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Gas-particle flows and erosion characteristic of large capacity dry top gas pressure recovery turbine

Liuxi Cai [a, *], Junfeng Xiao [a], Shunsen Wang [b], Song Gao [a], Jingyao Duan [a], Jingru Mao [b]

[a] Xi'an Thermal Power Research Institute Co. Ltd., Xi'an, 710054, PR China
[b] Institute of Turbomachinery, Xi'an Jiaotong University, Xi'an, 710049, PR China

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ABSTRACT

Based on the erosion rate model and the particle rebound model of blade material obtained through accelerated erosion test under high temperature, systematic numerical simulations of the complex gas-particle flows in inlet volute and cascade of a large capacity gas pressure recovery turbine are performed in this paper. The influence of inlet volute structure and cascade channel structure on the aerodynamic performance and erosion characteristics of turbine is first investigated. Results show that although mixing flows and vortex flows are formed in turbine intake volute, total pressure loss of volute is less than 0.7% because of low gas velocity. Erosion damage on the trailing edge of nozzles and rotating blades is mainly caused by high-speed cutting behavior of ash particles. The typical inlet volute structure results in an uneven erosion of first stage nozzles along circumferential direction. Nozzles located below the horizontal split are mainly eroded in blade root area, while erosion distribution of nozzles located above the horizontal split is irregular, and worse than the erosion degree of the lower half circle. Flow acceleration characteristics and cascade circumferential structure must be comprehensively considered so as to simultaneously improve the aerodynamic and anti-erosion performance of turbine.

1. Introduction

Top gas pressure Recovery Turbine (TRT) unit is internationally recognized as the most valuable secondary energy recovery equipment for steel companies [1,2]. With the employment of TRT, pressure energy and thermal energy of top gas can be converted into mechanical energy to drive the generator producing electricity, which can recycle about 30% of the energy consumed by blast furnace [3]. This kind of power generation process neither consumes any fuel, nor produces environmental pollution. In addition to the environmental and economic benefits, TRT has a very significant role for stabilizing blast furnace pressure.

However, due to bad working conditions, some problems inevitably occur in TRT units. Although dust filtration has been applied to top gas before entering turbine, dust loading of the top gas in the inlet of TRT is still much higher than conventional units, resulting in erosion and corrosion of turbine passage components. It is especially severe in the high-power dry TRT. This is because of the greater impact energy of fly ash particles caused by the higher gas temperature and pressure.

According to literature [4–6], notches were formed in blades and flow channel shape was changed in large amount of dry TRT after the operation of one to three years, resulting in performance degradation of units. In addition, the direct high intensity impingement of particles also causes stress concentration in local region, which not only reduces blade fatigue life, but also leads to frequent accidents of TRT blade fracture [7]. It is estimated that an overhaul of TRT units cost about 0.5 million dollars, and the maintenance cycle requires at least three months [8]. Obviously, erosion from fly ash particles has seriously affected the safe operation of TRT units. Therefore, reducing erosion damage of blades has been one of the key issues to maintain the efficiency and security operation of TRT, which is of great significance for energy efficient recycling.

At present, the most common method to alleviate erosion damage of TRT blades is hard coating technology, which extends the service life of units to some extent. Based on the erosion test of high velocity oxygen fuel (HVOF) coating, arc spraying coating and physical vapor deposition (PVD) coating, Dong et al. [8] found that HVOF coating of Co-87WC with surface hardness of 895HVexhibited the best anti-erosion performance, while PVD TiN coating was

* Corresponding author.
E-mail address: cailiuxi@tpri.com.cn (L. Cai).

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unsuitable for TRT working environment. With the employment of plasma spraying technology, Co-Cr coating with the thickness of 400 μm and surface hardness of about 902HV was obtained by Xia et al. [9], which showed good anti-erosion performance after more than one year operation.

In addition, for broken blades with initial notch or other damage, laser cladding technology can be used to repair blades so as to reduce the effect of blade erosion on the safe and economic operation of units. With this repair technology, surface hardness of TRT blades increased from 165HB to 190HB, anti-erosion performance of blades was significantly enhanced [10]. Similar study was conducted by Deng et al. [11], which indicated the service life of the repaired blade is lengthened.

With the development of computational fluid dynamics (CFD), numerical simulation techniques are employed to optimize the design of intake structure and TRT cascade channel structure. Based on three-dimensional numerical simulations of the overall performance and flow field details of a two stage TRT, Liu et al. [12] increased the turbine aerodynamic efficiency by 2% through modified design. Numerical simulation on TRT with different inlet volute structure by Xue et al. [13] showed that, direction of gas flow into blade passage would affect turbine performance, but the effect was limited within a certain range. Yuan et al. [14]performed optimization design on TRT turbine inlet volute using CFD methods, which significantly improved the overall performance of TRT. However, few researches pay attention to the gas-solid flow characteristics and particle erosion behavior in TRT cascade, resulting in frequent occurrence of particle erosion damage and the consequent blade fracture.

In view of the above stubborn ills in TRT, a large power TRT is chosen as the research target. Based on the erosion model and particle rebound model established through high temperature accelerated erosion test, systematic numerical simulations on the complex gas-particle flows in intake volute and TRT cascade are conducted in this paper. The influence of inlet volute structure and cascade channel structure on the erosion characteristic of TRT blade is first investigated. Results of this study will provide a technical basis for preventing and alleviating erosion in TRT.

2. Geometric model and numerical approach

2.1. Geometric model

Fig. 1 shows the intake volute and cascade channel of the large TRT calculated in this paper. Design flow rate of the turbine is 695,600 Nm^3/h, other design parameters are shown in Table 1. After dust removing, top gas with certain thermal and pressure energy flows into volute and turbine cascade, driving the turbine to generate electricity. When the process is finished, exhaust gas discharges into low-pressure pipe network. Two-stage cascade with efficiently twisted blade profile are designed in this turbine. Mounting angle of the first stator can be adjusted to meet the change of TRT flow rate and pressure ratio. The number of blade passage for the first stage stator (*S1*), first stage rotor (*R1*), second stage stator (*S2*) and second stage rotor (*R2*) is 20, 23, 30, and 23 respectively. The axial clearance between *S1*and *R1*, *R1* and *S2*, *S2* and *R2* is 290 mm, 305 mm, and 290 mm respectively. The total length of this turbine, including the intake volute and exhaust volute, is 4050 mm, and the maximum height is about 4200 mm. The inlet dimension of the intake volute is 2000 mm × 1170 mm. The hub radius of turbine blade is about 560 mm, while the shroud radius increases from 770 mm to 910 mm along the streamwise direction.

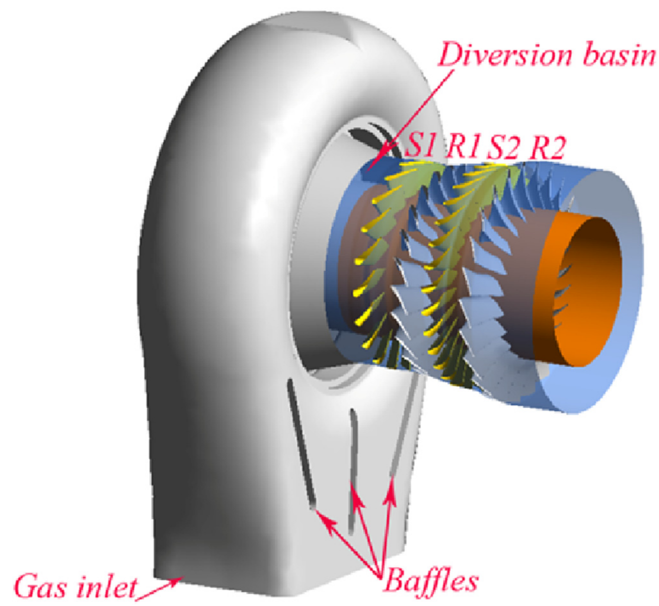

Fig. 1. Intake volute and cascade channel structure of TRT.

Table 1
Design parameters of TRT.

Parameters	Symbols	Designed value
Inlet volume flow rate	Q_v	695,600 Nm^3/h
local atmospheric pressure	P_a	101 kPa
Inlet pressure	P_0	390 kPa
Inlet temperature	T_0	130 °C
Outlet pressure	P_1	12 kPa
Rotate speed	N	3000r/min

2.2. Numerical approach

In this study, the following time-averaged continuity equation, Navier–Stokes (N–S) equation, and energy equation are solved by using a fully implicit discretization of the equations and a coupled solver to simulate the three-dimensional steady compressible viscous flow in turbine cascade.

$$\frac{\partial(\rho u_j)}{\partial x_j} = 0$$

$$\frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\mu+\mu_t)\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right] - \frac{2}{3}\frac{\partial}{\partial x_i}\left[(\mu+\mu_t)\left(\frac{\partial u_j}{\partial x_j}\right)\right] \tag{1}$$

$$\frac{\partial(\rho u_j h)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\lambda_{eff}\frac{\partial T}{\partial x_j}\right) + \frac{\partial}{\partial x_j}(u_j\tau_{ij}) + S_E$$

Where h is the fluid total enthalpy, λ_{eff} is the effective fluid heat transfer coefficient. $\partial(u_j\tau_{ij})/\partial x_j$ represents the part of energy conversion from mechanical energy to heat due to the effect of viscosity, which is called dissipation function. S_E is the inner heat source of fluid. Because of the better performance in the simulation of flow with high strain rates, swirl, and separation, therefore, in this article, the renormalization group (RNG) k-ε turbulent model is selected to estimate the turbulence viscosity μ_t in N-S equation. For