

Experiments on film cooling with sonic injection into a supersonic flow

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Abstract: Film cooling experiments with sonic injection were conducted to investigate the effects of the number of the injection holes, the mass flow ratio, and the hole spacing on the film cooling effectiveness. The mainstream was obtained by the hydrogen-oxygen combustion, entering the experimental section at a Mach number of 2.0. The nitrogen with ambient temperature was injected into the experimental section at a sonic speed. The measured mainstream recovery temperature was approximately 910 K. The mass flow ratio was regulated by varying the nitrogen injection pressure. The experimental results show that for the investigated cooling surface, the cooling effectiveness increases with the increase in the number of the injection holes with other parameters held constant. For a fixed cooling configuration, the cooling effectiveness increases with the increase in the mass flow ratio. Different from the subsonic film cooling, the optimal mass flow ratio is not observed. When the hole spacing is less than 4, no obvious difference is observed on the cooling effectiveness and lateral uniformity. With the mass flow ratio increasing further, this difference becomes much smaller. The shock wave also has an effect on the cooling effectiveness. Downstream the incident point of the shock wave, the cooling effectiveness is lower than that in the case without the shock wave.

Key words: supersonic film cooling; discrete hole; film cooling effectiveness; mass flow ratio; hole spacing

CLC number: V434

Document code: A

Nomenclature

A	area	T_r	recovery temperature
d	exit diameter of the injection hole	$T_{r,w}$	wall recovery temperature
H	distance between adjacent injection hole	$\dot{m}$	mass flow rate
Ma	Mach number	u	velocity
N	number of injection hole	x	distance downstream from injection point
Re	Reynolds number	η	film cooling effectiveness
s	height of the injection slot	λ	mass flow ratio
T	temperature	ρ	density
T_{aw}	adiabatic wall temperature		

Subscript

i	injection	∞	mainstream
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With the development of the space technology, the aerocrafts are expected to face much harsher thermal environment, which requires more effective heat protection methods. As a heat protection method, the supersonic film cooling was firstly proposed in 1960s. Goldstein

et al.^[1] has reported that compared with the subsonic film cooling, the supersonic film cooling can significantly increase the film cooling effectiveness. Consequently, the supersonic film cooling was widely used to protect the combustion chambers, rocket nozzles, nose cones, and

so on. It is also considered to be a promising way to protect the scramjet engine, especially in combination with the regenerative cooling^[2].

Previous investigations^[1-18] mainly tested or simulated the supersonic film cooling using a flat or axisymmetric surface with the film injected tangentially through the two-dimensional (2-D) continuous slots or concentrated 2-D discrete slots. However, the 2-D slots have two shortcomings: on one hand, it may destroy the structural integrity; on the other hand, it is difficult to manufacture the supersonic curved surface of the 2-D slot at small sizes. Considering the better structure integrity and easier manufacture, it is necessary to utilize the discrete axial symmetrical holes to achieve the supersonic film cooling.

In present paper, a series of experiments were conducted to investigate the supersonic film cooling using the discrete axial symmetrical holes. Mainstream was obtained by the hydrogen-oxygen combustion, entering the experimental section at a Mach number of 2.0. The nitrogen with ambient temperature was injected into the experimental section at a sonic speed. The influences of the number of the injection holes, the mass flow ratio, and the hole spacing on the film cooling effectiveness were experimentally investigated.

1 Experimental facility

Figure 1 shows the sketch of the experimental system. High pressure hydrogen and oxygen were reduced by the pressure regulator, and injected into the combustion chamber. High temperature gas with a total pressure of 0.92 MPa was obtained through the hydrogen-oxygen combustion. Through a Laval nozzle, the gas accelerated to a Mach number of 2.0, and then entered the experimental section. The nitrogen with ambient temperature was injected into the experimental section along the tangential direction at a sonic speed. A pressure regulator was used to adjust the injection pressure. The coolant temperature was measured using a thermometer, and the coolant mass flow rate was measured using a mass flowmeter.

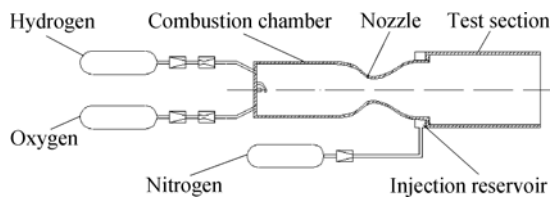


Fig. 1 Sketch of experimental system

Figure 2 shows the experimental section which was a straight pipe with the rectangular cross section. One of the surfaces was cooled by the film coolant. The experimental section was made of stainless steel with a thickness of 2.5 mm. On the outside surface of the experimental section, a total of 56 thermocouples were arranged in four lines along the flow direction. The distance between each line was 2 mm. In each line, the first thermocouple was 18 mm downstream of the injection point, and the distance between each thermocouple was 10 mm. At the exit of the coolant injection hole, another thermocouple was also installed to measure the film recovery temperature. The thermocouples were the standard K-type thermocouples with a diameter of 0.23 mm. Each thermocouple was connected with a transmitter whose range is 273–1073 K. Through the calibration, it is obtained that the total error of the thermocouple was 1%.

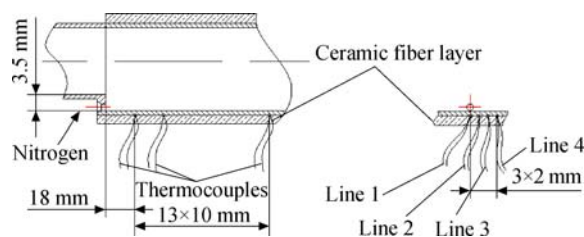


Fig. 2 Sketch of experimental section

To get the adiabatic condition, the radiation and convection from the outer wall to the surrounding should be avoided. Consequently, the experimental section was covered with the ceramic fiber which had a thickness of 4 mm. A thermocouple was installed on the outside surface of the ceramic fiber to assess the adiabatic performance. During the experiments without the film, the temperature of the outside surface

was about 335 K. According to the formula of heat transfer^[19], the heat flux between the ceramic fiber and surrounding was about 12 W, which was less than 1% of the heat generated in the combustor. Consequently, the good adiabatic condition can be expected in present experiments.

The experimental measurement system adopted the system of National Instruments (NI) made in the U. S. A. The total errors of the sensors and measurement system were less than 2.5%.

2 Experimental procedure

In the supersonic film cooling, the film cooling effectiveness is defined as

$$\eta = \frac{T_{r\infty} - T_{aw}}{T_{r\infty} - T_{ri}} \quad (1)$$

where $T_{r\infty}$ is the mainstream recovery temperature, and T_{ri} is the injection recovery temperature, respectively. The 2-D film cooling effectiveness is as a function of $x/(h_0)$. The mass flow ratio is defined as

$$\lambda = \frac{\rho_i v_i}{\rho_\infty v_\infty} \quad (2)$$

where ρ_i and ρ_∞ are the density of the injection and mainstream; v_i and v_∞ are the velocities of the injection and mainstream, respectively. According to the law of conservation of mass, the mass flow ratio can be obtained as

$$\lambda = \frac{q_{mi}/A_i}{q_{m\infty}/A_\infty} \quad (3)$$

where q_{mi} and $q_{m\infty}$ are the mass flow rates of the injection and mainstream; A_i and A_∞ are the outlet area of the injection and mainstream, respectively.

The mainstream mass flow rate, $q_{m\infty}$, was controlled by the sonic nozzles installed in the hydrogen and oxygen pipes. The flow characteristics of the sonic nozzles were calibrated in advance. During the experiments, the pressure regulator was used to adjust the inlet pressure of the sonic nozzles. When the inlet pressure reached the set value, the set mass flow rate can be expected. The injection mass flow rate, q_{mi} ,

was directly measured by a Coriolis force mass flowmeter made in Germany. The maximum range of the mass flowmeter was 42 g/s, and the measurement accuracy was 1%. The injection mass flow rate was adjusted by varying the injection pressure.

The adiabatic wall temperatures without injection were measured in three times to experiment the homogeneity and repeatability of the experimental results. The first and second experiments were performed before the experiment, while the third test was done after all the experiments.

Figure 3 shows three adiabatic wall temperature profiles on line 1. An obvious expansion process occurs when the mainstream flows past the step. Consequently, the adiabatic wall temperature is not a constant value, and increases along the flow direction. The minimum temperature is obtained at the entrance of the test section. Three profiles are basically identical, and the maximum difference is 10 K at the same location, which is only 1.2% of the maximum temperature. The averaged measurement is adopted as the mainstream recovery temperature $T_{r\infty}$. Figure 4 shows the mainstream recovery temperature profiles on four lines, which are basically identical. The maximum difference at the same location is about 11.3 K, which is only 1.2% of the maximum temperature.

The film cooling began when the experi-

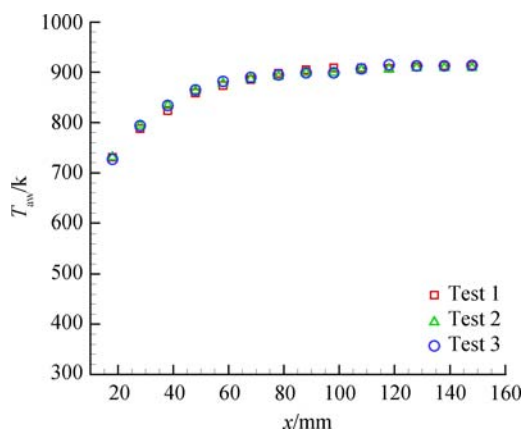


Fig. 3 Adiabatic wall temperatures without injection on line 1

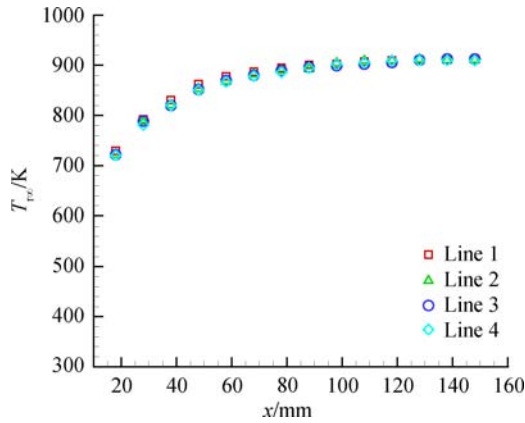


Fig. 4 Mainstream recovery temperatures on four lines

mental section was at ambient temperature. The coolant and mainstream were simultaneously injected into the experimental section, and the heat balance was expected when all measured temperatures did not change any more. Subsequently, T_{raw} and r_i were recorded. The film cooling effectiveness was calculated by the Eq. (1).

The relative error of the film cooling effectiveness was calculated as

$$\frac{d\eta}{\eta} = \left[\left(\frac{r_{\infty}}{T_{r\infty} - T_{\text{raw}}} \cdot \frac{d_{\text{raw}}}{r_{\infty} - r_i} \right)^2 + \left(\frac{T_{\text{raw}}}{T_{r_i} - T_{r\infty}} \cdot \frac{d_{\text{raw}}}{r_{\infty} - r_i} \right)^2 + \left(\frac{r_i}{r_{\infty} - r_i} \cdot \frac{d_{r_i}}{r_i} \right)^2 \right]^{\frac{1}{2}} \quad (4)$$

The maximum error of the measurement system was 2.5%, and the maximum error of the film cooling effectiveness was 6.6%.

3 Experimental results

In previous investigations, most of the injection structures are 2-D slots. Consequently, a 2-D slot with a height of 1 mm was used for comparison, as shown in Fig. 5. The slot flow was

at a Mach number of 1.0, and the mass flow ratio was 2.085. Table 1 shows the experimental parameters in Refs [1, 5, 14, 19], “normal” in Table 1 means ambient temperature. Figure 6 shows the film cooling effectiveness, which is close to the data in Ref. [5].

It should be noted that the Mach number of the mainstream and injection in Ref. [5] were 2.5 and 1.9, respectively, which were different from those in present paper. Two experimental results have no obvious difference, and the possible reasons are as follows:

1) The mass flow ratio and specific heat of the coolant are main factors influencing the film cooling effectiveness. Although there are some difference on the Mach number of the mainstream and injection between two investigations, the similar mass flow ratios result in little difference on the cooling effectiveness.

2) Within the range of $\lambda / (\lambda + 1) < 20$, two experimental results have an obvious difference, which may be related with the step heights of the mainstream and cooling surface. In present investigation, the step height between the mainstream and cooling surface was 3.5 mm. In Ref. [5], this value was approximately 5.2 mm. A larger step height decreased the interference of the mainstream on the coolant, resulting in a better cooling effectiveness.

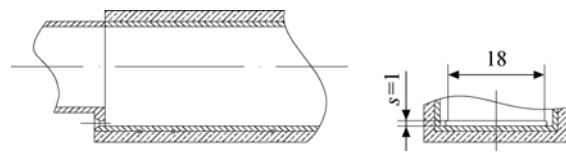


Fig. 5 Sketch of slot (unit:mm)

Table 1 Experimental parameters in Refs.

	Mainstream	Injection	Ma_{∞}	Ma_i	T_{∞}/K	T_i/K	p_{∞}/kPa	λ
Present	Gas	N ₂	2.00	1.0	910	Normal	119	2.085
Ref. [1]	Air	Air	3.00	1.0	Normal	232~363	7.51	0.12~0.048
Ref. [19]	Air	Air	1.00	1.0~3.0	470~700	Normal		2.097
Ref. [5]	N ₂	N ₂	2.50	1.9	810	Normal	110	2.064
Ref. [14]	Air	Air	2.44	1.2	Normal	238	6.51	0.4

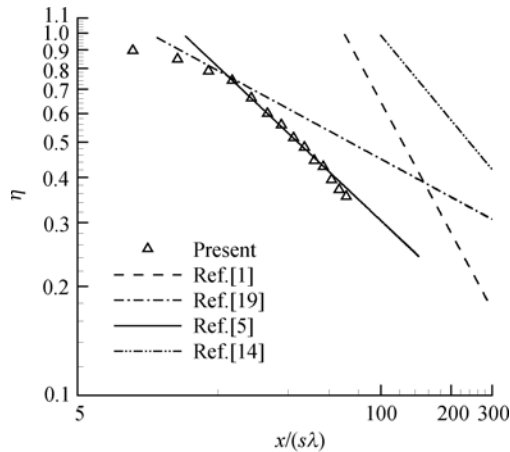


Fig. 6 Data comparison with the Refs.

Present investigation designed five kinds of injection holes arrangement, as shown in Fig. 7. The exit diameter of each injection hole was 2.0 mm. A stainless 15° body was used to generate the shock wave, as shown in Fig. 8. There was an obvious gas scour mark on it. Table 2 shows

all the experimental parameters.

Figure 9 shows the film cooling effectiveness on line 1 at different numbers of the injection holes with a fixed $\lambda=5.42$. The maximum film cooling effectiveness is obtained near the injection holes, and decreases along the flow direction. Consistent with the 2-D slot, the cooling effectiveness downstream the injection holes nearly achieves a linear decrease under the logarithmic coordinate system. With the increase in the number of the injection holes, the coolant covers more area in the experimental section, resulting in a higher cooling effectiveness. On one hand, it decreases the convection from the mainstream to the cooling surface; on the other hand, it significantly decreases the lateral temperature gradient at the cooling surface. Consequently, the multi-hole achieves a better film cooling effectiveness than the single-hole.

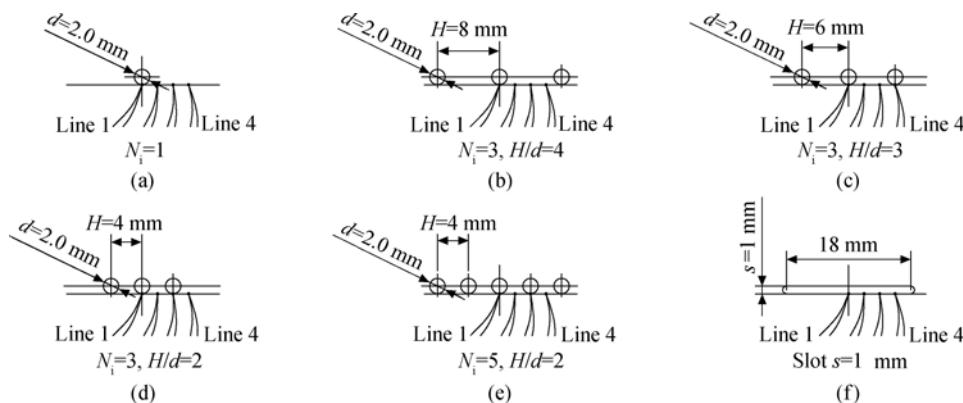


Fig. 7 Arrangements of injection holes

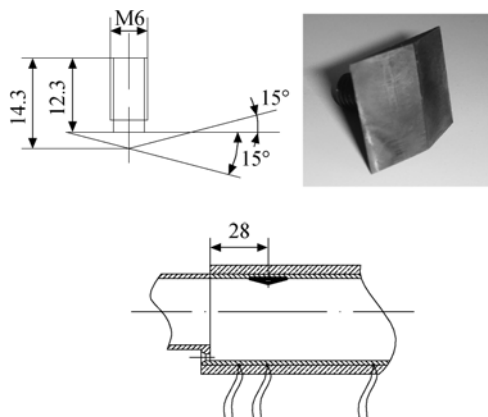


Fig. 8 Sketch, photograph and installation position of shock wave producer (unit:mm)

Table 2 Experimental parameters

No.	Ma_i	d/mm	N_i	λ	H/d
1	1.0	2.0	1	2.085	
2	1.0	2.0	1	5.42	
3	1.0	2.0	3	2.085	4
4	1.0	2.0	3	5.42	4
5	1.0	2.0	3	9.17	4
6	1.0	2.0	3	2.085	3
7	1.0	2.0	3	5.42	3
8	1.0	2.0	3	9.17	3
9	1.0	2.0	3	2.085	2
10	1.0	2.0	3	5.42	2

续表

No.	Ma_i	d/mm	N_i	λ	H/d
11	1.0	2.0	3	9.17	2
12	1.0	2.0	5	2.085	2
13	1.0	2.0	5	5.42	2
14	1.0	2.0	5	9.17	2
15	1.0	$s=1.0\text{ mm}$		2.085	

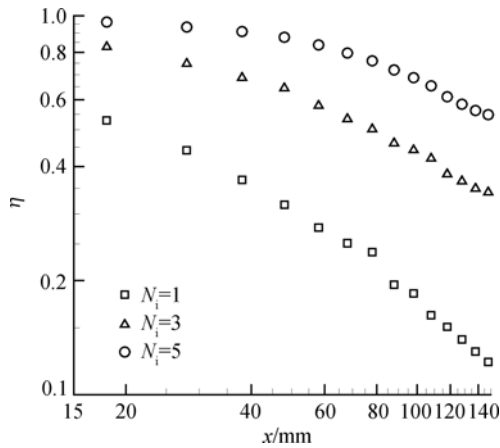
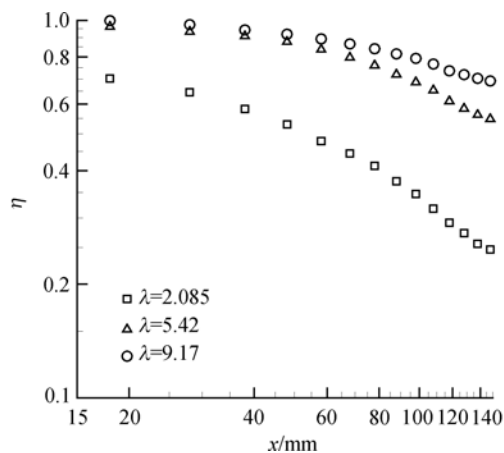
Fig. 9 Cooling effectiveness at different N_i ($\lambda=5.42$)

Figure 10 shows the film cooling effectiveness on line 1 at different mass flow ratios with a fixed $N_i=5$. The film cooling effectiveness increases with the increase in the mass flow ratio. At $\lambda=9.17$, the maximum film cooling effectiveness can reach 1.0 near the injection holes. However, this tendency is weakening. With the mass flow ratio exceeding a critical value, the cooling effectiveness will increase very slowly. This phenomenon is named as “saturation”,

Fig. 10 Cooling effectiveness at different λ ($N_i=5$)

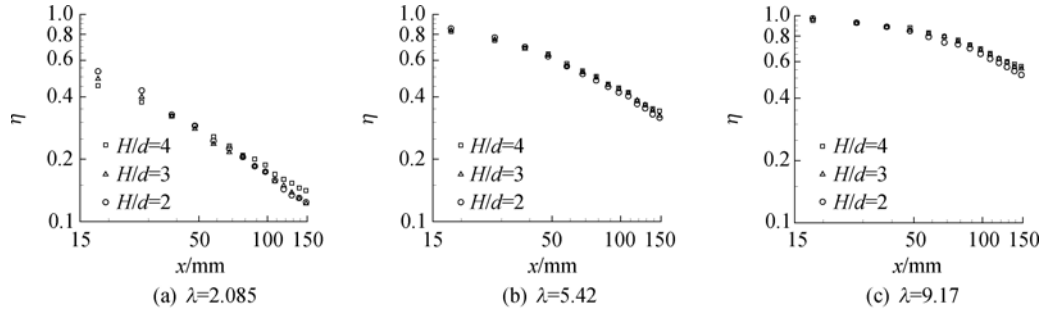
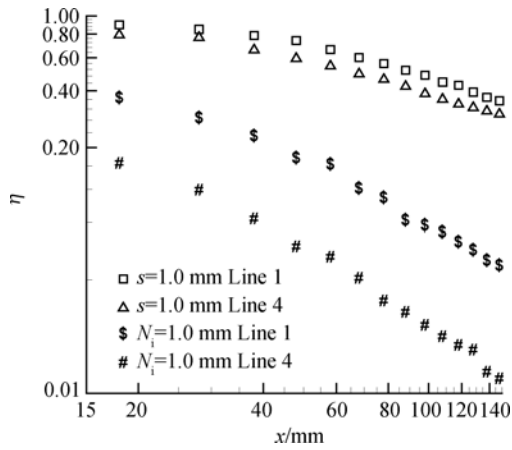
which should be avoided in the design of the cooling structure to get the best cooling effect.

For the film cooling of the discrete holes, the hole spacing, H/d , is an important parameter. At a smaller H/d , the discrete holes arrangement is close to the 2-D slot, which requires more coolant to achieve a better cooling effectiveness. At a larger H/d , less coolant is required, but the cooling effectiveness becomes unevenly distributed. Figure 11 shows the cooling effectiveness on line 1 at different hole spacing with a fixed $N_i=3$. The mass flow ratios were set to be 2.085, 5.42, and 9.17, respectively. At $\lambda=2.085$, the smaller H/d achieves a better film cooling effectiveness near the injection holes ($<40\text{ mm}$). However, this tendency is opposite when the axial distance exceeds 40 mm. This is because when the H/d is small, the convergence effect of the coolant injection is obvious. Consequently, the holes on line 1 are easier to achieve a better cooling effectiveness. However, a smaller H/d decreases the lateral coverage area, which decreases the cooling effectiveness in the region away from the injection holes. Lateral heat transfer in the experimental section becomes more intensive, resulting in a lower cooling effectiveness. However, at higher mass flow ratios ($\lambda=5.42$ and $\lambda=9.17$), this phenomena becomes indistinct.

Generally speaking, the discrete holes achieve an uneven cooling effect in the vertical direction compared to the 2-D slot. Figure 12 shows the cooling effectiveness of the single-hole and 2-D slot at $\lambda=2.085$. For the single-hole, the cooling effectiveness on line 1 (just under the injection hole) is obviously better than that on line 4 (away from the injection hole). It can be seen that the single-hole achieves a worse lateral uniformity of the cooling effectiveness.

For the film cooling of the discrete holes, the lateral uniformity can be offset by the appropriate arrangement of the coolant holes. The lateral uniformity coefficient, E_u , is defined as

$$E_u = \frac{|\eta_u - \eta_l|}{\eta_u} \quad (5)$$

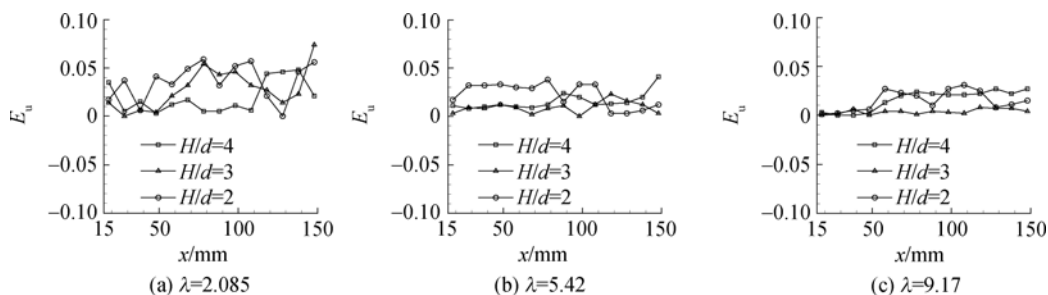
Fig. 11 Cooling effectiveness at different H/d ($N_i=3$)Fig. 12 Uneven distribution of cooling effectiveness
($\lambda=2.085$)

Where η_c refers to the cooling effectiveness just under the central injection hole, and η_l is the cooling effectiveness under the center line which is between the central injection hole and neighbor one. In present paper, η_u always refers to the cooling effectiveness at line 1. At $H/d=4$ (as shown in Fig. 7(b)), η_k refers to the cooling effectiveness at line 3. At $H/d=3$ (as shown in Fig. 7(c)), η_l is obtained by the polynomial interpolation of the cooling effectiveness at lines 1 to 4, respectively. At $H/d=2$ (as shown in Fig. 7(d)), η_k refers to the cooling effectiveness at line 2.

A smaller lateral uniformity coefficient re-

fers to the smaller difference between the central injection hole and center line, illustrating a more uniform lateral distribution of the cooling effectiveness. Figure 13 shows the lateral uniformity coefficient, E_u , along the flow direction at different λ . The mass flow ratios were set to be 2.085, 5.42, and 9.17, respectively. It can be seen that all the E_u is less than 0.1, illustrating that under the existing experimental parameters the λ has limited influence on the lateral uniformity. Considering that a larger λ can achieve a broader covering area, the cooling effect at $H/d=4$ is better than those at $H/d=2$ and 3. Furthermore, with the mass flow ratio increasing, the amplitude of the lateral uniformity coefficient gradually decreases. This is because the injection pressure increases with the increase of the mass flow ratio. The injected coolant at a larger injection pressure expands more intensively, which achieves a better coverage on the region between two holes.

Figure 14 shows the cooling effectiveness along the flow direction with and without shock wave at $\lambda=5.42$ and 9.17, respectively. The vertical broken line in Fig. 14 marks the calculated incident position of the shock wave. It is ob-

Fig. 13 Distribution of E_u

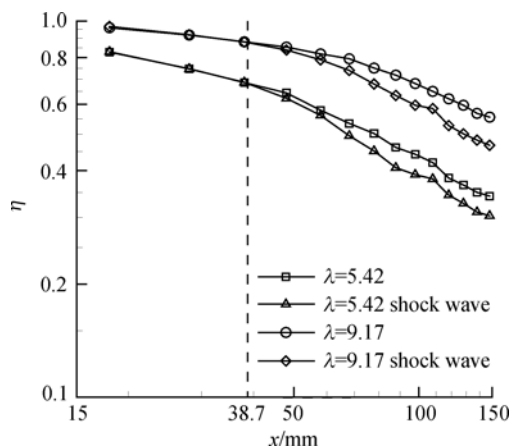


Fig. 14 Effect of shock wave ($N_i=3$, $H/d=4$)

vious that downstream $x=38.7$ mm, the cooling effectiveness in the case with the shock wave is less than that in the case without the shock wave.

4 Conclusion

A series of experiments have been conducted to investigate the supersonic film cooling using the discrete axial symmetrical holes, and some useful conclusions are obtained as follows:

1) For the investigated cooling surface, the film cooling effectiveness of the multi-holes injection is much better than that of the single-hole injection. With other parameters held constant, the increase in the number of the injection holes increases the film cooling effectiveness along the flow direction.

2) Different from the subsonic film cooling which has an optimum mass flow ratio, the film cooling effectiveness in the supersonic film cooling always increases with the increase in the mass flow ratio.

3) When the hole spacing, H/d , is less than 4, no obvious difference is observed on the cooling effectiveness and lateral uniformity. With the mass flow ratio increasing further, this difference becomes much smaller.

4) The shock wave occurring in the mainstream decreases the cooling effectiveness downstream the incident point of the shock wave.

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