Numerical study on film cooling characteristics of BESA hole with water mist/air two-phase flow

Huang Kang, Shi Pei-jie*, Jiang An-lin, Ma Hu-sheng
China Aerodynamics Research and Development Center, Mianyang 621000, China

Shipeijie@cardc.com; huangkang@cardc.com

Abstract. In view of a new type of film cooling hole, the backward-expanding shoulder arm (BESA) hole proposed by the author, a numerical model of two-phase flow film cooling with water mist is established. The numerical simulation of water mist / air two-phase flow film cooling characteristics shows that the comprehensive performance of water mist / air two-phase flow film cooling is significantly improved compared with pure air film cooling. For the round hole plate model, when the blowing ratio is 0.5, the film cooling efficiency of two-phase flow film cooling with 2% water spray is 37.5% higher than that of pure air film cooling (20D from the film hole outlet). When the blowing ratio is 1.0, the film cooling efficiency of the flat two-phase flow with 2% water spray is 49.0% higher than that of the pure air film cooling (20D away from the film hole outlet). When the spray amount of water is the same, the film cooling efficiency of the BESA hole is higher than that of the round hole, the expanding hole and the shoulder arm hole. For the flat film cooling model of the BESA hole, when other factors remain unchanged, the cooling efficiency of the two-phase flow film increases monotonously from 2% to 5%. The cooling characteristics of the two-phase flow film on the pressure surface of the turbine blade of the BESA hole are similar to those of the flat model, and the film coverage effect is better than that of the round hole, the expanding hole, and the shoulder arm hole.

1. Introduction
As one of the main cooling modes of gas turbine components, film cooling is widely used in turbine end wall, blade leading edge and blade trailing edge of gas turbine[1-3]. As the expected performance of gas turbines continues to improve, the contradiction between cooling demand and cooling gas volume becomes increasingly prominent: on the one hand, the amount of air used for cooling turbines in some advanced gas turbines has reached as high as 15%~20%, a large amount of high-pressure air used for
cooling will inevitably lead to the loss of power plant performance; on the other hand, while increasing the air compression ratio, it will inevitably increase the temperature of cooling air (the cooling air temperature of advanced gas turbine has reached 900K), reduce its heat absorption capacity, and make cooling more difficult[4-9]. Therefore, how to further tap the potential of film cooling technology and improve the effect of film cooling is one of the technical difficulties faced by heat transfer researchers.

A lot of research shows that improving the structure parameters such as film cooling hole type, film incidence angle and hole spacing can improve the film cooling effect. In recent years, researchers in the United States, Russia and other countries have found that spraying a small amount of water mist into the cooling gas can significantly improve the film cooling efficiency, which provides another feasible solution to the current contradiction between cooling demand and cooling gas volume.

In this paper, the heat transfer problems in two-phase flow film cooling with different film cooling hole and water mist / air two-phase flow film cooling mode are studied by means of steady numerical simulation, especially the backward-expanding shoulder arm(BESA) hole proposed by the author earlier.

2. Physical model
In order to reduce the computational complexity and facilitate the study of single influencing factors, a simplified physical model of the main flow gas and cooling air passages from the compressor exhaust port to the cooling stave surface is established. Fig. 1 is a flat film cooling model similar to the small curvature section of a turbine blade and Fig. 2 is a single channel turbine blade model. The main shapes of the film holes involved in this study are round hole, expanding hole, shoulder arm hole and backward-expanding shoulder arm(BESA) hole. The flow path diagrams of the holes involved are shown in Fig. 3, and the entrance diameters of the holes are the same. The shoulder arm hole is composed of a main jet hole and two side holes with an angle of 30 deg to the mainstream[10]. They are all round holes. The diameter d of the two side holes is half of the diameter D (D=3mm) of the main jet hole, and the width of the two side holes is 3D. The structure of the backward-expanding shoulder arm(BESA) hole is that the central plane of the two sides of the hole is inclined backward, and the angle between the central plane of the main jet hole and the central plane of the main jet hole is 10 deg. The main jet hole adopts a progressively expanding hole with an expansion angle of 5 deg. The expansion angle of expanding hole is 5 deg[11].

![Figure 1. Computing domain of flat model.](image1.png)  
![Figure 2. Computational domain of turbine blade model.](image2.png)
3. Numerical model and verification

3.1. Computational model
The volume fraction of water mist particles involved in this paper is less than 10%, so Discrete Phase Model is used to calculate the discrete phase. Assuming that the second phase is very sparse, the interaction between particles and particles and the effect of volume fraction on the continuous phase can be neglected. When particles are treated as discrete particles, the continuous phase flow field is first calculated, and then the force on each particle is solved by combining the flow field variables to obtain the particle velocity, so as to track the trajectory of each particle. The discrete phase model can not only calculate the trajectories of these particles, but also calculate the heat and mass transfer caused by the particles. In the process of calculation, the coupling between phases and the influence of the coupling results on the trajectories of discrete phases and the flow of continuous phases can be taken into account.

The interaction between droplets and walls is caused by many complex factors, such as wall material, solid wall temperature, wall roughness, incident angle of particles, incident velocity of particles, wall liquid film and so on. Because the inner surface temperature of the pipeline is higher than the boiling temperature of water, wall-jet model is used to deal with the process of droplet impingement.

In this paper, SST turbulence model is selected in the calculation process. The inlet turbulence is 5%. The inlet velocity of cooling gas is determined by the corresponding blowing ratio. The mainstream temperature is 1600K and the cooling gas inlet temperature is 800K. In order to calculate the adiabatic film cooling efficiency conveniently, the adiabatic wall is adopted. The two sides of the main gas channel are set as periodic boundary conditions; the wall velocity does not slip, and the convergence residual is less than $10^{-5}$ in the whole calculation process. Mass flow rate is 2%, 3.5% and 5%; main gas temperature is 1600K; droplet diameter is 10 μm.

3.2. Parameter definition and feasibility analysis of computing model
a. Blow ratio $M$

$$M = \frac{\rho_c U_c}{\rho_m U_w}$$ (1)
In the formula, $\rho_c$ is the density of the cooling gas and $\rho_m$ is the density of mainstream gas, $U_c$ is the velocity of the cooling gas and $U_m$ is the velocity of mainstream gas.

b. Adiabatic film cooling efficiency $\eta_{aw}$

$$\eta_{aw} = \frac{T_m - T_{aw}}{T_m - T_c}$$  \hspace{0.5cm} (2)

In the formula: $T_m$ - mainstream temperature, $T_c$ - cooling temperature, $T_{aw}$ - adiabatic wall temperature. It can be seen that the adiabatic film cooling efficiency is actually a dimensionless temperature value, hereinafter referred to as cooling efficiency.

c. Directional average adiabatic film cooling efficiency $\bar{\eta}_{aw}$

At present, the spread average adiabatic film cooling efficiency is widely used, which reflects the comprehensive cooling effect of a row of holes on downstream coverage, and has more practical significance in engineering. Therefore, the development of cooling efficiency along the mainstream direction is assessed by the spread average adiabatic film cooling efficiency in this project. Assuming that the spreading direction is x and its width is p, the spreading average adiabatic wall temperature is defined as:

$$\bar{T}_{aw} = \frac{1}{p} \int_0^p T_x \, dx$$  \hspace{0.5cm} (3)

The extended average cooling efficiency is defined as:

$$\bar{\eta}_{aw} = \frac{T_m - \bar{T}_{aw}}{T_m - T_c}$$  \hspace{0.5cm} (4)

$T_m$ - Mainstream temperature, $T_c$ - cooling temperature and $\bar{T}_{aw}$ - average adiabatic wall temperature. In this paper, the spread width p is taken as three times of the inlet diameter D of cooling gas.

3.3. Computing model verification

In order to verify the numerical calculation model in this paper, a geometric model with the same experimental conditions as in reference[12] is established. The comparison between the numerical calculation results and the experimental results is shown in Fig. 4. Although the calculated values are different from the experimental values, the trend of the numerical calculation model in this paper is in good agreement. It shows that the numerical calculation model established in this paper can be used for the trend comparison and analysis of various schemes.
Figure 4. Film Cooling Efficiency of Circular Hole Center Line at M=0.5.

4. Analysis of calculation results

4.1. Effect of Spray Rate of Water Mist on Cooling Air Temperature and Physical Properties

Fig.5 shows the average temperature ratio and constant pressure specific heat ratio of the cooling air at the outlet of the film cooling hole of the circular-hole flat-plate model when the blowing ratio is 1.0 with different water spraying quantity. It can be seen from the figure that: the average temperature of cooling air at the outlet of film hole decreases significantly with the increase of water mist injection; the average specific heat capacity of the cooling medium at the outlet of the film hole increases gradually with the increase of water mist injection.

This is mainly because the latent heat of vaporization of water reduces the temperature of cooling medium, and the specific heat capacity of water at constant pressure is larger. When water and cooling gas are mixed, the specific heat capacity of cooling medium at constant pressure is larger than that of pure air.

Figure 5. The influence of different water sprays on cooling air properties.
4.2. Effect of Spray Rate of Water Mist on Film Cooling in Two-Phase Flow of Flat Plate

Fig. 6 is a comparison of the extended average film cooling efficiency under different spray rates. It can be seen from the figure that the comprehensive performance of film cooling of water mist/air two-phase flow is significantly improved than that of traditional pure air film cooling. When the blowing ratio is 0.5, the film cooling efficiency of flat two-phase flow with 2% water injection is 37.5% higher than that of pure air film cooling at x/D=20. When the blowing ratio is 1.0, 2% water injection is added. Compared with pure air film cooling, the film cooling efficiency of flat plate two-phase flow at x/D=20 increases by 49.0%.

In order to further analyze the influence of water mist injection rate on film cooling effect of two-phase flow film cooling scheme with circular hole, the film cooling efficiency distribution on the cooling wall surface of two-phase flow film cooling with different water mist injection rate was analyzed in detail when blowing ratio was 0.5 and 1.0. Fig. 7 shows the distribution of adiabatic film cooling efficiency on the cooling stave of two-phase flow film cooling schemes with different water mist injection rates at blowing ratios of 0.5 and 1.0. After adding micro water mist into the cooling gas, the film cooling efficiency values along the downstream and forward direction of the film hole center line is significantly increased, and the value increases with the increase of water mist injection.

**Figure 6.** The influence of water injection rate of the circular hole on the spread average film cooling efficiency.

**Figure 7.** In this case simply justify the caption so that it is as the same width as the graphic.
4.3. Effect of hole geometry on Film Cooling of Flat Two-Phase Flow

Fig. 8 and Fig. 9 show the effects of different hole geometry on the film efficiency of two-phase flow under the conditions of blowing ratio 0.5 and blowing ratio 1.0, respectively, when the spray amount of water mist is 2%, 3.5% and 5%. It can be seen from the figure that the film cooling efficiency of two-phase flow in the scheme of the backward-expanding shoulder arm (BESA) hole is the highest, followed by expanding hole, and Shoulder-Arm hole is slightly higher than that of round hole, and the trend is more obvious with the increase of spray amount. It can be seen that the method of adding micro water mist to the cooling gas, combined with the selection of suitable hole geometry, can achieve better protection of the cooling stave surface under the same consumption of cooling gas. When other factors remain unchanged, the film cooling efficiency of BESA hole of two-phase flow increases monotonously with the increase of water mist injection from 2% to 5%.

In order to further explore the influence of hole geometry on film cooling efficiency of two-phase flow film cooling scheme, the film cooling efficiency distribution on the cooling stave surface of two-phase flow film cooling scheme with different hole geometry at blowing ratio of 1.0 was analyzed. Fig. 10 shows the distribution of adiabatic film cooling efficiency on the cooling stave of two-phase flow film cooling schemes with different hole geometry when blowing ratios at 1.0. It can be seen from the figure that the effective film coverage area of the four types of holes increases with the increase of water mist injection. Under the same water spray amount, the film cooling coverage of the backward-expanding shoulder arm (BESA) hole scheme is more uniform than that of the round hole, shoulder arm hole and progressively enlarged hole not only in the mainstream streamline direction, but also in the spreading direction.

![Figure 8](image.jpg)

**Figure 8.** The effect of hole geometry on the spread average film cooling efficiency when $M = 0.5$ with different water mist.
Figure 9. The effect of hole geometry on the spread average film cooling efficiency when $M = 1.0$ with different water mist.

![Graphs showing film cooling efficiency with different water mist and hole geometry.]

Figure 10. Effect of hole geometry on Film Cooling Efficiency Distribution with Different Water Mist Injection Rates when $M = 1.0$.

4.4. Effect of hole geometry on Two-Phase Flow Film Cooling of Turbine Blades

In order to study the effect of different hole geometry schemes on film cooling of two-phase flow in turbine blade, a row of film cooling holes were arranged on the pressure surface of turbine cascade with water mist injection rate of 2%.

Fig. 11 shows the film cooling efficiency distribution of different hole geometry schemes on the pressure surface of the turbine cascade. The blowing ratio of the cooling hole on the pressure surface is 1.0. From the figure, it can be seen that the air film distribution on the pressure surface is very uniform in scheme of BESA hole, and the blade surface can be well protected. The shoulder arm hole and the expanding hole form a good effective gas film covering along the main stream streamline direction on the pressure surface, but the coverage effect is slightly worse than that of the BESA hole.
scheme. The film cooling efficiency of the round hole scheme is lower than that of the other three hole schemes.

From the above results, it can be seen that the research results of different hole geometry schemes on the turbine cascade are basically the same as those obtained in the plate model. The film cooling effect of two-phase flow can be significantly improved by the use of BESA holes on flat plate model and turbine blade.

![Distribution Chart of Film Cooling Efficiency on pressure Surface of Turbine Blade.](image)

**Figure 11.** Distribution Chart of Film Cooling Efficiency on pressure Surface of Turbine Blade.

5. **Conclusion**

Through the study of film cooling characteristics of two-phase flow in flat plate model and turbine stator blade model with different water spray quantity, water spray location, blowing ratio, hole geometry, the following understandings are obtained:

1. Compared with single-phase pure air film cooling, the adiabatic film cooling performance of mist/air two-phase flow is significantly improved. For the circular hole plate model, when the blowing ratio is 0.5, the film cooling efficiency of two-phase flow with 2% water injection is 37.5% higher than that of pure air film cooling. When the blowing ratio is 1.0, the film cooling efficiency of two-phase flow with 2% water injection is 49.0% higher than that of pure air film cooling.

2. Under the same blowing ratio and other conditions, the spray volume of water mist increases from 0% to 5%, the dimensionless temperature of the mixture of cooling gas and water mist decreases from 1.0 to 0.498, and the dimensionless specific pressure heat capacity increases from 1.0 to 1.223.

3. Under the same blowing ratio and other conditions, the spray amount of water mist increases from 2% to 5%, and the spreading average film cooling efficiency of two-phase flow increases gradually, showing a monotonic increasing trend.

4. The effect of different hole geometry types on film cooling of two-phase flow was studied. It was found that, under the same other conditions, the film cooling efficiency of BESA hole was significantly higher than that of expansion hole, Shoulder-Arm hole and round hole. It was concluded that choosing appropriate pass types in film cooling of two-phase flow could further improve the cooling effect.

5. The study of the effect of the hole geometry on the film cooling of two-phase flow in turbine blade shows that the effect of the hole geometry on the film cooling of turbine blade is similar to that
obtained from the study of plate film cooling. The use of the BESA hole in both flat plate model and turbine blade can significantly improve the two-phase flow Film cooling efficient.

References
[1] Zhu Uan-xin, Tan Xiao-ming, Guo Wen, et al. Numerical Simulation on Effects of Different Film Cooling Holes on Plat[J]. Journal of Propulsion Technology, Apr. 2013, Vol. 34 No. 4.
[2] Ge Shao-yan, Xu Jing-zhong. Film cooling[M]. Bei Jing: Science Press, 1985.
[3] LI Shao-hua, SONG Dong-hui, LIU Jian-hong, et al. Numerical Simulations of Flat Plate Film Cooling Using Respectively Different Shaped Jet Holes[J]. Proceedings of the CSEE, Vol. 26 No. 17 Sep. 2006.
[4] Leylek J. H., Zerkle R. D. . Discrete Jet Film-cooling: A Comparison of Computational Results with Experiments. ASME Journal of Transaction, 1994, 116: 358-368.
[5] Goldstein R. J., Eckert E. R., Burggraf F. . Effects of Hole Geometry and Density on Three-dimensional Film Cooling. International Journal of Heat Mass Transfer, 17: 595-607.
[6] Okita Y, Nishiura M. Film Effectiveness Performance of an Arrowhead-Shaped Film-Cooling Hole Geometry. Journal of Turbomachinery. 2007, 129(2): 331-339.
[7] Kusterer K, Bohn D, Sugimoto T, et al. Double-Jet Ejection of Cooling Air for Improved Film Cooling. Journal of Turbomachinery. 2007, 129(4): 809-815.
[8] Goldstein, R. J. Adv. Heat Transfer[M]. 1971, 7, pp. 321–379.
[9] Gustafson R., Mahmood G I, and Acharya S. Flowfield in a Film-Cooled Three-Dimensional Endwall Passage: Aerodynamic Measurements[C]. ASME Paper 2007, No. GT2007-28154.
[10] James D, Heidmann , Srinath Ekkad. A Novel Antivortex Turbine Film-Cooling Hole Concept[J]. Journal of Turbomachinery, JULY 2008, Vol.130/031020-1.
[11] Huang Kang, Ma Hu-sheng. Numerical simulation on cooling characteristics of plate film from backward-expanding shoulder arm hole [J]. ACTA AERODYNAMICA SINICA. 2017, Vol 35, No.6 886–889.
[12] Sinha A K, Bogard D G, Film cooling effectiveness downstream of a single row of holes with variable density ratio[J]. ASME Journal of Turbomachinery, 1991, 113(3); 441-449.
[13] Kapadia S, Roy S, and Heidmann J. First Hybrid Turbulence Modeling for Turbine Blade Cooling[J]. Thermophys Heat Transfer, 2004, 181, pp.154–156.
[14] Bunker R. S., Film Cooling Effectiveness Due to Discrete Holes Within a Transverse Surface Slot[C]. ASME Paper 2002, No. GT-2002-30178.
[15] Dhungel S, Phillips A, Ekkad S V, et al. Experimental Investigation of a Novel Anti-Vortex Film Cooling Hole Design[C]. ASME Paper No. GT2007–27419.
[16] Bogard D G, and Thole K A. Gas Turbine Film Cooling.[J]. Propul Power, 2006, 222, pp. 249–270.
[17] Ekkad S V, Ou S, and Rivir R. B. Effect of Jet Pulsation and Duty Cycle on Film Cooling From a Single Jet on a Leading Edge Model[C], ASME J. Turbomach., 2005, 128, pp. 564–571.
[18] Heng-jie Shan, Dao-rui Zhang, Rui-hua Li, et al. Analysis and Treatment of Vibration for an Adjustable Primary Axial Fan[J]. Chinese Journal of Turbomachinery, 2017(02).
[19] Ma Xin, Sun Lili, Chen Yan, et al. Design of Supported Thrust Bearing in Single Stage Recycle
Gas Compressor[J]. Chinese Journal of Turbomachinery, 2014(03).

[20] Chen Huaxin, Hou Bairong. Vibration Analysis and Solution of Rotor Blade Adjustable Axial Induced Draft Fan for 1000MW Thermal Power[J]. Chinese Journal of Turbomachinery, 2015(02).

[21] Zhang Dengchun, Chen Huanxin, Chen Yazhou, et al. Numerical Simulation of Internal Airflow Field in a Centrifugal Blower[J]. Chinese Journal of Turbomachinery, 2015(03).

[22] Jing Ling, Qian-kun Liu, Zhen-qin Ji, et al. Effect of the Cascade Solidity on the Performance of a Multi-blade Centrifugal Fan[J]. Chinese Journal of Turbomachinery, 2017(03).