Effect of the nonaxisymmetric endwall on wet steam condensation flow in a stator cascade

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Abstract
Steam turbines are critical pieces of power equipment in the electric power industry, and the study of wet steam condensation flow is important for improving the efficiency and safety of steam turbines. Wet steam nucleation, which is the main reason for thermodynamic losses, usually occurs downstream of the stator cascade. The mechanism of secondary flow loss control by the nonaxisymmetric endwall is the change of pressure distribution in the cascade channel. This mechanism also affects the wet steam condensation phenomenon. The positive/cosine function was proposed for endwall modification in the nucleation stage of a steam turbine. The design method presented in this paper can be used to produce endwall protrusions with different heights at different axial chords. To analyze the influence of the endwall protrusion design parameters on the condensation flow, nine endwall protrusion models were set up at varied axial positions. In comparison with the original cascade, the total pressure loss coefficient and outlet wetness were found to be ideal when the endwall protrusion maximum height was located at the 50% axial chord length of the stator and the protrusion was 3% of the blade height. The ideal incidence angle of this modified cascade was from −2° to +10°.

KEYWORDS
condensation flow, nonaxisymmetric endwall, steam turbine, thermodynamics, wet steam

1 | INTRODUCTION

The mathematical theory of nucleation and water-droplet growth in nonequilibrium condensation flow was listed as one of the 100 most important scientific problems of the 21st century. In 2017, thermal power and nuclear power generation capacity accounted for approximately 77.43% of China’s power generation capacity. China’s power generation in the next few decades will continue to depend on steam turbines. The last few low-pressure cylinder stages of a condensing steam turbine in a traditional power plant and all stages of a water-cooled nuclear reactor steam turbine operate in the wet steam zone. Wet steam causes two major issues with a steam turbine: First, the thermodynamic losses and water droplets produced during the condensation process reduce the efficiency of the unit. Second, the droplet trajectories in the wet steam flow lead to water erosion in several stages at the end of the turbine. The main method of improving the efficiency of the steam cycle is to increase the steam parameters and reduce the back pressure. Spontaneous two-phase condensation flow in a steam turbine is highly complex; the study of such flow involves numerous disciplines of computational fluid dynamics, multiphase flow, heat and mass transfer, statistical thermodynamics and gas dynamics. Existing
research on wet steam condensation flow can be divided into four approaches: condensation theory, experimental research, numerical research, and analytical research. Condensation theory includes the nucleation model and the water-droplet growth model. However, the calculation of nonequilibrium condensation flow involves many uncertainties.

The complex flow in turbomachinery will cause various losses, among which the secondary flow loss cannot be ignored. A nonaxisymmetric endwall forms a depression near the suction surface and forms a bulge near the pressure surface. Thus, the local velocity and pressure distribution are changed and the secondary flow loss is suppressed. The convex streamline curvature can reduce the local static pressure and raise the flow velocity. Moreover, the concave streamline curvature can raise the local static pressure and reduce the flow velocity. Researchers at Durham University have previously studied the nonaxisymmetric endwall. Several achievements have been reported. In 1981, Kopper et al. studied the effect of the nonaxisymmetric endwall on secondary flow loss control. Various nonaxisymmetric endwall modelling methods have subsequently been proposed by Germain et al., Harvey et al., Hartland et al., Ingram et al. and Axtmann et al.; these methods were applied to turbine guide vanes. Through numerical simulation and a straight cascade blow test, a nonaxisymmetric endwall was found to have an inhibitory effect on the secondary flow loss. Logo revealed the mechanism by which the nonaxisymmetric endwall restrains secondary flow loss and concluded that the nonaxisymmetric endwall can reduce secondary flow loss by 70% and endwall loss by 20%. Germain et al. found that the nonaxisymmetric endwall can increase the stage efficiency by 1%. Ingram conducted similar studies and found that the nonaxisymmetric endwall can increase the efficiency of the high-pressure stage of an aircraft turbine by 0.4%. Li et al. reviewed the existing nonaxisymmetric endwall technology and proposed a new endwall modelling method. At present, asymmetric endwall technology has been applied in some high-performance gas turbines and compressors. The mechanism by which to improve the aerodynamic performance of the cascade is to control the pressure distribution by changing the curvature of the endwall surface. The pressure distribution in the low-pressure cylinder of the steam turbine has an important influence on the wet steam condensation flow. In this paper, we discuss the influence of the nonaxisymmetric endwall on the condensation flow characteristics in a stator cascade.

In recent years, scholars have proposed various nonaxisymmetric endwall modelling methods, including the medial camber line rotation method, the Fourier series method, the attenuation function method, the trigonometric function modelling method and the differential pressure modelling method. Despite the many developed modelling methods, existing commercial software does not include a nonaxisymmetric endwall modelling function. Here, to provide such a function, the following steps are applied. First, dense control points are generated by the program. Next, the control points are fitted with three dimensions to obtain the nonaxisymmetric endwall modelling. The circumferential curve in the attenuation function method is superimposed by the cosine function, and the space surface is formed by the attenuation function along the direction of the streamline. Because the trigonometric function has periodicity, symmetry, and infinite order derivability, the height and position of the nonaxisymmetric endwall modelling can be controlled. The surface of the endwall is smooth to ensure that it does not affect the flow of steam. In addition, the triangle function modelling method can quickly generate the space lattice, resulting in a shorter pre-processing time than the other methods. Moreover, the curved surface of various shapes can be chosen flexibly in the endwall modelling process. Therefore, in this paper, the triangle function modelling method is used to generate the nonaxisymmetric endwall. The position and height of the convex surface can be determined by the modelling formula.

**Highlights**

- A positive/cosine function for endwall protrusions design in nucleation stage.
- Influence of the endwall design parameters on the condensation flow.
- Ideal maximum height of endwall protrusion and its position were obtained.

## 2 | CALCULATION MODEL

The nucleation and growth processes of droplets both occur on the nanometric scale. The surface tension and heat and mass transfer of microdroplets have long been a difficult topic to investigate. The most widely used calculation models of wet steam condensate flow are the classical nucleation model and the Gyarmathy droplet growth model. The classical nucleation rate per unit volume is given as

$$J_{\text{CL}} = \frac{q_c}{\rho_l} \left( \frac{2\pi}{\rho \pi m^3} \right)^{1/2} \exp \left( -\frac{4\pi r_c^2 \sigma}{3kT_g} \right)$$

(1)

where $k$ is the Boltzmann constant; $q_c$ is the coefficient of condensation; $r_c$ is critical droplet radius, m; and $\sigma$ is the surface tension of a droplet, N/m. However, classical nucleation theory assumes that the temperatures of all water droplets are equivalent to the gas-phase temperatures. Kantrowitz nonisothermal nucleation model was selected for calculating the nucleation rate. The equation is as follows

$$J_{\text{NCL}} = \frac{J_{\text{CL}}}{1 + q_c \frac{\rho \pi m^3}{\sigma} \frac{RT_f}{2} \left( \frac{h_v}{RT_f} - \frac{1}{3} \right)}$$

(2)
where $\alpha$ is the heat-exchange coefficient for the surface of the molecular aggregations with critical radius, W/(m²•K); and $h_{fg}$ is the latent heat of vaporization, kJ/kg.

The nucleation time is brief. Therefore, when nucleation is completed, the water droplet will grow until reaching the outlet. The whole process of water droplet growth is accompanied by heat and mass transfer. Young developed a correction droplet growth model using the three-layer theoretical model proposed by Langmuir.\(^{27}\) The droplet growth model is as follows:

\[
\frac{dr}{dt} = \frac{\lambda_g \Delta T (1 - \frac{r}{r_c})}{\rho_d h_{fg} r \left[ \frac{1}{1 + 1.5 \delta_k} + 3.78 (1 - \delta) \frac{\lambda_k}{P_{fg}} \right]}
\]  

where $\lambda_g$ is the thermal conductivity of steam, W/(m•K); $\Delta$ is the degree of supercooling, K; $h_{fg}$ is the latent heat of condensation, kJ/kg; $P_{fg}$ is the Prandtl number; and $\delta$ is a semi-empirical correction coefficient.

\[
\delta = \frac{3.25 \Psi(P)}{q_c} \cdot \frac{1}{2 \cdot 2q_c} \cdot \Psi(P) = 3.25 \left[ 1 - \tanh \left( \frac{p}{10^4} - 2 \right) \right] \tag{4}
\]

where $\gamma$ is the specific heat capacity ratio of steam.

The mass condensation rate is calculated as follows:

\[
\dot{m} = 4 \pi \rho_i r_c^3 \dot{J}_{NCL} + 4 \pi \rho_i r_c^2 \rho_m N \frac{dr}{dt} \tag{6}
\]

The wetness calculation equation is as follows:

\[
Y = \frac{4}{3} \pi \rho_i r_c \rho_m N \tag{7}
\]

The continuity equation is as follows:

\[
\begin{align*}
\frac{\partial \rho_g}{\partial t} + \frac{\partial (\rho_g u_i)}{\partial x_j} &= -\frac{\partial p}{\partial x_i} + \frac{\partial T}{\partial x_i} + \Delta \rho g - F_D - \rho_m u_i \dot{m} \\
\frac{\partial \rho_d}{\partial t} + \frac{\partial (\rho_d u_i)}{\partial x_j} &= \rho_d \dot{S} + F_D + \rho_m \dot{m} (u_g - u_d) \tag{8}
\end{align*}
\]

where $\rho_d$ is the volume average density of liquid phase, $\rho_d = \rho_m Y$. The equation of the conservation of vapor in the two-fluid model is as follows:

\[
\begin{align*}
\frac{\partial (\rho_g u_i)}{\partial t} + \frac{\partial (\rho_g u_i u_j)}{\partial x_j} &= -\frac{\partial p}{\partial x_i} + \frac{\partial T}{\partial x_i} + \Delta \rho g - F_D - \rho_m u_i \dot{m} \\
\frac{\partial (\rho_d u_i)}{\partial t} + \frac{\partial (\rho_d u_i u_j)}{\partial x_j} &= \rho_d \dot{S} + F_D + \rho_m \dot{m} (u_g - u_d) \tag{9}
\end{align*}
\]

The energy equation is as follows:

\[
\begin{align*}
\frac{\partial (\rho_g u_i e)}{\partial t} + \frac{\partial (\rho_g u_i u_j e_j)}{\partial x_j} &= -\frac{\partial p}{\partial x_i} + \frac{\partial T}{\partial x_i} + \Delta \rho g - F_D - \rho_m \dot{m} (u_i - h_i) \\
\frac{\partial (\rho_d u_i e_d)}{\partial t} + \frac{\partial (\rho_d u_i u_j e_d_j)}{\partial x_j} &= \rho_d \dot{S} + F_D + \rho_m \dot{m} (u_g - u_d) \tag{10}
\end{align*}
\]

where $h_i$ is the steam enthalpy.

3 | CASCADE GEOMETRY AND SIMULATION SETUP

Among the relevant references regarding unbalanced condensing flow, the research results reported by Bakhtar and White are the most representative. White\(^{28}\) provided accurate test data for wet steam condensing flow that can be used to validate the numerical model in the present paper. For this cascade, the designed Mach number at the outlet is 1.2, the inlet...
flow angle is 0°, the designed outlet angle is 71°, the blade spacing is 87.59 mm, the blade chord length is 137.51 mm, and the blade installation angle is 45.32°. The inlet and outlet are pressure boundary conditions, and the passages are the periodic boundary conditions, as shown in Figure 1.

The ICEM software was used to compute the grid generation. The flow field of a single channel was calculated under different grid numbers: $1.62 \times 10^4$, $2.43 \times 10^4$, $3.21 \times 10^4$, and $4.84 \times 10^4$. When the grid number is greater than $3.21 \times 10^4$, the flow rate approaches a constant value. Thus, the grid number of $3.21 \times 10^4$ corresponds to grid independence. The inlet pressure was 40.9 kPa, the inlet temperature was 354 K, and the outlet pressure was 19.4 kPa. Figure 2 compares the calculated values and the test values of the blade surface pressure ratio. As shown in Figure 3, the results calculated in the present work are in good agreement with the reported experimental values. The deviation of the pressure surface mean between the calculated value and the test value is 1.20%. The deviation of the suction surface mean between the calculated value and the test value is 2.54%. These differences indicate that the model proposed in the present work is accurate.

In this work, the triangular function modelling method was used to design the nonaxisymmetric endwall shape. By adjusting the control functions of the $xy$ plane, the $yz$ plane, and the $xz$ plane, we varied the convex modelling. The control functions are as follows:

\begin{align}
xy plane: x(y) &= S_1 \cos(ay) \\
xy plane: y(z) &= S_2 \cos(bz) \\
yz plane: x(z) &= S_3 \cos^2(cz)
\end{align}

where $a$, $b$ and $c$ are the angular velocity of plane trigonometric control functions and $S_1$, $S_2$, and $S_3$ are the control parameters of amplitude of the trigonometric function. To solve the equation, along with the features of nonaxisymmetric endwall modelling, the following three definite solution conditions were added:

\begin{align}
a &= \frac{\pi}{2|S_2|} \\
S_3 &= S_1 \cos(ay) \\
c &= \frac{\pi b}{2|\arccos(y/S_2)|}
\end{align}

The nonaxisymmetric endwall modelling is shown in Figure 3. In the effective interval of the control function, the region was discretized in the $y$ direction and the $z$ direction, and a series of dense control lattice was calculated by the control function. The discrete dot matrix was imported into UG NX10.0 software to fit the surface. The original leaf-type data were taken from the nucleation stage of a 300 MW steam turbine. There are five stages in the low-pressure cylinder. The steam at the outlet of the fourth stage is still superheated because the blade surface heating technology is used. This stage consists of 60 stator cascades and 80 rotor cascades. In this paper, the stator cascade was used as the research object. The original cascade model was generated by the BladeGen software. Next, via rotation, translation and shearing, the fitting surface and prototype cascade model were sutured in the UG NX10.0 software. The geometric model of a stator cascade with a nonaxisymmetric endwall was obtained, as shown in Figure 4. Using the ANSYS ICEM software, we divided the whole cascade channel into structured hexagonal grids. The grids of the throat, front, tail, and nonaxisymmetric endwall were densified. The structured hexagonal grid could effectively realize boundary fitting. This approach has many advantages, including high calculation speed, high precision, and a simple data structure. The use of structured grids greatly reduces the calculation time and improves the accuracy of the calculation.

The “H" orthogonal grid was used for the inlet, outlet and tip clearance of the cascade channel. To ensure the quality of the calculation results, the thickness of the first layer mesh of the blade surface was on the order of $10^{-6} m$, which satisfies the requirements of the $k$-$\varepsilon$ model. As the other wall functions refine mesh in a normal direction along the wall, the numerical results deteriorate when $y+<15$. The scalable wall function method was applied to the near-wall flow area because $y+$ values are less than two for the first layer near the wall. The mesh expansion ratio in the boundary layer is 1.2. The maximum mesh aspect ratio in the boundary layer is 115. In this paper, ANSYS CFX software was employed to carry out numerical calculation of the aforementioned models. To eliminate the error caused by the grid factors, it is necessary to verify the grid independence. Computational grids with the same topology of $2.35 \times 10^5$, $4.36 \times 10^5$, $6.56 \times 10^5$ and $8.28 \times 10^5$ are
selected to verify the grid independence. We found that when the number of grids was greater than $4.36 \times 10^5$, the pressure of the blade surface changed little with an increasing number of grids. Because the number of grids of $4.36 \times 10^5$ satisfies the requirements of grid independence, $4.36 \times 10^5$ grids were used in the calculation in the present work.

According to the research target, the amplitude and phase of the modelling function were constantly changed and a series of asymmetric endwall models was generated. In this paper, the endwall structure was designed in two aspects: to change the height of the protrusion (3%, 5%, or 10% of blade height) and to change the location (30%, 50%, or 80% of the axial chord length of the stator) of the endwall protrusion maximum height. The overall axial length of this shape is 20% of the axial chord length of the stator. As a result, nine types of endwall protrusion models were developed; the naming convention is shown in Table 1. For convenience of discussion, the original cascade is named ORI. For different endwall models, the naming convention is based on the position and height. For example, the endwall protrusion maximum height at 3% blade height and located at 30% axial chord length is named AC30H03. By analysing the influences of these endwall moulding schemes on the parameters of wet steam condensation, we can obtain the best modelling scheme to achieve the objective of controlling the wet steam condensation flow. Through the study of these modeling schemes, we can get the control effect of nonaxisymmetric endwall on the parameters of cascade, and find out the best schemes, which makes the follow-up research go smoothly.

Combined with the homogeneous multiphase flow model and the water vapor nonequilibrium phase transition model, the finite volume method was used to solve the three-dimensional compressible steady-state Reynolds time-averaged N-S equation. The high-order upwind scheme was adopted for the convection term. The convergence rate of the numerical residuals was RMS $< 10^{-5}$. The IAPWS-IF97 “steam3vl” model was used to calculate the working fluid physical property parameters. The inlet pressure was 28.5 kPa, the inlet temperature was 346 K, and the average static pressure at the outlet was 17.9 kPa.

### CALCULATION RESULTS AND ANALYSIS

#### 4.1 The effects of height

Figure 5 shows the distribution of the surface pressure ratio of the ORI, AC50H03, AC50H05, and AC50H10 schemes at

| Naming convention of endwall protrusion moulding schemes |
|----------------------------------------------------------|
| 3% blade height | 5% blade height | 10% blade height |
|-----------------|-----------------|-----------------|
| 30% axial chord | AC30H03         | AC30H05         | AC30H10         |
| 50% axial chord | AC50H03         | AC50H05         | AC50H10         |
| 80% axial chord | AC80H03         | AC80H05         | AC80H10         |
different blade heights. Under different blade heights, the pressure ratio distribution of the \textit{AC50H03}, \textit{AC50H05}, and \textit{AC50H10} schemes coincides with that of the \textit{ORI} scheme; however, the results of the 68% to 95% axial chord lengths of the suction surface differ. Compared with the blade load of the modified cascade in the \textit{ORI}, that in 68% to 75% axial chord lengths of the suction surface is smaller. In 75% to 85% axial chord lengths of the suction surface, the blade load of modified cascade is slightly higher than that of the \textit{ORI}. The blade load of the modified cascade is less than that of the \textit{ORI} at 85% to 95% axial chord lengths of the suction surface. Although the transverse pressure difference increases and decreases at different positions, the pressure ratio curve of the modified cascade is smoother at 75% to 95% axial chord length. The area of the pressure ratio curve of the modified cascade is slightly less than that of the \textit{ORI} and has a certain control effect on the transverse pressure difference of the cascade; that is, the modified cascade can control the secondary flow to a certain extent. The second pressure discontinuity degree of the modified blade suction surface is lower than that of the \textit{ORI}, thereby reducing the accumulation of reverse pressure gradient and reducing the intensity of the condensation shock.

Figures 6 and 7 show the distribution of the total pressure loss coefficient and the Mach number at the outlet, respectively, of the \textit{ORI}, \textit{AC50H03}, \textit{AC50H05}, and \textit{AC50H10} schemes. Each point on the curve is the average value of the current blade height of the outlet. By comparison, the nonaxisymmetric endwall moulding is found to mainly affect the distribution of the total pressure loss coefficient and the Mach number in the range of 15% blade height. Steam flowing through the nonaxisymmetric endwall structure will cause an additional pressure drop and velocity decrease, thus causing the total pressure loss coefficient to increase and the Mach number to decrease. In the blade-height range of 10% to 50%, the distribution of the total pressure loss coefficient of the four moulding schemes is approximately the same. The average total pressure loss coefficients of the \textit{ORI}, \textit{AC50H03}, \textit{AC50H05}, and \textit{AC50H10} schemes are 0.1808, 0.1934, 0.1903, and 0.1819, respectively. Therefore, the difference in

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{figure5.png}
\caption{Surface pressure ratio distribution at different blade heights}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{figure6.png}
\caption{Distribution of the total pressure loss coefficient at the outlet}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{figure7.png}
\caption{Distribution of the Mach number at the outlet}
\end{figure}
the total pressure loss coefficient only exists near the blade root. Thus, the effect of nonaxisymmetric endwall protrusion modelling on the working performance of the whole stage is very limited. In the blade-height range from 10% to 50%, the distributions of the Mach number of the AC50H05 and ORI schemes are approximately the same. The Mach number of the AC50H03 and AC50H10 schemes is less than that of the ORI scheme. In the range of 10% blade heights, the average outlet Mach number of the AC30H03 scheme is 0.90% lower than that of the ORI scheme and the average outlet Mach number of the AC50H05 and AC50H10 schemes is 0.20% and 0.26% higher than that of the ORI scheme, respectively. In the range of 50% blade height, the average outlet Mach number of the ORI scheme is 0.52%, 0.29%, and 0.12% higher than those of the AC50H03, AC50H05, and AC50H10 schemes, respectively. In general, the nonaxisymmetric endwall structure has little effect on the total pressure loss coefficient and the Mach number of the outlet.

Figure 8 shows the nucleation rate distribution of the condensing flow under the four moulding schemes. First, the nucleation rate distributions in region A of the four moulding schemes are compared. At 10% blade height, the nucleation rates of schemes AC50H03, AC50H05, and AC50H10 are lower than that of the ORI scheme, primarily because the nonaxisymmetric endwall squeezes the steam from pressure surface to the suction surface, thereby increasing the pressure on the suction surface and reducing the supersaturation of the steam, thus inhibiting the condensation of zone A. At 20% and 30% blade heights, the nucleation rates of AC50H03, AC50H05, and AC50H10 are slightly lower than that of ORI because the nonaxisymmetric endwall protrusion can only affect the flow field near it, and the influence degree gradually decreases with increasing blade height. For region B, the nucleation rate distributions of AC50H03 and AC50H05 are similar to that of ORI, and the AC50H10 nucleation rate distribution is greater than that of ORI because AC50H10 better inhibits the condensation in region A. The amount of steam squeezed by AC50H10 in the range of 10% blade heights is the largest, but the nucleation rate of region B is substantially greater than that of ORI after the steam is pushed to the pressure surface. In general, AC50H03 has a good inhibition effect on the nucleation rate.

Figure 9 shows the outlet wetness distribution of schemes ORI, AC50H03, AC50H05, and AC50H10 in the range of 0% to 50% blade heights. In the range of 0% to 15% blade heights, the average outlet wetness of the ORI scheme is 1.285%. The average outlet wetness of the AC50H03, AC50H05, and AC50H10 schemes is 0.302%, 0.313%, and 0.293% lower than that of the ORI scheme. Therefore, the nonaxisymmetric endwall protrusion can well restrain the condensation near the root of the blade. In the range of 15% to 50% blade heights, the average outlet wetness of AC50H05 and AC50H10 is 0.03% higher than that of the ORI. The average outlet wetness of AC50H03 is 0.04% lower than that of ORI. However, with the increase of blade height, the difference of outlet wetness between the ORI and the modified cascade becomes progressively less obvious. The nonaxisymmetric endwall protrusion modelling only exerts an obvious influence on the steam flow around it. At 50% blade height, the average outlet wetness of the ORI is 1.5056%. Compared with the results of ORI and AC50H03, the average outlet wetness value of AC50H03, AC50H05, and AC50H10 decreased by 0.12021%, 0.08371%, and 0.07672%, respectively. In general, the effect of AC50H03 on the outlet wetness control is better.

The results show that the second pressure jump of the three modified cascade schemes is lower than that of the ORI scheme. The accumulation of the inverse pressure gradient is reduced, and the intensity of the condensation shock wave is weakened. To a certain extent, the secondary flow phenomenon is suppressed. Differences in the total pressure loss coefficient only exist near the root of the blade. Because the nonaxisymmetric endwall protrusion structure has little

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**FIGURE 8** Nucleation rate distribution at different blade heights

**FIGURE 9** Wetness distribution at the outlet
effect on the total pressure loss coefficient and the Mach number of the cascade outlet, it has very limited influence on the whole stage promote work. Three modified cascades have certain control effect on the nucleation rate and outlet wetness. AC50H03 has the best control effect, reducing the average outlet wetness by 0.12021%.

4.2 The effects of location

The main parameters affecting the condensation are pressure and degree of supercooling. Nonaxisymmetric endwall protrusion modelling is a three-dimensional space modelling approach that can be used to determine the circumferential parameters and identify the influence of the axial parameters. Because of the existence of the nonaxisymmetric endwall protrusion, the radius of the streamline curvature near the pressure surface decreases, leading to the increase in flow velocity and the decrease in the pressure of the blade surface. This change leads to the decrease of the pressure gradient of the pressure surface to the suction surface; as a result, the secondary flow phenomenon can be alleviated to a certain extent. Figure 10 shows the distribution of the surface pressure ratio of the ORI, AC30H05, AC50H05, and AC80H05 schemes at different blade heights. There are two pressure jumps in the suction surface: one at 15% axial chord length, and the other at 75% axial chord length. The first pressure jump is caused by the aerodynamic shock wave of the steam after the expansion of the suction surface. The swallowtail wave at the edge of the adjacent blade shocks the suction surface, leading to the second pressure jump. The pressure ratio distribution of the AC30H05 and AC50H05 schemes coincides with that of the ORI scheme; however, a difference is observed between the 70% to 90% axial lengths of the suction surface. The AC30H05’s blade load slightly decreased in the range from 68% to 75% of the axial chord length of the suction surface. From 75% to 85% axial chord length, AC30H05’s blade load is slightly higher than that of the ORI; however, from 85% to 95% axial chord length, its blade load is less than that of the ORI. For AC30H05, although the transverse pressure difference at different locations increase and decrease, the area of the load curve is slightly smaller than that of the ORI, that is, it has a certain control effect on the transverse pressure difference. The change regulation of AC50H05 is basically the same as that of AC30H05. The pressure ratio of AC80H05 is slightly smaller than that of the ORI, and the area of the load curve is larger than that of the ORI at 10% blade height. At 20% and 30% blade heights, the distribution of pressure ratio of AC80H05 is similar to that of AC30H05.

Figure 11 shows the total pressure loss coefficient at the outlet in the range of 50% blade heights with the different schemes. In the range of 15% to 50% blade heights, the total pressure loss coefficient of the AC80H05 and AC30H05 schemes is similar to that of the ORI scheme, and the total pressure loss coefficient of the AC50H05 scheme is 2.6% higher than that of the ORI scheme. In the range of 3% to 15% blade heights, the total pressure loss
coefficients of the $AC30H05$, $AC50H05$, and $AC80H05$ are 17.03%, 12.51%, and 8.96%, respectively, which are higher than that of the $ORI$. These results show that the closer the asymmetric endwall structure to the entrance, the greater the total pressure loss coefficient. The total pressure loss coefficients of $C30H05$, $AC50H05$, and $AC80H05$ are 4.65%, 5.20%, and 0.17%, respectively, which are higher than that of the $ORI$ in the range of 50% blade heights. The total pressure loss coefficient of the three modified cascades is slightly larger than that of the $ORI$, indicating that the flow phenomenon of the modified cascade has been deteriorated because the expansion process of the steam through the endwall protrusion is not sufficient, and the total pressure loss increases. The Mach numbers at the outlet in the range of 50% blade heights for the different schemes are shown in Figure 12. In the range of 50% blade heights, the average Mach number of the three modified cascades is 2.3% lower than that of the $ORI$, in accordance with the regularities of the total pressure loss coefficient. The increase in the total pressure loss coefficient is certain to reduce the speed at the outlet, thereby reducing the Mach number at the outlet.

The nucleation rate distributions of the 10%, 20%, and 30% blade heights are shown in Figure 13. No nucleation in the front half of the cascade is observed, and a large number of condensing nodules are produced quickly after reaching the cascade throat. The nucleation rate distributions of the different modelling cascades are basically the same. The peak area of nucleation rate is located at the tail edge of pressure surface (region B) to the middle part of the suction surface of the adjacent cascade (region A). Because of the flow separation near 60% axial chord length of the suction surface, the fluid detaches from the blade surface, causing the observed pressure drop; thus, the steam begins to nucleate, corresponding to the second pressure jump in the suction surface in Figure 10. The steam near the tail edge of the pressure surface suddenly lost the shackles of the blade, and the rapid decrease of the pressure results in a sudden increase in the nucleation rate. At 10% blade height, the nucleation rates of the three modified cascades are significantly lower than that of the $ORI$. The nucleation rates of region A in $AC30H05$ and $AC80H05$ are one order of magnitude lower than that of the $ORI$, and the nucleation rates of region B in $AC30H05$ and $AC80H05$ are two orders of magnitude lower than that of the $ORI$. These results show that the nonaxisymmetric endwall protrusion modelling has good control effect on the condensation near the blade root. At 20% blade height, the nucleation rate of the three modified cascades is two orders of magnitude lower than that of the $ORI$ in region B and the peak area of region A is slightly smaller than that of the $ORI$. In general, the nonaxisymmetric endwall protrusion modelling of different positions can inhibit nucleation to a certain extent.

The wetness distributions at the outlet in the range of 0% to 50% blade heights with different schemes are shown in Figure 14. In the range of 0% to 15% blade heights, a great difference is observed in the wetness distributions of the different schemes. The average outlet wetness of the $ORI$ scheme is 1.285%, whereas those of the $AC30H05$, $AC50H05$, and $AC80H05$ schemes are 0.942%, 0.993%, and 1.057%. That is, the three modified cascades have a certain control effect on the wetness of the outlet and can reduce the wetness losses. In the range from 15% to 50% blade heights, the outlet wetness of the three modified cascades is basically the same as that of the $ORI$. In general, the average outlet wetness of the $ORI$ is 1.5056%. Compared with the $ORI$ cascade, the average wetness of the $AC30H05$, $AC50H05$, and $AC80H05$ is reduced by 0.11476%, 0.07695%, and 0.065303%, respectively.

The results show that in the range from 65% to 95% axial chord length, the three modified cascades can reduce transverse pressure difference, thereby affecting the secondary
flow control. The total pressure loss coefficient of the three modified cascades is slightly larger than that of the ORI, and that of the AC80H05 scheme is relatively small. The nonaxisymmetric endwall protrusion can restrain the nucleation, at least to a certain extent. The three modified cascades have a certain control effect on the wetness and can reduce the wetness losses of the cascade. According to the Baumann rule, if the average wetness increases by 1%, then the efficiency is reduced by 1%. Scheme AC30H05 has the best control effect, reducing the average outlet wetness by 0.11476%.

The results of the previous calculations show that the average wetness values of AC50H03 and AC30H05 are 0.12021% and 0.11476% lower than that of ORI, respectively. To determine the endwall protrusion modelling scheme with better wetness control, we used the aforementioned research method to calculate the average outlet wetness of the other structures. The results are shown in Table 2, which reveals that the AC50H03 scheme has the best effect on wetness control. Schemes AC30H05 and AC30H03 also achieved good wetness control.

The spontaneous condensation process releases a large amount of condensation latent heat, heating the surrounding steam and causing the sudden change in the condensation flow parameters near the nucleation zone, which causes the unsteady condensation flow phenomenon and the condensation shock wave. The latent heat of spontaneous condensation cannot be fully utilized by the vapor phase to produce irreversible thermodynamic losses. Nonaxisymmetric endwall modelling can weaken the wet steam nucleation phenomenon to a certain extent, which can reduce irreversible thermodynamic losses.

The primary droplets deposited on the surface of the stator blade form a water film. Under the action of both inertia force and centrifugal force, the water film accumulation is thicker near the trailing edge of the stator blade. The water film near the trailing edge turns into secondary droplets that are pulled and torn by steam flow. The radius of the secondary droplets can be determined by the critical Weber number. The velocity triangle of the secondary droplet at the entrance of the rotor

| Table 2 Average outlet wetness/% |
|-----------------------------|----------------|----------------|----------------|----------------|
| ORI | AC30H03 | AC30H05 | AC30H10 | AC50H03 |
| 1.5056 | 1.38752 | 1.39082 | 1.41572 | 1.38537 |
| AC50H05 | AC50H10 | AC80H03 | AC80H05 | AC80H10 |
| 1.42187 | 1.42886 | 1.42531 | 1.44027 | 1.51242 |

**FIGURE 13** Nucleation rate distribution at different blade heights

**FIGURE 14** Wetness distribution at the outlet
blade is different from that of the main steam flow. This part of the droplets will deviate from the direction of the main steam flow, thus hitting the leading edge of the rotor blade, reducing the working capacity of the rotor and producing the brake loss. As the local wetness of the steam flow that enters the rotor row tip decreases, the number of droplets that enter the rotor row tip will also decrease. The nonaxisymmetric endwall modelling can reduce both the brake loss and the water erosion damage on the surface of the rotor blade.

4.3 The effects of incidence angle

Because of the impact of load scheduling, the turbine is often operated under nondesign conditions. With the change of back pressure during the operation of the turbine, a large deviation is found between the actual operating conditions and the design conditions. The change of the operating conditions of the steam turbine can be equivalent to the change of the incidence angle. The effect of the incidence angle on the condensation flow and its intrinsic mechanism will be discussed in this section. The AC50H03 with better outlet wetness control was selected. Under the condition where the other import conditions are unchanged, the influence of seven incidence angles on condensation flow is analyzed. To facilitate the discussion of the latter, the naming convention for different working conditions is shown in Table 3.

The pressure ratio distributions of the blade surface at seven incidence angles are shown in Figure 15. Two pressure jumps occur in the suction surface: one at 15% axial chord length and the other at 75% axial chord length. In the 10% blade height, the distribution difference of the pressure ratios of various working conditions is mainly located in the suction surface of 30% axial chord length. The blade load curve area of the negative incidence angle is less than inc = 0°. The incidence angle can reduce the transverse pressure difference in the front of the cascade and can control the secondary flow phenomena to a certain extent. The blade load curve area of the positive incidence angle is larger than inc = 0°. The positive incidence angle will aggravate the secondary flow phenomena in the front of the cascade. In the case of 20% and 30% blade heights, there are differences in 75% to 95% axial chord lengths of the suction surface compared with the results in the case of a 10% blade height. Here, the pressure jumps of inc = 2° and inc = −2° are more obvious than that of inc = 0°, and the other working conditions are gentler than that of inc = 0°. In general, the blade load of the negative incidence angle is less than that of the positive incidence angle. The smaller the incidence angle, the smaller the cascade load.

The total pressure loss coefficient of different incidence angles in the range of 50% blade heights is shown in Figure 16. For the range of 5% blade heights, the total pressure loss coefficient is not dependent on the different incidence angles. In the range of 5% to 20% blade heights, the total pressure loss coefficient changes substantially. The total pressure loss coefficient of the positive incidence angles is higher than that of inc = 0°, and the total pressure loss coefficient of the negative incidence angles is lower than that of inc = 0°. At 12.5% blade height, the total pressure loss coefficient of inc = 10° is 8.94% higher than that of inc = 0°. At 11% blade height, the total pressure loss coefficient of inc = −10° is 4.99% lower than that of inc = 0°. In the range of 20% to 50% blade heights, the total pressure loss coefficient of each working condition is basically similar to that of inc = 0°. Among them, inc = 5° and inc = 2° are almost completely overlapped with inc = 0°, and inc = −5° and inc = −10° are slightly less than inc = 0°. In the range of 50% blade heights, the average total pressure loss coefficient of inc = 0° is 0.1934 and those corresponding to the other working conditions are shown in Table 4. The average total pressure loss coefficient of each working condition is less than that of inc = 0°, indicating that the AC50H03 has a strong adaptability to incidence angles in the range of −10° to + 10°.

The Mach numbers of different incidence angles in the range of 50% blade heights are shown in Figure 17. The distribution of Mach numbers is opposite the distribution of the total pressure loss coefficient. For the range of 5% blade heights, the difference between the Mach number of each condition is not significant. In the range of 5% to 20% blade heights, the Mach number at the outlet of the positive incidence angle is less than inc = 0°, whereas that of the negative incidence angle is more than inc = 0°. The maximum deviation of inc = 10° is at 12.5% blade height, where the Mach number is 0.55% lower than that of inc = 0°. The maximum deviation of inc = −10° is at 11% blade height, where the Mach number is 0.41% higher than that of inc = 0°. In general, the average Mach number at the outlet is 0.786 at incidence angles in the range from −2° to + 5°, irrespective of the incidence angle change.

The nucleation rate distributions at the 10%, 20%, and 30% blade heights are shown in Figures 18 and 19. The nucleation rate distributions of different working conditions are basically the same. The peak area of the nucleation rate is located at the tail edge of the pressure surface (region B) to the middle part of the suction surface of the adjacent cascade (region A). At 10% blade height, the peak area of nucleation rate in region A of the negative incidence angle is substantially greater than that of the positive incidence angle, revealing that the positive incidence angle can inhibit

| Table 3 | The naming convention of different incidence angles |
|---------|-----------------------------------------------------|
| Incidence angle | −10° | −5° | −2° | 0° | 2° | 5° | 10° |
| Name | inc = −10° | inc = −5° | inc = −2° | inc = 0° | inc = 2° | inc = 5° | inc = 10° |
FIGURE 15  Surface pressure ratio distributions at different blade heights
the condensation near the suction surface. At 20% and 30% blade heights, the distributions of nucleation rates at different working conditions are basically the same. In general, the positive incidence angle can inhibit the nucleation in the cascade to a certain extent.

The outlet wetness distribution in the range of 50% blade heights is given in Figure 20. In the range of 2% blade heights, the wetness distribution of each condition is very close to inc = 0°. In the range of 2% to 13% blade heights, the wetness of the positive incidence angle is less than that of

\[ \text{FIGURE 16} \quad \text{Distribution of total pressure loss coefficient at the outlet} \]

\[ \text{FIGURE 17} \quad \text{Distribution of the Mach number at the outlet} \]

\[ \text{TABLE 4} \quad \text{Average total pressure loss coefficient of different working conditions} \]

| Working conditions | inc = 10° | inc = 5° | inc = 2° | inc = −2° | inc = −5° | inc = −10° |
|--------------------|-----------|----------|----------|-----------|-----------|-----------|
| ξ                  | 0.1915    | 0.1913   | 0.1922   | 0.1935    | 0.1912    | 0.1931    |
| Compare with inc = 0° | −5.12%   | −4.99%   | −5.74%   | −6.20%    | −4.92%    | −5.99%    |

\[ \text{FIGURE 18} \quad \text{Nucleation rate distribution of negative incidence angle} \]
inc = 0°. The wetness of inc = −10° was found to decrease the most. At 9% blade height, the outlet wetness of inc = 10° is 0.296% lower than that of inc = 0°. The wetness of the negative incidence angle is higher than that of inc = 0°, and inc = −10° is the maximum. The outlet wetness of inc = −2° and inc = 2° almost coincide with that of inc = 0°. In the range of 13% to 50% blade heights, the wetness of all the working conditions is greater than that of inc = 0°. The average outlet wetness of all the working conditions in the range of 50% blade heights is shown in Figure 21. The average outlet wetness of inc = 0° is 1.3913%. Except for inc = 10°, the average outlet wetness declines with the increase of the incidence angle. For the negative incidence angle, the average outlet wetness is greater than inc = 0°. Thus, the wetness losses caused by the negative incidence angle are larger. The ideal incidence angle of the AC50H03 modified cascade is from −2° to +10° in this work.

5 | CONCLUSIONS

The condensation flow of wet steam must be studied to improve the efficiency of condensing steam turbines. The positive/cosine function was proposed for endwall modification
in the nucleation stage of a steam turbine to improve the efficiency. To analyze the influence of endwall protrusion design parameters on the condensation flow, nine endwall models were set up, with three different cases at each of 30%, 50%, and 80% of the axial chord length. The condensation parameter distribution rule and the factors that influence the characteristics were discussed. The following findings were obtained from this study.

1. The second pressure discontinuity degree of the modified blade suction surface is lower than that of the ORI, thereby reducing the accumulation of reverse pressure gradient and reducing the intensity of the condensation shock. Nonaxisymmetric endwall protrusion modelling can inhibit the nucleation and has little effect on the total pressure loss coefficient and the Mach number. Nonaxisymmetric endwall modelling can reduce both irreversible thermodynamic losses in the stator cascade and brake loss and water erosion damage in the rotor cascade.

2. In the range of 0% to 15% blade heights, a great difference is observed in the wetness distributions of the different schemes. The average outlet wetness of the ORI is 1.285% in the range of 0% to 15% blade heights, whereas those of the AC30H05 and AC50H03 are 0.343% and 0.302% lower than that of the ORI. In the range of 0% to 50% blade heights, the average wetness of the AC50H03 and AC30H05 is 0.12021% and 0.11476% lower than that of the ORI. By comparison with the original cascade, the total pressure loss coefficient and outlet wetness were found to be ideal when the endwall protrusion maximum height was located at the middle of the stator cascade and the protrusion was 3% of the blade height.

3. The positive incidence angle can inhibit the condensation near the suction surface, resulting in reduced wetness losses. The ideal incidence angle of AC50H03 is from −2° to +10°.

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CONFLICT OF INTERESTS

The authors declare that there are no conflicts of interest regarding the publication of this paper.

NOMENCLATURE: SYMBOL DESCRIPTION

| Symbol | Description |
|--------|-------------|
| $e$    | energy density, kJ·m$^{-3}$ |
| $F_D$  | viscosity resistance, N |
| $h$    | relative blade height |
| $h_t$  | steam enthalpy, kJ kg$^{-1}$ |
| $h_{lg}$ | condensation latent heat, kJ kg$^{-1}$ |
| $J$    | nucleation rate, (m$^3$ s)$^{-1}$ |
| $k$    | Boltzmann constant |
| $m$    | mass of a single molecule, kg |
| $\dot{m}$ | mass condensation rate, kg m$^{-3}$ s$^{-1}$ |
| $N$    | water droplet quantity per unit volume, m$^{-3}$ |
| $p$    | pressure, Pa |
| $q_c$  | condensation coefficient |
| $R$    | vapor constant, J·(mol K)$^{-1}$ |
| $r$    | radius of a water droplet, m |
| $r_c$  | critical water droplet radius, m |
| $T$    | temperature, K |
| $\Delta T$ | degree of subcooling, K |
| $u$    | axial velocity, m s$^{-1}$ |
| $v$    | radial velocity, m s$^{-1}$ |
| $x$    | direction along the blade height |
| $Y$    | wetness |
| $y$    | circumferential direction of the cascade |
| $z$    | direction of the axial |
| $\sigma$ | water droplet surface tension, N m$^{-1}$ |
| $\lambda_s$ | thermal conductivity of steam, W·(m K)$^{-1}$ |
| $\delta$ | semi-empirical correction coefficient of water droplet growth |
| $\rho$ | density, kg m$^{-3}$ |
| $\gamma$ | specific heat capacity ratio of steam |
| $\xi$  | total pressure loss coefficient |
| Subscript | |
| $d$    | volume average parameters of liquid phase |
| $g$    | vapor phase parameter |
| $l$    | liquid phase parameter |
| $m$    | two-phase flow parameter |
| $s$    | parameter of saturation |

Abbreviations

ACiHj modified cascade, the endwall protrusion maximum height is $j$% blade height and located at $i$% axial chord length

$K_n$ Knudsen number

$Ma$ Mach number

ORI original cascade

$Pr_{rg}$ Prandtl number
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