Research Article

EROSION BEHAVIOUR OF STEAM TURBINE BLADES OF GLASS-EPOXY

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ABSTRACT

The erosion caused by wet steam flow reduces the efficiency of the last stage rotor blades of steam turbines and makes their service life shorter. Water droplet erosion is one of the major concerns in the design of modern steam turbine because it causes serious operational problems such as performance degradation and reduction of service life. An erosion model has been used in the present study for the prediction of water droplet erosion of rotor blades operated in wet steam conditions. It is used to analyze the erosion behavior of nickel coated glass epoxy steam turbine blades. The major erosion parameters to find incubation time is rate of mass loss under varying conditions of dryness fraction of steam (x) ,steam temperature (T), coating thickness (h_c) and size of the water droplets(d) are involved in the model so that it can also be used for engineering purpose at the design stage of rotor blades. Results are showing greater improvement in the erosion characteristics like incubation period and rate of mass loss due to application of Ni coating on the glass epoxy blades. According to that suitable operational factors have been defined to obtain the best possible performance of steam turbines.

KEY WORDS: Water droplet erosion; Steam turbine blade; Coating thickness; L.P. stage.

INTRODUCTION

The phenomenon of steam turbine blade erosion is now well known. The erosion in the low pressure stages of steam turbine is due to the presence of water droplets in the wet steam. This water after condensation is deposited on the trailing edges of the diaphragm blades and then is swept off the trailing edges by expanding steam. Relatively large and slow moving water droplets strike the back of the leading tip of moving blades. This impact gives rises to highly localized surface stress which promote gradual break down of material.[1]

The 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 in erosion of steam turbine blades. [2]. 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 render components exposed to liquid impingement inefficient or even useless. 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. [3, 4]

EROSION MECHANISM

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. [5]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.[6,7]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 1000μm 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. [8]

LIQUID DROPLET EROSION

For the assessment of the erosion resistance of a material it is necessary to verify the dependence on the peripheral velocity and droplet size. The ordering of the materials and their shields as to the erosion resistance may vary depending on the impact velocity and droplet diameter variation. Fatigue plays an important role in the erosion process, particularly in the early stage of the process corresponding to the incubation period. This concept is used in the analysis and a mathematical model is used on the basis of fatigue theorems. [9] Experimental evidence indicates that under a wide range of conditions the mass loss of a material subjected to repeated impingements of liquid droplets varies with time. For some period of time (referred to as incubation time) the weight loss is insignificant. 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 "steady rate erosion" region. Past this region the relationship between the weight loss and the exposure time becomes more complex and this region referred as "final erosion" region. In the present work only the incubation period and the steady rate erosion region has been considered. 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:

$m = 0, \quad n < n_i$

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

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.

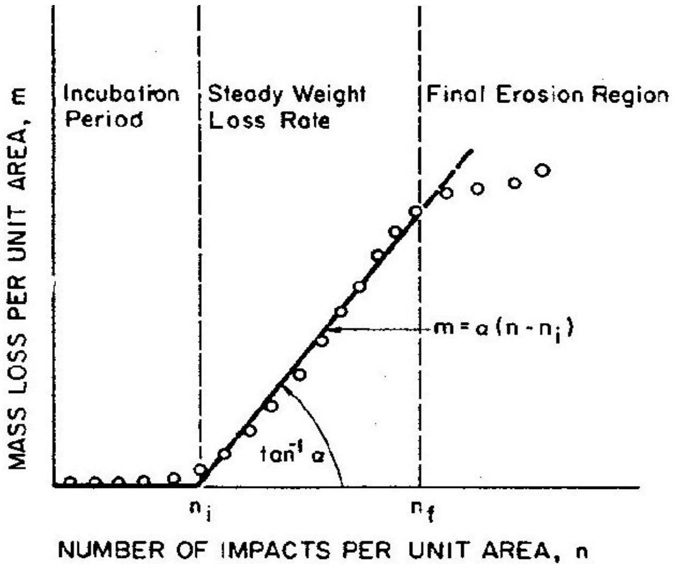

Figure 1. Erosion model showing different regimes

EROSION OF FIBER -REINFORCED COMPOSITES

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. Fiber-reinforced composite material composed of unidirectional filaments embedded in a matrix, which is covered by a coating made of a homogeneous material.

EROSION OF COATED FIBER-REINFORCED 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 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 (Glass-Epoxy) covered by a single layer of coating (Nickel) of the coating thickness h_c, shown in figure-2. Most uncoated composites have relatively poor resistance to erosion and must be coated for protection. [10]Composite materials may be constructed in different ways. The erosion of composites under study in which:

(1.) Fibers are randomly distributed.
(2.) Fibers are not continuous.
(3.) Fibers are parallel to the surface.

By treating the composite as homogeneous, we are neglecting the effect of microstructure on the erosion phenomenon.

DATA USED IN ANALYSIS

The data used in the analysis are listed in table 1. The values in table 1, are the inputs for computer program for prediction of erosion behavior of steam turbine blades.

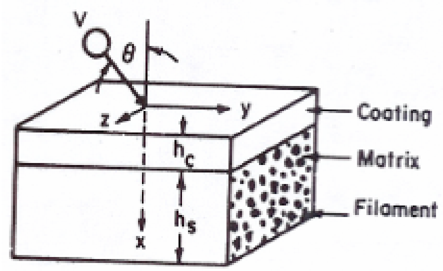

Figure 2. Droplet impingement on coated fiber-reinforced composite

Table 1. Data used in analysis

Parameters	Values
Speed of turbine (N)	3000 r.p.m.
Size of L.P. 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
Dryness fraction of steam (x)	0.96, 0.97, 0.98
Steam temperature (T)	140ºC, 150ºC, 160ºC
Size of water droplets (d)	0.05, 0.075, 0.10, 0.125, 0.15 mm
Thickness of Nickel coating (h_c)	0.2, 0.3, 0.4 mm

PROPERTIES OF SUBSTRATE AND COATING

The properties of substrate and coating material used for erosion analysis are listed in table 2.

Table 2. Properties of Substrate and Coating material

Glass-Epoxy (Substrate)	Nickel (Coating)
$\sigma_{um} = 5.74\times10^{7} N/m^{2}$	$\sigma_{uc} = 3.17\times10^{8} N/m^{2}$
$\nu_{12} = 0.25$	$\nu_c = 0.3$
$\nu_f = 0.65$	$\rho_c = 8100 kg/m^{3}$
$\rho_s = 1840 kg/m^{3}$	$\rho_L = 1000 kg/m^{3}$
$\rho_L = 1000 kg/m^{3}$	$C_c = 5055 m/s$
$C_S = 2273 m/s$	$C_L = 1463 m/s$
$C_L = 1463 m/s$	$E = 2.07\times10^{11} N/m^{2}$
$E_m = 2.21\times10^{10} N/m^{2}$	$b_c = 20.9$
$E_{11} = 4.62\times10^{10} N/m^{2}$	
$G_{12} = 6.89\times10^{09} N/m^{2}$	
$G_{23} = 2.07\times10^{09} N/m^{2}$	
$b_m = 20.9$	

RELATIONS USED FOR UNCOATED COMPOSITE MATERIAL (MATRIX- EPOXY, FIBER-GLASS)

Strength of the substrate material is given by:

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

Water hammer pressure at surface is given by:

$$P = \frac{\rho_L C_L V \cos\theta}{1+\frac{\rho_L C_L}{\rho_S C_S}} N/m^2$$

Velocity of blade is given by:

$$V = \frac{\pi D N}{60} m/\sec$$

Number of droplets per unit volume is given by:

$$q = \frac{6\nu \times 10^9}{\pi d^3}$$

Number of impacts on the surface of substrate is given by:

$$n_i = \left(\frac{8.9}{d^2}\right)\left(\frac{S}{P}\right)^{5.7} impact/m^2 \quad , \quad t_i = \frac{8.9}{qV\cos\theta d^2}\left(\frac{S}{P}\right)^{5.7} impact/m^2$$

Incubation period is given by:

$$t_i = \frac{n_i}{qV\cos\theta} \text{ sec.}$$

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

$$\alpha = 73.3\times10^{-6}\rho_s d^3\left(\frac{P}{S}\right)^4 kg/impacts$$

Mass loss of the substrate material is given by:

$$m = \alpha(n_t - n_i)kg/m^2 \quad , \quad n_i = (t_i.q.V)impact/m^2$$

RELATIONS USED FOR COATED FIBER REINFORCED COMPOSITE MATERIAL

Impedance of the coating material is given by:

$$Z = \rho.C \ g/cm^2 \ sec.$$

Water hammer pressure at the liquid- coat interface is given by:

$$P = \frac{\rho_L C_L V \cos\theta}{1+\frac{\rho_L C_L}{\rho_S C_S}} N/m^2$$

Strength of coating is given by:

$$S_{ec} = \frac{4\sigma_{uc}(b_c - 1)}{1-2\nu_c}\times\frac{1}{1+2K[\psi_{SC}]} N/m^2$$

Incubation period for coating material is given by:

$$n_{ic} = \left(\frac{8.9}{d^2}\right)\left(\frac{S_{ec}}{\sigma^0}\right)^{5.7} impacts/m^2 \quad , \quad t_{ic} = \frac{n_{ic}}{qV\cos\theta}\sec$$

Rate of Mass loss of coating material is given by:

$$\alpha_c = 73.3\times10^{-6}\rho_c.d^3\left(\frac{\sigma^0}{S_{ec}}\right)kg/impact$$

Mass loss of coating material is given by :

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

$$n_{tc} = (t_{ic}.q.V)impact/m^2$$

RESULTS, DISCUSSION AND ANALYSIS

In the present work the computed results have been plotted between mass loss vs. incubation time, incubation time vs. droplet diameter, incubation time vs. coating thickness. The curves have been drawn for the uncoated and Ni coated blades of glass-epoxy.

The results have been presented in figure-3 to figure-6 for' Glass-Epoxy' as substrate material and coating of 'Nickel' on it. The water droplet diameters (d) are 0.05, 0.075, 0.10, 0.125 and 0.15 mm. Steam temperature (T) are taken as 140^{0}C, 150^{0}C and 160^{0}C. Dryness fraction (x) is taken as 96%, 97% and 98%. For coated blades, the coating thickness (h_c) are 0.2, 0.3, 0.4 mm.

The figure-3 shows the variation of mass loss and incubation time for uncoated glass-epoxy blades, with an increase in the velocity, the incubation time is reduced and also the rate of mass loss is much more.

The figure-4 shows the mass loss variation as plotted against incubation time for glass-epoxy blades coated with nickel. There is a substantial increase in the incubation time and the rate of mass loss is much less, for coated blades. The incubation time also increases with an increase in the coating thickness.

The figure-5 shows the relationship between droplet diameter and incubation time at T=160^{0}C, x=0.98 for nickel coated glass-epoxy blades. As droplet diameter increases from 0.05 to 0.15 mm the incubation time also increases as velocity changes. At higher velocity incubation time increases very rapidly.

The figure-6 shows that for nickel coated glass-epoxy blades, the incubation time increases with an increase in the coating thickness. The conditions are T= 140^{0}C, x= 0.96, V= 125.66 m/s. This figure clearly shows that as we are increasing the coating thickness from 0.2 mm to 0.4 mm the incubation time increases smoothly. At some instant, incubation time is 1.56E38 and mass loss for uncoated glass–epoxy blades is 2.03E16 and for nickel coated glass-epoxy blades are 2.56E15, 1.19E15, 7.64E14 for coating thickness of 0.2 mm, 0.3 mm and 0.4 mm respectively. This clearly shows that by applying coating on glass-epoxy blades, an appreciable reduction in mass loss of material is observed.

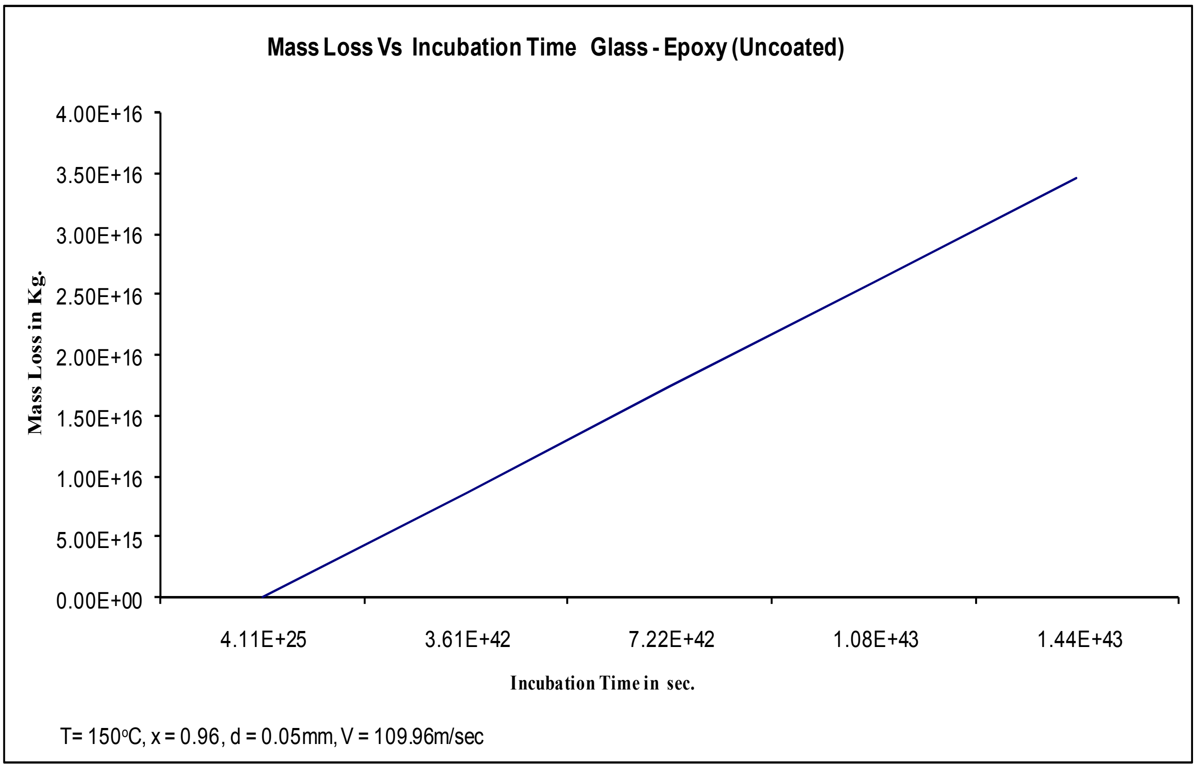

Figure 3. Mass loss Vs Incubation Time for Uncoated Glass- Epoxy

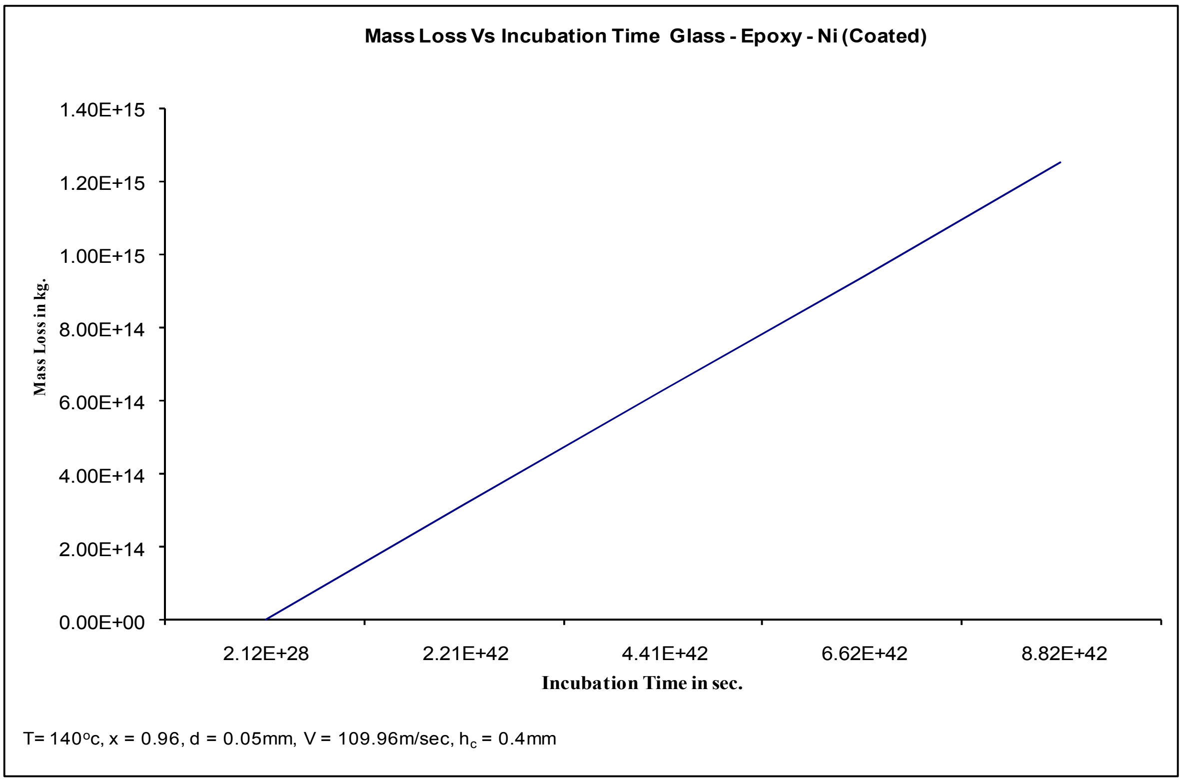

Figure 4. Mass loss Vs Incubation Time for Ni coated Glass-Epoxy

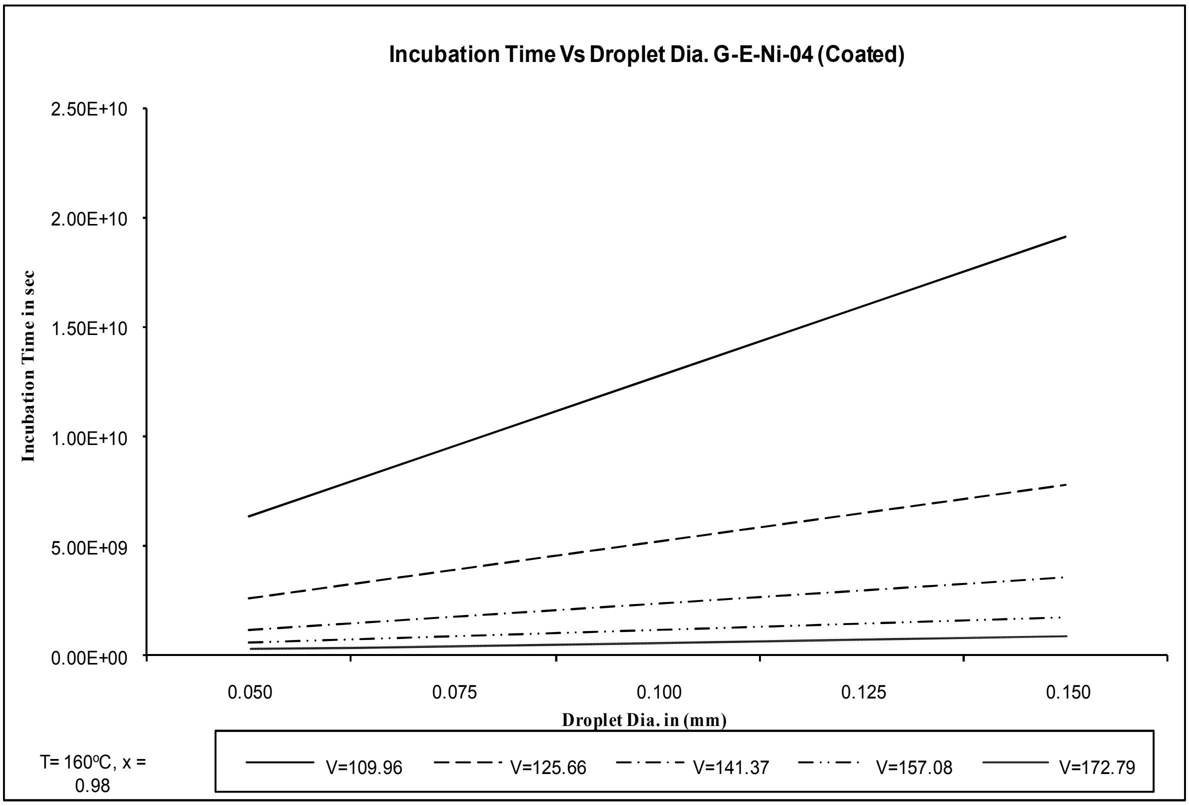

Figure 5. Incubation Time Vs Droplet Dia. for Ni coated Glass-Epoxy

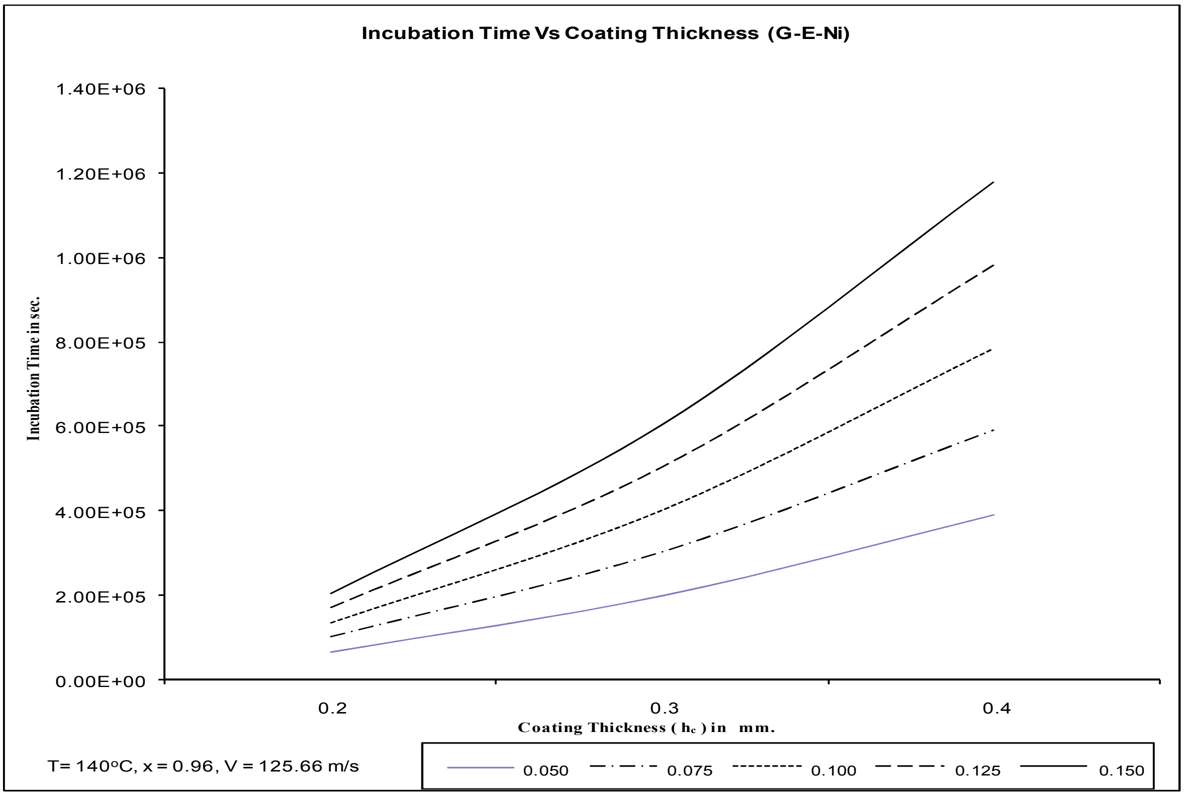

Figure 6. Incubation Time Vs Coating Thickness for Ni coated Glass-Epoxy

CONCLUSIONS

The Erosion model has been successfully used to predict the water droplet erosion of last stage rotor blades operated in practical steam turbine. In the present work erosion characteristics of uncoated glass-epoxy and nickel coated glass-epoxy blades in the last stage of turbine have been studied. The erosion characterizes by parameters like incubation time, mass loss, rate of mass loss etc. Analysis has been made of above and the results are discussed in the present work and the following conclusions have been drawn: (1) For the coated glass-epoxy blades the incubation time increases and rate of mass loss decreases as compared to that for uncoated glass-epoxy blades significantly, (2) Generally the incubation time increases with an increase in the drop diameter and also it decreases rapidly with an increase in the impact velocity for coated and uncoated glass-epoxy blades, (3)As the coating thickness increases, the incubation time increases and rate of mass loss reduces at different droplet diameters. The erosion model used in the present study 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.

NOMENCLATURE

b−Constant for substrate material [-]
d−Droplet diameter, [mm]
D−Rotor blade dia.,[m]
m−Mass loss/unit area,[kg m^{-2}]
n−Number of impacts per unit area, [m^{-2}]
n_i−Number of impacts per unit area during the incubation period,[m^{-2}]
n_t−Number of impacts per unit area during the time period T
P−Impact pressure, [Nm^{-2}]
q−Number of droplets per unit volume of rain, [m^{-3} of rain]
S_c −Strength parameter for coating,[Nm^{-2}]
t_i−Incubation time, [s]
t_L−Duration of impact,[s]
σ_u−Ultimate tensile strength for substrate material, [m^{-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 $impacts^{-1}$]
ν−Poisson's ratio for substrate material,[-]
θ−Angle of impact, [0]
ρ_L−Density of liquid,[$g.cm^{-3}$]
ρ_s −Density of substrate material,[$g.cm^{-3}$]
ρ_c−Density of coating material,[$g.cm^{-3}$]
C_s−Velocity of sound in substrate material, [ms^{-1}]

C_L−Velocity of sound in liquid material, [ms^{-1}]
Cc−Velocity of sound in coating material, [ms^{-1}]
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]

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