

PAPER • OPEN ACCESS

Numerical studies on sediment erosion due to sediment characteristics in Francis hydro turbine

To cite this article: Ujjwal Shrestha *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **240** 042001

View the [article online](#) for updates and enhancements.



IOP | ebooks™

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the collection - download the first chapter of every title for free.

Numerical studies on sediment erosion due to sediment characteristics in Francis hydro turbine

Ujjwal Shrestha¹, Zhenmu Chen¹, Su Hyeon Park² and Young Do Choi^{3*}

¹Graduate School, Department of Mechanical Engineering, Mokpo National University, 1666 Youngsan-Ro, Cheonggye-Myeon, Muan-Gun, Jeonnam, 58554, Republic of Korea

²Institute of New and Renewable Energy Technology Research, Mokpo National University, 1666 Youngsan-Ro, Cheonggye-Myeon, Muan-Gun, Jeonnam, 58554, Republic of Korea

^{3*}Department of Mechanical Engineering, Institute of New and Renewable Energy Technology Research, Mokpo National University, 1666 Youngsan-Ro, Cheonggye-Myeon, Muan-Gun, Jeonnam, 58554, Republic of Korea

^{3*}ydchoi@mokpo.ac.kr

Abstract

Sediment erosion is the wear phenomenon from the hard abrasive particle found in the rivers. Sediment erosion is an inevitable process in the hydropower. It deteriorates the turbine shape and structure and increasing the maintenance expenses. There are various methods to improve the runner to operate against the sediment erosion. Firstly, the turbine material can be modified to the harder material but it will be costly and difficult for the manufacturing. Secondly, regular maintenance of the turbine needs to be done but it is the tedious task and hinder the power generation from the hydropower. Thirdly, the critical area of the runner blade surface which is vulnerable to sediment erosion need to identify and modification of the turbine shape according to it by altering the design parameter of the blade. The modification such as a change in thickness, blade angle and coating is possible for minimizing the effect of sediment erosion. The determination of the vulnerable area in the runner for the sediment erosion is a difficult task considering the many parameters included in sediment erosion phenomenon. The parameter such as sediment size, sediment shape, sediment concentration, sediment velocity, sediment hardness, impact angle and operating condition of hydropower. The precise prediction of the sediment erosion in the turbine is the difficult task due to the synergetic effect of parameters. The accurate and precise indication of the sediment erosion required both experimental and computational analysis. After identification of the susceptible area of sediment erosion, modification and optimization will be performed to reduce the effect of the sediment erosion without falling in the performance of the turbine.

1. Introduction

Francis turbine is one of the main turbines in the turbomachinery which is applicable in the various head. It is applicable from the low head to high head. There are many difficulties to achieve full output from the Francis runner due to the sediment erosion. Due to sediment erosion turbine potential and life expectancy decline gradually. Sediment is the sand particles which are found in the river basin. There are different types of sediment that present in the rivers. The sediment of which hardness number is greater than the hardness number of the turbine material are considered for the erosion. Sediment erosion is the synergetic function of the sediment shape, size, concentration, velocity and physical properties



including the operating condition of the hydropower [1]. Sediment erosion will lead to change in the flow phenomenon and streamline in runner by removal of the material from the surface of runner. Based upon the previous study, there is few study that indicate the correlation and encounter the effect of sediment characteristics on sediment erosion.

Sediment physical properties are very much important in the study of the erosion. Most of the rivers encounter the composition of the minerals like quartz, garnet, feldspar, mica, calcite and many more. Among all the sediment particles, quartz is considered as the major cause of sediment erosion because of its physical properties. Quartz hardness number on the Mohs scale is 7 [2] [3]. In Mohs hardness scale, value ranges from 1 for minimum and 10 for maximum. Generally, particles having hardness number greater than 6-6.5 Mohs are more responsible for the sediment erosion. This is because Mohs hardness number for the turbine generally ranges from 6-6.5 [3] [4].

Table 1. Sediment particle hardness properties [3]

Mineral	Mohs Hardness Number
Tourmaline	7-7.5
Quartz	7
Garnet	6.5-7.5
Feldspar	6-6.5
Calcite	3
Carbonate	3
Biotite	2.5-3
Mica	2.5
Muscovite	2-3

2. Erosion Mechanism

Erosion is defined as the interaction on abrasive particle on the surface. Erosion mostly depend upon the size and velocity of the abrasive particles. The erosion occurring in the turbomachinery are of abrasive and erosion wear. In abrasive wear, turbomachinery is exposed to the particles with equal or greater hardness number than turbo machinery material. In erosion wear, solid, liquid or gas strike turbomachinery at the certain impact angle to erode the material from the turbomachinery. The erosion on the ductile material and brittle material is quite different. Erosion occurs ductile material by a process of plastic deformation in which material is removed by cutting action of particle. On the other hand, erosion in brittle material occurs through the occurrence of the crack in the surface [5].

Erosion is mostly depended upon the physical properties and velocity of the particle. In the turbomachinery, it is not necessary to be the velocity of the particle equal to the velocity of the fluid. The most of the erosion calculation is based upon the empirical relation.

Table 2. Empirical relation of the erosion [6]

<i>Erosion</i> \propto <i>velocity</i> ⁿ	
Tsuguo erosion model	$W = \beta_t C^x a^y K_1 K_2 K_3 V^n$
Dimensionless mass	$E = k V_p^3 f(\gamma)$
Thapa erosion model	Loss of material, $y = 6e^{-5x^{3.13}}$
Bajracharya erosion rate	$E_r \propto a(\text{size})^b$
Abrasive depth	$S = W^3 P k_m k_f$

3. Computational Methodology

3.1. Governing Equations

The numerical analysis for the fluid flow is guided by continuity equation represented by equation 1 and momentum equation represented by equation 2.

$$\nabla(\rho u_i) = 0 \quad (1)$$

$$\rho \left(\frac{du_i}{dt} + u_j \frac{du_i}{dx_j} \right) = \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\mu \frac{du_i}{dx_j} - \rho \bar{u}_i' \bar{u}_j' \right) \quad (2)$$

where ρ and μ are density and dynamic viscosity respectively, p is the pressure scalar, u is velocity and $\rho \bar{u}_i' \bar{u}_j'$ is apparent turbulent stress tensor.

3.2. Particle Transport Modelling

Eulerian-Eulerian, Eulerian-Lagrangian and drift-flux modules are available in CFX ANSYS 18.1 [7] for the particle transport modelling. Brown discussed advantage and disadvantages of the three models for the accurate and precise modelling of the fluid-particle interaction modelling [8]. The accurate model can be selected by calculating the particle mass loading, β and Stokes number, S_t [9].

The particle mass loading is expressed as:

$$\beta = \frac{\text{particle mass per unit volume of flow}}{\text{fluid mass per unit volume of flow}} = \frac{r_p \rho_p}{r_f \rho_f} \quad (3)$$

where r is a volume fraction, ρ is density and p and f stands for particle and fluid respectively.

The selection of one-way and two-way particle-fluid coupling can be determined by the value of particle mass loading. $\beta = 0.2$ is the critical value for the selection of particle-fluid coupling model. The value of β less than 0.2 prefers to the one-way coupling between particle-fluid and greater than 0.2 prefers to the two-way coupling between particle-fluid.

The Stokes number indicates the relation between particle and fluid motion while interaction between them.

$$S_t = \frac{\rho_p d_p^2 V_s}{18 \mu_f L_s} \quad (4)$$

where d_p is diameter of particle, μ_f is dynamic viscosity of fluid, V_s is characteristics velocity and L_s is characteristics length in the flow.

$$S_t \begin{cases} > 2.0 \text{ highly inertial particle flow dominated by particle wall interaction} \\ < 0.25 \text{ particle-fluid coupled by viscous drag and negligible particle wall interaction} \\ < 0.05 \text{ strong particle-fluid coupling, and particle and fluid flow is similar} \end{cases} \quad [10]$$

3.3. Erosion Model

There are two erosion models supported in CFX, namely Finnie, and Tabakoff and Grantt. Tabakoff model provides more scope of customization because of larger number of coefficient. However, larger number of coefficients are the causes of error in numerical scheme and difficult to determine the exact value for the coefficient to run the suitable simulation [11]. Erosion rate is expressed as the amount of material removed per unit mass of impacting particles.

$$E = k_1 f(\gamma) V_p^2 \cos^2 \gamma [1 - R_T^2] + f(V_{PN}) \quad (5)$$

$$f(\gamma) = \left[1 + k_2 k_{12} \sin \left(\gamma \frac{\pi/2}{\gamma_0} \right) \right]^2 \quad (6)$$

$$R_T = 1 - k_4 V_p \sin \gamma \quad (7)$$

$$f(V_{PN}) = k_3 (V_p \sin \beta_1)^4 \quad (8)$$

$$k_2 = \begin{cases} 1 & \text{if } \beta_1 \leq 2\beta_0 \\ 0 & \text{if } \beta_1 \geq 2\beta_0 \end{cases} \quad (9)$$

In Finnie's Erosion model, wear of the wall due to the erosive effect of particle impact is a complex function of particle impact angle and wall properties [7].

$$E = k V_p^n f(\gamma) \quad (10)$$

$$f(\gamma) = \frac{1}{3} \cos^2 \gamma \quad \text{if } \tan \gamma > \frac{1}{3} \quad (11)$$

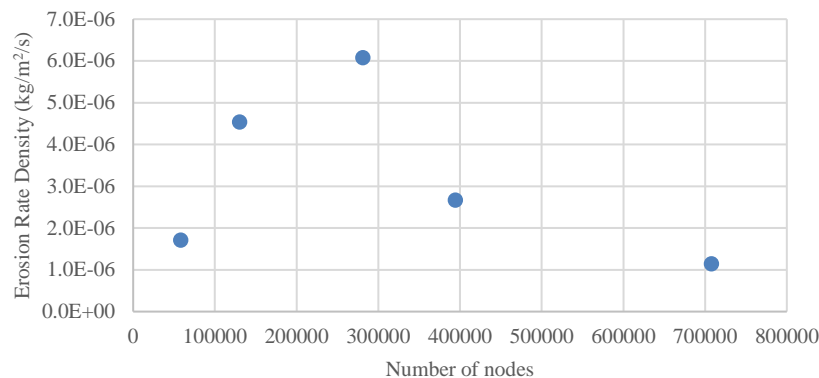
$$f(\gamma) = \sin(2\gamma) - 3 \sin^2 \gamma \quad \text{if } \tan \gamma < \frac{1}{3} \quad (12)$$

$$k = \frac{1}{V_o^n} \quad (13)$$

3.4. Numerical Mesh and Boundary Condition

All the simulation are accomplished in the CFX ANSYS 18.1 [7]. The Francis model is used for the investigation of sediment erosion. The inlet and outlet diameters of the runner are 3172 mm and 4338 mm respectively. The number of runner blade, guide vane and stay vane are 12, 20, and 20 respectively. The design point of the Francis hydro turbine model is $H = 38.7$ m for effective head, $Q = 132$ m³/s for water flow rate, and rotational speed is $N = 150$ rpm.

The Turbo-grid ANSYS 18.1 [7] is used to generate the hexahedral mesh for the runner, ICM ANSYS 18.1 [7] is used for the mesh generation of stay vane and guide vane. The one channel of a blade with stay vane and guide vane is considered for the analysis. The inlet boundary condition is mass flow rate and outlet is the constant static pressure. Quartz is considered as the major sediment particle for the sediment erosion due to its high Mohs hardness number. The particle property of quartz is used for the sediment erosion analysis with density 2.65 gm/cm³ and molar mass 60.3 gm/mol [12]. The other properties of the sediment are considered as a variable which is changed according to simulation condition. If the mesh size is less than the sediment diameter than particle flow cannot be encountered because the large particle size cannot pass through smaller cell size. If finer mesh around the wall is used then the wall velocity will be close to zero and only minimum amount of kinetic energy to sediment, which cannot show the erosion effect precisely [13]. Figure 1 shows the variation of the erosion rate density with number of nodes. 397562 number of nodes with wall distance of 0.275 mm is used for the simulation. The simulation is performed under the one way coupling because the particle mass loading is 0.02. Finnie erosion model is choose over Tabakoff model because Tabakoff model has large number of input parameters which increase the computation time and errors in numerical scheme.

**Figure 1.** Mesh Independency Test

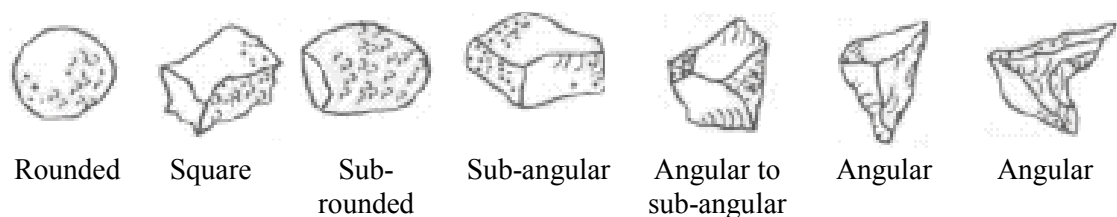
4. Result and Discussion

4.1 Effect of sediment shape on erosion

The shape of the sediment does not affect the erosion directly but it changes the impact angle of the particle and surface. Sediment shape can be classified by the cross-section area. According to Poudel et.al sand particles are categorized by radius, elongation, triangularity, squareness, and asymmetry. The further sub-classification of the sediment shape is carried on to define 21 different morphological shapes.

Table 3. Sand Shape Particle Descriptor [14]

Sand Index	Sand shape specific name	Sand Index	Sand shape specific name
1	Well-rounded with high sphericity	12	High angular with low sphericity
2	Well-rounded with low sphericity	13	Slight elongation
3	Rounded with high sphericity	14	Moderate elongation
4	Rounded with low sphericity	15	High elongation
5	Sub rounded with high sphericity	16	Slight square
6	Sub rounded with low sphericity	17	Moderate square
7	Rounded angular with high sphericity	18	High square
8	Rounded angular with low sphericity	19	Slight triangular (irregular)
9	Low angular with high sphericity	20	Moderate triangular (irregular)
10	Low angular with low sphericity	21	High triangular (irregular)
11	High angular with high sphericity		

**Figure 2.** Characteristics of sediment in terms of shape [14]

The 21 morphologies can be predicted by the CFX ANSYS 18.1 [7]. The particle shape factor in the CFX pre value ranges from 0 to 1 where 0 represents the irregular shape and 1 represents the rounded shape. The further modification of the shape can be applied by changing the value of surface area factor from 0 to 1. The impact angle between sediment and material is dependent on the shape of the sediment. However, the sediment erosion rate density is not high in the extremities. The analysis is performed by considering sediment diameter, concentration and velocity are 0.1 mm, 7.57 ppm, and 10 m/s respectively but shape factor is variable from 0 to 1. Figure 3 indicates that the impact of the sediment which shape factor 0.25 is maximum impact angle. The sediment erosion rate density variation with sediment shape is highly unpredictable. The sediment erosion rate density high when shape factor is 0.25 for the runner but for the stay vane and guide vane when the shape factor is about 0.75.

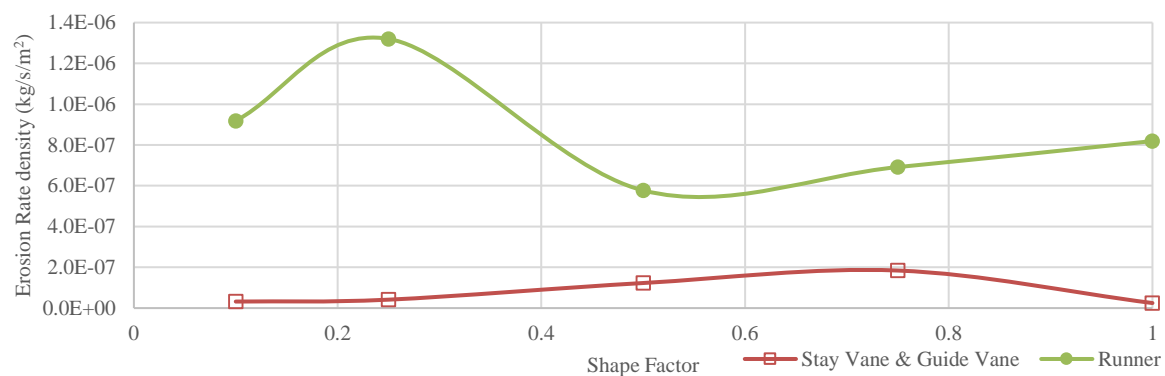


Figure 3. Sediment erosion rate density at runner, stay vane and guide vane versus shape factor

The sediment erosion rate density with shape factor 0.25 is high and it affects the trailing edge of the runner. Similarly, the shape factor 1 has effect on the same region but the low intensity as shown in figure 4. Considering only sediment shape factor in affect in the erosion rate density, the mid-section of the trailing edge is highly affected. It is due to the impact angle of the sediment to the surface. The sediment size of 0.1 mm is used in this simulation which very small in size causes sediment effect on trailing edge due to change in momentum equation in the interaction between solid-fluid interaction.

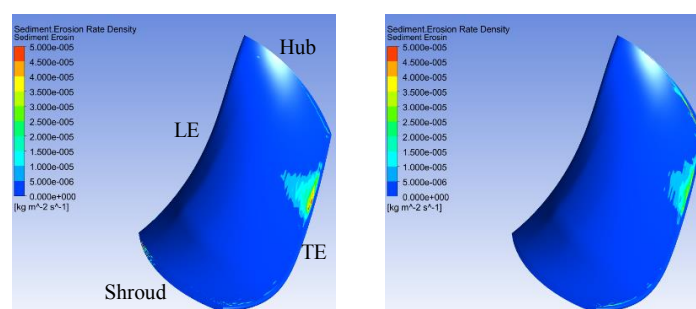


Figure 4. Sediment erosion density rate with shape factor 0.25(left) and 1(right)

4.2 Effect of sediment size on erosion

The size of the sediment determines the erosion rate in the turbine. The sediment size refers to the diameter of the sediment particle. The larger the size greater the impact of erosion in a turbine. The figure 5 shows the effect of the sediment size in the erosion on the runner considering value of sediment shape factor, concentration and velocity are 0.25, 7.575 ppm and 10 m/s respectively. The sediment erosion decreases when the size is increased from 0.1 mm to 0.25 mm. The sediment greater than 0.25 mm size are considered as the critical for the erosion because the force of impact generation from tiny

particles are negligible to produce significant impact on runner. The maximum erosion occurs when the sediment size reaches 0.75 mm. Further than the greater size doesn't affect to increase erosion rate density of the runner. But, it is seen that with the greater size of the sediment erosion rate density at the casing increases. However the sediment size generally less than 1 mm is passed through the settling basin of the hydropower. The sediment size less than 0.09 mm has an insignificant effect on the erosion of the blade [2].

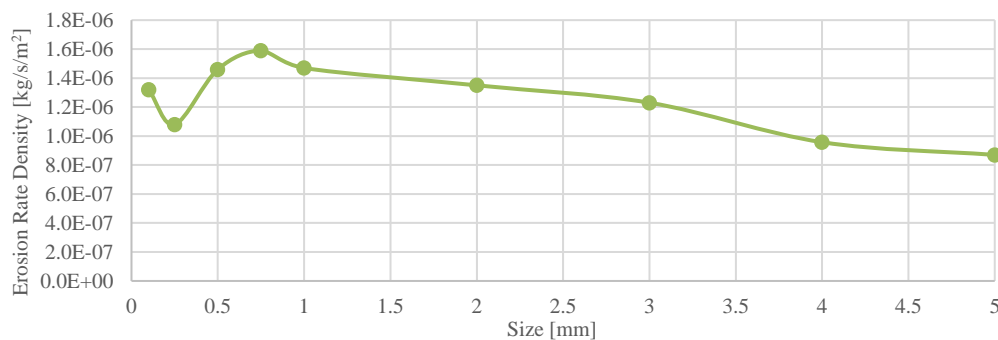


Figure 5. Erosion rate density vs sediment size in runner

The clear indication of the sediment erosion due to the sediment size is shown in figure 6. The sediment size 0.75 mm which has the highest sediment erosion on the trailing edge of the runner. Although the larger sediment size 5 mm is used, affecting area is same. The greater sediment size does not increase the sediment erosion in the runner but it concentrates on the bottom corner of the trailing edge. However, the smaller size sediment effects the on the lower surface of the blade with distributed erosion rate.

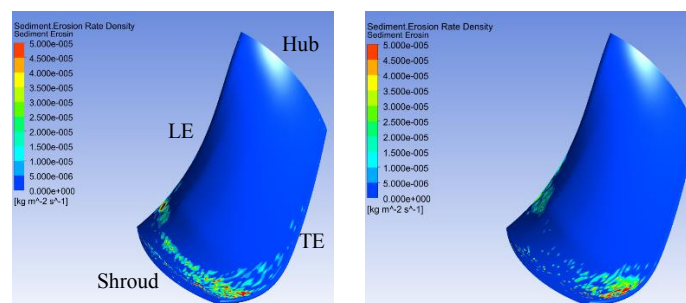


Figure 6. Sediment erosion in runner with sediment size 0.75 mm and 5mm

4.3 Effect of sediment concentration on erosion

The sediment concentration is the amount of sediment per unit of the water. The increase in the sediment concentration increases the number of particle contact with the wall surface per unit time. With an increase in the sediment concentration, the number of impact particles is also increased. The figure 7 suggests that the erosion rate density increases linearly with increase in the concentration of the sediment. The affected surface of the blade is same but the intensity of erosion is different. The erosion rate is negligible with the low concentration of sediment. While considering the sole effect of concentration, the erosion is mainly in the shroud region of the blade as shown in figure 8. For this analysis the values of sediment shape factor, size, and velocity are 0.25, 0.75 mm and 10 m/s respectively.

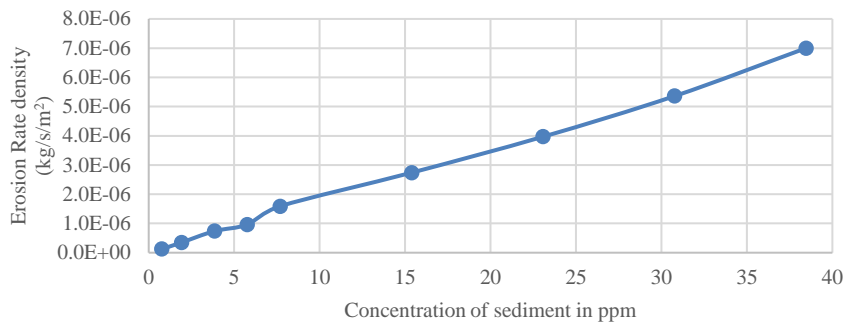


Figure 7. Erosion rate density at runner versus concentration of sediment

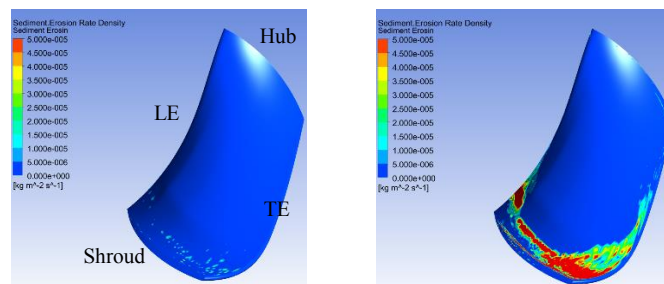


Figure 8. Sediment erosion with concentration 7.5 ppm (left) and 38 ppm (right)

4.4 Effect of sediment velocity on erosion

According to the Finnie, sediment erosion rate is directly proportional to the velocity of the sediment. However, there is no clear indication of the sediment erosion rate relation with velocity of sediment. The erosion rate density in figure 9 indicates the erosion rate density varies with the velocity of the sediment. Firstly, the sediment erosion trend is decreasing and then after increasing with the increase in the velocity. Since the computation is carried out with considering sediment shape factor, size and concentration as 0.25, 0.75 mm and 7.575 ppm. But it shows that the critical value of the velocity might differ with sediment properties like shape, and size. Likewise sediment size and concentration, sediment velocity affects the lower span of the blade. With the variation of the sediment velocity, the intensity of erosion variation is slightly low. The figure 10 indicates that with vast difference in the velocity of the sediment, the erosion rate density has negligible difference.

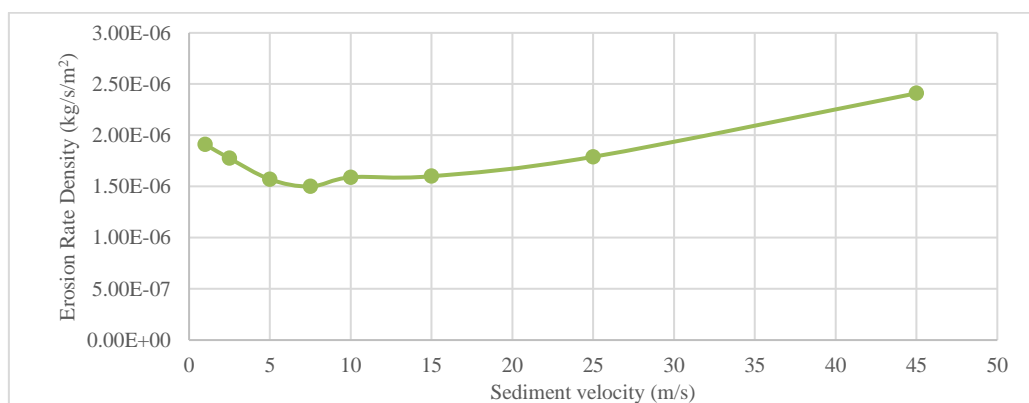


Figure 9. Sediment erosion rate density at runner versus sediment velocity

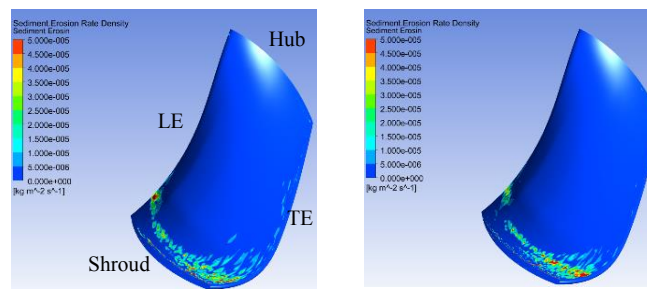


Figure 10. Sediment erosion rate density with sediment velocity 2.5 m/s (left) and 45 m/s (right)

4.5 Impact of sediment properties on erosion rate density

The sensitivity analysis is used to analyse the influence of sediment properties on sediment erosion rate density. Figure 11 indicates that sediment shape factor and concentration has major effect on erosion in runner blade.

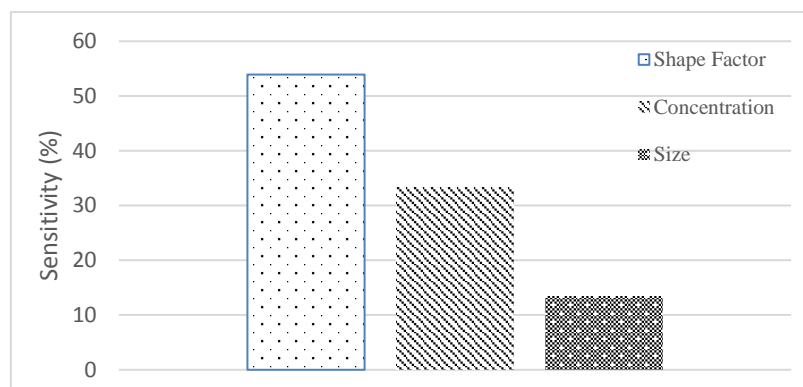


Figure 11. Sensitivity analysis of sediment properties on erosion

5. Conclusion

The various parameter of the sediment is considered to determine the correlation and most vulnerable location of the runner. It is concluded that the trailing edge and shroud region are the most vulnerable for the erosion. The concentration of the sediment has the direct relation with erosion rate density but the other parameter consists the critical value which might be dependent or independent of each other. The sediment size, shape, and velocity relation with erosion rate density is unpredictable. However the sediment shape factor and concentration have most influence on erosion rate density in runner.

Acknowledgement

This work has supported by the New and Renewable Energy of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korean Government Ministry of Trade, Industry and Energy (No. 20163010060350).

Nomenclature

n	exponent of velocity
K_{mat}	material constant
K_{env}	constant depending upon environment
C	concentration of particle
V_p	velocity of particle

β_t	turbine coefficient of erode part
V	relative flow velocity
K_1	shape coefficient
K_2	hardness coefficient
K_3	abrasion resistant coefficient of material
x,y	exponential value for concentration and size coefficient
k	abrasive constant
a,b	empirical constant
W	characteristic velocity
P	particle load obtained from particle concentration
K_m	material factor
K_f	flow factor

References

- [1] Hamed A and Tabakoff W 2006 Erosion and Deposition in Turbomachinery *Journal of Propulsion and Power* **22**(2) 350-360
- [2] Poudel L, Thapa B, Shrestha B P, and Shrestha N K 2012 Impact of sand on hydraulic turbine material: A case study of Roshi khola, Nepal *Hydro Nepal* 60-65
- [3] King H M Mohs Hardness Scale: Minerals: Geology <https://geology.com>
- [4] Koirala R, Chitrakar S, Regmi S N, Khadka M, Neopane H P and Thapa B 2015 Analysis of sediment samples and erosion potential: A case study of Upper Tamakoshi hydroelectric project *Hydro Nepal* 28-31
- [5] Finnie I 1960 Erosion of surfaces by solid particles *Wear* **3** 87-103
- [6] Thapa B S, Thapa B, Dahlhaug O G and Cervantes M 2012 Empirical modelling of sediment erosion in Francis turbines *Energy* **41**(1) 386-391
- [7] ANSYS Inc. ANSYS Customer Portal <https://support.ansys.com/AnsysCustomerPortal>
- [8] Brown G J 2002 Erosion prediction in slurry pipeline tee-junctions *Applied Mathematical Modelling* **22** 155-170
- [9] Brown G J 2006 Use of CFD to predict and reduce erosion in an industrial slurry piping system *Fifth International Conference on CFD in the process Industries* Melbourne
- [10] Tu J Y, Fletcher C A J, Morsi Y S, Yang W and Behnia M 1998 Numerical and experimental studies of turbulent particle-laden gas flow in an in-line tube bank *Chemical Engineering Science* **53**(2) 225-238
- [11] Noon A A and Kim M H 2017 Erosion wear on Francis turbine components due to sediment flow *Wear* **378** 126-135
- [12] Eltvik M 2013 Sediment erosion in Francis turbines *NTNU Trondheim*
- [13] Dahl G A 2014 Hydraulic design of a Francis turbine that will be influenced by sediment erosion *NTNU Trondheim*
- [14] Poudel L, Thapa B, Shrestha B P, KC B and Shrestha N K 2010 Erosive effect on hydro-mechanical components: A case study Roshi Khola in Nepal *6th International Conference on Hydropower Norway*