ARTICLE IN PRESS

Energy xxx (2015) 1–12

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

The influence of nozzle chamber structure and partial-arc admission on the erosion characteristics of solid particles in the control stage of a supercritical steam turbine

Liu-xi Cai [a], Shun-sen Wang [a], Jing-ru Mao [b, *], Juan Di [a], Zhen-ping Feng [a]

[a] Institute of Turbomachinery, Xi'an Jiaotong University, Xi'an 710049, PR China
[b] State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China

ARTICLE INFO

Article history:
Received 30 September 2014
Received in revised form
11 January 2015
Accepted 14 January 2015
Available online xxx

Keywords:
Supercritical steam turbine
Solid particle erosion
Numerical simulation
Nozzle chamber
Partial-arc admission
Erosion weight-loss

ABSTRACT

Reducing solid particle erosion of blades is one of the most urgent problems for supercritical steam turbine power generation technology. Based on the erosion rate models and the particle rebound models of blade materials obtained through accelerated erosion test under high temperature, systematic numerical simulations of the complex steam-particle flow in high pressure inlet flow channel and governing stage cascade of a supercritical steam turbine with four control valves was performed in this paper. The influence the typical nozzle chamber structure and partial-arc admission on the erosion characteristics of control stage blades was first investigated. Results show that erosion condition of nozzles in the same nozzle segment vary greatly along circumferential direction, while erosion damage to the leading edge of different circumferential rotating blades is uniform. Compared with four-valve opening condition, erosion weight-loss of the whole nozzle segment increases by 14% and 25% under three-valve opening condition and two-valve opening condition, respectively. Besides, under the partial-arc admission conditions, some large particles coming from the steam admission nozzle segment will collide back and forth between vanes and rotating blades in the downstream nozzle segment without steam admission, thus causing certain erosion to the trailing edge of nozzle suction side.

1. Introduction

SPE (solid particle erosion) problems of steam turbine components, such as nozzles and the rotor blades, especially in the governing stage, have been a problem of concern to power company for many years. It is generally agreed that erosion damage is caused by the high hardness iron oxide particles exfoliated from the inner wall of the boiler and steam pipeline. These particles entrained in the high pressure steam flow, causing serious erosion to steam path and turbine components. As described in publication [1], erosion of blades results in lower efficiency of steam turbine, shorter repair cycle and higher maintenance costs. In literature [2], systematic numerical simulations had been carried out to investigate SPE on the performance of first stage nozzles, which 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%. Based on the field investigation in a power plant, Khaimov et al. [3] pointed out that, the unit efficiency decreased by 0.35% under the rated load and decreased by as much as 2.16% in the part load operation due to the oxide particle erosion. With the development of ultra-supercritical technology, although the heat rate of units and the cost of electricity decreased in some extent based on the thermodynamic analysis and design optimization of an ultra-supercritical steam turbine in literature [4], the economic advantage would be heavily discounted by SPE. Therefore, reducing SPE of control stage blades to maintain the efficiency and security operation of units has been one of the key issues for experts and scholars around the world. Hamed et al. [5] observed that particles would directly impacted stator PS (pressure surface) when entering the cascade passage, and the erosion conditions become worsen along the flow direction. With numerical simulation method, Campos-Amezcua et al. [6] found that the erosion rate increased with the increase of solid particle flow, and deceased with the increase of particle size. According to Mazur Z et al. [7], a step on the PS near nozzle trailing edge could change the particle impact angle and impact position, and results in 50% reduction of nozzle erosion rate.

* Corresponding author. Tel.: +86 29 82667808; fax: +86 29 82668704.
E-mail address: jrmao@mail.xjtu.edu.cn (J.-r. Mao).

http://dx.doi.org/10.1016/j.energy.2015.01.044
0360-5442/

Li YF et al. [8] stated that the erosion rate of nozzle is sensitive to fluctuations in the flow field, and not entirely dependent on the solid particle size. Literature [9] systematically discussed the effect of the oxide particle size on the erosion of control stage nozzles, and considered that small particles would impact the trailing edge of nozzle PS with high impingement velocity and small angle, while particles with large size would rebound back and forth in the nozzle passage, which caused great destruction to the coating of SS (suction surface). Besides, Dai LP et al. [10] who had performed systematic numerical simulations to the anti-erosion performance of control stage nozzles with different geometry profile believed that nozzles with end-wall contouring could effectively reduce the local erosion rate and erosion area by 40% and 30%, respectively. With the employment of experimental and numerical simulations, Wang SS et al. [11] pointed out that the weight-loss of nozzle could be reduced by 50% and nozzle efficiency was improved by 0.4%~0.5% by improving the end-wall contouring of nozzle. What's more, based on the systematic research on SPE, Wang et al. [12] further proposed that the impact intensity of particles on nozzle trailing edge could be reduced through the optimization of nozzle profile and cascade structure characteristic parameter G, where $G = (B_2 - t)/B$(B_2 is circumferential width of blade, t is the pitch of cascade and B is the axial width of blade). Numerical simulation results about the full circle control stage nozzles in a subcritical steam turbine with six control valves in publication [13] revealed that particles were concentrated to erosion a small number of nozzles or the local area of one nozzle because of the upstream pipelines, which greatly accelerated the erosion damage of nozzle segment.

From the above works, it is can be seen that most of the above studies only performed numerical simulation to the erosion conditions of a single control stage nozzle passage. Although a annulus of control stage nozzles had been simulated in literature [13], the results could not fully reveal the real erosion conditions of governing stage blades in supercritical steam turbine because the control stage rotor blades were not considered. Fig. 1 shows the particle erosion morphology of control stage blades in a typical supercritical steam turbine with four control valves. It can be seen that erosion condition of nozzles in the same nozzle segment vary greatly along the circumferential direction (the length of erosion notches in some nozzle cascades has amounted to 20% of the chord length, yet some nozzle cascades still remained intact), but erosion condition of the corresponding rotor blades in different circumferential location is very similar, which is rarely mentioned in the present studies. Moreover, as more supercritical units are used to undertake peak regulation task, it is unavoidable that these units will operate under different load conditions alternately. Therefore, it is particularly necessary to explore the motion behavior of oxide particles in control stage cascade under partial-arc admission conditions.

In this paper, systematic high temperature erosion tests about the supercritical steam turbine blade materials are conducted based on the high temperature high speed accelerated erosion test rig, the erosion rate models and particle rebound models of blade materials under the simulated operating conditions of the steam turbine in power plant are then established. With the employment of these models, comprehensive numerical simulation on the gas-particle flow in the high pressure nozzle chamber and control stage cascade of a supercritical steam turbine with four control valves is performed in this paper using three-dimensional numerical simulation method. The influence of this typical nozzle chamber structure and partial-arc admission on the erosion characteristics of control stage blades is detailedly investigated. The research results in this paper reveal and perfect the blade erosion mechanism of oxide particle in steam turbine governing stage, providing a theoretical basis for preventing and reducing SPE of control stage cascade.

2. High temperature high speed accelerated erosion tests

2.1. Introduction of high temperature high speed accelerated erosion test system

Fig. 2 shows the high temperature and high speed accelerated erosion test system, which can be used to model material erosion behavior under a wide range of conditions: test temperature 20 °C–700 °C, particle impingement angles 12°~90°, particle impingement velocity 0–420 m/s. The test system consists of three parts: particle feeding system, high temperature gas system and erosion testing system. The basic working principle of the facility is stated as follows. First, the compressed air with the flow mass of 10 Nm^3/min is heated in the combustor producing the required high-temperature gas. Then, the high-temperature gas flow is divided into two pipelines. Gases in one pipeline directly flow into the test chamber to heat the specimen and establish the high temperature erosion environment. Gases in the other pipeline enter the pneumatic nozzle for accelerating solid particles. Solid particles from the screw feeder are carried directly into the acceleration nozzle throat by the secondary air. After the acceleration by high temperature flue gas, a uniform gas–solid mixture meeting the test requirements of temperature and velocity is produced in the nozzle and followed by impinging the test target at an incidence angle β in the test chamber. Erosion rate of the target can be obtained by measuring the cumulative mass of the particle involved in the erosion and the target mass before and after the erosion.

(a) (b)

Fig. 1. Erosion morphology of control stage blades in a supercritical steam turbine: (a) Erosion of control stage nozzle; (b) Erosion of control stage rotating blades.

Please cite this article in press as: Cai L-x, et al., The influence of nozzle chamber structure and partial-arc admission on the erosion characteristics of solid particles in the control stage of a supercritical steam turbine, Energy (2015), http://dx.doi.org/10.1016/j.energy.2015.01.044