When 316stainless steel was subjected to abrasive slurry, its electrochemical corrosion rate was much greater than its normal corrosion rate. The corrosion rate was strongly influenced by solids content & impeller speed due to removal of the chromium oxide film. An increase in temperature did not affect the corrosion rate appreciably but increased the pure erosion and total wear rates. The corrosion rates of A514 steel and REM 500 were strongly influenced by temperature. The corrosion rates of these alloys were moderately affected by the amount of solids in the slurry. The results indicate that oxidation products from both of these alloys did not adhere to their surfaces and thus no anodic passivation of these alloys resulted. The synergism between the erosion and corrosion components of wear can account for one-third to nearly two-thirds of the wear.

Catterfeld [33] has invented a highly wear-resistant composite impeller for centrifugal slurry pumps. This invention relates to pumps and is particularly directed to a composite impeller for use in centrifugal coal slurry pumps and the like. The impeller construction comprising a base and a cover plate formed of material which can be worked with relative ease and an insert sandwiched between said base and cover plate formed of high temperature and wear-resistant material, such as tungsten carbide, aluminium oxide, and the like. Haentjens & Stirling [34] have also invented centrifugal pump having resistant components. A centrifugal slurry pump includes wear resistant (such as hardened steel and the like) inserts on the wear faces of the first impeller shroud and the wear face of the front pump housing in the impeller chamber. In a centrifugal slurry pump, the area of greatest water is the region adjacent the inlet where the impeller face is closely adjacent a stationary face of the pump housing. A recirculating or leakage, flow occurs in this area as the result of reduced pressure at the inlet of the pump and increased pressure at the impeller outlet at opposite sides of this area. A forced flow through the area, potentially carrying abrasive solids from the slurry, thus wear occurs in this region is three times greater than the wear occurring in the next most wear prone region of the pump.

Aiming et al. [35] have worked on failure analysis of the impeller of a slurry pump subjected to corrosive wear. The phosphoric acid and gypsum are yielded in the form of mixed slurry. They found under the service conditions of the wet phosphoric acid process in the Yunnan Phosphate Fertilizer Plant the erosive wear attack is the primary cause for the failure of a slurry pump impeller. The abrasion action accelerates the corrosion which also promotes wear process again. The weight loss of corrosive wear is affected by the impact velocity and its tangential and normal components in different areas of the impeller. The area where the impact velocity is below the critical value is a uniform corrosive wear area and its weight loss is very small. The area where the impact velocity is above the critical value is a non-uniform corrosive wear area, and its weight loss increases rapidly with the increase in impact velocity. The areas where the tangential component of impact velocity is larger, the main mechanism is of a cutting mode. On the contrary, in the areas where the normal component of impact velocity is larger, the failure mode consists of the formation of micro cracks and the removal of second phases.

Franek et al. [36] have reported advanced methods for characterisation of abrasion/erosion resistance of wear protection materials. They give an overview over a selection of relevant test equipment and procedure. Abrasion and erosion processes are dominant wear mechanisms that reduce lifetime of costly machine parts. Kumar & Ratol [5] have experimentally investigate erosive wear on the high chrome cast iron impeller of slurry disposal pump using response surface methodology. They observed the ash concentration in slurry and kinetic energy of the moving particles highly contributes to erosive wear of pump impeller as compared to the ash particle size. Patil et al. [12] have characterized slurry erosion wear of pump impeller of gun metal bronze IS 318. They analysed the impeller material shows maximum erosion wear at 45⍰ impact angle and further increasing the impact angles erosion wear decreases and observed minimum at normal impact angle. Increasing the velocity of the erodent increases the erosion rate and the average slope for velocity is observed 2.34. Thus the kinetic energy of the impacting particle is responsible for material removal from the target surface.

Liu et al. [37] have studied on erosive wear and novel wear-resistant materials for centrifugal slurry pumps. Measurements of the erosive wear of selected cast iron (FC20), AISI 316L stainless steel, 26Cr-6Mo cast iron and alumina ceramic used in centrifugal slurry pumps have been studied in a simple slurry pot tester in aqueous slurry of SiC sand as impingement particles. They observed the erosive wear of the pressure surface is more serious than that of the suction surface. They found alumina ceramic shows excellent anti-wear performance comparing with the cast iron (FC20), AISI 316L stainless steel and 26Cr-6Mo cast iron. So, alumina ceramic can applied in centrifugal slurry pump field.

Lu et al. [38] have worked on improvement in erosion-corrosion resistance of high-chromium cast irons by trace boron. Study on an existing HCCI with 35 wt. % chromium and 3 wt. % carbon for oil sand slurry handling was modified by six HCCIs with nominal chemical compositions of 35 wt. % chromium, 3 wt. % carbon, and various concentrations of boron: 0, 0.12, 0.2, 0.4, 0.48, 0.6 wt. %, respectively, balanced by iron were fabricated using an induction furnace. They noted that the B-doped alloys show lower resistance to high-speed solid particle erosion at 90^0 impingement angle, but the slurry-erosion test with an impingement angle of 45^0, the samples with doped boron, which strengthened the material, showed considerably increased to resistance to the slurry erosion. B-doped alloys are harder than the base alloy.

Upadhayay & Kumar [39] have done numerical investigation of silicon carbide particle suspension behaviour for enhancing uniform suspension in erosion wear test rig. Model of the subject was developed in CFD modeller Gambit. FLUENT was used as post processor for obtaining results. The results of the study portray particle suspension behaviour at various cross sections in the tank. They show a methodology to model the fluid domain and test the two phase model for find out path lines contours at various cross-sections of the fluid domain. This methodology can be used to validate experimental results for weight fractions obtained at different planes in a slurry pot tester. The experimental results if validated through simulation can be used in estimating accuracy of the pot tester in estimating the wear rate. Wu et al. [40] have given numerical simulation and analysis of solid–liquid two-phase three- dimensional unsteady flow in centrifugal slurry pump. Based on RNG k-ε turbulence model and sliding grid technique, solid–liquid two-phase three-dimensional (3-D) unsteady turbulence of full passage in slurry pump was simulated by means of Fluent software. The effects of unsteady flow characteristics on solid–liquid two-phase flow and pump performance were researched under design condition. Solid phase and liquid phase gradually separate due to the density difference, so solid particles with a high velocity and relative velocity angle will wear the blade tail.

Salim et al. [41] have investigated the performance of a centrifugal slurry pump with clinker slurry. The subject matter of this investigation is to find the effect of size of clinker and its concentration on the performance of slurry pump at different pump speeds. The investigation was carried out experimentally at three pump speeds (2200 rpm, 2600rpm and 300 rpm), for three clinker sizes (4 mm, 13 mm and 20 mm) and three slurry concentrations (5%, 10% and 15%). For comparison tests were also carried out with clear water. They noted that the head developed by pump and pump efficiency decreased with the increased concentration of the slurry. Power input to the pump increase with increase in concentration. The head developed by pump and its efficiency decreased with the increased size of the slurry. Power input to the pump increase with increase in size of slurry. Compared to water the maximum decrease in the head produced by the pump at operating point was found to be 64% for clinker size 4mm for 5% slurry concentration and at 2200rpm. The maximum efficiency loss at operating point for clinker was found to be 58% for clinker size of 20mm with 5% slurry concentration at 2200rpm. The maximum increase in power consumption at operating point was found to be 15% for clinker size of 4mm size with 15% slurry concentration at 2200rpm.

Chandel et al. [42] have experimental studied on erosion wear in a centrifugal slurry pump using coriolis wear test rig. Systematic experiments have been conducted on brass and mild steel specimen to establish the effect of solid particle size, solid concentration and rotational speed on wear. Slurries of fly ash and mixtures of fly ash and bottom ash in the ratio 4:1 and 3:2 have been used at different concentrations in the range of 20 to 65 wt. % and rotational speed of 600rpm and 1100rpm. Erosion wear increases with increase in solid concentration for a given sample and rotational speed. They observed when the fly ash slurry concentration increases from 20% to 65% by weight the increment in erosion wear at 600 rpm is around 65% and 62% for brass and mild steel, respectively. Increase in the rotational speed from 600 to 1100 rpm results in a large increase in wear rate. The size, shape, and size distribution of solid particles have tremendous influence on erosion wear of specimens. The larger and more angular particles generate higher wear on materials. Increases in the particle size increase in the wear by 300% for brass specimen and 350% for mild steel specimen.

Zengwen & Jinhai [43] have reported the effect of operating conditions on the wear of wet parts in slurry pumps. Main factors affecting the service lives of wet parts in slurry pumps are the medium conditions (particle size, shape, hardness, concentration), operation parameters (rotational speed), hydraulic design of the pump, and material selection. The family of $Cr_{15}Mo_3$ high alloy white iron used to make the wet parts of slurry pumps usually offers a long service life. In some cases, the abrasion resistance of engineering ceramic is much superior to that of $Cr_{15}Mo_3$. Engineering ceramic is the most cost-effective non-metal material with potential capacity demanding prompt development. Attention must be paid to the manufacture of wet parts, to eliminate defects in the casting and heat treatment & to make full use of the abrasion resistance of the material selected.

Yassine et al. [44] have experimentally investigated the performance characteristics of centrifugal slurry pump using different sand concentrations ranging from 0 to 15 wt. %. They observed the head and efficiency of the pump decrease with increase in sand concentration. Power consumption increases with increase in sand concentration. The results can be explained with the change in viscosity and the presence of suspended solid particles. The study on the pump has shown that the power consumption increases with increase in solid concentration at a rate that is higher than the rate of increase of the mixture specific gravity.

Kesana et al. [45] have investigated the effect of particle size and liquid viscosity on erosion in annular and slug flow. Erosion measurements in multiphase slug and annular flow regimes have been made in a horizontal 76.2mm diameter pipe. Experiments are performed with superficial gas velocities ranging from 15.2 m/s to 45.7 m/s and superficial liquid velocities ranging from 0.46 m/s to 0.76 m/s, for liquid viscosities of 1 cP and 10 cP. Three different sand sizes (20, 150, and 300 μm sand) were used for performing tests. Erosion measurements are obtained using electrical resistance (ER) probes which relate the change in electrical resistance to the change in the thickness of an exposed element resulting from erosion. Two probes are placed in a bend and another probe is placed in a straight section of pipe. The probes in the bend are flat-head probes, and they are placed flush with the outer wall in the 45^0 and 90^0 positions. 300 μm particles create more metal loss in the flow lines compared to other particle sizes used (150 μm and 20 μm) in this study irrespective of the liquid viscosity. In the annular flow pattern, experiments with the 10 cP liquid viscosity created lower erosion in the bend compared to 1 cP liquid viscosity. The more viscous liquid film surrounding the bend reduces the particle impact velocities at the wall. Irrespective of the flow pattern, liquid viscosities and particle sizes; flat-head ER probe mounted at 45^0 to the bend measured higher erosion than the probe at 90^0 to the bend.

Khalid & Sapuan [46] have analysed the wear on centrifugal slurry pump impellers. An impeller of open type with 165mm diameter made of cast iron was selected for the analysis. The wear medium selected consists of solid particles (sands and crushed stones mean diameter of 6.64 mm) and water. The tests were conducted by letting the impeller to rotate in slurry. The wear data collection are divided into impeller's weight loss, impeller's diameter loss, impeller blade's thickness loss, impeller's blade height loss and impeller's thickness change. The major type of wear that takes place in this experiment is erosion. The weight loss of the impeller is due to the material removal from the impeller as result of erosion wear. The diameter loss of the impeller is attributed to the impingement of solid particles on the surface area. The surface topography under the microscope indicates that the region near the centre of impeller encounters less wear compared to the region at the rim of the impeller. From this study, among all the parameters studied, the height loss of impeller blades encounters the highest percentage of wear.

Madadnia & Kusnan [47] have done an analysis of severe erosion in industrial centrifugal slurry pumps and reported on erosion-effects of slurry flows on a number of industrial centrifugal pumps selected from an active copper mine field. The field samples include three metallic pumps operating in a serial-arrangement, and a number of worn pump components with fully rubber-lined or metallic wetted surfaces. Samples were also collected and photographed under an electronic microscope. Examination of enhanced erosion regions in the slurry pumps has identified three severely worn regions in the proximity of suction throat with low pressure and flow velocities and only one region in the proximity of discharge throat in the high pressure and velocity region. Severe erosions in the vicinity of the suction throat include tip of the impeller, inside and outside of shroud and front-liner or throat bush. Accelerated erosion was also noticed on the cut water and its vicinity on the volute. Similar erosion patterns, directional groves, ripples-formations; pitting, cavities and holes are seen in all the four identified regions above. Examination of severe erosion regions suggested an erosion model where slurry particles are targeting the wall under a combination of frictional, centrifugal and Coriolis forces similar to the cavitation.

Kumar et al. [48] have worked on performance characteristics of centrifugal slurry pump with multi-sized particulate bottom and fly ash mixtures. The performance characteristic of the pump was experimentally evaluated at rotational speed 1450 rpm for bottom ash slurries with and without the addition of fly ash in the concentration range of 10% to 50% (by weight). They reported that the addition of fly ash in bottom ash slurry decreases the relative viscosity of the mixture. The head and efficiency ratios not only depend on the solid concentration of slurry but are also affected by the properties of the slurry. The addition of fly ash to bottom ash improves the centrifugal slurry pump performance in terms of head ratio and efficiency. The increases in head are 0.09 m, 0.22 m, and 0.24m for mixture of bottom ash and fly ash in the ratio of 9:1, 8:2, and 7:3, respectively. The decreases in input power are 1.72%, 3.38%, and 3.41% for the mixture of bottom ash and fly ash in the ratio of 9:1, 8:2, and 7:3, respectively.

Rayan & Shawky [49] have evaluated the wear in a centrifugal slurry pump. They present some experimental results of erosive wear in a centrifugal slurry pump. The objective of this investigation is to study the relation between erosive wear in a centrifugal pump impeller and solid particle concentration. They observed erosion wear rate is proportional to the flow velocity and erosive wear depends on the transport concentration. In medium and low concentrations the mechanism of erosion is similar to cavitation erosion. The weight loss rate versus time curve is of 's' type similar to cavitation erosion.

Walker & Bodkin [50] have given empirical wear relationships for centrifugal slurry pumps side-liners. In this study the impeller and side-liner hydraulic shape, impeller rotational speed, particle concentration and the particle size have each been individually varied over a range of operating flow rates to determine the specific effects on pump side-liner wear. The wear rate for the high efficiency design varies with the square of the particle size. The wear rate for the standard heavy duty and reduced eye designs did not vary significantly with particle size. The wear rate was constant for varying solids concentration and impeller tip speed. Walker [51] again studied on slurry pump side-liner wear. Different field wear patterns have been photographed and categorised on the basis of particle size. He observed the metal high efficiency side-liner wears better than the standard heavy duty for $d_{85} < 300$ μm slurries. It was also found from the field results that for smaller particle slurries ($d_{85} < 700$ μm) that rubber side-liners give lower wear rates than the metal. The field wear patterns showed close similarity to the lab wear patterns particularly in the areas of localised gouging. Overall trend of wear with particle size for the white iron parts was similar to the grey iron. Walker & Robbie [52] have given comparison of some laboratory wear tests and field wear in slurry pumps. Laboratory work included two different slurry jet erosion (SJE) tests, a Coriolis test and an ASTM dry sand rubber wheel (DSRW) test. The DSRW and SJE lab tests found that 35% Cr hypereutectic white iron wear rate was higher than that of the standard 27% Cr eutectic white iron (i.e. opposite of field trial). The SJE, Coriolis and jet eductor lab test found that the natural rubber wear rates were much lower than that of the standard 27% Cr eutectic white iron (i.e. opposite of field trial).

Zhao et al. [53] have worked on slurry erosion properties of ceramic coatings. The effectiveness of ceramic coatings on pump impellers used in the acidic gypsum-fly ash slurry environments in desulphurisers was assessed by using two kinds of slurry erosion tester. They observed at optimum manufacturing conditions, ceramic coatings are about two times as resistant as the base metal. Levy & Paul [54] have investigate erosion of steels in liquid slurries. The jet impingement test where coal-particle containing liquids are directed at flat specimens was used to determine the erosion rates and its mechanism. They noted that in steels maximum erosion by liquid-solid particle slurry flows occurs at an impingement angle of 90° with secondary peak erosion occurring at impingement angles of 40° - 60° in some alloys. In low alloy steels in coal-solvent slurry erosion, greater ductility results in lower erosion rates and variations in the strength of the steels have a minor effect on erosion rates.

3. CONCLUSIONS

The few decades of research works are summarized in this paper and the following points are concluded:

- Wear in the slurry pump increases rapidly with flow velocity and is often reported as being approx. ∝ (velocity)^3, or ∝ (pump head)$^{3/2}$.
- The corrosion rate was strongly influenced by solids content & impeller speed due to the removal of the chromium oxide film.
- The solid concentration in slurry and kinetic energy of the moving particles highly contributes to erosive wear of pump impeller as compared to the solid particle size.
- Head and efficiency of the slurry pumps decrease with increase in the concentration of the slurry but decrease with increase in the solid particle size in the slurry.
- Wear on the slurry pump and power input to the slurry pump increases with increase in solid particle concentration and solid particle size in the slurry.
- For ductile materials, the maximum erosion usually occurs around 20▯-30▯impact angle whereas, in brittle materials, maximum erosion occurs at 90▯impact angle.
- Ceramic shows excellent anti-wear performance comparing with the materials.
- MMCs can also be used for making the components of a slurry pump to overcome the wear and to increase the life of the parts.

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