Numerical Analysis of the Strength of the Wet Steam Turbine Blade

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Abstract. A method to examine the influences of inlet wetness fraction and inlet angle on the strength performance of the rotating blade considering the effects of wet steam non-equilibrium condensation was proposed. A widely verified numerical model was employed to simulate the wet steam flow to obtain the pressure distribution on the blade surface. Based on the finite element method, the strength analysis was carried out. Results show that the von-Mises stress of the rotor blade would increase with the inlet wetness fraction and the inlet angle. The sensitive range of studied inlet condition is located at $A_{in} \in [0, 15]$, $W_{in} \in [0.03, 0.04]$, in which the increases of the von-Mises stress are over 40%.

1 Introduction

Excessive stress may shorten the effective life of the rotating blades and threaten the safety of turbo-machinery. Especially for the turbine operating on wet steam, such as nuclear turbines and the last stage of low pressure gas turbines, in which the non-equilibrium condensation (NEC) process of the wet steam may greatly enhance the extent of flow non-uniformity to generate more intense fluid excitation and induce higher stress of the rotating blade. Hence, it is of great practical interest in the design of wet steam turbines to predict the strength performance of the rotating blades considering the effects of the NEC.

Currently, research on the fluid excitation generate from the NEC of wet steam is still insufficient. Generally, the condensation of wet steam is regarded as an equilibrium process, either or the condensation is ignored and the wet steam is simplified as an ideal gas. After above simplifications, the vortex shedding from the upstream blade is regarded as the major fluid excitation, i.e. the wake excitation. A lot of studies about the wake excitation and its induced vibration have been carried out, to name a few, Lau [1] used the Karman vortex street (KVS) to model the wake excitation and analyzed the vortex-induced vibrations of a 2D airfoil. García [2] numerically calculated the wake excitation acting on the rotor blade of the last stage of 110MW steam turbine. However, the strength performance of the rotating blade considering the effects of NEC hasn't been well clarified due to the difficulty in calculating NEC-induced excitation.

In this paper, the effects of wet steam NEC on the strength performance of the rotating blade are numerically studied. In which the NEC-induced excitation (pressure distribution on the blade surface

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during NEC process) can be obtained from the numerical simulation of the wet steam flow field based on the non-isothermal nucleation theory and the droplet growth model [3-5] that implemented in ANSYS CFX. Once the NEC-induced excitation is obtained, the strength performance of the rotating blade can then be analyzed use the finite element method (FEM) through the strength calculation under the pressure load with commercial software ANSYS Workbench. Besides, the influences of the wet steam inlet conditions (intake angle and wetness fraction) are analyzed.

2 Wet steam model

The effects of NEC on the strength performance of the rotating blade are determined through the pressure distribution on the blade surface during NEC process. To obtain the pressure distribution, a NEC model of wet steam is necessary. The wet steam is a mixture of two-phases, in which the primary phase is the gaseous-phase consisting of water-vapor (denoted by the subscript v), the secondary phase is the liquid-phase consisting of condensed-water droplets (denoted by the subscript l).

The numerical calculations can be carried out based on a compressible Navier-Stokes equations using Eulerian–Eulerian approach to govern the condensing flow. The equations are given by [6]

$$\frac{\partial}{\partial t} \begin{pmatrix} \rho \\ \rho V_i \\ \rho H \end{pmatrix} + \frac{\partial}{\partial x_i} \begin{pmatrix} \rho V_i \\ \rho V_i V_j + p - \mu_i \frac{\partial V_i}{\partial x_j} \\ \rho H + p - \lambda_i \frac{\partial T_v}{\partial x_j} \end{pmatrix} = 0 \quad (1)$$

$$\frac{\partial \rho W}{\partial t} + \nabla \cdot (\rho \vec{V} W) = \Gamma \quad (2)$$

$$\frac{\partial \rho \varepsilon}{\partial t} + \nabla \cdot (\rho \vec{V} \varepsilon) = \rho I \quad (3)$$

in which, V is the flow velocity. Subscript i and j denote the tensor notation. ρ and H are the density and the entropy values of the mixture phase. W and ε are the wetness fraction and the number of droplets per unit volume. Γ and I are the liquid mass generation rate and the nucleation rate respectively. The NEC model is applied to describe the wet steam properties based on the nucleation theory and the droplet growth model. The nucleation rate I and the non-isothermal correction factor θ are used to calculate the droplet formation.

$$I = \frac{q_c}{(1+\theta)} \left(\frac{\rho_v^2}{\rho_l} \right) \sqrt{\frac{2\sigma}{M_m^3 \pi}} \exp \left(-\frac{4\pi r_*^2 \sigma}{3K_b T} \right) \quad (4)$$

$$\theta = 2 \frac{(\gamma-1)}{(\gamma+1)} \left(\frac{h_{lv}}{RT} \right) \left(\frac{h_{lv}}{RT} - 0.5 \right) \quad (5)$$

where q_c is the evaporation coefficient, k_b is the Boltzmann constant, M_m is the mass of one molecule, σ is the liquid surface tension, ρ_l is the liquid density, h_{lv} is the specific enthalpy of evaporation at pressure p and γ is the ratio of specific heat capacities. The droplet growth is modelled as given by

$$\Gamma = \frac{4}{3} \pi \rho_l I r_*^3 + 4 \pi \rho_l \varepsilon \bar{r}^2 \frac{\partial \bar{r}}{\partial t} \quad (6)$$

$$\frac{\partial \bar{r}}{\partial t} = \frac{p}{h_{lv} \rho_l \sqrt{2\pi RT}} \frac{\gamma+1}{2\gamma} C_p (T_l - T_v) \quad (7)$$

where r^* is the Kelvin-Helmholtz critical droplet radius.

Besides, the steam properties are based on the IAPWS standard. The NEC model is coupled with $k-\omega$ shear stress transport (SST) turbulence model, which is suitable for the turbo-machinery applications. The above models have been wildly validated against the experimental data from the nozzle flows [7] and the cascade flows [8] as well as the turbine flows [9].

3 Results and discussion

The last stage rotor blades of a wet steam turbine run at 1500rpm are taken for the investigated case. In which the calculation domain can be minimized as one blade passage using periodic boundary condition. In order to improve the calculation accuracy, the H-O-H structured grids are used as shown in Figure 1. ANSYS CFX is employed to solve the Reynolds-averaged Navier-Stokes equations and the $k-\omega$ SST turbulence model. The boundary conditions are given in table 1. The rotor blade is meshed use element soild185 in ANSYS Workbench. The material and geometric properties of the blade are given in table 2.

Figure 1. Calculation domain using periodic boundary condition

Table 1. Boundary conditions

Inlet total pressure	Inlet total temperature	Pressure ratio
39.597 kPa	300 K	1.71

Table 2. Material and geometric properties of the blade

Elasticity modulus	Density	Poisson's ratio	Length
198 GPa	7750 kg/m ³	0.3	1200 mm

The pressure distribution and its induced stress of the rotating blade at different intake angles (A_{in} =0°, 15°, 30°) and wetness fractions (W_{in} = 0.03, 0.04, 0.05) are simulated and calculated in ANSYS CFX and ANSYS Workbench respectively, as shown in Figures 2-5.

Figure 2 shows the pressure distribution on 50% blade span at different wetness fractions when the inlet angle is 0°. It can be found that the maximum of pressure is slightly increased with the wetness fractions. As a result, the maximum of von-Mises stress of the rotating blade is increased with the wetness fractions, as shown in Figure 3. Note that when the wetness fraction increased from 0.03 to

0.04, the von-Mises increased by 40.25%, while when the wetness fraction increases from 0.04 to 0.05, the von-Mises only increase by 0.54%.

Figure 2. Comparison of the pressure distribution on the 50% blade span of three different wetness fractions.

Figure 3. Comparison of the von-Mises stress on the surface of blade of three different wetness fractions.

Figure 4 shows the pressure distribution on 50% blade span at different inlet angles when the wetness fraction is 0.03. It can be found that the maximum of pressure is increased with the inlet angle. As a result, the maximum of von-Mises stress of the rotating blade is increased with the inlet angle, as shown in Figure 5. Note that when the inlet angle increased from 0° to 15°, the von-Mises increased by 41.61%, while when the wetness fraction increases from 0.04 to 0.05, the von-Mises only increase by 0.36%.

Figure 4. Comparison of the pressure distribution on the 50% blade span of three different inlet angles.

Figure 5. Comparison of the von-Mises stress on the surface of blade of three different inlet angles.

The above results show that the higher inlet wetness fraction and/or bigger inlet angle would induce lager von-Mises stress of the blade. The maximum stress points are located in the trailing edge of the blade root, where should be to pay attention in the design.

4 Conclusions

This paper proposes a method to examine the influences of inlet wetness fraction and inlet angle on the strength performance of the rotating blade considering the effects of wet steam NEC. A wildly verified NEC model was employed to numerically simulate the wet steam flow with ANSYS CFX to obtain the pressure distribution on the blade surface. Applying the NEC-induced excitation, the strength analysis was carried out with ANSYS Workbench. Several conclusions were drawn as follows:

- (1) Considering the effects of wet steam NEC, the von-Mises stress of the rotor blade would increase with inlet wetness fraction and let angle.
- (2) The sensitive range of studied inlet condition is located at $A_{in} \in [0, 15]$, $W_{in} \in [0.03, 0.04]$, in which the increases of von-Mises stress are over 40%. It could be inferred that the stress of blade working in wet steam might be reduced by adjusting the inlet conditions.
- (3) The presented method to calculate fluid excitation generated from wet steam NEC and its resulting stress of the blade could be extended into the design and analysis of wet steam turbines to meet the needs of engineering.

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Nomenclature

A	Inlet angle,	r^*	Kelvin-Helmholtz critical droplet radius, m
C_p	specific heat, J/(kg K)	S	super saturation ratio = $p/p_{sat}(T)$
H	total enthalpy of mixture phase, J/kg	T	temperature of mixture phase, K
h_{lv}	specific enthalpy of evaporation, J/kg	V	flow velocity, m/s
I	nucleation rate	W	wetness fraction
k_b	Boltzmann constant = 1.3807×10^{-23} , J/K	γ	vapor specific heat ratio
L	blade height, m	Γ	liquid mass generation rate
p	pressure, Pa	ε	number of droplets per unit volume =

$p_{sat}(T)$	equilibrium saturation pressure, Pa	θ	$\beta\rho_g/(1-\beta)V_d\rho_l$ non-isothermal correction factor
q_c	condensation coefficient	λ_t	effective thermal conductivity, W/(m K)
r	droplet radius, m	μ_t	effective dynamic viscosity, kg/(m s)
R	gas specific constant, J/(mol K)	ρ	density of mixture phase= $\rho_g/(1-\beta)$, kg/m ³
R_d	radius of shaft, m	σ	liquid surface tension, N/m

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