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Research Paper

Optimization design of separators for removing solid particles from main steam pipeline of high-parameter steam turbine

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HIGHLIGHTS

- Particle rebound models were developed using high temperature test results.
- η_p of 100 μm particle can reach up to 78% under a small amount of transferring steam.
- Q_s equals to 0.25% is recognized as the optimum separation point.
- Particle trap B with annulus inlet is the optimal one considering η_p and ΔP.
- Effect of particle trap on the heat rate of thermal system is less than 0.15%.

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ABSTRACT

In this paper, particle separators with different structures are designed based on main steam pipe of an ultra supercritical steam turbine. With the employment of particle rebound model established through high temperature particle rebound experiment, systematic numerical simulations on the influence of particle trap structure, steam mass flow for transporting particles on separation performance and pressure loss characteristic of separation system are carefully conducted. Besides, the effect of particle separation system on the working performance of thermal system is also analyzed. Results show that particle separation efficiency of three traps increases with the increase of amount of steam for transferring particles first, which then stabilize after a certain value is reached, while pressure loss of particle separation system is basically constant. With a small amount of transporting steam, separation efficiency of 100 μm particle in trap B can reach up to 78%, and pressure loss of the system is below 13 kPa. Effect of particle separation system on the heat rate of 1000 MW thermal system is less than 0.15%, which is well below the profits earned through the reduction of solid particle erosion to turbine blades. The result of this paper will provide new ideas for thoroughly solving erosion problem of high parameter steam turbine.
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1. Introduction

Solid particle erosion (SPE) of steam flow path remains an ongoing concern for the efficient and safe operation of units in coal-fired power plants. It is generally recognized that oxide particles exfoliate from the inner surface of boiler tubes and steam pipes under the dramatic changes of operation load. After entraining in the high pressure steam flow, oxide scales impact the surface of stop valves, control valves and turbine blades, resulting in regulation malfunction of valves, reduction of blade economic life and higher maintenance costs [1–3]. Khaimov et al. [4] pointed out that, the unit efficiency decreased by 0.35% under the rated load and decreased by 2.16% in the part load operation due to the oxide particle erosion. Through systematic numerical simulation on the performance deterioration of first stage nozzles, Wang et al. [5] indicated that the change of nozzle surface roughness would reduce the nozzle efficiency by 2%, while the change of nozzle profile would decrease the efficiency by 1.1%. Besides, under the combined action of centrifugal force and high temperature, some particles entering the turbine would accumulate and stack on the inner surface of blade shroud, as shown in Fig. 1(a). This will not only change the throughflow characteristics of units, but also threaten the balance of unit shaft, inducing to serious accidents. Therefore, reducing the effect of SPE on steam turbine blades has been the focus of interest for power institutes and companies around the world.

At present, there are mainly two ways to alleviate the erosion damage of steam turbine blades, namely the optimization of blade

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Nomenclature

A_f	windward area of spherical particles (m^2)
C_D	particle drag coefficient, defined by Eq. (6) (–)
Q_s	ratio of the amount of steam for transporting particles to the total amount of main steam (–)
Re_p	particle Reynolds number, defined by Eq. (7) (–)
T	surface temperature of target in the test (K)
V	particle impingement velocity (m/s)
V'	slip velocity between the particle and the fluid velocity (m/s)
V_{N1}	normal incidence velocity (m/s)
V_{N2}	normal rebound velocity (m/s)
V_{T1}	tangential incidence velocity (m/s)
V_{T2}	tangential rebound velocity (m/s)
d_p	particle diameter (μm)
e_N	normal velocity restitution coefficients (–)
e_T	tangential velocity restitution coefficients (–)

Greek symbols

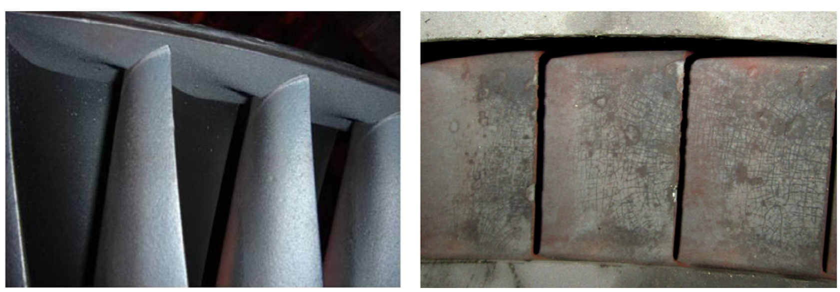
β	particle incidence angle (°)
Δ	equivalent sand diameter (μm)
ΔP	pressure loss of particle separation system (μm)
ρ_f	gas density (kg/m^3)
ρ_p	density of particles (kg/m^3)
φ	defined as $\varphi = A/S$, particle shape factor (–)
η_p	separation efficiency (–)

Subscripts

p	particle phase
N	normal direction
T	tangential direction

Abbreviations

SPE	solid particle erosion
CFD	computational fluid dynamics
PIV	particle velocity imaging
CCD	charge coupled device
HP	high pressure cylinder
HPH	high pressure heater



(a) Deposition in the inner wall of rotor shroud

(b) Erosion of coating on nozzle suction surface

Fig. 1. Solid particle erosion and deposition morphology in steam turbine cascade. (a) Deposition in the inner wall of rotor shroud (b) erosion of coating on nozzle suction surface.

profile and hard coating technology. In 1990s, in order to reduce the serious erosion of steam turbine blades, new SPE-resistant nozzles are designed and employed in power companies around the world, which eased the severe erosion situation to some extent [6]. In recent years, with the development of computational fluid dynamics (CFD) technology, Mazur Z et al. [7] pointed out that a step on the pressure surface near nozzle trailing edge could reduce the erosion rate by 50%. Based on systematic numerical simulations, Dai et al. [8] and Wang et al. [9] believed that, nozzles with end-wall contouring could effectively reduce the local erosion rate and erosion area by 40% and 30%, respectively.

In the application of hard coatings, many experimental studies had been carried out in the lab. Based on extensive experiment studies at high temperature, Tabakoff et al. found super D-GUN coating with high hardness and dense structure demonstrated stronger erosion resistance than plasma deposit coating [10,11]. Test results from Linsey et al. [12] showed that erosion rate of Cr_3C_2-NiCr coating was only 1/10 that of 422 stainless steel, while Qureshi et al. [13], Mann [14] and Cai et al. [15] all considered that thermal diffusion coatings with dense structure, such as boride coating, were more recommended. However, due do coating defects and the variation of oxide particle properties and impingement parameters, hard coatings often presented limited anti-erosion performance in engineering application. Fig. 1(b) showed serious erosion of boride coating on nozzle suction surface, which was just put into use for one and a half years after retrofitting [16]. Therefore, the current study does not resolve the SPE problem of turbine blade fundamentally.

Careful analysis shows that, if oxide particles greater than 150 μm can be separated from main steam, with the employment of blade profile optimization and hard coating technology, efficient service life of turbine blade will be significantly extended.

Among the current researches, only a few studies focus on the particle separating technology in steam turbine units. Ronald [17] designed a particle separator in the steam pipe using centrifugal separation principle, but the application effect has also not been reported. In literature [18], hydraulic losses and separating efficiency of three different particle separators were compared, which indicated that pocket trap structure is the optimal one. It is obviously that the installment of particle separator on steam pipeline will inevitably produce pressure loss to main or reheat steam. Therefore, trying to purify steam before entering turbine and minimize the effect of particle separator on the economy of units simultaneously should be the development direction of particulate separation technology. This is of great significance for solving SPE of high-parameter steam turbine blade at the source.

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