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Research Paper

ANALYSIS OF LIQUID DROPLET EROSION FOR STEAM TURBINE BLADES OF COMPOSITE MATERIAL

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The moisture content in steam of low pressure stages of a turbine for a turbo-alternator can cause erosion of the moving blades and the rate of erosion is believed to increase rapidly with increasing velocity of impact of water droplets on blades. Liquid droplet erosion is one of major concerns in the design of modern large fossil steam turbines because it causes serious operational problems such as performance degradation and reduction of service life. An erosion model has been used to analyze the erosion behavior of Co-Cr alloy coated steam turbine blades of composite material. Various relations have been used to find parameters like: incubation period, mass loss rate under changing conditions of steam quality, steam temperature, coating thickness and diameter of the water droplets. Results have been plotted and discussed, showing a distinct improvement in the erosion characteristics like: incubation period and mass loss rate due to the application of coating on the turbine blades. Accordingly suitable operational parameters have been defined to obtain the best possible performance of the steam turbine.

Keywords: Steam, Erosion, Turbine blades, Coating thickness

INTRODUCTION

Power shortage in the country due to the tremendous pressure on power generation engineers for generating the cheaper power which leads to the design and development of modern large power stations (more than 500 MW onwards). These power stations are run by large steam turbines which require huge quantities of steam. In low pressure stage of these turbines the steam flows in wet conditions. The water particles thus formed causes erosion of the blades (Krzyzanowski, 1974; and Krzyzanowski and Szperngiel, 1978).

A number of investigators have worked both experimentally as well as theoretically to find a solution for controlling and curbing the bad effects of erosion. The paper emphasizes the

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use of following parameters like-density, wet steam quality, impact velocity, size of the droplet, ultimate tensile strength, thickness of the material, impact-pressure, temperature and viscosity which plays a vital role as far as erosion is concerned (Ansari, 1986; and Leyzerovich, 2008).

On the other hand in the last row of the blades of large steam turbines about 6% of the total heat drop of the steam flowing through the turbine is converted into mechanical energy.

Since these two factors-high output and quality of energy conversion—are also influenced by the last stage, particular attention has been paid to these blades during the few years. The steam in last stage blades becomes wet and the water particles thus formed can cause pits, cracks in the surface or subsurface, or the mass loss of the material. The damage called erosion, weakens the material significantly and renders components exposed to liquid impingement inefficient or even useless (Springer, 1976; and Field, 1999). Erosion becomes more severe as the lengths and hence tip speeds or the last stage blades increase. It is very important to understand the mechanism of erosion and to develop improved means for controlling it (Adler, 1995).

The production cost of the last stage blades for large turbines is very high. Therefore the turbine manufacturers make all the efforts to manufacture and market a product which will give a trouble free service for long time. Thus, when designing and manufacturing the L.P. stage blades alone, the factor of erosion is strongly considered (Moore *et al.*, 1967; and Stanisa and Ivusic, 1995).

MECHANISM OF EROSION

In the low pressure stages of a condensing steam turbine, steam expands below the saturation line. Moisture gets precipitated in the form of drops. It is always desirable to permit as high a degree of wetness as possible at the exhaust, in order to get more work from steam but pressure of water drops in the steam gives rise to certain losses which are most undesirable. Hence, there is a practical limit of wetness in exhaust steam. The main detrimental effects due to the presence of water drops in steam are:

1. Reduction of thermodynamic efficiency due to drag of water drops at high relative speeds.
2. Erosion of moving blades due to impingement of water drops at high relative speeds.

In these two, erosion is more detrimental since it not only reduces the life of moving blades but is also deteriorates the efficiency of the stage (Gillette, 1992).

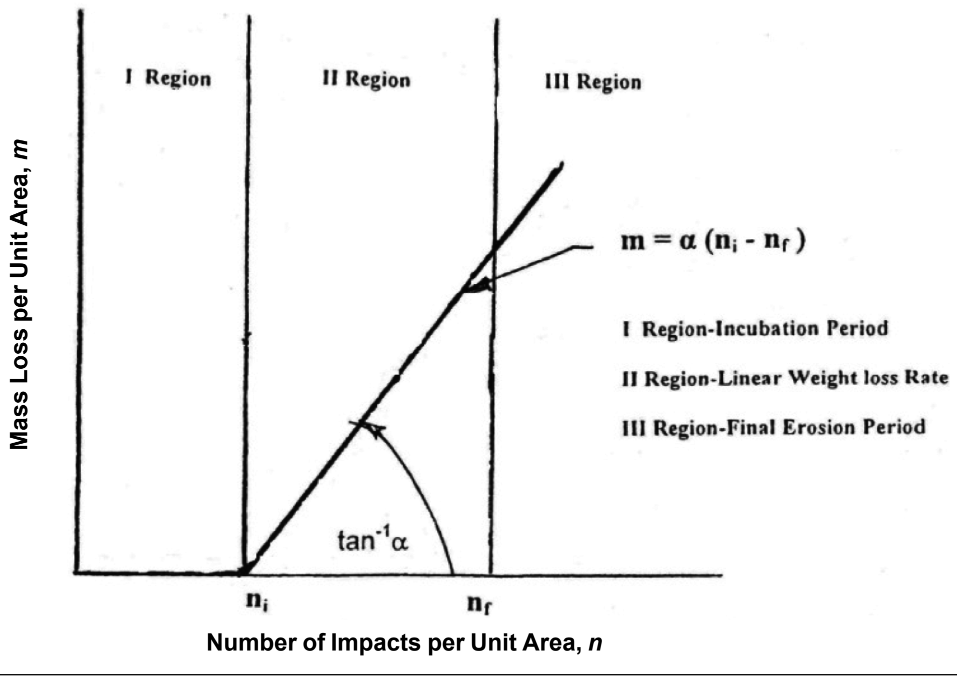
Water drops present in the steam hit the moving blades with high relative velocity thereby causing impact erosion of moving blades. This erosion is very severe and has a very detrimental effect on the stage efficiency. It is almost universally established that a film of water exists on the surface of fixed blades. The deposition rate will depend on droplet sizes.

The water on the fixed blades flow to the trailing edge under the influence of three factors, force produced by the steam drag, the impulse of the fog deposition and the pressure drop along the blade (Ruml and Straka, 1995; and Schofield, 1997). Water, on reaching the trailing edge of fixed blades collects into large drops and those are sprayed off by steam flow. Some of these drops may be too large in size to be stable. Drops of size 500 to 1000 m will come under this category. They do not remain stable and hence, under the influence of aerodynamic forces and internal flashing they disintegrate quickly. These drops of two different diameters—one with smaller diameter, which probably contain much of the greater weight of water and have same velocity as that of steam and other with large diameter 100-200 micron or even more up to 500 micron and with high relative velocity approach the moving blades. The drops of large diameter will go straight and hit the moving blade, thereby causing erosion of blades. It is the normal components of impact velocity against the blade which causes erosion and the tangential component can be ignored (Curtis and Dorey, 1989).

EROSION BY LIQUID DROPLET

Experimental evidence indicates that under a wide range of conditions the weight loss of a material subjected to repeated impingements of liquid droplets varies with time as shown in Figure 1. It is shown in that for some period of time the weight loss is insignificant, this region is known as 'incubation period'. For some time after the incubation period the rate of weight loss is nearly constant and the weight loss varies linearly with time, this region is designated as the 'linear rate erosion' region. Past this region the relationship between the weight loss and the exposure time becomes more complex and this region is referred as 'final erosion region'. In the present work only the incubation period and the steady rate erosion region has been considered (Byeong *et al.*, 2003).

Figure 1: Erosion Model Showing Different Erosion Region



The number of impacts per unit area at the end of incubation period is designated by n_i and at the end of linear rate erosion region by n_f. For convenience, we assume that the erosion is uniform across the entire surface area and replace the total weight loss of the material with the mass loss per unit area '*m*' and '*n*' as the time parameter. The parameters '*m*' and '*n*' are represented in Figure 1. According to this the mass loss is specified by the expressions:

$$m = 0, \qquad n < n_i$$

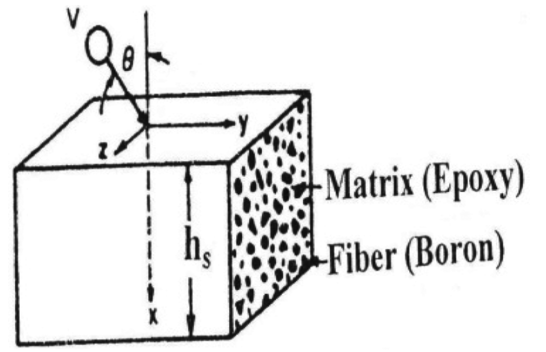
$$m = \alpha(n - n_i), \qquad n_i < n < n_f$$

The material loss '*m*' produced by a certain number of impacts '*n*' can be calculated once the incubation period n_i and the rate of subsequent mass loss (as characterized by the slope α) are known. The Figure 1 shows, the different regimes of erosion, which are important for analysis of steam turbine blades. Therefore, the problem is to determine the parameters n_i, α and n_f.

EROSION OF COMPOSITE MATERIALS

Composite materials have been receiving ever-wider application due to their high strength-to-weight ratio, good magnetic and optical properties and satisfactory performance at elevated temperatures. In order to utilize the full capability of composite materials, the response of composite materials to liquid droplet erosion is analyzed by using mathematical relations. Fiber-reinforced composite material composed of unidirectional filaments embedded in a matrix as shown in Figure 2, which is covered by a coating made of a homogeneous material.

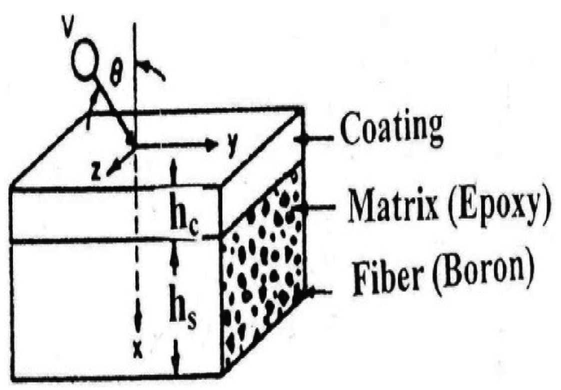
Figure 2: Droplet Impingements on Uncoated Composite Material



Wave reflections will be neglected in uncoated composites and in the substrate of coated composites. Composite materials, which are unable to withstand the damage caused by rain impact, can frequently be protected and their usefulness extended by a protective layer of homogeneous material coating. However, the coating cannot be selected randomly. Coatings provide optimum protection only if they are made of the proper material and are of the proper thickness.

The material to be studied is a fiber reinforced substrate h_s (Boron-Epoxy) covered by a single layer of coating (Co-Cr alloy) of the coating thickness h_c, as shown in Figure 3.

Figure 3: Droplet Impingements on Coated Composite Material



Composite materials may be constructed in different ways. The erosion of composites under study in which:

- Fibers are randomly distributed.
- Fibers are not continuous.
- Fibers are parallel to the surface.
- There is a perfect bond between the matrix and the fibers and, in case of coated composites, between the coating and the substrate.

In this the composite as homogeneous, we are neglecting the effect of microstructure on the erosion phenomenon.

Most uncoated composites have relatively poor resistance to erosion and must be coated for protection (Springer and Yang, 1975; and Stanisa, 2003).

RELATIONS USED IN ANALYSIS

Relations Used for Uncoated Composite Material (Matrix-Epoxy, Fiber-Boron)

Following relationships are used for uncoated composite materials to calculate the required incubation time and mass loss for the substrate material (Springer, 1976).

Strength of the uncoated composite material substrate is given by:

$$S_r = \frac{4\sigma_{um}(b_m - 1)}{E_m}\left[\frac{3}{8}\left(\frac{1}{E_{11}} + \frac{1}{E_{22}}\right) + \frac{1}{8}\left(\frac{1}{G_{12}} - \frac{2\nu_{12}}{E_{11}}\right.\right.$$

$$\left.\left. - \frac{2\nu_{12}}{E_{11}} + \frac{1}{4}\left(\frac{1+2\nu_{12}}{E_{11}} + \frac{1}{E_{22}} - \frac{1}{G_{12}}\right)^{-1}\right]^{-1} \quad \ldots(1)$$

Impact pressure at surface of substrate is given by:

$$P = 1000\,\frac{\rho_L C_L V\cos\theta}{1+\rho_L C_L/\rho_S C_S} \quad \ldots(2)$$

Velocity of steam turbine blade is given by:

$$V = \frac{\pi DN}{60}\, m/\sec \quad \ldots(3)$$

Number of droplets per unit volume of steam is given by

$$q = \frac{6\nu \times 10^9}{\pi d^3}\, drplets/m^3 \;\; steam \quad \ldots(4)$$

Number of impacts per unit area during the incubation period on the surface of substrate material is given by:

$$n_i = \left(\frac{8.9}{d^2}\right)\left(\frac{S_r}{P}\right)^{5.7} impacts/m^2 \quad \ldots(5)$$

Incubation time is given by:

$$t_i = \frac{n_i}{q(V\cos\theta)}\sec \quad \ldots(6)$$

Rate of mass loss of the substrate material is given by:

$$\alpha = 73.3\times 10^{-6}\rho_s d^3\left(\frac{P}{S_r}\right)^4 kg/impacts \quad \ldots(7)$$

Mass loss of the substrate material is given by:

$$n_t = (t_i \cdot q \cdot V)\; impact/m^2 \quad \ldots(8)$$

$$m = \alpha(n_t - n_i)\; kg/m^2 \quad \ldots(9)$$

Relations Used for Coating Material (Co-Cr alloy)

Following relationships are used for coating material to calculate the required incubation time and mass loss for the coating material (Springer, 1976).

Impedance of the coating material is given by:

$$Z = \rho \cdot C \; g/cm^2 \sec \qquad \ldots(10)$$

Stress at the liquid-coat interface at the instant of impact is given by:

$$P = 1000 \frac{\rho_L C_L V \cos\theta}{1 + \rho_L C_L / \rho_C C_C} N/m^2 \qquad \ldots(11)$$

Strength of the coating material is given by:

$$S_{ec} = \frac{4\sigma_{uc}(b_c - 1)}{1 - 2\nu_c} \times \frac{1}{1 + 2k|\Psi_{SC}|} N/m^2 \qquad \ldots(12)$$

Number of impacts per unit area during the incubation period on the surface of coating material is given by:

$$n_{ic} = \left(\frac{8.9}{d^2}\right)\left(\frac{S_{ec}}{\sigma^0}\right)^{5.7} impacts/m^2 \qquad \ldots(13)$$

Incubation time is given by:

$$t_{ic} = \frac{n_{ic}}{q(V\cos\theta)} \sec \qquad \ldots(14)$$

Rate of Mass loss of coating material is given by:

$$\alpha_c = 73.3 \times 10^{-6} \rho_c \cdot d^3 \left(\frac{\bar{\sigma}^0}{S_{ec}}\right) kg/impact \qquad \ldots(15)$$

Mass loss of coating material is given by:

$$n_{tc} = (t_{ic} \cdot q \cdot V) \; impact/m^2 \qquad \ldots(16)$$

$$m_c = \alpha_c (n_{tc} - n_{ic}) \; kg/m^2 \qquad \ldots(17)$$

DATA USED IN ANALYTICAL STUDY

The following data's are used in calculation of erosion parameters for steam turbine blades of composite material. The values in Table 1. are the inputs for computer program for the prediction of erosion behavior of steam turbine blades.

Table 1: Data Used in Analysis

Parameters	Values
Speed of turbine (*N*)	3000 r.p.m.
Size of LP stage blades (*D*)	0.35, 0.40, 0.45, 0.50, 0.55 m
Velocity of blades (*V*)	109.9, 125.66, 141.37, 157.08, 172.79 m/s
Steam quality (*x*)	0.96, 0.97, 0.98
Steam temperature (*T*)	140 ºC, 150 ºC, 160 ºC
Size of water droplets (*d*)	0.05, 0.075, 0.10, 0.125, 0.15 mm
Thickness of Co-Cr alloy coating (h_c)	0.2, 0.3, 0.4 mm

Properties of Coating and Substrate

The material properties of coating (Co-Cr alloy) and substrate (Boron-Epoxy) are listed in Tables 2 and 3 respectively.

Table 2: Material Properties of Co-Cr Alloy (Coating)

Ultimate tensile strength	$\sigma_{uc} = 9.65 \times 10^8$ N/m^2
Endurance limit	$\sigma_l = 4.83 \times 10^8$ N/m^2
Poisson's ratio	$\nu_c = 0.3$
Density	$\rho_c = 8230$ kg/m^3 $\rho_L = 1000$ kg/m^3
Speed of sound	$C_c = 5100$ m/s $C_L = 1463$ m/s
Modulus of elasticity	$E = 2.07 \times 10^{11}$ N/m^2
Constant	$b_c = 20.9$

Table 3: Material Properties of Boron-Epoxy (Substrate)

Ultimate tensile strength of matrix	$\sigma_{um} = 5.79 \times 10^7$ N/m^2
Poisson's ratio	$\nu_{12} = 0.22$
Fiber content	$\nu_f = 0.63$

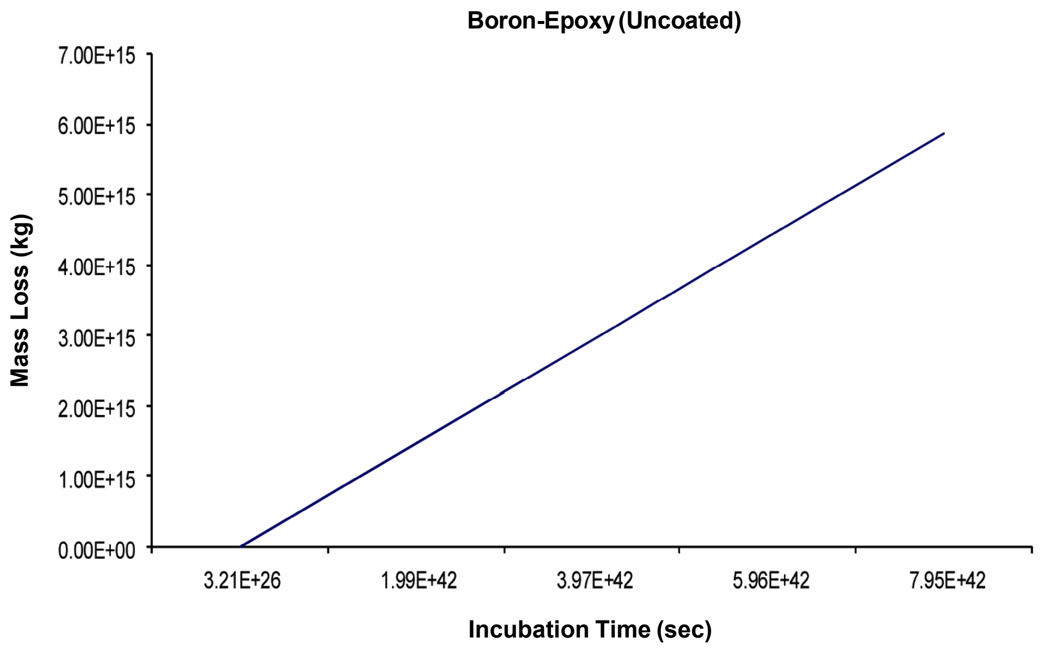
Table 3 (Cont.)

Density	ρ_s = 2190 kg/m^3 ρ_L = 1000 kg/m^3
Speed of sound	C_S = 3327 m/s C_L = 1463 m/s
Modulus of elasticity	$E_m = 2.21 \times 10^{10}$ N/m^2 $E_{11} = 2.07 \times 10^{11}$ N/m^2 $E_{22} = 2.07 \times 10^{10}$ N/m^2
Modulus of rigidity	$G_{12} = 6.89 \times 10^{09}$ N/m^2 $G_{23} = 5.52 \times 10^{09}$ N/m^2
Constant	b_m = 20.9

RESULTS AND DISCUSSION

The computer program has been made by using the above mentioned relationships for uncoated and coated blades of boron-epoxy. By using the value of properties of boron-epoxy (as substrate) and cobalt-chromium alloy (as coating material), results have been computed in form of tables and graphs. In the present analysis the computed results have been plotted between various erosion parameters like mass loss, incubation time, droplet diameter, coating thickness of blade material and dryness fraction of steam. The curves have been drawn for the uncoated and coated blades of boron-epoxy. For a realistic approach to meet the latest trend in the power industry, boron-epoxy has been selected as substrate material while the coating material selected as cobalt-chromium alloy on boron-epoxy. The results have been presented in graphs from Figures 4 to 9 for the selected substrate and coating material. The selected values of water droplet diameters (d) are 0.05, 0.075, 0.10, 0.125 and 0.15 mm. The temperature of steam (T) is taken as 140 °C, 150 °C and 160 °C. The dryness fraction of steam (x) is taken as 96%, 97% and 98%. For the coated blades, the coating thickness (h_c)

Figure 4: Mass Loss vs. Incubation Time for Uncoated B-E Blades



Note: T = 140 °C, x = 0.96, d = 0.05 mm and V = 109.96 m/s.

values are 0.2, 0.3, 0.4 mm. The Figure 4 shows the variation of mass loss and incubation time for uncoated boron-epoxy blades, with an increase in the velocity of blades from 109.96 m/sec to 172.79 m/sec, the incubation time is reduced and the mass loss of substrate material increases linearly with an increase in incubation time.

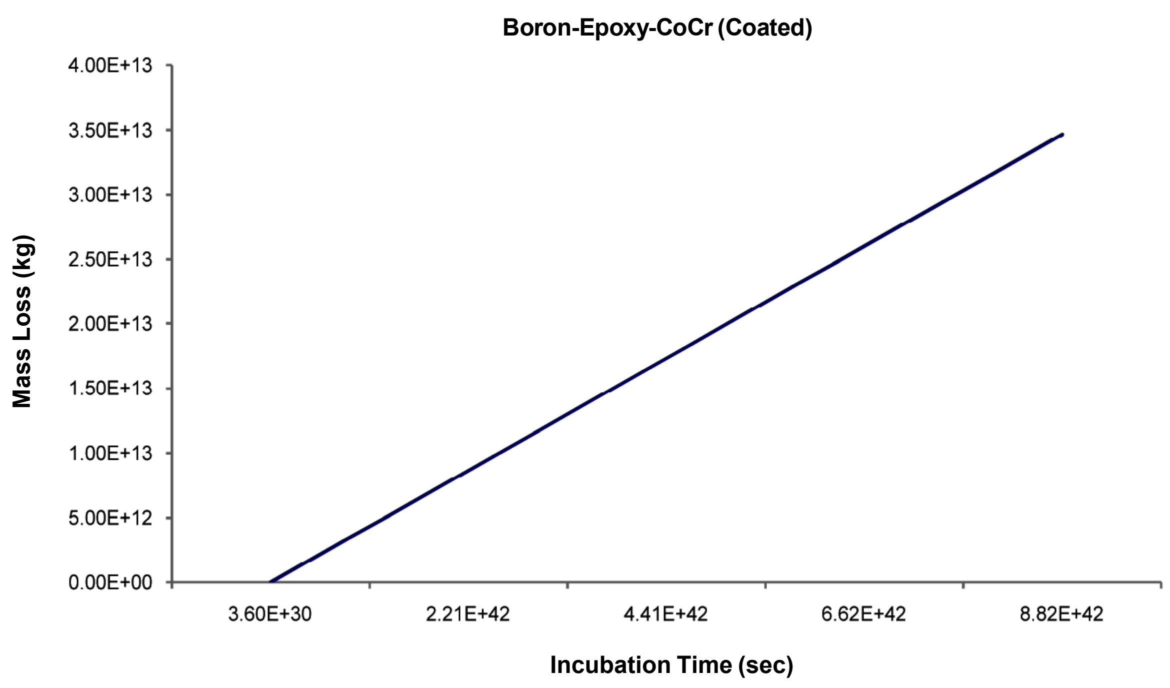
The Figure 5 shows the variation of mass loss and incubation time for boron-epoxy blades coated with Co-Cr alloy. There is a substantial increase in the incubation time and also the mass loss is much less, for coated blades. The incubation time also increases with an increase in the coating thickness.

The Figure 6 shows the variation of incubation time and droplet diameter at T = 140 °C, x = 0.96 for coated boron-epoxy blade material. As the droplet diameter increases from 0.05 mm to 0.15 mm, the incubation time also increases as velocity of blade changes from 109.96 to 172.79 m/sec.

The Figure 7 shows the variation of incubation time and coating thickness at T = 140 °C, x = 0.98, V = 125.66 m/sec, the incubation time increases with an increase in the coating thickness. This figure clearly shows that as we are increasing the coating thickness from 0.2 mm to 0.4 mm there is a very much reduction in the mass loss of the material.

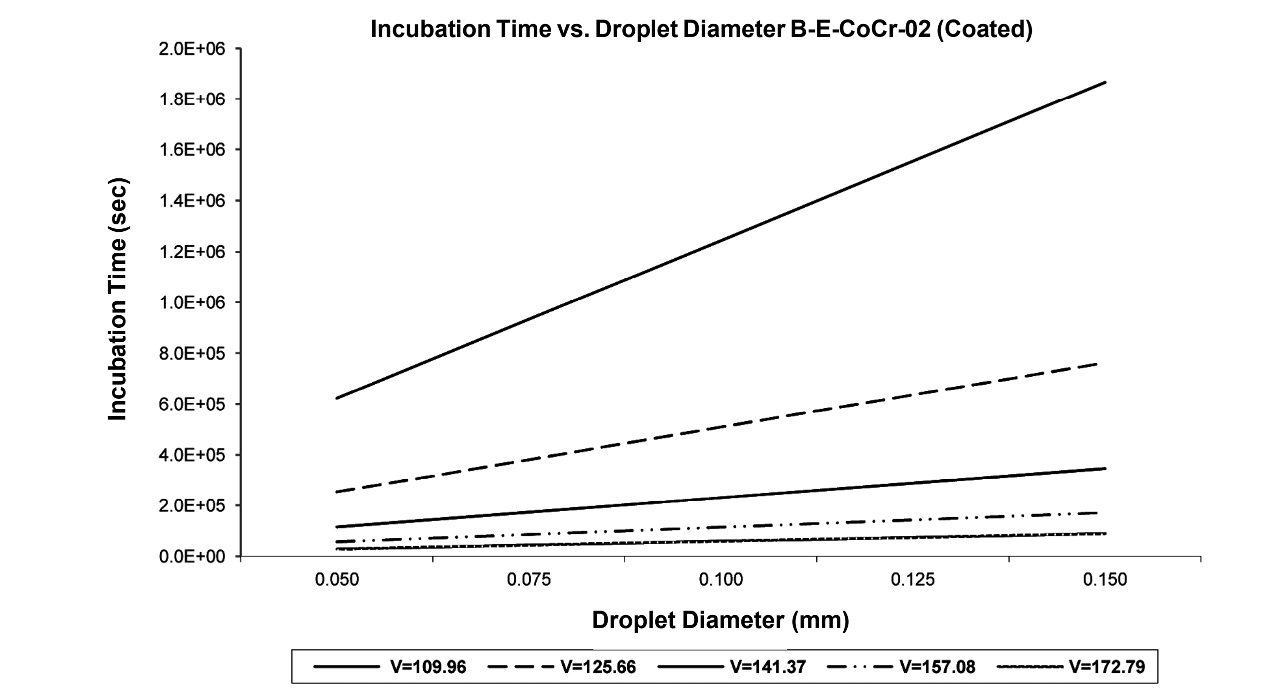
The Figure 8 shows the variation of incubation time and dryness fraction for uncoated and Co-Cr alloy coated boron-epoxy blades at T = 140 °C, d = 0.05 mm, V = 109.96 m/sec. The incubation time increases with an increase in dryness fraction from 96% to 98% and the rate of increase of incubation time is

Figure 5: Mass Loss vs. Incubation Time for Co-Cr Alloy Coated B-E Blades



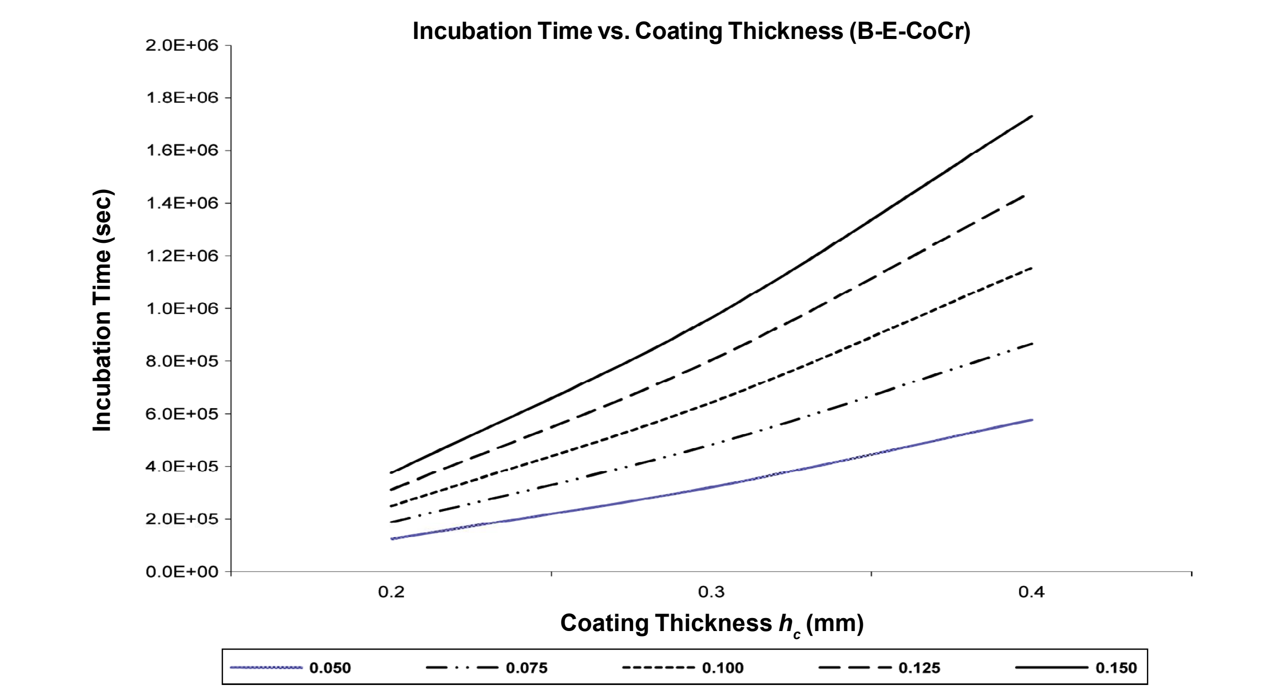
Note: T = 140 °C, x = 0.96, d = 0.05 mm, V = 109.96 m/s and h_c = 0.2 mm.

Figure 6: Incubation Time vs. Droplet Diameter for Co-Cr Alloy Coated B-E Blades



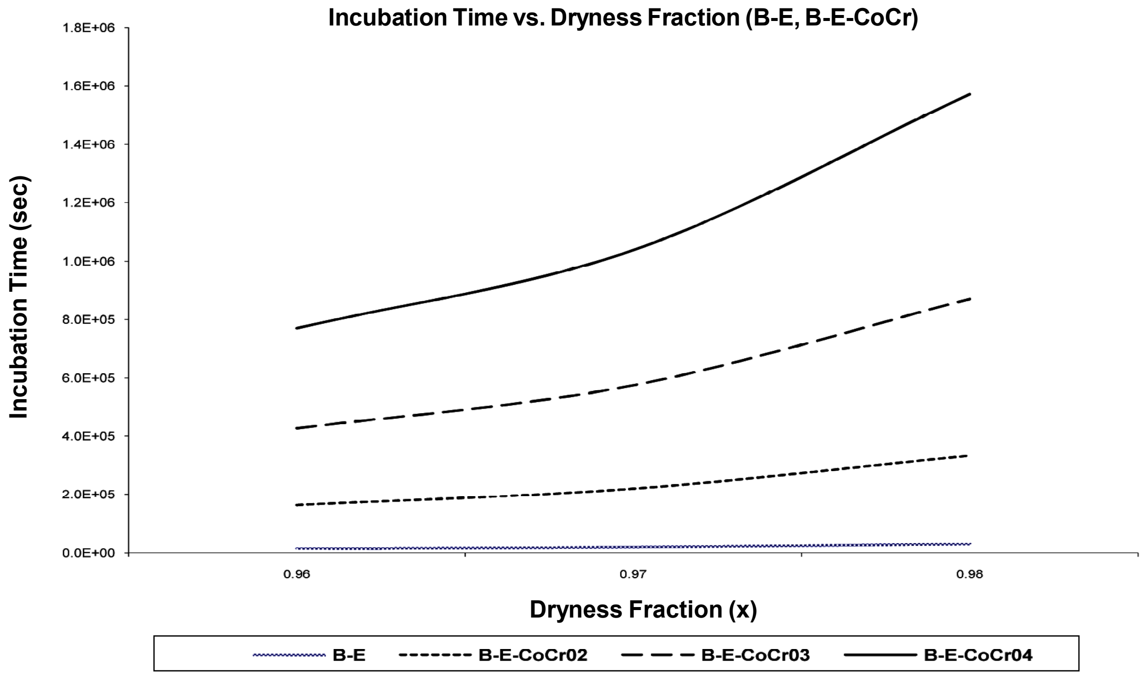
Note: T = 140 °C and x = 0.96.

Figure 7: Incubation Time vs. Coating Thickness Co-Cr Coated B-E Blades



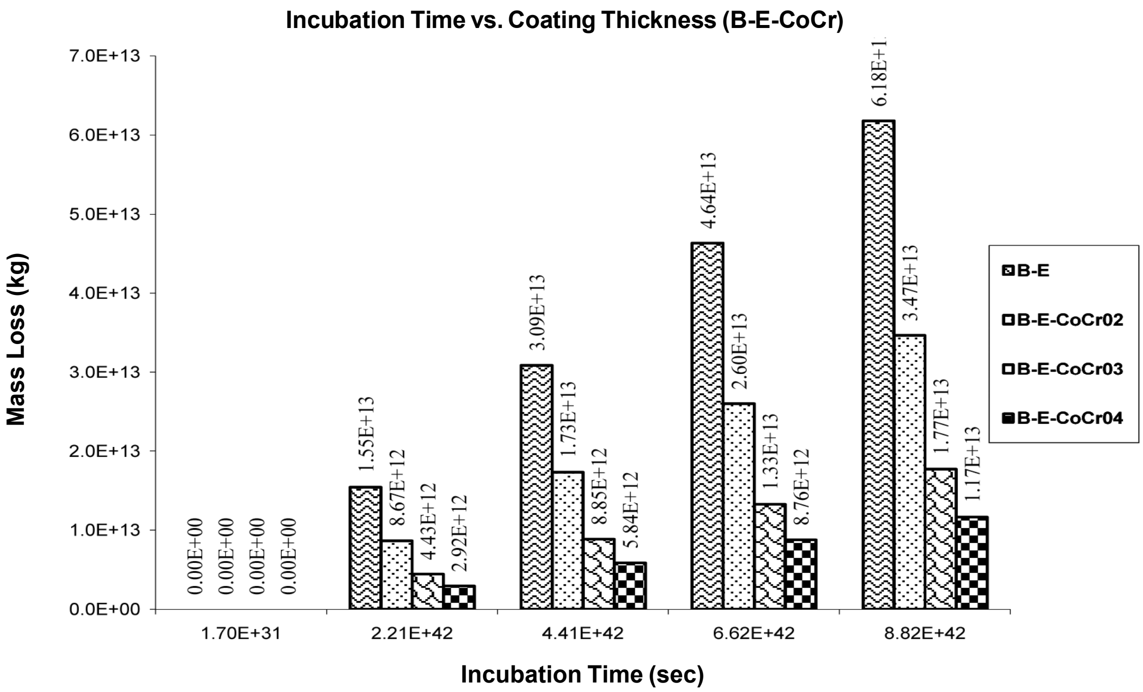
Note: T = 140 °C and x = 0.98.

Figure 8: Incubation Time vs. Dryness Fraction for Uncoated and Coated B-E Blades



Note: T = 140 °C, d = 0.05 mm and V = 109.96 m/s.

Figure 9: Mass Loss vs. Incubation Time for Uncoated and Coated B-E Blades



Note: T = 140 °C, x = 0.96, d = 0.05 mm and V = 109.96 m/s.

being more for Co-Cr alloy coated boron-epoxy blades.

The Figure 9 shows the variation of mass loss and incubation time for uncoated and Co-Cr alloy coated boron-epoxy blades. The conditions are T = 140 °C, x = 0.96, d = 0.05 mm, V = 109.96 m/sec. As the coating thickness increases from 0.2 mm to 0.4 mm, there is a very much reduction in mass loss of blade material takes place. At some instant in the bar chart, the incubation time is 4.41E42 and mass loss for uncoated boron- epoxy blade material is 3.09E13 and for the Co-Cr alloy coated boron-epoxy blades the values of mass loss are 1.73E13, 8.85E12 and 5.84E12 for coating thickness of 0.2, 0.3 and 0.4 mm respectively. So the bar chart clearly shows that by applying the coating of Co-Cr alloy on boron-epoxy blades, an appreciable reduction in mass loss of material takes place.

CONCLUSION

The erosion model has been successfully used to predict the liquid droplet erosion of last stage rotor blades operated in practical steam turbine. In the present work, erosion characteristics of uncoated and Co-Cr alloy coated boron-epoxy blades in the last stage of turbine have been analyzed. The erosion characterizes by parameters like incubation time, mass loss, droplet diameter, coating thickness, etc. Analysis has been made by using above parameters and the results are discussed in the present work. From the present work, the following conclusions can be drawn:

- For the coated boron-epoxy blades the incubation time increases and mass loss decreases as compared to that for uncoated boron-epoxy blades significantly.
- Generally the incubation time increases with an increase in the drop diameter and also it decreases rapidly with an increase in the impact velocity blades for the coated and uncoated boron-epoxy blade material.
- As the coating thickness increases, the incubation time increases and mass loss reduces at different droplet diameters.
- As the dryness fraction of steam increases from 96% to 98%, the incubation time increases at different layers of coating thickness from 0.2 mm to 0.4 mm.
- Bar chart clearly shows that the incubation time increases and mass loss reduces, as the coating thickness increases from 0.2 to 0.4 mm and the mass loss is maximum in case of uncoated boron-epoxy blade material.
- The erosion model used in the present analysis can be used for engineering purpose, such as new design of last stage rotor blades, selection of rotor blade base material and the prediction of life expectancy of commercially operated rotor blades operated in wet region.

REFERENCES

1. Adler W F (1995), "Particulate Impact Damage Predictions", *Wear*, Vols. 186-187, pp. 35-44.
2. Ansari A R (1986), "Blade Erosion Problem in Steam Turbine", *Journal of Institution of Engineers (India)-Mechanical Engineering*, Vol. 67, pp. 1-3.
3. Byeong-Eun Lee, Kap -Jong Riu, Se-Hyun Shin and Soon-Bum Kwon (2003), "Development of a Water Droplet Model

for Large Steam Turbine Blades”, *KSME International Journal*, Vol. 17, No. 1, pp. 114-121.

4. Curtis P T and Dorey G (1989), “Fatigue of Composite Materials”, *Proc. Instn. of Mech. Engrs.*, Vol. 203, No. G1, pp. 31-37.

5. Field J E (1999), “Liquid Impact: Theory, Experiment, Applications”, *Wear*, Vols. 233-235, pp. 1-12.

6. Gillette S M (1992), “End-Use Applications for Coated Fabrics”, *Journal of Coated Fabrics*, p. 22.

7. Krzyzanowski J (1974), “Correlation Between Droplets Steam Structure and Steam Turbine Blading Erosion”, *ASME Journal of Engineering for Power*, Vol. 96, pp. 256-266.

8. Krzyzanowski J and Szperngiel Z (1978), “The Influence of Droplet Size on Turbine Blading Erosion Hazard”, *ASME Journal of Engineering for Power*, Vol. 100, pp. 561-565.

9. Leyzerovich A S (2008), *Steam Turbines for Modern Fossil Fuel Power Plant*, The Fairmont Press Inc., Georgia, USA.

10. Moore M J, Langford R W and Tipping J C (1967), “Research at C E R L on Turbine Blade Erosion”, *Proc. Instn. Mech. Engrs.*, Vol. 182, No. 3H, pp. 61-68.

11. Ruml Z and Straka F (1995), “A New Model for Steam Turbine Blade Materials Erosion”, *Wear*, Vols. 186-187, pp. 421-424.

12. Schofield P (1997), “Steam Turbine Sustained Efficiency”, GER- 375 °C, Technical Report of GE Power Systems.

13. Springer G S (1976), *Erosion by Liquid Impact*, John Wiley & Sons, New York, USA.

14. Springer G S and Yang C I (1975), “A Model for the Rain Erosion of Fiber Reinforced Composites”, *AIAA Journal*, Vol. 13, pp. 877-883.

15. Stanisa B and Ivusic V (1995), “Erosion Behavior and Mechanism for Steam Turbine Rotor Blades”, *Wear*, Vols. 186-187, pp. 395-400.

16. Stanisa B, Schauperl Z and Grilec K (2003), “Erosion Behavior of Turbine Rotor Blades Installed in the Krsko Nuclear Power Plant”, *Wear*, Vol. 254, pp. 735-741.

APPENDIX

Nomenclature

A	–	Area of the surface [m^2]
b	–	Constant for substrate material [–]
C_s	–	Velocity of sound in substrate material [ms^{-1}]
C_L	–	Velocity of sound in liquid material [ms^{-1}]
C_c	–	Velocity of sound in coating material [ms^{-1}]
d	–	Droplet diameter [mm]
D	–	Rotor blade dia. [m]
E	–	Young's modulus [Nm^{-1}]
E_{11}	–	Longitudinal young's modulus [Nm^{-2}]
E_{22}	–	Transverse young's modulus [Nm^{-2}]
G_{12}	–	Longitudinal shear modulus [Nm^{-2}]
G_{23}	–	Transverse shear modulus [Nm^{-2}]
h_c	–	Thickness of coating material [mm]
m	–	Mass loss/unit area [kg m^{-2}]
n	–	Number of impacts per unit area [impact m^{-2}]
n_i	–	Number of impacts per unit area during the incubation period [impact m^{-2}]
n_f	–	Number of impacts per unit area prior to final erosion region [impact m^{-2}]
P	–	Impact pressure [Nm^{-2}]
q	–	Number of droplets per unit volume of steam [droplets m^{-3}]
S_r	–	Strength for uncoated composite [Nm^{-2}]
S_{ec}	–	Strength for the coating [Nm^{-2}]
t_i	–	Incubation time [sec]
σ_u	–	Ultimate tensile strength for substrate material [Nm^{-2}]
σ_l	–	Endurance limit [Nm^{-2}]
V	–	Relative velocity between surface and impacting droplet [ms^{-1}]
x	–	Steam quality [%]
Z	–	Impedance [g.s cm^{-2}]
α	–	Rate of mass loss [kg $impact^{-1}$]
ν	–	Poisson's ratio for substrate material [–]
θ	–	Angle of impact [0]
ρ_L	–	Density of liquid [kg m^{-3}]
ρ_s	–	Density of substrate material [kg m^{-3}]
ρ_c	–	Density of coating material [kg m^{-3}]