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EFFECT OF SURFACE TENSION CORRECTION COEFFICIENT ON NON-EQUILIBRIUM CONDENSATION FLOW OF WET STEAM

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Abstract: In view of the non-equilibrium characteristics of water vapor in the condensation process, there are deviations in the prediction of condensation process by various models. The surface tension of water droplets appears in the exponential term of nucleation rate in the form of third power, which has a significant impact on the distribution of parameters such as condensation location, number of water droplets and steam wetness. The correction coefficient was used to modify the plane surface tension calculation model. The non-equilibrium condensation process in the Moses&Stein nozzle was simulated. By comparing with the experimental data, the influence of the surface tension correction coefficient on the calculation accuracy of the model was analysed. And the functional relationship between the inlet subcooling and the optimal surface tension correction coefficient was further obtained. Taking case 252 as an example, with the surface tension correction coefficient increasing from 0.9 to 1.05, the condensation position moves from 3.1cm to 4.2cm, and the optimal correction coefficient is 0.98. There is a significant positive correlation between the optimal tension correction coefficient and inlet subcooling under different working conditions. The results can provide a reference for the calculation of wet steam condensation flow.

INTRODUCTION

The problem of wet steam flow is accompanied by the emergence of steam turbine. The condensation in wet steam stage of steam turbine will produce thermodynamic loss, droplet resistance loss, braking loss, working medium loss and so on, which make the efficiency of the stage greatly reduced. The thermodynamic loss mainly occurs in the nucleation stage and the non-equilibrium condensation stage of last stage. Besides nucleation stage, braking loss is the most significant part of wetness loss (Li et al., 2014). Baumann studied the wetness losses in 1912(Moore et al., 1976). After summarizing many turbine experimental data, the conclusion that the average wetness will cause the stage efficiency to decrease by 1% every 1% increase. For nuclear power generation, all stages of steam turbine work in wet steam area. The steam with high wetness will make the flow passage of steam turbine and pipe surface often covered with a layer of water film, which will cause the pressure drop and water film flash evaporation during load rejection (Deng et al., 2109). At the same time, the air velocity increases rapidly, resulting in overspeed. In addition, the blade will cause strong vibration and even the blade fracture under the long-term water erosion. The deep study on the wet steam flow is the foundation to solve these problems.

The water vapor will show remarkable unbalanced characteristics when it condenses in high-speed expansion. The characteristic is that with the continuous expansion of water vapor, the degree of deviation from the equilibrium state also increases gradually, which is reflected in its rapid temperature reduction and reaching saturation state. The saturated steam does not condense immediately, but reaches the supersaturated state with the continuous decrease of temperature, the supercooling is also increasing. When the supercooling reaches the limit, many condensation cores are produced in a very short time. The water vapor molecules deposit on the surface of the condensation core to form small droplets, and release latent heat to surrounding environment. These energies are suddenly released into the surrounding gas components, which causes the pressure, temperature, and density of the gas to rise in a certain range and continue to decline, showing a sudden jump (condensation shock phenomenon). By comparing the equilibrium and non-equilibrium condensation characteristics of water vapor in Laval nozzle, it is found that there is a significant difference between the two results when the inlet pressure is low (Deng et al., 2020). At present, the design of wet steam turbine in China's steam turbine industry is still carried out according to the law of equilibrium condensation flow. The design method fails to reflect the characteristics of non-equilibrium condensation flow in actual steam turbine, which causes additional losses (Chai et al., 2012). Because of its complexity, the process of unbalanced condensation has attracted the interest of scholars at home and abroad.

With the extensive applications of CFD technology, more and more researchers have found that the numerical simulation results sometimes deviate from the experimental data to some extent, which means that the existing numerical model of non-equilibrium condensation flow of wet steam still has defects. There are many reasons affecting the accuracy of wet steam condensation numerical simulation, such as water droplet growth model, nucleation model, turbulence model and so on. Yu Xinggang (Yu, 2015) and Yu Xinfeng (Yu, 2011) adopted the non-isothermal modified Kantrowitz nucleation model and obtained good results. The expression of nucleation rate is also used in this paper; Yu Xinggang (Yu, 2015) used the classical droplet growth model proposed by gyarmathy in his research, but the model cannot make a good prediction at low pressure. In this paper, the droplet growth model modified by young's low pressure is selected to obtain a more accurate simulation. Yu Xinfeng (Yu, 2011) deduced k- ε turbulence model for gas phase and has obtained high accuracy in the subsequent wet steam condensation simulation. Bakhtar modified the classical nucleation theory (Bakhtar et al., 2005), thought that due to the uncertainty of cluster properties and the unknown energy transfer rate in the non-isothermal process, the accurate theoretical prediction of nonequilibrium condensation process cannot be obtained by simple engineering calculation. The surface tension appears in the exponential position of nucleation rate expression in the form of third power. A small change in the surface tension of the condensed droplet may lead to a sharp fluctuation in the nucleation rate. Therefore, it is very important to determine the surface tension of micro droplets. Bakhtar and Gerber et al. believed that the surface tension value of condensed nuclei formed by a small number of molecules may be different from those measured by using the continuous hypothesis theory (Bakhtar et al., 2005; Gerber, 2008). Based on this theory, the method of controlling the intensity of condensation process by dimensionless correction of surface tension is being widely used.

Yu Xinggang simulated the non-equilibrium condensation of steam in Moore Nozzle (Yu, 2015). The change of the surface tension (NBTF) between 0.85 and 0.92 made the accuracy of pressure distribution and droplet number calculation improve greatly. And the condensation location was simulated accurately. The steam non-equilibrium condensation in White cascade was simulated by similar method. The optimal NBTF value was 0.85-1 under three experimental conditions. Peng Shuxuan had made a simulation of spontaneous steam condensation in Laval nozzle and Bakhtar cascade (Peng et al., 2020). The results show that the optimal value of a is not related to the inlet total temperature but positively related to the inlet total pressure. In the numerical simulation of four nozzles, Sriram found that with the increase of NBTF, the nucleation rate shows a decreasing trend, and the condensation position moves 60mm after the NBTF increases from 0.7 to 1.0. For different nozzles, it is found that NBTF which is consistent with experimental data is not a fixed value (Sriram et al., 2018). In the derivation of the two-phase flow model of wet steam, Yu Xinfeng modified the plane water surface tension coefficient with a=1.07 to reduce the deviation from the experimental value (Yu, 2011). Wang Zhi modified the vapor condensation coefficient to 0.95 when calculating the droplet growth, which greatly improved the accuracy of the parameters such as pressure ratio, droplet growth rate and droplet radius (Wang, 2010). The above results greatly promote the development of non-equilibrium condensation flow. Based on the existing researches, the surface tension of droplets in the condensation flow was modified in this paper. By comparing with the existing experimental data, the influence of correction coefficient on the accuracy of calculation was analyzed. And the correlation between the inlet supercooling degree and the optimal value of the correction coefficient was studied. The results can provide some reference for the calculation of condensation flow of wet steam.

MODEL ESTABLISHMENT

Mathematical model

The Euler-Euler model is adopted in numerical model of wet steam two-phase condensation flow. Wet steam is a mixture of vapor and many small water droplets. Due to the droplets, which produced in the spontaneous condensation process, are very small (the radius is usually less than 0.1μm), it can be assumed that they move with the steam flow (Wang et al., 2018).

The nucleation and water droplet growth in steam spontaneous condensation have been studied for a long time. In this paper, the nucleation rate is expressed by Kantrowitz after considering the non-isothermal effect on the classical nucleation theory (Kantrowitz, 1951):

$$J = \frac{1}{1+\varphi} q_c \sqrt{\frac{2\sigma}{\pi m_m^3}} \frac{\rho_g}{\rho_l} \exp\left(-\frac{4\pi r_c^2 \sigma}{3K_n T}\right) \quad (1)$$

Where φ is the non-isothermal correction coefficient and r_c is the critical radius.

$$\varphi = \frac{2(\gamma-1)}{\gamma+1} \frac{h_{fg}}{RT} \left(\frac{h_{fg}}{RT} - \frac{1}{2}\right) \quad (2)$$

$$r_c = \frac{2\sigma T_S}{\rho_l h_{fg} \Delta T} \quad (3)$$

The water droplet growth model adopts the expression proposed by Gyarmathy and modified by Young (White et al., 1996).

$$\frac{\mathrm{d}r}{\mathrm{d}t} = \frac{\lambda_g \Delta T}{\rho_l h_{fg} r\left[\frac{1}{1+4K_n} + 3.78(1-\upsilon)\frac{K_n}{P_{rg}}\right]} \quad (4)$$

Where υ is defined as:

$$\upsilon = \frac{R_g T_s}{h_{fg}} \left[\alpha - \frac{1}{2} - \frac{2-q_c}{2q_c} \left(\frac{\gamma+1}{2\gamma}\right) c_p \frac{T_s}{h_{fg}}\right] \quad (5)$$

ΔT is supercooling degree:

$$\Delta T = T_s - T \quad (6)$$

The wetness calculation formula is defined as follows:

$$Y = \frac{4}{3}\pi \rho_d r^3 N \quad (7)$$

In addition, the equation of state of water vapor has many forms, and the calculation time and accuracy are closely related to the selected equation of state. In this paper, IAPWS-IF97 standard issued by International Water and Steam Association is selected. The two-phase turbulence model is based on k-ε which is suitable for compressible fluid flow.

1.2 Physical model

The validation of the wet steam model depends heavily on the experimental data obtained from condensation flows in nozzles, which mainly due to the flow in nozzle is much simpler than that in a turbine. The specially designed nozzles can produce a stable and close to one-dimensional flow that can reproduce the parameters of real steam turbine, such as expansion rate, pressure distribution, Mach number, temperature field and subcooling conditions (Starzmann et al., 2018).

In this paper, the non-equilibrium condensation flow of wet steam in the Moses&Stein nozzle is simulated (Moses et al., 1978). ANSYS ICEM CFD is used for generating the structural mesh. As shown in Figure 2, the boundary layer is set near the wall of the nozzle. The dimensionless distance y+ is 33, which ensures that the first layer of grid is located in the turbulent core of the mainstream. It is assumed that the wall is smooth, adiabatic and no slip boundary condition. The mesh refinement is carried out at the location where condensation occurs.

The profile of the Moses&Stein nozzle is shown in Figure 1. The longitudinal section of the transonic and supersonic segments is a circular arc with a radius of 68.6cm, which is smoothly connected with the arc of 5.3cm radius to form the subsonic inlet. The abscissa of nozzle throat is 0, the inlet is -5cm and the outlet is 6.5cm. The expansion rate of the throat is about 6500s^{-1}, and the expansion rate in the condensation zone is between 9000s^{-1} and 10000s^{-1}.

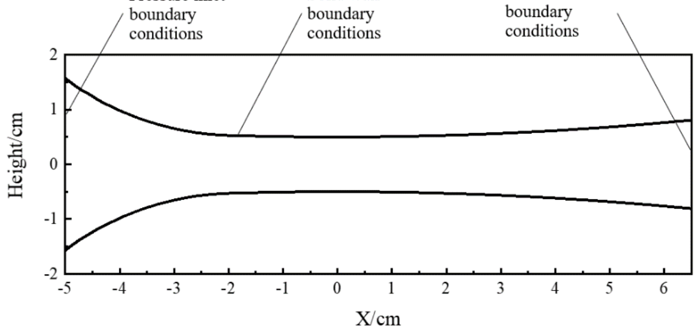


Fig. 1 Schematic Diagram of Nozzle Profile

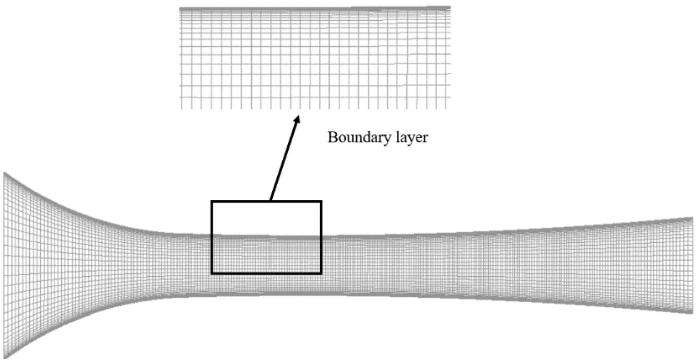


Fig. 2 Schematic Diagram of Nozzle Grid

Working conditions

Five cases in the reference (Moses et al., 1978) are selected for numerical simulation. The specific nozzle inlet parameters are shown in Table 1. Among them, p_0 and T_0 are the total pressure and total temperature at the nozzle inlet respectively.

Table 1 Inlet Parameters

CASE	P_0/KPA	T_0/K
252	40.05	374.30
193	43.02	366.15
410	70.73	377.15
411	42.28	385.15
428	54.70	373.15

Model verification

In order to verify the reliability of the mathematical model, the non-equilibrium condensation flow of water vapor is simulated in Moses&Stein nozzle. The flow conditions are taken from the corresponding case 252 in reference (Moses et al., 1978). The total pressure of inlet p_0=40.05kPa, and the total temperature of inlet T_0=374.3K. The case is calculated by selecting 50000, 250000, 960000 and 1550000 grids respectively. Figure 3 shows the comparison of the pressure ratio distribution along the nozzle axis with experimental data under different grid numbers. The results indicate that the pressure ratio distributions of four scales of grid are in good agreement with the experimental data. It reveals the reliability of the numerical model established in this paper. Further analysis points out that the four scales of grid have a great difference in the abscissa range of 3.5cm to 4.5cm, which is the initial stage of condensation. The main reason is that the condensation model still has defects to a certain extent, and cannot fully and accurately simulate the condensation process of high-speed wet steam, especially in the area where the pressure mutation. Compared with the grid scales of 960000 and 1550000, the grid pressure ratio curves of 50000 and 250000 have greater fluctuation. In order to reduce the impact of the number of grids on the calculation results, and improve the calculation efficiency, the model with the grid number of 960000 is selected for subsequent calculations.

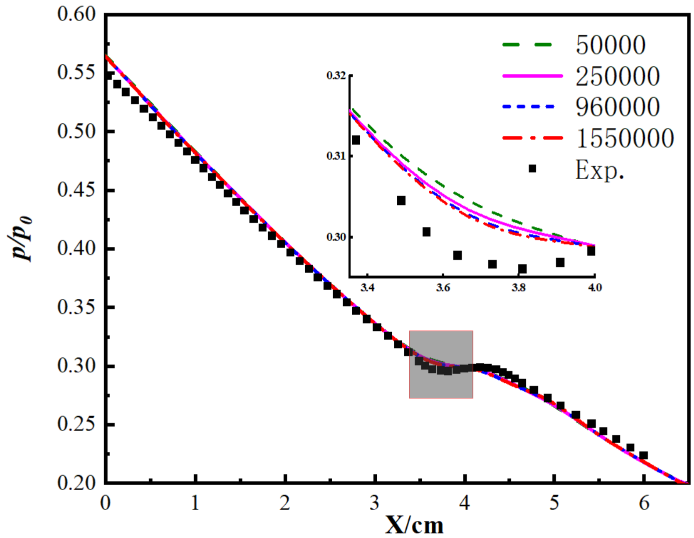


Fig. 3 Model Validation

RESULTS AND DISCUSSION

Influence of surface tension correction coefficient on calculation accuracy

Taking the case 252 in the Moses&Stein nozzle experiment as an example, the surface tension correction coefficient is adjusted to match the simulation results and experimental data.

In order to analysis intuitively, the regions of starting and stable condensation are selected in Figure 4. It can be seen that the pressure ratio decreases along the x-axis positive direction and reaches the condensation position (Wilson point), which is about 3.7cm away from the throat of the nozzle. Due to the small space in the nozzle, the release of latent heat makes the steam flow heated. Therefore, the local pressure gradient becomes very large. The pressure jumps suddenly and produces condensation shock wave, then continues to drop to the outlet pressure.

Due to the difference of surface tension correction coefficient, the axial pressure ratio distribution of nozzle presents obvious difference in the condensation area. But the overall pressure drops trends are almost the same. It can be seen that with the increase of the surface tension correction coefficient, the condensation position is closer to the outlet, and the range of pressure mutation also decreases. When the surface tension correction coefficient is not corrected, that means the value is 1, there is a big difference between the numerical simulation result and the experimental data in the area of pressure mutation. The maximum deviation is 3.43%, and the average deviation is 1.54%. When the surface tension correction coefficient is 0.98, the simulation result is in the best agreement with the experimental data. The maximum deviation is 2.31%, and the average deviation is 1.42%. It is found that the accuracy of simulation results can be improved by adjusting the value of surface tension correction coefficient.

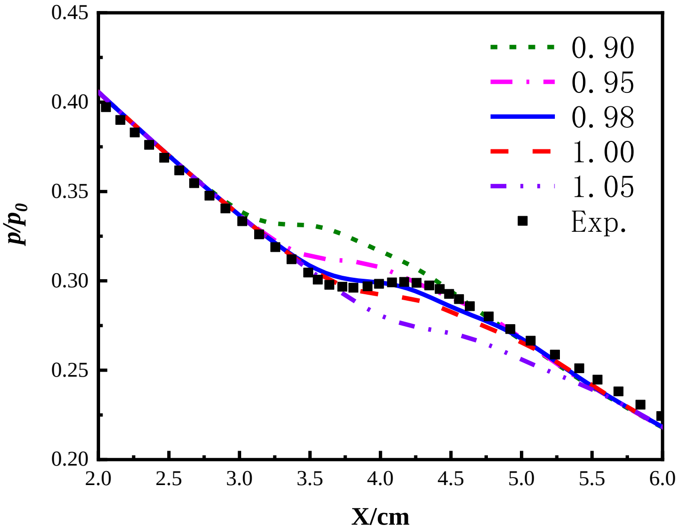
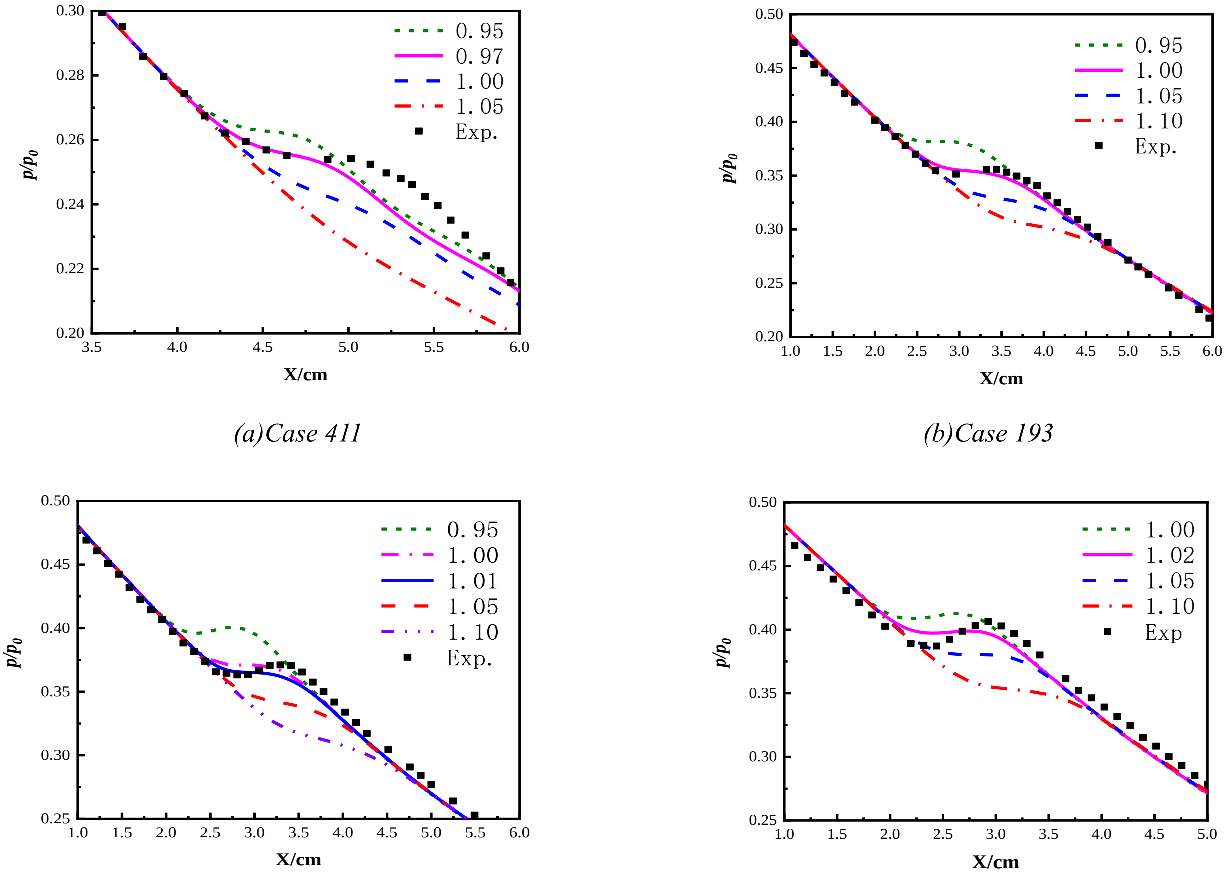


Fig. 4 Axial Pressure Ratio Distribution of The Nozzle with Different Correction Coefficient Under Case 252

Fig. 5 shows the distribution of axial pressure ratio of nozzle under various working conditions. It can be seen from Fig. 5 (a) that for case 411, when the surface tension correction coefficient is 0.97, although there is a little difference between the simulation result and the experimental data at 5cm to 5.7cm from the nozzle throat, the prediction in the area before and after Wilson point is in good agreement with the experimental data. The longitudinal comparison shows that when the coefficient is 1.05, the axial pressure has no mutation, which is inconsistent with the experimental results. The reasonable value of the surface tension correction coefficient has a considerable impact on the simulation results. According to Fig. 5 (b), when the surface tension correction coefficient is 1, the simulation result is in good agreement with the experimental data in both initial and stable condensation zone. Comparing with Fig. 5 (c) and (d), when the surface tension correction coefficient are 1.01 and 1.02 respectively, the simulation results are slightly lower than the experimental data at the location of pressure mutation. Except for this, the overall consistency is high.



(a)Case 411 *(b)Case 193*

(c)Case 428 *(d)Case 410*

Fig. 5 Pressure Ratio Distribution of Nozzle Axis Under Various Conditions

In order to obtain the further influence of surface tension correction coefficient on the calculation accuracy, based on the experimental data of axial pressure ratio under various cases, the deviation between the calculation results and the measured values is analysed in this paper. The results are listed in Table 2. It can be seen from the table that except case 193, compared with the results without correction (i.e., the correction coefficient is 1.00), the maximum deviation and average deviation between the corrected simulation value and the experimental value under each working condition are significantly reduced, and the simulation accuracy is improved.

Relationship between inlet subcooling and the optimal value of surface tension correction coefficient

In terms of the above simulation results, it can be found that different inlet parameters have certain influence on the optimal value of surface tension correction coefficient. Considering the correlation between the inlet pressure and temperature on the correction coefficient (Peng et al., 2020), the inlet supercooling is selected to analyse. The inlet supercooling is the degree of the steam inlet temperature lower than the saturation temperature corresponding to the inlet total pressure. It is the physical quantity that combines both inlet pressure and temperature, which can better reflect the state of the inlet steam. According to the simulated conditions, Figure 6 selects four typical conditions to give the scatter chart of optimal surface tension correction coefficient and corresponding inlet supercooling. It is obvious from the figure that the optimal value of the surface tension correction coefficient has significant positive effects on the inlet subcooling degree.

Table 2 Calculation Deviation

Case	Correction coefficient	Maximum deviation /%	Average deviation /%
411	0.97	5.20	1.02
	1.00	6.76	1.65
193	1.00	2.41	1.06

428	1.01	3.17	1.61
	1.00	3.76	1.73
252	0.98	2.31	1.42
	1.00	3.43	1.54
410	1.02	3.75	2.00
	1.00	6.10	2.94

In order to quantitatively express the dependent relationship between the inlet supercooling degree and the surface tension correction coefficient, assuming that they fit the quadratic polynomial regression model. These scattered data are fitted by quadratic polynomial, and the fitting equation is as follow:

$$F = a\Delta T_{in} + b(\Delta T_{in})^2 + c \qquad (8)$$

Where F is the surface tension correction coefficient, ΔT_{in} is the inlet subcooling of the working fluid, and a, b and c are constants.

$$a = 0.00493 \pm 0.00563\,;$$

$$b = 6.744\times10^{-5} \pm 1.25669 \times10^{-4}\,;$$

$$c = 1.05844 \pm 0.05596$$

Case 410 is selected to verify the fitting result, and the result of verification is listed in Table 3. Inlet subcooling under case 410 is -11.2 K, and the optimal value of surface tension correction coefficient F is among 1.00302~1.02035. Consistent with simulation result (1.02), the maximum relative error of fitting value is 1.6647%, which is within the acceptable range.

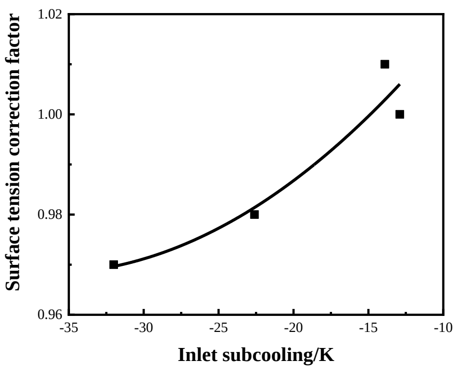


Fig. 6 Fitting Curve of Inlet Subcooling and Surface Tension Correction Coefficient

Table 3 Validation of Fitting Results

Case	ΔT_{in}/K	Calculated value	Fitting value (min)	Fitting value (max)	Relative error (max)/%
410	-11.2	1.02	1.00302	1.02035	1.6647

CONCLUSIONS

The non-equilibrium condensation process in the Moses&Stein nozzle is numerically simulated in this paper, and the optimal simulation results under various conditions are obtained by adjusting the surface tension correction coefficient. The influence of inlet parameters on the optimal value of the surface tension correction coefficient is analyzed and summarized.

(1) With the increase of the surface tension correction coefficient, the condensation position is closer to the nozzle outlet and the pressure mutation is also reduced;

(2) The accuracy of simulation results can be improved by adjusting the value of surface tension correction coefficient, which is different for different working conditions;

(3) According to the quadratic polynomial fitted by the simulation results, the surface tension correction coefficient can be determined in the range of inlet subcooling from -32K to -11.2K.

NOMENCLATURE

σ	——	surface tension, N/m
m_m	——	molecular weight of water, kg
ρ_g	——	density of vapor phase, kg/m^3
ρ_l	——	density of liquid phase, kg/m^3
h_{fg}	——	latent heat of condensation, J/kg
R	——	gas constant of water vapor
T_s	——	saturation temperature, K
K_n	——	Boltzmann constant, J/K
P_{rg}	——	Prandtl constant
c_p	——	specific heat of gas, J/(kg·K)
λ_g	——	thermal conductivity, W/(m·K)
q_c	——	condensation coefficient
α	——	correction coefficient of droplet growth

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Disclosure statement

No potential conflict of interest was reported by the author(s).

REFERENCES

Bakhtar, F. (2005). Classical Nucleation Theory and Its Application to Condensing Steam Flow Calculations. *J. Mechanical Engineering Science,* 219(12), pp. 1315-1333.

Chai, X., Li, L., Chen, Q., and Feng Z. (2012). Development and Application of Non-Equilibrium Condensation Streamline Curvature Method. *Journal of Engineering Thermophysics*, 33 (08), pp. 1309-1312.

Deng, Q., Li, J., Feng, Z. et al. (2019) Development Status and Trend of Large Power Generation Technology. *Thermal Turbine*, 48 (03), pp. 175-181.

Deng, Q., Hu, L., Feng, Z. et al. (2020). Effect of Inlet Steam Parameters on Spontaneous Condensation of Water Vapor in Laval Nozzle. *Journal of Xi'an Jiaotong University*, 54 (10), pp. 116-123.

Gerber, A. G. (2008). Inhomogeneous Multifluid Model for Prediction of Nonequilibrium Phase Transition and Droplet. *Journal of Fluids Engineering,* 130(3), pp. 031402-1-031402-11.

Kantrowitz, A. (1951). Nucleation in Very Rapid Vapor Expansions. *The Journal of Chemical Physics*, 19(9), pp. 1097-1100.

Li, L., Li, Y., Xie, X., and Li, J. (2014). Quantitative Evaluation of Wetness Losses in Steam Turbines Based on Three-Dimensional Simulations of Non-Equilibrium Condensing Flows. *Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 228(6), pp. 708-716.

Moore, M. J., and Sieverding, C. H. (1976). Two-Phase Steam Flow in Turbines and Separators. *Washington, DC: Hemisphere Publishing Corporation.*

Moses C. A., and Stein G. D. (1978). On the Growth of Steam Droplets Formed in a Laval Nozzle Using Both Static Pressure and Light Scattering Measurements. *Journal of Fluids Engineering*, 100(3), pp. 311-322.

Peng, S., Yang, A., and Chen, E. (2020). Study on the Correlation Between the Surface Tension Correction Coefficient of Droplet and the Steam Expansion Rate and Inlet Parameters. *Journal of Power Engineering*, 40 (06), pp. 460-468.

Sriram, A. T., Mistry, H., Moraga, F., et al. (2011). Numerical Sensitivity Studies on Nucleation of Droplets in Steam Turbine. *Asme Power Conference Collocated with Jsme Icope*.

Starzmann, J., Hughes, F. R., Schuster S., et al. (2018). Results of the International Wet Steam Modeling Project. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 232(5), pp. 550-570.

Wang, X., Li, L. and Wang, S. (2018). *Two-phase high-speed flow of expanding wet steam.* 1st ed. Xi'an Jiaotong University Press, pp. 158-163.

Wang, Z. (2010). *Numerical Study on Wet Steam Two-Phase Condensation Flow in Steam Turbine*. Ph.D. North China Electric Power University.

White, A. J., Young, J. B., and Walters, P.T. (1996). Experimental Validation of Condensing Flow Theory for A Stationary Cascade of Steam Turbine Blades. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 354(1704), pp. 59-88.

Yu, X. (2011). *Numerical Simulation of Wet Steam Two Phase Flow Based on Two Fluid Model*. Ph.D. Harbin Institute of Technology.

Yu, X. (2015). *Numerical Study on Wet Steam Flow Characteristics in Low Pressure Stage of Steam Turbine*. Ph.D. Wuhan University.