Numerical Study on the Unsteady Film Cooling Characteristics of Turbine

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Abstract. In view of the main flow pulsation phenomenon and the new pulsating film cooling mode in the aeroturbine engine, the numerical calculation method is used to study the film cooling characteristics under the condition of the main flow velocity pulsation and cooling gas velocity pulsation with the classical circular film hole as the research object. In order to eliminate the influence of other factors on the film cooling characteristics of turbine blades as much as possible, a circular film hole of flat plate model similar to the small curvature section of turbine blades was established, and the influence of different cooling air pulse frequency, blowing ratio and mainstream pulse frequency on the film cooling characteristics was analyzed in depth. The results show that: with the increase of cooling air pulse frequency, the film cooling efficiency of cooling gas pulsation scheme can be achieved approximately the steady-state condition with blowing ratio of 1.0 while only half of the cooling air flow is consumed; at high blowing ratio, the cooling effect will be better when using the cooling air pulsating film cooling scheme compared with the steady-state scheme; in the main pulsating frequency range of the study, the frequency of main flow pulsation has little effect on film cooling efficiency.

1 Introduction

Film cooling is one of the main cooling methods of the hot parts of the aero gas turbine engine, which has been widely used in the leading edge, basin, back and tail edge of the turbine blades[1]. At present, about 20%–25% of compressor flow is used to cool turbine components in high-performance aeroturbine engine. This part of gas not only does not participate in thermal cycle, but also produces a lot of flow and mixing losses in the process of flow in cooling channel and discharge from film hole into main stream. Therefore, turbine cooling designers have been trying to ensure the cooling effect and reduce the cooling gas consumption as much as possible. In order to achieve this goal, it is necessary to have a clear understanding of the film cooling characteristics in the actual working process of turbine blades.

In the past many related literatures[2-8], the research on the film cooling technology is mainly focused on the influence of aerodynamic parameters and structural parameters such as the shape and arrangement of the film holes and the blowing ratio on the cooling effect of turbine blades. Few people pay attention to the research on the characteristics of
pulsating film cooling. In fact, the flame combustion of almost all engines is highly pulsating, so the high-temperature gas entering the turbine is also pulsating (temperature and pressure). This pulsation causes the change of the outlet pressure of the film hole of the turbine blade, and then causes the pulsation of the air-conditioning injection. The other reason is that the relative motion of the turbine stator and the rotor makes the aerodynamic parameters in the passage of the cascade occur around the periodic pulsation will also lead to the periodic change of the injection quantity of the air film hole on the blade.

Whether the film cooling structure designed under the steady condition can effectively deal with the pulsation of the mainstream gas, and whether it can make use of the periodic pulsation characteristics of the mainstream, and control the cooling gas supply to a regular pulsation form correspondingly, so as to realize the fine design of film cooling and reduce the consumption of air-conditioning, is still a problem that needs further research.

In this paper, the classical circular hole of flat plate model is taken as the research object, and the film cooling characteristics under the condition of main flow velocity fluctuation and cooling gas velocity fluctuation are studied to obtain the film cooling characteristics under the unsteady condition and the potential to further improve the film cooling efficiency by combining the pulsating cooling gas control.

2 Numerical model and verification

2.1 Physical model

The calculation domain and geometry of film hole channel of this paper is shown in Figure 1. The shape of the gas film hole adopts the classic round hole. The diameter of the inlet of the round hole is \( d = 3 \text{mm} \), and the length diameter ratio is 4.

![Figure 1. Calculation domain of plate model and geometry of film hole channel.](image)

2.2 Calculation model

In the research process of this paper, the steady-state simulation method and the transient simulation method are used. The \( k - \omega \) turbulence model is used in the turbulence model, and the solid surface is treated by non slip adiabatic wall. Air is used as the flow medium in the calculation of cooling gas and high-temperature mainstream. In order to ensure the convergence effect of the calculation results, the RMS of each physical residual is taken as an important detection index, which is required to be reduced to less than \( 10^{-5} \) in the calculation.

In the calculation of the main flow pulsation and cooling air pulsation scheme, the basic flow parameters selected are the same as the steady-state calculation conditions, except that the inlet boundary of the main flow/cooling air is given differently, the inlet speed is given according to the sine wave change rule, the given rule is \( u = u_0 + a \sin (b \cdot t) \), \( u_0 \) is the steady-state speed corresponding to the time average value, \( u \) is the instantaneous speed, \( a \) is the amplitude of pulsation, and the period is \( t = 2 \pi/b \).

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In the study of the effect of pulsating cooling gas on the cooling performance of flat gas film cooling, the main flow velocity is 102 m/s, the cooling gas velocity is given according to the time average of corresponding blowing ratio, the main flow temperature is 1450 K, and the cooling temperature is 725 K. In this paper, there are three kinds of cooling air pulse frequency: 15.9 Hz, 159.2 Hz and 1592 Hz. There are three kinds of blowing ratio schemes: 0.5, 1.0 and 1.5.

In the study of the influence of the main flow pulsation on the cooling performance of flat film cooling, the time average value of the main flow velocity is 102 m/s, the cooling gas velocity is given according to the corresponding blowing ratio, the main flow temperature is 1450 K, and the cooling temperature is 725 K. In this paper, there are three main pulse frequencies: 15.9 Hz, 159.2 Hz and 1592 Hz. The parameter definition and verification of calculation model is same as reference [9].

3 Analysis of calculation results

3.1 Effect of cooling air pulse frequency on cooling efficiency of flat film

In this section, the film cooling efficiency of different cooling air pulse frequency schemes is compared. In the comparison schemes, the instantaneous maximum blowing ratio is 1.0, and the values of different pulse frequency schemes are 15.9 Hz, 159.2 Hz and 1592 Hz, respectively. The speed fluctuation of different cooling air pulse frequency schemes and the efficiency comparison results of the time average film cooling of different cooling air pulse frequency schemes are shown in Figure 3. It can be seen from the figure that with the increase of pulse frequency, the value of average film cooling efficiency increases. When the pulse frequency is 1592 Hz, the average film cooling efficiency is slightly higher than the steady-state scheme with blowing ratio of 1.0 in 3D < x < 10d along the streamline direction, and slightly lower than the steady-state scheme outside the interval. Therefore, it can be seen that the cooling air pulsation (sine wave) scheme is adopted with the increase of frequency, the film cooling efficiency of cooling pulse scheme can be achieved approximately of steady-state condition with blowing ratio of 1.0 while half of cooling gas consumption is consumed.

![Figure 3. Velocity fluctuation of different cooling air pulse frequency schemes and comparison of time average film cooling efficiency.](image)

In order to further analyze the reason for the increase of time averaged film cooling efficiency with the increase of cooling air pulse frequency. For different pulse frequency schemes, the instantaneous film cooling efficiency at dimensionless time such as T/4, T/2, 3T/4 and T is compared, and the comparison results are shown in Figure 4. It can be seen
from the figure that the cloud chart of film cooling efficiency distribution in T/4, T/2 and T dimensionless time is not different for different cooling air pulse frequency; the cloud chart of film cooling efficiency distribution in 3T/4 dimensionless time is obviously different and increases with the increase of cooling air pulse frequency.

Figure 4. Comparison of film cooling efficiency of different cooling air pulse frequency schemes.

3.2 Effect of blowing ratio on cooling efficiency of pulsating film cooling

In this section, the scheme with pulsating frequency of 1592Hz and instantaneous maximum blowing ratio of 0.5, 1.0 and 1.5 respectively is compared with the scheme with steady blowing ratio of 0.51.0 and 1.5. The comparison results are shown in Figure 5. It can be seen from the figure that: when blowing ratio of 0.5, the average cooling efficiency of steady-state scheme is higher than that of pulsating film cooling scheme. When the blowing ratio is 1.0, the average film cooling efficiency along the streamline direction is slightly higher than that of the steady-state scheme with blowing ratio of 1.0 in 3D < x < 10d and slightly lower than that of the steady-state scheme outside the interval. When the blowing ratio is 1.5, the pulse cooling gas scheme can obtain higher average film cooling efficiency after x > 2D. Therefore, in the case of high blowing ratio, the pulsating film cooling scheme may achieve better cooling effect while only half of gas consumption compared with the steady-state scheme.
3.3 Comparison of film cooling efficiency with different mainstream pulsation frequency

In this section, the pulsation amplitude is 10m / s, and the time averaged average film cooling efficiency of different mainstream pulsation frequency schemes is compared. In the comparison scheme, the time averaged blowing ratio is 1.0, and the values of different pulsation frequency schemes are respectively 15.9Hz, 159.2Hz and 1592Hz. The speed pulsation of different cooling pulsation frequency schemes and the time averaged film cooling efficiency of different schemes is shown in Figure 6. It can be seen from the Figure 6 that the average value of the time average film cooling efficiency in one cycle has little difference with the instantaneous film cooling efficiency distribution in the same dimensionless time, which shows that the main flow frequency has little influence on the film cooling efficiency in the frequency range studied.
4 Conclusion

In this paper, the unsteady film cooling characteristics of the flat film cooling model with circular hole are studied, with the emphasis on the influence of the main flow/cooling pulse frequency and blowing ratio on the cooling efficiency of the adiabatic film. The main conclusions are as follows:

(1) With the increase of cooling air pulse frequency, the film cooling efficiency of pulse scheme can be achieved same as steady state scheme of M=1.0 while only half of cooling air is consumed;

(2) Compared with the steady-state scheme, the pulsating film cooling scheme can achieve better cooling effect at high blowing ratio;

(3) In the studied frequency range, the effect of mainstream frequency on film cooling efficiency is small.

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References