Development of novel approach based on statistical technique to predict slurry erosion behavior of AISI 304 steel

Mithlesh Sharma[1], Deepak Kumar Goyal[2], Gagandeep Kaushal[3]

[1]Mechanical Engineering Department, IKGPTU, Kapurthala, Punjab 144603, India
[2] Mechanical Engineering Department, IKGPTU Main Campus, Kapurthala, Punjab 144603, India
[3]Mechanical Engineering Department, YCOE, PU Guru Kashi Campus, Talwandi saboo, Bhatinda.

ABSTRACT
This paper presents a novel approach to predict the slurry erosion behavior of AISI304 steel substrate using mathematical modeled equation based on statistical method. To develop the modeled equation physical experimentation based on Taguchi L_9 Design matrix was carried out by varying three operating process parameters, such as slurry concentration, impact velocity and impact angle. The output parameter in terms of erosion loss is measured. The effect of various parameters was analyzed using Taguchi analysis. It was observed that slurry concentration and impact velocity have a noteworthy influence on slurry erosion behavior of the target material. Based on the experimental result of the steel, mathematical model based on regression approach was developed. To assess the effectiveness of mathematical model equation, results were predicted for range of condition and compared with the experimental results. It was found that predicted results are in good conformity with experimental results.

Keywords: Slurry erosion, Composite coatings, High velocity oxy Fuel, Taguchi.

1. INTRODUCTION

Slurry erosion is the major problem faced in hydropower plants all along the world [1-8]. Particularly in context of Asian countries problem is much more serious and grave. The water available in these hydropower plants come from the glaciers which on melting, feed the water to the reservoir. These water flows from the mountainous terrain, which along with water comprises some content of silt particles such as sandstone, pebbles and clay etc., which leads to the erosion of various components such as stay and guide vanes, turbine blades and labyrinth seals [8-12]. It has been learnt from the literature that AISI 304 steel due to its some unique properties such as low density, high specific strength and manufacturability, widely used in manufacturing of such components. However, its use is restricted for some applications due to certain properties such as low wear resistance, corrosion resistance [13-18]. These restrictions impose a limitation for widely use of the above said material in engineering field, where surface phenomenon such as wear, erosion and corrosion resistance are significant [25-27].
To investigate the behavior of material under stimulated conditions researchers had devised different type of laboratory test rigs to identify the slurry erosion rate and degradation mechanism of material under different operating conditions as available in hydro power plant. Different test rigs are slurry erosion test rig [1], Jet impingement tester [2], Slurry pot tester [3], Coriolis erosion tester [4], Centrifugal erosion

tester [5], concentric cylindrical test rig [6]. Slurry erosion wear is complex phenomenon, it is very much required to identify the most significant parameter which affects the erosion wear. Prediction of significant factors helps in mitigating the erosion behavior. Researchers revealed that slurry erosion depends on various parameters such as impact velocity, impact angle, particle size and slurry concentration [6-8].

To analyze the effect of various operating parameters, proper interactions among all parameters are very much required. This can be achieved by the Design of experiment technique which helps to identify the optimum significant parameters for any process and application [9-10]

Patnaik et al. [19] worked on dry erosion test rig to investigate erosive wear behavior of glass fibre and polyester based composite as target material under range of conditions. It was observed that particle size is the significant factor which affects the erosion wear in comparison with fiber loading, impingement angle and impact velocity. Mishra et al. [20] investigated the erosive wear behavior of ceramic coating using dry erosion test rig. It was revealed that impact angle was the most significant parameter in comparison with other parameters such as erodent size, impact velocity and standoff distance. Furthermore it was observed that due to brittle nature of coating, the erosion wear increased and attained maximum value at an impact angle of 90°. Sahu et al. [21] had studied the erosive wear of fly ash alumina coating material using dry erosion test rig. It was found that impact velocity was the most significant parameter which affects the erosion wear. Furthermore it was revealed that erosive wear increased due to poor adhesive strength of the coating due to input power variation to the torch. Mantry, et al. [22] investigated the effect Cu slag Al composite coatings using plasma sprayed method to find out the erosive wear using dry erosion test rig. It was observed that impact velocity was the most significant factor among all other factor chosen for the study. Yogandha et al [23] studied the wear behavior of Nickel based white cast iron under mining condition using water jet erosion test rig. They identified the maximum wear angle and material degradation mechanism at an impact angle of 30, 60 and 90. It was revealed that water velocity is the most significant parameter which effects the slurry erosion. Goyal et al [24] studied the slurry erosion behavior of HVOF sprayed Cr_2O_3 coating on turbine steel using high speed erosion test rig. It was revealed that HVOF coated target surface was better than uncoated surface.

This paper investigates the slurry erosion behavior of AISI 304 steel under range of slurry erosion conditions obtained by using slurry collected from Maneri-Bhali Stage 1, Uttarkashi, India, on laboratory developed impact test rig. Influence of various parameters on slurry erosion behavior of AISI 304 steel was investigated. Further an attempt has been made to develop a modeled equation based on Taguchi Approach which is able to predict the slurry erosion behaviour of the material under range of condition. To authenticate the developed modeled equation, confirmation test was carried out which revealed that result obtained from modeled equation are in conformity with the experimental result.

2. EXPERIMENTAL DETAILS

In the present study Maneri Bhali stage-1 Hydropower plant, which is situated at Uttarkashi, Uttarakhand, India on the Bhagirathi River has been chosen for a case study. Spectroscopy test of the eroded blade section of Francis turbine revealed that turbine blades are made up of AISI304 steel, hence AISI304 steel is taken as the base material for the present study. The nominal composition of the above said material was provided in Table 1.

Table1. Nominal chemical composition of the AISI304 grade of ASTM A240 stainless steel (wt. %)

Grade	C_{max}	Si	Mn	P	S	Ni	Cr	Fe
AISI 304 Steel	0.02	0.475	1.85	.40	0.0302	8	18	Balance

Mechanical properties such as micro hardness, apparent porosity and surface roughness of steel were obtained by using Vickers micro hardness tester (SHV-1000, SLIET, Longowal, India and surface roughness tester (Surftest Sj301, Mitutoyo, IET Bhaddal, Ropar, India). The values of micro-hardness (HV) and roughness for AISI304 steel substrates are shown in Table 2, at an applied load of 300gm for 10s dwell time. An average micro-hardness of 237 HV_{300} was observed for uncoated AISI304 substrate. The value of Roughness was measured using surface roughness tester by Mitutoyo SJ 301. It was observed that the uncoated substrate sample has lower roughness as seen in the Table 2.

Table 2. The Micro hardness, apparent porosity and Surface roughness Ra values of investigated specimens

Materials	**Avg. micro hardness (HV_{300})**	**Roughness, Ra (μm)**
AISI304 steel	237	1.56

Slurry erosion testing of the AISI 304 steel specimens were carried out using laboratory developed slurry erosion test rig. The schematic view of the slurry test rig used for carrying out experimentation in the present study is shown in Fig.1.

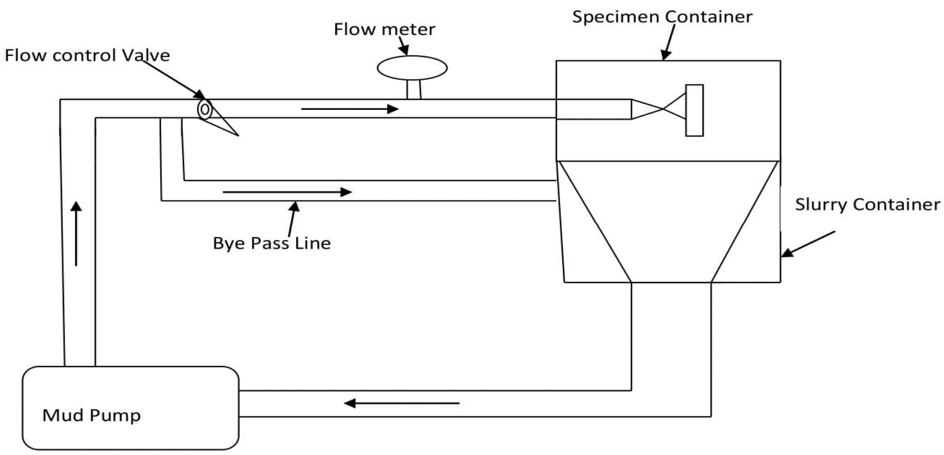

Fig.1. Schematic view of Slurry erosion impact test Rig

The typical morphology of erodent particle used in the present study is visualized using SEM facility as shown in Fig. 2. It was depicted that erodent particles were comprised of unsymmetrical shapes particles with pointed corners or sharpen edges. Predetermined quantity of silt particle of varied size distributions were mixed in order to obtain slurry with average particle size of 155µm. The EDS (Emissive Dispersive Spectroscopy) of the slurry particle was carried out to determine the composition of erodent particle as shown in Fig. 3.

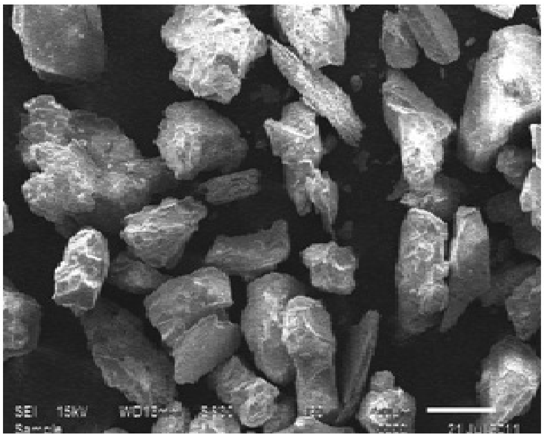

Fig.2. SEM micrograph of erodent particles used in present investigation

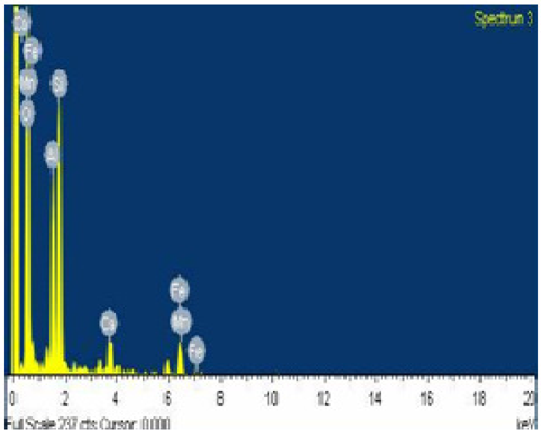

Fig.3. EDS micrograph of erodent particle used in present investigation

To carry out experimentation effectively, Taguchi's L_9 orthogonal array approach under MINITAB 17V software has been used to prepare design of experiments between the various process parameters such as impact velocity, impact angle and slurry concentration. Table 4 presents the experimental parameters used in present study. To further analyze the effectiveness of various parameters Taguchi analysis was carried out using objective function of smaller the better approach. S/N ratio for this function is determined by:

$$\eta = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^{2}\right) \quad (1)$$

Table 3. Three parameters with their values at three levels used in the present study

Parameter	Slurry concentration (ppm)	Impact velocity (m/s)	Impact angle (°)
Level 1	10000 (1% by mass)	25	30
Level 2	20000 (2% by mass)	50	60
Level 3	30000 (3% by mass)	75	90

The time taken for slurry erosion testing is 120 mins per sample. The testing samples were cleaned prior and after the testing so that no impurities are left with the samples. For analyzing the mass loss from the given sample under experimental condition, weight balance having an accuracy of 0.001gram is used for comparison of the material removal from the sample prior and post testing. The mass loss rate is calculated by considering the initial mass loss and final mass loss after testing. Following formula is used for calculating the mass loss.

$$\text{Mass loss } (mg/cm^2) = (W_i - W_f) / \text{Surface area} \quad (2)$$

Where W_i is the initial mass of each sample, mg and W_f is the final mass after 120 min erosion testing, mg, surface area in cm^2

3. RESULT AND DISCUSSIONS

3.1 Erosion Wear Analysis Using Taguchi Experimental Design

The Minitab 17v software package has been used for the experimental analysis of the results. The L9 orthogonal design matrix has been chosen for the proper interaction of various parameters in the experimentation work. Result obtained from the experimental work is presented in table 4. Slurry erosion was further converted into S/N ratio using Taguchi analysis. It was found that slurry concentration was most influencing significant control parameter among all the three parameters causing slurry erosion as shown in Fig. 5. The remaining parameters such as impact velocity and impact angle are ranked second and third respectively in influencing slurry erosion on AISI 304 steel. Main effect plots are shown by fig. 4. From the figure, it was observed that mass loss due to slurry erosion was effected by all the respective parameters. It was found that slurry erosion is lower at 10000ppm followed by 20000ppm and 30000ppm. At 60° impact angle erosion wear is minimum in comparison with 30 and 90 impact angle. In case of Impact velocity it was observed that slurry erosion is minimum at 25m/s impact velocity with further increase in velocity slurry erosion increases further. Therfore, it is pertinent to mention here that impact velocity and slurry concentration are significant factor which affects the behavior of AISI 304 steel.

Table 4. Mass loss under varied condition of slurry erosion

Run No.	Slurry concentration (ppm)	Impact angle (°)	Velocity (m/s)	Mass loss AISI304 (mg/cm^2)	S/N Ratio (db)
1	10000	30	25	6.875	-16.7455
2	20000	30	50	11.650	-21.3265
3	30000	30	75	12.180	-21.7129
4	10000	60	50	9.125	-19.2047
5	20000	60	75	12.430	-21.8894
6	30000	60	25	12.810	-22.1510
7	10000	90	75	11.120	-20.9221
8	20000	90	25	8.750	-18.8402
9	30000	90	50	11.870	-21.4890

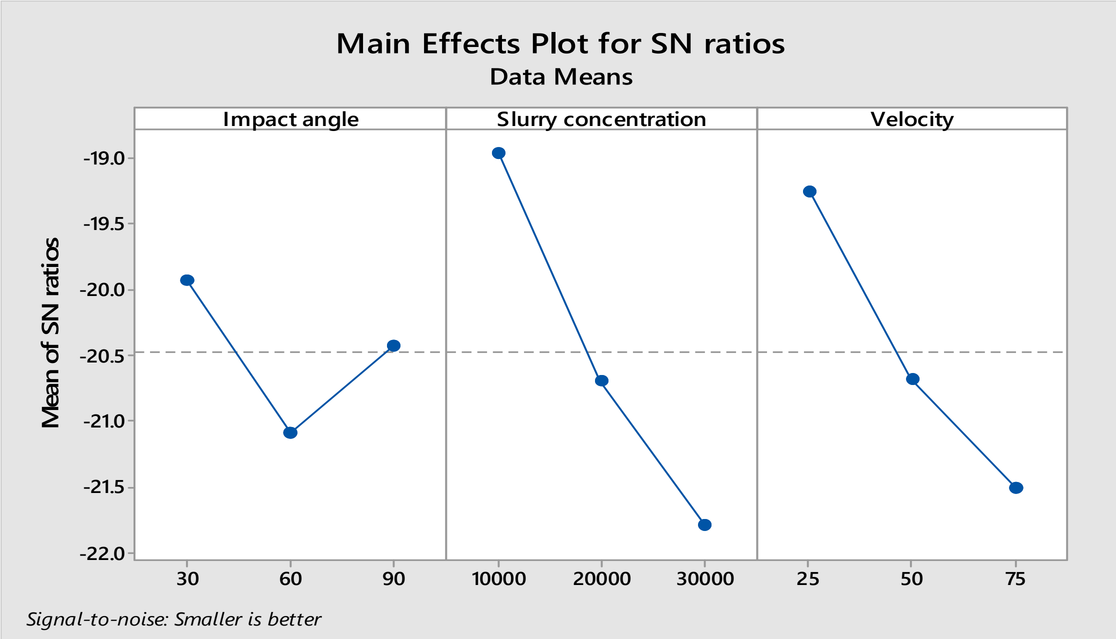

Fig. 4 Main Effect plots of S/N ratio of AISI 304 steel

3.2 Slurry Erosion modeled equation

To develop the modeled equation to predict the slurry erosion behavior of AISI 304 steel, regression n approach was used. Regression approach based modeled equation using Minitab 17v was predicted. This equation shows the relationship between the erosion wear and various parameters effecting slurry erosion. Using regression method following form of regression equation was obtained:

E_w = e + (a x Impact angle) + (b x velocity) + (c x Slurry concentration) (3)

Where E_w - erosion wear rate, a, b, c are the constant; V-Impact velocity (m/s), A-impact angle (°), S-slurry concentration (ppm)

The values of all constants were calculated using data fit in Minitab 17v software and by using these values in equation (4), the final regression based modeled equation are as follows

Erosion loss = 4.73 + 0.0057 Impact angle + 0.000162 Slurry concentration + 0.0486 Velocity (4)

Where, E_w - erosion wear rate, a, b, c are the constant; V-Impact velocity (m/s), A-impact angle (°), S-slurry concentration (ppm)

Table 5. S/N ratio Response table using the characteristics of smaller the better

Level	Impact angle	Slurry concentration	Impact velocity
1	-19.93	-18.96	-19.25
2	-21.08	-20.69	-20.67
3	-20.42	-21.78	-21.51
Delta	1.15	2.83	2.26
Rank	3	1	2

The accuracy of the constants obtained was confirmed by the high correlation coefficient (r^2) obtained from analysis which predicted the value to be 0.984 from the equation 5. The comparison between the experimental results and predicted results from the modeled equation was obtained and shown in Table 6. To further assess the closeness between the two values percentage error was calculated. It was found that obtained results were in closer approximation to experimentally obtained results.

3.3 SEM Analysis

To analyze the wear mechanism of samples, SEM analysis was carried out using JEOL 6610LV which is known for its high resolution. A close observation of SEM images, as shown in Fig.5, reveals that the surface of substrate AISI304 steel prior to erosion testing contains small cracks, surface irregularities in the form of pits, coincident cracks and fracture fragment on the surface.

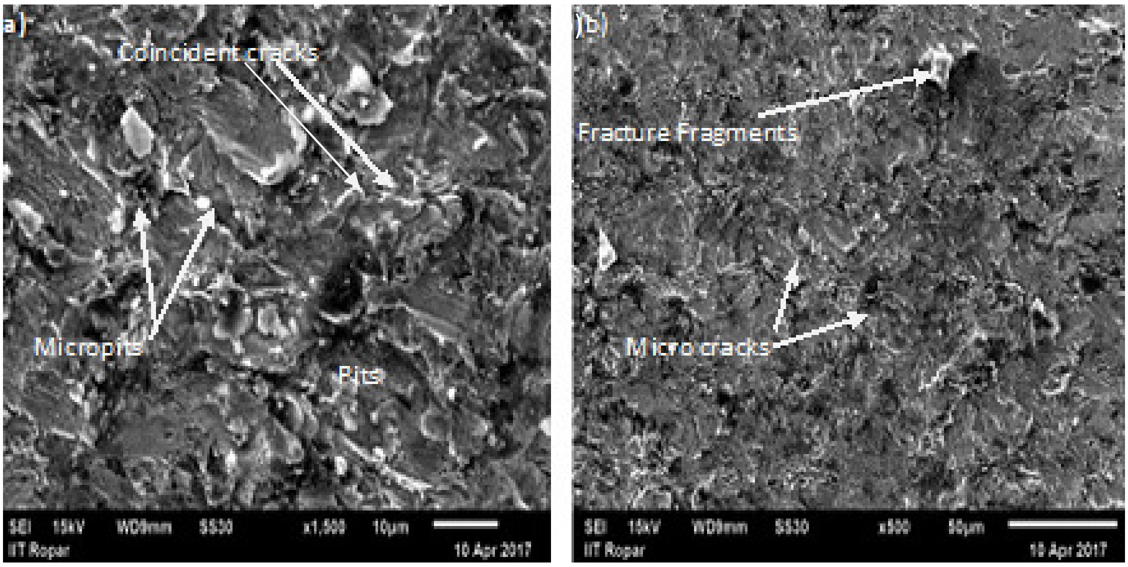

Fig. 5. SEM images of AISI304 Steel prior to erosion testing (a) SEM x1500 (b) SEM X500

It was attributed that the erosion damage at all impact angles were characterized by high wear debris on the surface. After conducting erosion tests on the sample with wide range of parameters, it was observed that the eroded surface of substrate consist of plastically deformed craters and fractured fragments as shown in Fig. 6 (a). In relation to the wear damage on AISI304 steel at an impact angle 30^o, the cutting action of the particles led to pitting and ploughing actions which are observed in the form of small grooves on the eroded surface. These small grooves seem to be filled with the fracture fragments after impact. In regard to the wear damage at impact angle 60^o, the main mechanisms were high wear debris characterized by large fracture fragments which were filled the groove and micro pits on the surface AS shown in the fig. 6 (b). At this particular impact angle, plastic deformation was assessed as a wear mechanism which occurred due to sliding of abrasive particles. Also, It was observed that some of the wear debris was flattened or smeared on the specimen surface. Furthermore, it was noticed that maximum erosion among all the impact angles has taken place in the case of 60^o. It was attributed with the most efficient cutting action of the abrasive particles which led to higher removal of material from the surface which resulted in an increase of the wear damage. In relation to impact angle at 90°, it was observed that more craters are formed on the surface of substrate as shown in fig. 6 (c), it was associated with the fact that particle plow into the surface and leaves the surface after removal of the material. Further, it was observed that erosion is caused by the platelet mechanism. These observations are in agreement with finding of Goyal et al. [24,28]

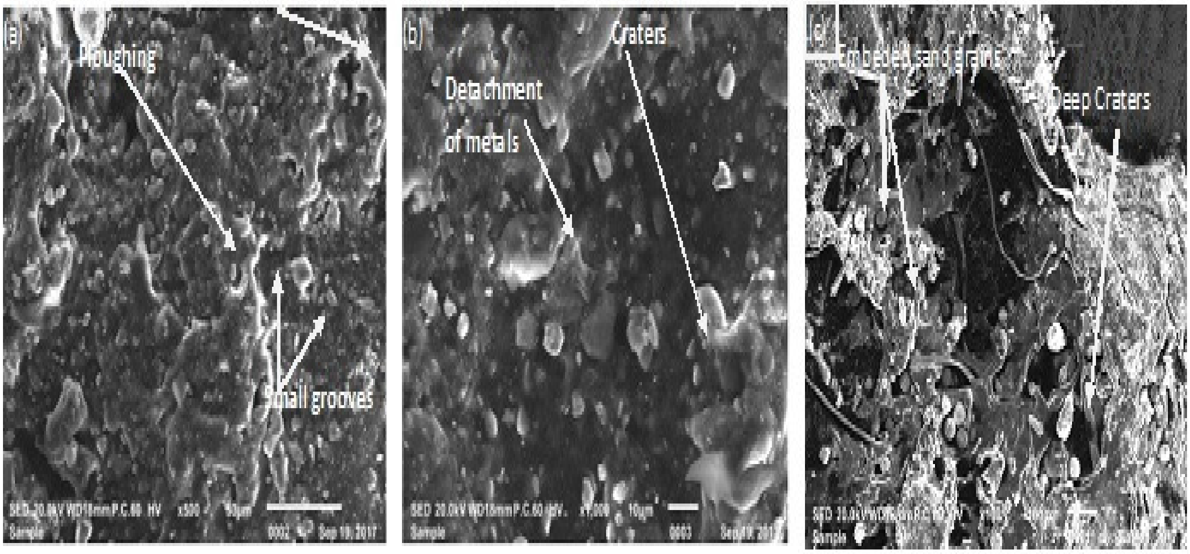

Fig. 6. SEM images of AISI 304 Steel Post 120mins of Erosion testing at different impact Angle (a) 30° (b) 60° (c) 90°

3.4. Confirmation Test

The confirmation test was carried out on AISI 304 steel by considering the optimal parameters where slurry erosion is least i.e. impact velocity 25m/s, Slurry concentration 10000ppm and impact angle 30°. The erosion wear rate obtained in AISI 304 steel material due to slurry erosion wear are shown in table 7. By comparing the experimental and analytical results, it was found that a deviation of only 2.3 % was exist which is in agreement with the obtained results. This validates the derived non linear regression equation which presented the slurry erosion wear rate of the material with various control factors within a reasonable degree of approximation.

Table 6. Comparison of predicted and Experimental result

Exp. No.	Result Obtained from Experiments Results	Obtained from Predictive Equation	Percentage Error (%)
1	6.875	7.736	-11.1298
2	11.650	10.571	10.20717
3	12.180	13.406	-9.14516
4	9.125	9.122	0.032888
5	12.430	11.957	3.955842
6	12.810	11.147	14.91881

7	11.120	10.508	5.824134
8	8.750	9.698	-9.77521
9	11.870	12.533	-5.29003

Table 7. Confirmation results for optimal values

Impact velocity (m/s)	Slurry concentration (ppm)	Impact angle	Mass loss experimentally (mg/cm2)	Mass loss by model (mg/cm2)	% Error
25	10000	30	7.522	7.736	2.3

4. CONCLUSIONS

The experimental study of the various influencing parameters on slurry erosion behavior of AISI 304 steel using slurry erosion test rig leads to the following

• Among all the factors, slurry concentration is the most significant factor affecting the slurry erosion wear of AISI 304 steel followed by impact velocity and impact angle respectively.

• Maximum slurry erosion took place at an impact angle of 60° showing mixed response (ductile and brittle) of the metal AISI 304 steel to slurry erosion wear.

• To analyze the surface morphology of the eroded surface at various impact angles, SEM analysis was carried out. At 30° impact angle, ploughing and small grooves formation takes place. Similarly at 60° detachment of particles and crater formation takes place. At 90° impact angle, deep indentation and deep crater formation takes place at some places which cause embedment of the sand particles in the spalation layers of the material.

• The deviation in percentage between predicted and experimental result was between 0 to 12%. A higher correlation coefficient value of (r^2) is 0.987 shows the correctness of the mathematical model used. So, the model is more suitable for further study.

• From this investigation, it can be concluded that the slurry erosion wear is minimized by controlling the influencing parameters such as slurry concentration and impact velocity which enhance the working life of the hydraulic components.

References

[1] Zu JB, Ihtchings IM, Burstein GT, *Wear* 1990, 140, 331-344.
[2] Lin FY and Shao HS, *Wear* 1991, 143(2), 231- 240.
[3] Desale GR, Gandhi BK, Jain SC, *Wear* 2005, 259, 196–202.
[4] Harsha AP, Bhaskar DK, *Mater. Design* 2008, 29 (9), 1745–1754.
[5] Hawthorne HM, Xie Y, SK Yick, *Wear* 2003, 255, 170-180.
[6] Hayashi N, Kagimoto Y, Notomi A, Takeda Y, Kato K, *Wear* 2005, 258, 443- 457.
[7] Zhao HX, Yabuki A, Matsumura M, Takahashi T, Yamamoto M, *Wear* 1999, 233- 235, 608-614.
[8] Bajracharya TR, Joshi CB, Saini RP, Dahlhaug OG, *Wear* 2008, 264,177–184.
[9] Grewal HS, Arora HS, Agrawal A , Singh H, Mukherjee S, *Procedia Engineering* 2013, 68484 – 490.

[10] Chawla V, Sidhu BS, Puri D, Singh P, *Journal of the Australian Ceramic Society* 2008, 44, 56-62.
[11] Sidhu BS, Puri D, Prakash S, *Journal of Materials Processing Technology* 2005, 159, 347–355.
[12] Goyal R, Buta SS, Grewal JS, *International Journal of Engineering Studies* 2010, 3, 351-357.
[13] Santa JF, Espitia LA, Blanco JA, Romo SA, Toro A, *Wear* 2007, 267, 160–167.
[14] Okonkwo PC, Rana AS, Moustafa MZ, Adel Mohamed A, *Metals* 2016, 6, 232-240.
[15] Bitter JGA, *Wear* 1963, 6 (1), 5-21.
[16] Desale GR, Gandhi BK, Jain SC, *Wear* 2005, 259, 196-202.
[17] Patela M, Patela D, Sekar S, Tailor PB, Ramana PV, *Procedia Technology* 2016, 23, 288 – 295.
[18] Desu RK, Krishnamurthy HN, Balu A, Gupta AK, Singh SK, *Journal of Materials Research and Technology* 2016, 5 (1), 13-20.
[19] Patnaik A, *Journal of reinforced plastics and composites* 2008, 27 (10), 1-19.
[20] Mishra SC, Praharaj S, Satpathy A, *Journal of manufacturing Engineering* 2009,4 (2), 241-246.
[21] Sahu SP, Satapathy A, Patnaik A, Sreekumar KP, Anantpadmanabhan PV, Material and Design 2010, 31,1165-1173.
[22] Mantry S, Behera D, Mishra SK, Debashish D, Jha BB, Mishra BK, *Tribology transactions* 2013, 56, 196-202.
[23] Yogandha J, Natrajan S, Kumaresh SP, Journal of material engineering and performance 2013, 22, 2534-2541.
[24] Goyal D, Singh H, Kumar H, Sahni V, Journal of Thermal Spray Technology 2012, 21, 838-851.
[25] Peat T, Gallowa A, Toumpis A, Harvey D, Yang WH, *Surface & Coatings Technology* 2016, 300,118–127.
[26] Taillon G, Pougoum F, Lavigne S, Laurent T, Schulz R , Bousser E, Savoie S , Martinu L, *Wear* 2016, 364-365, 201–210.
[27] Thakur L, Arora N, *Surface Coating Technology* 2016, 25.
[28] Goyal DK, Singh H, Kumar H, Sahni V, *Journal of Tribology* 2014,136 , 0416021-0416032.