Development of a Water Droplet Erosion Model for Large Steam Turbine Blades

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Water 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. A new erosion model has been developed in the present study for the prediction of water droplet erosion of rotor blades operated in wet steam conditions. The major four erosion parameter ; impact velocity, impacting droplet flow rate, droplet size and hardness of target are involved in the model so that it can also be used for engineering purpose at the design stage of rotor blades. Comparison of the predicted erosion rate with the measured data obtained from the practical steam turbine operated for more than 90,000 hours shows good agreement.

Key Words: Water Droplet Erosion, Steam Turbine Blade

1. Introduction

Water droplet erosion of the last stage rotor blades causes serious operational problems in many large steam turbines because of reduced efficiency and service life. This is because degradation of the steam turbine efficiency is mainly governed by the shape change of its steam path (Schofield, 1997). Recently, however, supercritical units requiring higher steam pressure and temperature than subcritical ones have been constructed for an increased thermal efficiency (Oeynhausen, 1993). Moreover, longer last stage rotor blades having active length of 40 inches have also been employed in large steam turbines. These two facts make the water droplet erosion of the last stage rotor blades severer because of following two reasons. Firstly, supercritical units have expansion line shifted to the left in the Mollier diagram compared with subcritical ones because of higher pressure. Therefore, higher moisture content is present in the supercritical units. In addition, the back-end loading of the supercritical units is lower than that of the subcritical ones for the same rating. Therefore, the lower steam flow does not accelerate the droplets from stationary blade to rotor blade as well. This causes higher water droplet impact velocity with rotor blade, as can be imagined in Fig. 1. Secondly, both peripheral rotation velocity and relative droplet velocity increase with the length of rotor blade. The water droplet erosion is significantly affected by relative droplet velocity (impact velocity), as will be discussed in Section 3.1. In practice, for a typical large fossil steam turbine with last stage rotor blades 20 inches or longer, all materials experience some level of water droplet erosion. For these reasons, intensive research works in terms of water droplet erosion

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of rotor blades have been performed recently by many workers (Stanisa and Ivusic, 1995 ; Krzyzanowski et al., 1994 ; Tsubouchi et al., 1990).

Although many workers (Krzyzanowski et al., 1994 ; Ruml and Straka, 1995) have developed water droplet erosion models, there have been no practical models, those can be used to determine the service life of blades accurately using its operating conditions and material properties. In the present paper, a new erosion model is reported. All major erosion parameters such as impact velocity, impacting droplet flow rate, droplet size, and target hardness are included in the model. Therefore, the model can also be used for engineering purpose to minimise erosion due to impact of water droplet. The erosion rate predicted using the model developed in the present study is compared with the field data obtained from a practical steam turbine.

2. Procedure of Water Droplet Erosion of Blades

The last one or two stages of the low pressure turbine are designed to operate in the wet region for modern large fossil steam turbines. Water droplets, which are initially very small and called primary droplets, are formed by the condensation as the steam are expanded in the wet region of the Mollier diagram. These primary droplets are then carried along with the new saturated steam as a wet steam mixture. These droplets are grown mainly by successive coalescence and relatively large ones collides with the leading edge and concave side of stationary blades to form liquid films because of its inertia force. When the water films reach the trailing edges of the stationary blades by the dragging action of the steam, the water films are then torn off and joined with main stream in the form of large secondary droplets.

The actual erosion occurs on the suction side of the leading edge of the rotor blade. This is because the rotor blade impacts with the slower moving water droplets since the rotor blade velocity is higher than that of the water droplets, as shown in Fig. 1.

Water droplet erosion of steam turbine blades is a purely mechanical phenomenon. When a water droplet collides with target surface with a great velocity, the high pressure, so-call "water-hammer" pressure, is generated. It is well known that most of erosion damage is caused by this high pressure lasting while the edge of the contact area between the impacting liquid and the solid moves supersonically with respect to shock speed in the liquid. The details for this are well discussed and reviewed by Field (1999).

The titanium alloys have been employed as

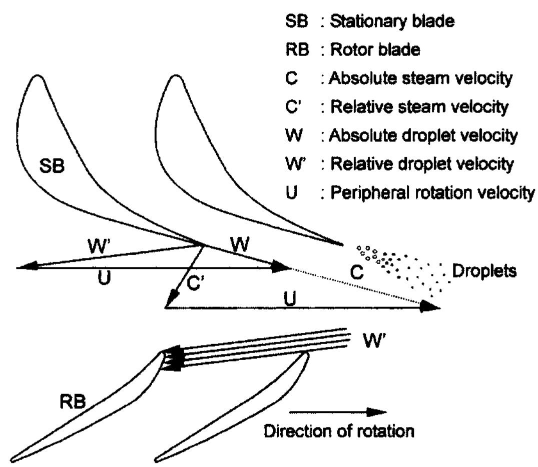

Fig. 1 Velocity triangles of steam and droplets

Table 1 Chemical composition of materials used for last stage steam turbine blades

Alloy	Chemical composition
12Cr stainless steel	12%Cr, 1.1%Mo, 1.0%W, 0.7%Mn, 0.7%Ni, 0.25%V
Pure Ti	Ti
Ti-6Al-4V	6.09%Al, 4.2%V, 0.12%Fe
Ti-5Al-2.5Sn	5%Al, 2.5%Sn
Ti-15Mo-5Zr-3Al	15%Mo, 5%Zr, 3%Al
Stellite	Co-30%Cr, 5.5%W, 2.1%Ni, 1.37%Mn, 1.0%C

base blade material as well as erosion shield material for the last stage rotor blades used in large fossil steam turbines because of their higher strength to weight ratio and better erosion/corrosion resistance. Therefore, water droplet erosion of titanium alloys has been studied by many workers (Tsubouchi et al., 1990; Robinson and Reed, 1995; Gerdes et al., 1995; Drahy, 1988). The chemical composition of the base materials used for the last stage steam turbine blades are summarized in Table 1.

3. Important Parameters Causing Water Droplet Erosion of Blades

It is generally agreed that the water droplet erosion of the last stage rotor blades operated in the wet steam conditions is mainly affected by such parameters as impact velocity, impact angle, droplet size, number of droplets (impact frequency), hardness of target metal. A fundamental understanding of various erosion parameters is essential in order to prolong the life of blades operated in the wet steam conditions. Several erosion parameters, those will be involved in the erosion model, are described for a better understanding of water droplet erosion.

3.1 Impact velocity

The impact velocity is the one of the most important parameters because the erosion rate is strongly dependent on the impact velocity. It has been discovered empirically that water droplet erosion rate is proportional to approximately the fifth power of the impact velocity if all other parameters remain constant (Tsubouchi et al., 1990).

Recently, longer blades having active length of 40 inches have been employed in the large steam turbines. This is because the stage efficiency is increased with the active length of rotor blade. However, the erosion condition becomes severer as the length of the blade is increased because of increased peripheral rotation speed of the blade.

3.2 Impact angle

Stanisa and Ivusic (1995) observed from water droplet eroded blades operated in practical steam turbine that the craters formed by the impact of droplets are developed parallel to the impact direction of the droplets. In general, the impact angle influences the erosion before craters are formed on the target surface. However, if the incubation period is short enough the effect of impact angle can be neglected.

3.3 Droplet size

The erosion rate increases with droplet size, if the number of impacting droplets is constant. It is important to establish the influence of droplet size on the erosion of blades, since water droplets have a broad size distribution, with a diameter from one to hundred microns. Normally, the mean diameter is used in the prediction of erosion for convenience.

It can be imagined that the diameters of droplets at the exit plane of stationary blade are closely related to the trailing edge thickness of the stationary blade that has been used as an erosion parameter by turbine manufacturers (Leyzerovich, 1997). The final sizes of the impacting droplets are mainly determined by the breakup caused by velocity lag between a continuous medium and droplets. The fundamental concepts of droplet breakup in flows with velocity lag have been reviewed intensively by Gelfand (1996).

3.4 Droplet shape

Adler (1995) found that the water droplet erosion damage is strongly affected by the radius of curvature of the droplet at the point of impact and not the mass of a distorted droplet. This fact is also can be explained by the theory of liquid impact (Field, 1999). Therefore, distorted droplets having radii larger than their initial diameters are more erosive. However, the shapes of water droplets are assumed as perfect spheres in the present study.

3.5 Number of droplets

The water droplet erosion increases linearly with impact frequency, number of impacting droplets. This is because, when the droplets collides with target, those are deposited on the target surface. On the contrary, if there are many droplets rebounded from target surface as in solid particle erosion, the incident droplets may collide with the rebounded droplets and lose their velocity. In that case, erosion rate may not be linear against the number of droplets.

3.6 Hardness of target material

Hardness of the target material influences significantly the erosion rate. In general, the erosion rate decreases as the hardness of target increases. Normally, different families of materials have different erosion characteristics.

4. Development of a New Erosion Model

From the viewpoint of blade design, it is desirable that an erosion model should be as simple as possible. In addition, each erosion parameter should be determined quantitatively without any difficulties. An erosion model must contain all important erosion parameters as separate variables and all excluded minor erosion parameters should be included in the erosion constant. The basic structure of the erosion model is organised to include the four most important erosion parameters discussed in the previous section as shown in Equation (1).

$$E=k\cdot f(m)\cdot g(V)\cdot h(d)\cdot j(Hv) \tag{4}$$

where, k is the erosion constant, $f(m)$ is the impacting droplet flow rate term, $g(V)$ is the droplet impact velocity term, $h(d)$ is the droplet size term, and $j(Hv)$ is the target material hardness term.

It is well known that water droplet erosion may be observed after a certain incubation period (Stanisa and Ivusic, 1995; Krzyzanowski et al., 1994; Krzyzanowski and Szprengiel, 1978). The length of incubation period is mainly governed by major erosion parameters, such as impact velocity, droplet size, and blade material. In general, the incubation period should be taken into account in the development of erosion models. However, it is relatively short if the impact velocity is high enough so that the erosion conditions become much severer. In practice, Tsubouchi et al. (1990) found that the erosion rate becomes steady after around 20 hours under the similar operating conditions with the practical large steam turbines. This time is much shorter compared with service life of the practical rotor blades. Therefore, the incubation period is not included in the model developed in the present study.

5. Calibration of Erosion Parameters

Tsubouchi et al. (1990) performed well controlled experiments for the study of erosion parameters using the high speed erosion test facility. They produced detailed erosion data for several blade materials, 12Cr stainless steel, stellite, and titanium alloys, used for last stage rotor blades. Those data are used in the calibration of erosion parameters in the present study.

5.1 Impacting droplet flow rate

The effect of impacting droplet flow rate on erosion rate is given in Fig. 2. It can be seen from this figure that the mass flow rate term can be expressed by a linear curve in the logarithmic scale. Therefore, the erosion rate can be described by a power law of mass flow rate as following:

$$E=k_a\cdot f(m)=k_a\cdot\left(\frac{m}{m_{ref}}\right)^a \tag{2}$$

where m_{ref} means the reference flow rate and used to make impacting droplet flow rate term dimensionless form. The gradients of the curves

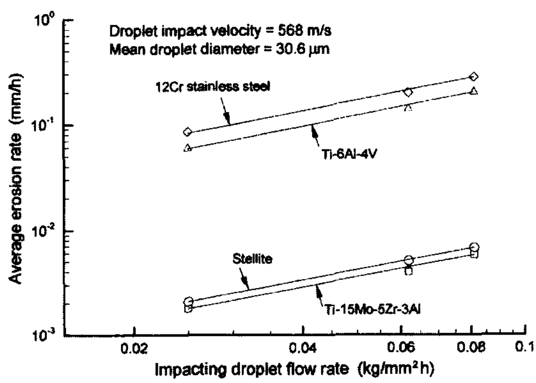

Fig. 2 Effect of impacting droplet flow rate on erosion rate

are almost one (1) and this result agrees well with the fact that water droplet erosion increases linearly with the number of impacting droplets, as discussed in Section 3.4.

5.2 Impact velocity

The effect of droplet impact velocity on erosion rate is given in Fig. 3. The erosion rate also can be described by a power law of droplet impact velocity as following:

$$E=k_b\cdot g(V)=k_b\cdot\left(\frac{V}{V_{ref}}\right)^{\alpha} \tag{3}$$

where V_{ref} means the reference impact velocity. The values of α, gradients of the curves, are 5.1 for all materials used in the experimental works.

5.3 Droplet size

The effect of droplet size on erosion rate is shown in Fig. 4. The erosion rate also can be described by a power law of droplet size, as following:

$$E=k_c\cdot h(d)=k_c\cdot\left(\frac{d}{d_{ref}}\right)^{\beta} \tag{4}$$

where d_{ref} means the reference droplet diameter. The values of β are 2.0 for both 12Cr stainless steel and Ti-6Al-4V those are used for blade materials, and 4.5 for both stellite and Ti-15Mo-5Zr-3Al those are used for erosion shield materials. It can be concluded from this fact that each family of blade materials shows different erosion behaviours for the droplet size variation.

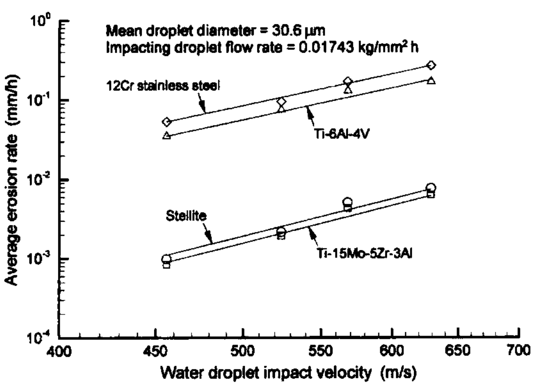

Fig. 3 Effect of droplet impact velocity on erosion rate

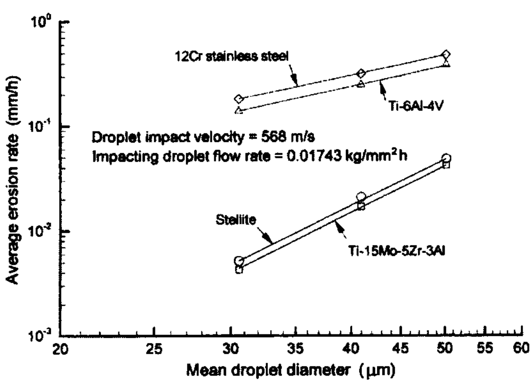

Fig. 4 Effect of droplet size on erosion rate

5.4 Hardness of target material

The effect of target material hardness on erosion rate is shown in Fig. 5. Unlike other parameters, the x-axis is not logarithmic scale. However, the y-axis is logarithmic scale. Therefore, the erosion rate can be described by an exponential function as following:

$$E=k_d'\cdot j(Hv)=k_d\cdot 10^{\gamma Hv} \tag{5}$$

where Hv means Vickers hardness and γ is the constant to be determined. The values of γ are -0.0036 and -0.0048 for 12Cr stainless steel and titanium alloys, respectively.

Finally, the erosion model developed in the present study is described as follows:

$$E=k\cdot\left(\frac{m}{m_{ref}}\right)\cdot\left(\frac{V}{V_{ref}}\right)^{\alpha}\cdot\left(\frac{d}{d_{ref}}\right)^{\beta}\cdot 10^{\gamma Hv} \tag{6}$$

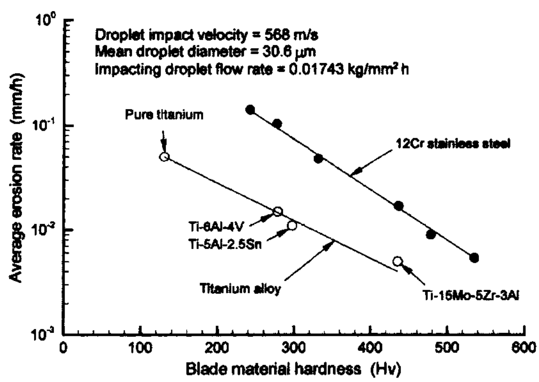

Fig. 5 Effect of target material hardness on erosion rate

Table 2 Summary of calibration results

Blade materials	Erosion const., k (mm/h)	Flow Rate, m_{ref} (kg/mm^2-h)	Impact vel.		Droplet dia.		Hard-ness
			V_{ref} (m/s)	α	d_{ref} (μm)	β	γ
12Cr stainless st.	2.0746	.01743	568	5.1	30.6	2.0	−0.0048
Stellite	0.1704					4.5	−0.0036
Ti-6Al-4V	0.1469					2.0	
Ti-15Mo-5Zr-3Al						4.5	

Table 3 Summary of erosion parameters

	Value*	Assumptions
m	0.00385	
V	255	Absolute droplet velocity=0.48×(absolute steam velocity)
d	not given	
Hv	421	
E	0.0000613	Erosion rate of DIN X20Cr13=14×(erosion rate of stellite)

* : The dimensions of erosion parameters are the same as defined in Table 1.

It should be mentioned that the impacting droplet flow rate is used instead of the number of impacting droplets because of lack of experimental data. In addition, the number of Vickers hardness is used directly. Therefore, reference hardness to make dimensionless term is not needed. The calibration results for the new model are summarised in Table 2.

6. Validation of a New Erosion Model

Stanisa and Ivusic (1995) investigated water droplet erosion process and measured erosion damage of the last stage rotor blades operated in practical steam turbine for more than 90,000 hours. They described detailed operating conditions of the turbine in terms of water droplet erosion. Each erosion parameter was determined using the operating conditions and summarized briefly in Table 3.

The droplet size could not be determined from operating conditions given by Stanisa and Ivusic (1995). Therefore, the erosion rate was calculated with four different droplet sizes selected under the base of experimental results performed by Tsubouchi et al. (1990). The erosion rates calculated using the new model developed in the present study are described in Table 4.

Table 4 Calculated erosion rates

d (μm)	E (mm/h)
30.6	0.0000193
35.0	0.0000353
40.0	0.0000644
45.0	0.0001095

It can be seen from Table 4 that the predicted erosion rates are smaller than the measured one by Stanisa and Ivusic (1995) as shown in Table 3 if the mean droplet diameters are less than 40 microns. On the other hand, the predicted one is very close to measured one if the mean droplet diameter is 40 microns. According to the experimental data obtained by Tsubouchi et al. (1990), however, the mean diameter of the impacting droplets is smaller than 40 microns. The possibility of the under-prediction, when the fact that the mean droplet diameters are smaller than 40 microns is definitely true, may be explained by the fact that the number of water droplets is greater at the tip section than at the root section of blade because of two reasons : 1) The water films formed on the surface of rotor blade of penultimate stage (L-1) are moved to radial direction and torn off at the tip of the blade. However, this is only true when the rotor blades of penultimate stage are operated in the wet steam conditions. 2) Basically, water droplets towards tip section before those come into rotor blade by the centrifugal force because the steam flow is vortex flow. Therefore, the concentration of water droplets is denser at the tip than mean value. In conclusion, it is desirable that the concentration of droplet along the radial direction at the inlet plane of the last stage rotor blade should be taken into account in the prediction of water droplet erosion.

7. Conclusion

A new erosion model was developed for the prediction of water droplet erosion of rotor blades operated in wet steam conditions in the present study. The model has been successfully used to predict the water droplet erosion of the last stage rotor blades operated in practical steam turbine. From the present study, the following conclusions can be drawn :

(1) Impact velocity, droplet size, impacting droplet flow rate, and hardness of target material are the most important parameters in rotor blade erosion caused by the impact of water droplets.

(2) Impact angle is not important in water droplet erosion. However, it influences the erosion before craters are formed on the target surface.

(3) It is desirable that the concentration of droplet along the radial direction at the inlet plane of the last stage rotor blade should be taken into account for more accurate prediction of water droplet erosion.

(4) The erosion model developed 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 the commercially operated rotor blades operated in wet region.

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