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Numerical Simulation of Spray Cooling Gas with High Temperature and Velocity in Compressor Inter-Stage

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To investigate the effects of nozzle number, spray parameters, airflow velocity and airflow temperature on cooling efficiency of airflow, a numerical simulation of the water jet cooling in the compressor is carried out in a simplified three-dimensional model, about the preliminary study of compressor inter-stage cooling technique. The results showed that increasing the number of nozzles could promote the mixing of the gas and droplet further to improve the evaporation efficiency. The heat transfer temperature variations are increasing with the gas temperature rising. It showed that 8 % improvement in evaporation rate was achieved by increase gas temperature from 383 K to 413 K. Smaller droplets evaporate faster because they provided more surface area per unit volume than larger droplets, and 20 % improvement in evaporation rate was achieved by decreasing droplet diameters from 40 μm to 20 μm. When the inlet flow velocity was small, the droplet evaporated for more time and the evaporation rate is higher, which can improve the cooling effect by increasing the spray cone angle and raising the initial droplet velocity. As the inlet flow velocity decreased from 100 m/s to 25 m/s, the evaporation rate could reach 80 %.

1. Introduction

All along, the field of thermal cycling continues to try to improve the gas turbine thermal cycle performance. The current mainstream compressor optimization cycle technology mainly included compressor intercooling technique and compressor inter-stage cooling technique. The intercooling technique is injecting cooling water into where between the low-pressure compressor and high-pressure compressor, which cooling the high pressure and temperature gas from the low-pressure compressor. Reduced the compressive power and compressor exhaust temperature by reducing the high-pressure compressor inlet temperature and increasing mass flow. The inter-stage cooling technique involves injecting cooling water into each stage, reducing the compressor power consumption and reducing the compressor outlet temperature by reducing the gas temperature in each stage. Both cycles increase the return heat temperature by reducing the outlet temperature of the compressor, and increase the compression efficiency by reducing the compressive power consumption of the compressor. Inlet cooling technology has been mature application, and the intercooling technology has a small amount of research.

On the basis of previous studies, this paper intended to do preliminary exploration for the inter-stage cooling technology include analysing the evaporation of water droplets in the narrow channel. At present, it is rare to study the inter-stage cooling of gas turbine compressor at home and abroad. It mainly focuses on the study of compressor inlet cooling and gas compression, which injects high specific heat medium such as water or oil, to improve compression efficiency. Siddhartha et al. (2015) for the instability of wind power generation, compressed hydrogen in the cylinder by using the excess wind energy, explored the best compression by trying to install the nozzles on different location. Giuseppe et al. (2015) conducted a corresponding study on the oil spray cooling in the scribe compressor, focusing on the effect of different pressures and spray cone angles for compression performance of the pressure nozzles. The best compression result is the vane compressor at the spray pressure of 20 bar and the spray angle of 30°. However, the oil droplets are used as the cooling medium in the experiments, there was no oil and gas filtration and separation device and no exploring the best oil flow. Tang and Cui (2014) according to the temperature and air humidity for different areas in different periods, they worked out the empirical formula of the inlet cooling water flow for the gas turbine compressor of the power plant at different times, and the economic performance index parameters. Dong and Lin (2013) simulation calculated and experiments verification the flow relationship between water and gas of the three-axis gas turbine compressor intercooling system. The results show that when the ratio between water and gas is 0.45 %, the output power increases by about 7.5 %, the efficiency is increased by about 1.8 %, and the NO emission is reduced by about 10 %. Wang and Li (2015) reduced the diesel engine and submarine exhaust temperature from 673 K to 378 K by installing a two-stage water cooling device in the exhaust gas pipe, he experimented and simulated the effect of the nozzle installation location, spray cone angle and spray flow on spray cooling performance. Abdullah et al. (2016) used Fluent simulation study the effect of air flow velocity, droplet size and droplet initial speed on the cooling efficiency, the results showed that droplet transport and evaporation strongly depend on droplet size and air velocity. Hamid and Bert (2015) think that air dry bulb temperature, air humidity and gas-liquid relative velocity have a significant effect on water spray cooling. In their case, the cooling efficiency increases from about 21 % for w = 0.0130 % to 37 % for w = 0.0026 %. Most of the above studies focus on the cooling effect in normal temperature or low velocity airflow, and did not research the cool airflow with high temperature and high velocity. Most of the spray cooling studies focused on the analysis of single nozzle, ignoring the gas mixed effect.

This paper mainly explores the relationship between the number of nozzles, the inlet air temperature, the inlet air velocity and the evaporation rate, and the influence of the spray parameters on the evaporation.

2. Particle Population Equilibrium Model

Because of the turbulent flow in the moving blades of the compressor, the mathematical model involved the turbulence model, the discrete item model and the component transport model. The governing equations uses the N-S equation that suit for incompressible fluid flow:

$$\frac{D\rho}{Dt}+\rho\nabla\cdot\vec{V}=\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\vec{V})=0 \tag{1}$$

$$\frac{D}{Dt}\iiint_{\tau_0}\rho\left(e+\frac{V^2}{2}\right)d\tau_0=\oiint_{A_0}q_\lambda dA_0+\iiint_{\tau_0}q_R\rho d\tau_0+\iiint_{\tau_0}\left(\vec{f}\cdot\vec{V}\right)\rho d\tau_0+\oiint_{A_0}\left(\vec{p_n}\cdot\vec{V}\right)dA_0 \tag{2}$$

$$\frac{D\vec{V}}{Dt}=\vec{f}-\frac{1}{\rho}\nabla\mathrm{P}+\frac{1}{\rho}\mu\nabla^2\vec{V} \tag{3}$$

The time-averaged N-S equations with the Realizable k-ε model were used to model turbulence effects. The Realizable k-ε model used the mathematical model to improve the computational performance based on the Standard k-ε model, and the accuracy of the calculation is better than the RNG k-sink model, which can be used at a medium-intensity swirling and circular jet. Simulations were performed using the finite volume CFD software, Fluent (version 16.2). Gas inlet boundary condition is the velocity entrance, the outlet is the pressure outlet, the wall is no sliding insulation wall. Gas-liquid heat transfer model is the discrete model. The nozzle type is a cone nozzle in the discrete model. The droplet type is the Droplet, due to its own evaporation and heat transfer function could simulate the droplets evaporation well.

3. Physical model and boundary conditions

In this paper, the study of the spray cooling characteristics of the gas with high temperature and high velocity in the rotor blades where is a small space. The simplified three-dimensional model that select the throat distance and chord length as reference size to establish a cylindrical geometric model, which is ∅ 160X40. As shown in Figure 1, there are 19 nozzles in the inlet surface. A nozzle is at the centre of the bottom surface. Since the air flow is very fast, in order to mix gas and water well, 6 nozzles are uniformly arranged on the circumference of 50 mm, 12 nozzles are uniformly arranged on the circumference of 100 mm. Taking Figure 1 as an example, in order to enhance the mixing effect of droplets and gas, there is a series of similar geometrical models of the bottom with 37, 61, and 127 nozzles were established. The boundary conditions and spray parameters are according to the Table 1 six groups of conditions to set, to compare the cooling effect with different spray parameters and boundary conditions, and the water flow is according to suppose temperature is reduced by 15 K. The total flow of the spray is q = $9.9969\cdot10^{-3}$ kg/s, except the case with different air velocity, because the gas flow change with the gas speed. And the water flow is calculated in the same way as before.

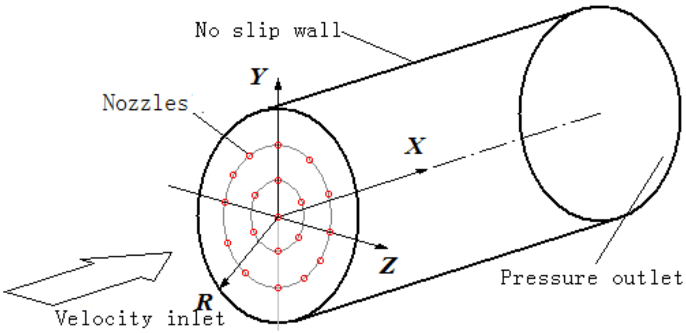

Figure 1: The schematic diagram of three-dimensional model

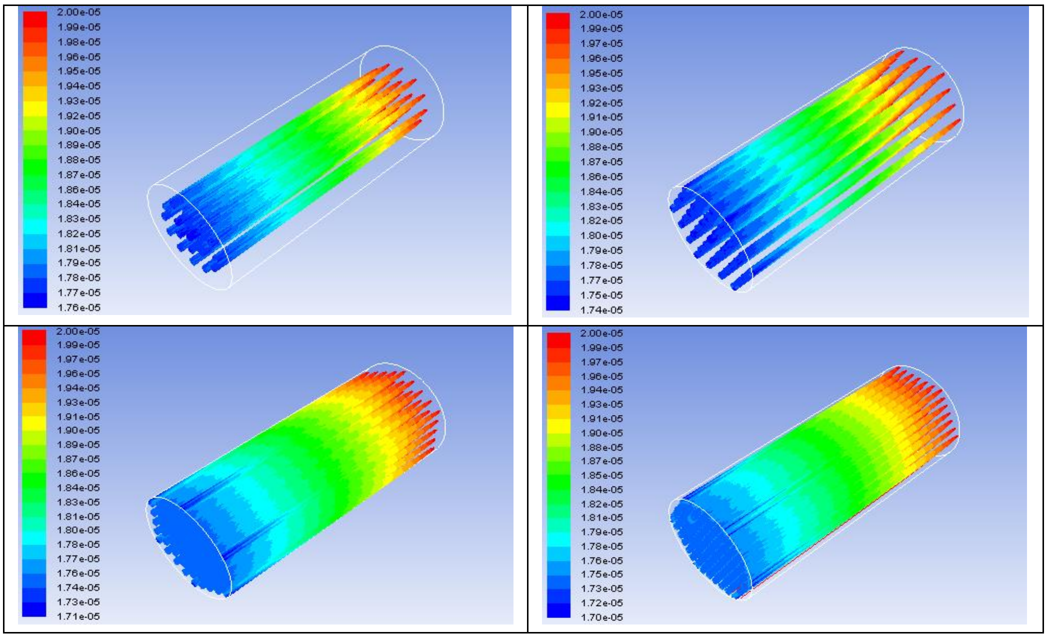

Figure 2: The droplet trajectories are displayed by the droplet size variation

Table 1: Boundary condition and spray parameters

	Numbers	Droplet speed m/s	Cone °	Droplet size µm	Air temperature K	Air velocity m/s
1	19,37,61,127	10	100	20	413	100
2	127	5,10,15,20	100	20	413	100
3	127	10	80,90,100,110	20	413	100
4	127	10	100	10,15,20,30,40	413	100
5	127	10	100	20	383,393,403,413	100
6	127	10	100	20	413	25,50,75,100

4. Results and discussion

In the following section, firstly, the effects of different nozzles, droplet initial velocity, spray cone angle and droplet size on the evaporation efficiency were analysed. And authors explored the effects of different gas temperature and different gas velocities on the droplet evaporation based on former results.

4.1 Effect of nozzle numbers on droplet evaporation and transport

The initial velocity of the droplets that can be reached from the nozzle is limited and the velocity of the gas in the flow channel is much higher than the initial velocity of the droplet, and the droplets are dragged by the air stream, so that the droplets and the gas cannot be sufficiently mixed and the cooling effect is poor. Enhancing gas-liquid mixing is an important way to improve the efficiency of evaporation, so try to increase the number of nozzles to enhance the mixing effect. The change in the evaporation efficiency and the outlet temperature was analyzed by changing the number of nozzles (19, 37, 61, 127) when the total flow rate of the injected cooling water was constant, the boundary conditions and spray parameters are set according to Case 1 in Table 1. With the increasing of the number of nozzles, the mixing between the gas and liquid has improved better, the more the number of nozzles, the more gas-liquid heat transfer area, the evaporation of water droplets more complete. As shown in Figure 3(a), the average temperature of the outlet decreases as the number of nozzles increases, and a significant increase in the evaporation rate. By the limit of flow space, the evaporation efficiency changes are relatively small, almost no significant increasing when the number of nozzles increased to 61, 127. Taking the actual material stress into account, it is not advisable to continue to increase the number of nozzles.

4.2 Effect of particle initial velocity on droplet evaporation and transport

The initial velocity of the droplets and the spray cone angle are important parameters of the nozzle, which determines the velocity and trajectory of the droplets. The effect of the initial velocity (5 m/s, 10 m/s, 15 m/s, 20 m/s) on the cooling effect was analyzed by setting the boundary conditions and the spray parameters according to Table 1, Case 2. As shown in Figure 3(b), the evaporation rate increased when the spray rate changed, but the change is not obvious due to the excessive gas flow rate. Theoretically, there is a certain speed difference between the gas and liquid is more conducive to the mixing and heat transfer. However, because the gas flow rate is relatively large, the water droplets are injected and dragged by the drag force, the trajectories of the droplets are basically followed the trajectories of the airflow. Therefore, the evaporation efficiency is not obvious increased when the droplet velocity is changed.

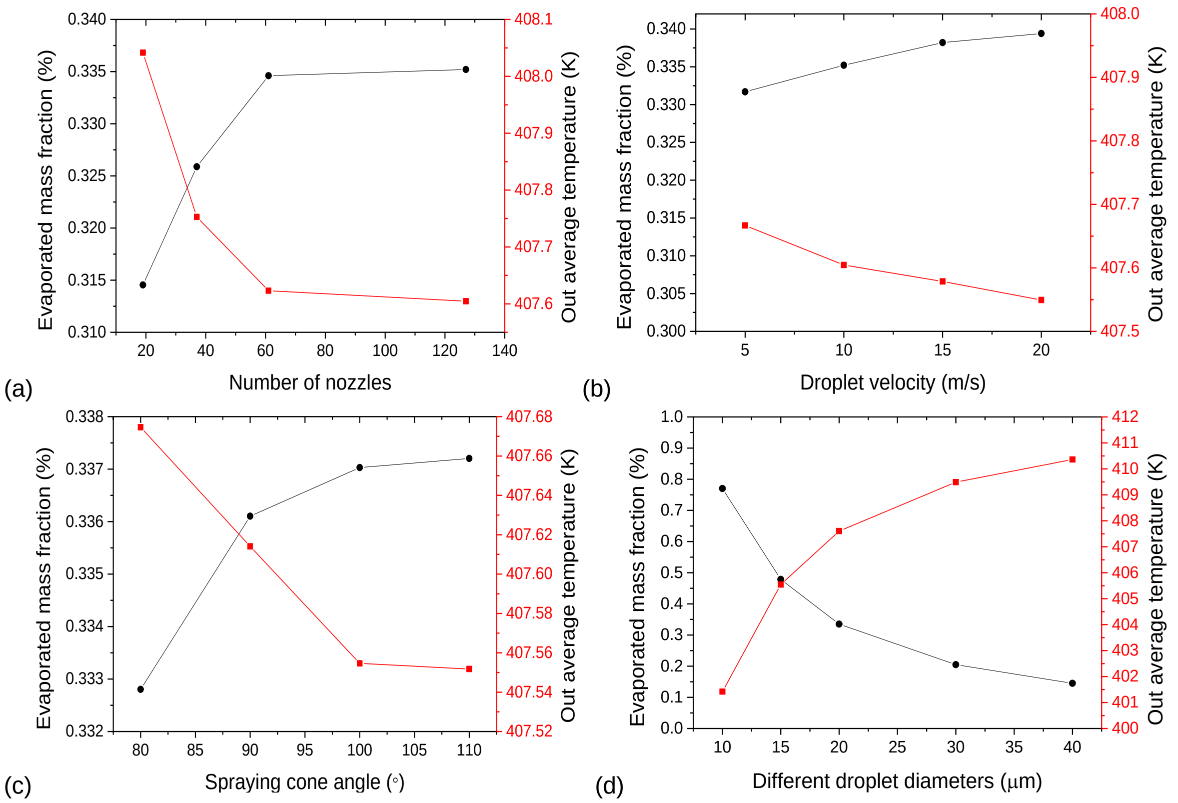

Figure 3: The out average temperature and evaporated fraction changed with different spray parameters: (a) the nozzle numbers, (b) the liquid velocity, (c) the spray cone angle, (d) the initial diameter of droplets

4.3 Effect of spraying cone angle on droplet evaporation and transport

The spray cone angle is also one of the important parameters to determine the performance of the nozzle. The spray cone angle determines the initial expansion direction range of the droplet, which is an important parameter that affects the mixing of gas and droplets. The influence of the spray cone angle (80, 90, 100, 110 °) on the cooling effect was analysed by setting parameters according to Table 1, Case 3. In general, the larger the spray cone angle is, the more beneficial to the diffusion of the droplet after discharge, so that the distribution of droplets is wider and the contact area between the gas and the droplets is improved. As shown in Figure 3(c), with the increase of the spray cone angle, the evaporation efficiency increased, but the growth trend is obviously weakened. As described in 4.1.2, the gas flow velocity is big. The droplets are dragged by the drag force after sprayed out. The droplet does not diffuse and is trapped by the airflow. The trajectory of the droplet changes basically with the trajectory of the airflow. Consequently, the evaporation efficiency is not obvious increased when the spray cone angle is changed.

4.4 Effect of particle initial size on droplet evaporation and transport

Droplet size is one of the important parameters that affecting spray cooling. The effect of the initial particle size (10, 15, 20, 30, 40 μm) on the cooling efficiency was analysed by setting the boundary conditions and the spray parameters according to Table 1, Case 4. As shown in Figure 3(d), the average temperature of the outlet is significantly increased as the initial diameter of the droplet increases, and the evaporation rate decreases significantly. 20 % improvement in evaporation rate was achieved by decrease droplets diameter from 40 to 20 μm. Smaller droplets evaporate faster because they provide more surface area per unit volume than larger droplets and evaporation only occurs at the water/air interface. Evaporation rate per unit volume of droplets in gaseous media is related to the square of the droplet diameter and increases rapidly when droplet diameter is decreased. At present, the minimum spray size of the project is about 20 μm, then select the model of the spray cone angle of 100°, droplet velocity of 10 m/s and 127 nozzles to investigate the effect of air velocity and temperature on the evaporation efficiency.

4.5 Effect of inlet gas temperature on droplet evaporation

With reference to the results of 4.1, select the optimal value of the parameters to analysis the effect of gas flow velocity and the initial temperature on the evaporation rate. The spray parameters were set according to the Case 5 in Table 1 to analyse the effect of the inlet air temperature on the cooling effect. As shown in Figure 4(a), with the inlet temperature decreases, the difference between the inlet temperature and the average outlet temperature is significantly reduced and the droplet evaporation rate decreases. When the gas temperature is high, the heat transfer temperature variations are large, the evaporation rate is high, and the cooling effect is remarkable. It showed that 8 % improvement in evaporation rate was achieved by increase gas temperature from 383 K to 413 K.

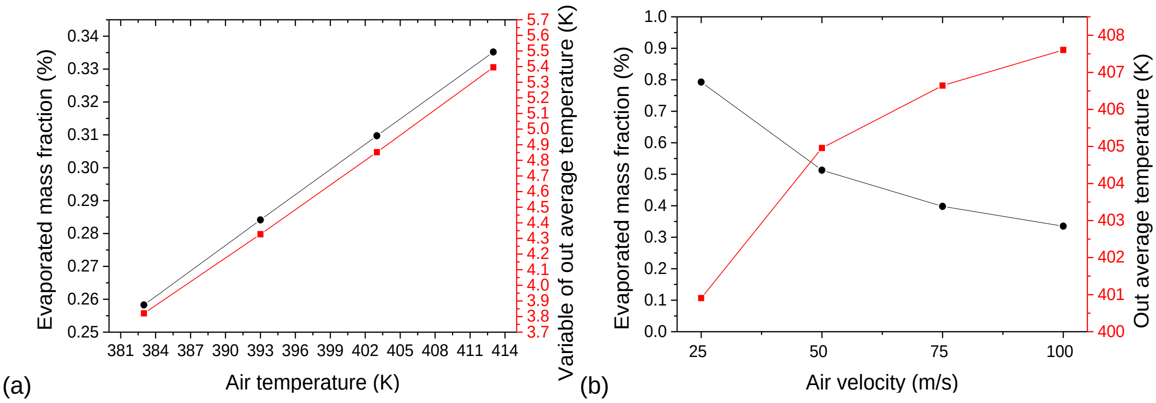

Figure 4: The out average temperature and evaporated fraction changed with different: (a) inlet gas temperature; (b) inlet gas velocity.

4.6 Effect of inlet gas velocity on droplet evaporation

Air velocity had a large influence on droplet trajectory and evaporation efficiency. The effect of air velocity was investigated comparing four air velocities (25 m/s, 50 m/s, 75 m/s, 100 m/s) under the same ambient condition according to Case 6 in Table 1. As shown in Figure 4(b), the evaporation rate is significantly increased from 34 % to 80 % as the air flow velocity decreases from 100 m/s to 25 m/s. On the one hand, because the difference of airflow velocity and droplet speed is very large, the droplet spray from nozzles will soon be the same as the gas flow velocity due to the drag force. The flow path is small, the flow conditions are harsh, and the smaller flow velocity means longer evaporation time, which is beneficial to the increase of evaporation rate. On the other hand, with the decrease of the air velocity, the effect of airflow on the droplet trajectory is weakened, the droplet diffusion is enhanced, the gas-liquid mixing is enhanced, and the heat transfer efficiency is improved by increasing the heat transfer area.

5. Conclusions

The main conclusions from this study are as follows:

1. The flow path size is small, it is difficult to add gas-liquid mixing device to enhance heat transfer, but increasing the number of nozzles can increase the mixture, and improve the evaporative cooling effect.
2. Smaller droplets evaporate faster because they provide more surface area per unit volume than larger droplets and evaporation only occurs at the water/air interface.
3. When the gas temperature is high, the heat transfer temperature variations are large, the evaporation rate is high, and the cooling effect is remarkable.
4. With the decrease of the air velocity, the effect of airflow on the droplet trajectory is weakened, the droplet diffusion is enhanced, the gas-liquid mixing is enhanced, and the heat transfer efficiency is improved by increasing the heat transfer area.

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