Experiment on Adiabatic Film Cooling Effectiveness in Front Zone of Effusion Cooling Configuration

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Abstract: Experimental investigation is performed to investigate the cooling characteristics in the front zone of effusion configuration. Effects of blowing ratio, multi-hole arrangement mode, hole-to-hole pitch and jet orientation angle on the adiabatic film cooling effectiveness are concentrated on. The results show that the film layer displays an obvious "developing" feature in the front zone of effusion cooling scheme, for either the staggered or inline multi-hole arrangement. The varying gradient of the laterally-averaged adiabatic cooling effectiveness along the streamwise direction is greater for the staggered arrangement than that for the inline arrangement. The holes array arranged in staggered mode with small hole-to-hole pitches is in favor of obtaining developed film coverage layer rapidly.

Key words: effusion cooling; adiabatic film cooling effectiveness; front zone; cooling film development

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1 Introduction

As a matter of fact, the inlet and exit temperature levels are progressively getting higher in modern gas-turbine combustors while the percentage of compressed air available for cooling purpose becomes more limited. Undoubtedly, the decrease of the quantity of cooling air available and the increase of the gas temperature in the combustor are contradictory elements of the problem, which presents a great challenge for engineers to design an efficient cost-effective cooling system to meet combustor durability requirement.

In order to improve the reliability of the combustor liner exposed to hot gas, two technical routes are obligatory for satisfying this requirement. One is to improve the combustor liner material characteristics, and the other is to develop advanced combustor liner cooling configuration. As far as the latter is concerned, effusion cooling or fully coverage film cooling has shown advantage to protect and increase the lifetime of combustor liner for contributing high cooling effectiveness, as well as uniform temperature distribution [1-4].

A lot of investigations on the mechanism of enhanced cooling of an effusion cooling scheme have been performed by many researchers. In reality, an effusion cooling scheme consists of three cooling effects: (1) the reduction of the wall temperature for an adiabatic wall as a direct result of the coolant jets; (2) the conduction of heat through the wall due to the thermal conductivity of the wall material and the heat transfer to the

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backside flow; (3) the heat transfer to the coolant flow from the inner surface of the injection holes when coolant passes through the holes. The relative importance of each effect depends critically on the geometrical features of the wall and the operating conditions of the cooling system.

Although many studies have been conducted to investigate the effects of main geometric and aero-thermal factors on the thermal and aerodynamic performances of effusion cooling scheme[5-16], such as the arrangement of effusion holes, hole shape, hole diameter and hole inclination angle, and blowing ratio, etc., there is few concentration on the cooling characteristics in the front zone of effusion configuration. Previous works have shown that the forming of "continuous" or "developed" coverage film layer comes through a developing process of the coolant jets injected from the front rows of film holes[17-19]. The effusion cooling feature in the developing zone is significantly different from that in the developed zone. The motivation of the presented experimental study is to explore the cooling characteristics in the front zone of effusion configuration. Effects of blowing ratio, multi-holes arrangement mode, hole-to-hole pitch and jet orientation angle on the adiabatic film cooling effectiveness are concentrated on.

2 Experimental Procedures

2.1 Experimental setup

The experimental setup is sketched in Fig. 1. The primary stream comes from compressed air supply (0.8 MPa) and passes through a calibrated orifice flow meter, after being heated by a 60 kW heater, which can heat the air to a free-stream temperature of 80 °C. The heated stream is then routed through a section with baffles to ensure adequate mixing of the hot air to obtain a uniform temperature at the cross-section of 150 mm width and 60 mm height. This cross-section makes the primary stream flow at 25 m/s. The primary stream temperature is continuously monitored at the inlet of the test section by a thermocouple. The secondary stream or coolant air is provided from a separate compressed air supply and routed through a buoyage flow meter, which is controlled by a gate valve and introduced into the plenum cavity. To eliminate the impingement effect of the coolant air at the plenum inlet, multiple layers of grids are placed in the plenum cavity. The coolant stream is then ejected through the effusion cooling holes into the primary flow passage. The test section is made of transparent plastic plate with thickness of 5 mm. The length of the test section is 300 mm. An infrared viewing window, which is 80 mm wide and 120 mm long, is mounted on the test section for directly viewing the measured surface by an infrared camera.

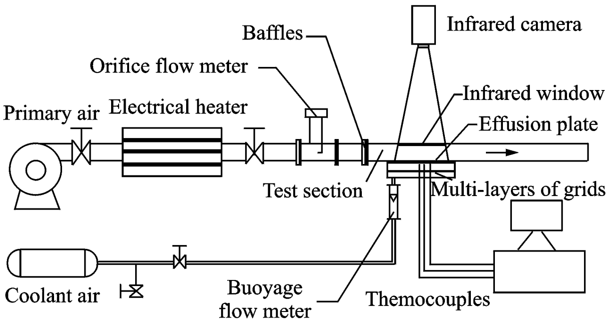
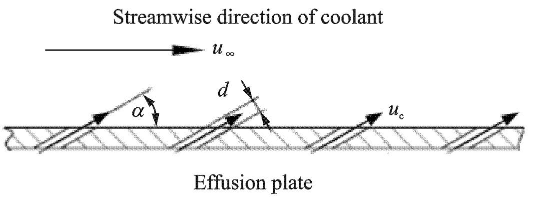


Fig. 1 Schematic diagram of experimental setup

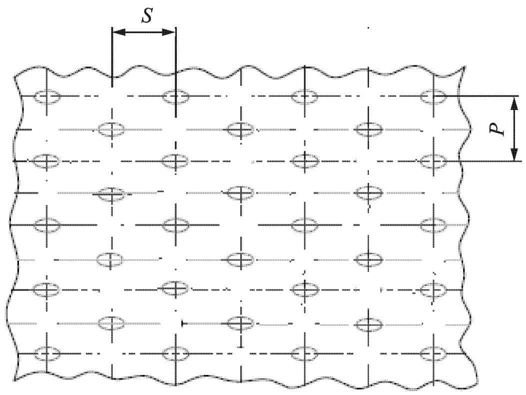
2.2 Experimental models

The experimental model for an effusion cooling configuration is shown in Fig. 2(a). The effusion plate is made of epoxy resin with thickness of 3 mm. The holes inside the perforated plate are arranged in the staggered mode or the inline mode, as shown in Figs. 2(b, c). In the present study, the effusion holes have the same diameter ($d = 2$ mm). The streamwise pitch ratio (S/d) and spanwise pitch ratio (P/d) are varied from 3 to 5. The inclined angle (α) is set as 35° and 90°, respectively. The effusion plate has length of 120 mm and width of 150 mm, which is mounted inside the test section.

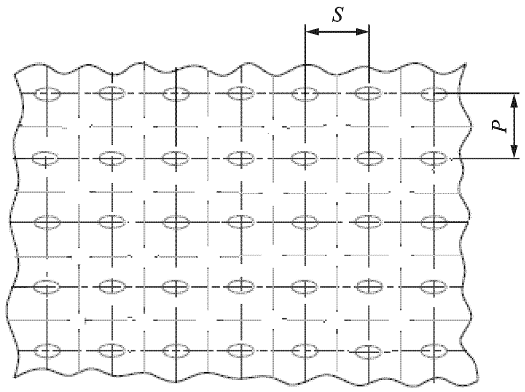
The geometries of the effusion plates are summarized in Table 1.



(a) Details of test section



(b) Staggered arrangement of holes



(c) Inline arrangement of holes

Fig. 2 Schematic diagram of effusion cooling scheme

Table 1 Effusion plate geometries

S/d-P/d	d/mm	α/(°)	Arrangement	Row number
3-3	2	35/90	Staggered/inline	17
4-4	2	35/9	Staggered/inline	13
5-5	2	35/90	Staggered/inline	11

2.3 Measurement and parameter definition

To study the effect of various amount of coolant flow on the film cooling for a fixed mainstream flow, a parameter known as the blowing ratio (M) is defined as

$$M=\frac{\rho_c u_c}{\rho_\infty u_\infty} \tag{1}$$

where ρ_c and u_c are the density and velocity of the secondary flow or coolant flow at the effusion hole exit, respectively; and ρ_∞ and u_∞ are the density and velocity of the primary flow, respectively.

The adiabatic wall cooling effectiveness (η_{ad}) is defined as

$$\eta_{ad}=\frac{T_\infty - T_{aw}}{T_\infty - T_c} \tag{2}$$

where T_c is the coolant flow temperature, T_∞ the primary flow temperature, T_∞ the primary flow temperature, T_{aw} the adiabatic wall temperature at the effusion surface suffering the primary flow. Since the thermal conductivity of effusion plate is about 0.4 W/(m • K), the heat transfer on the backside surface and inside effusion holes of the effusion plate is very weak. Therefore, the temperature on the effusion surface may be regarded approximately as the adiabatic temperature.

The temperature distributions on the face of the effusion plate are measured by an infrared camera operating in the middle infrared band (8～14 m) of the infrared spectrum. The test surface is viewed through the infrared camera window (Fig. 1). The infrared camera calibration is conducted using a series of thermocouples placed on the black painted test surface to act as the benchmark[20-22]. These thermocouples are used to estimate the emissivity of the test surface. The emissivity of the black painted test when viewed without the window is about 0.96. The calibrated transmissivity for the infrared camera window is about 0.85.

To eliminate the effect of the edge area on the data treatment, the laterally-averaged adiabatic cooling effectiveness is determined on the centric zone of effusion plate.

Experimental uncertainty in the overall film effectiveness measurement is estimated to be about ±8.4% using the methodology of Moffat[23]. The individual uncertainties of primary mainstream temperature (T_∞), coolant temperature (T_c), and surface temperature (T_{aw}) are ±1 °C, ±0.5 °C, ±2.0 °C, respectively.

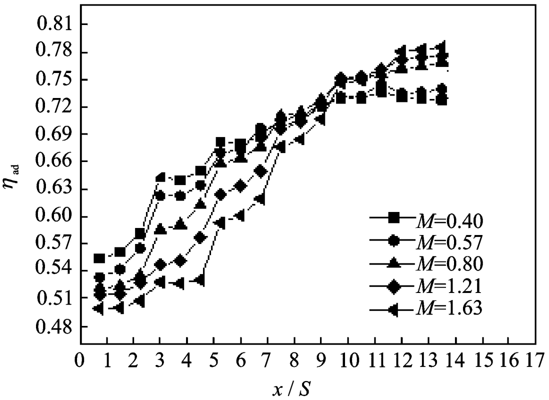
3 Results and Discussion

Fig. 3 presents the laterally-averaged adiabatic cooling effectiveness distributions along the streamwise direction at different blowing ratios. Here the original coordinate is located at the centre of the first row film holes.

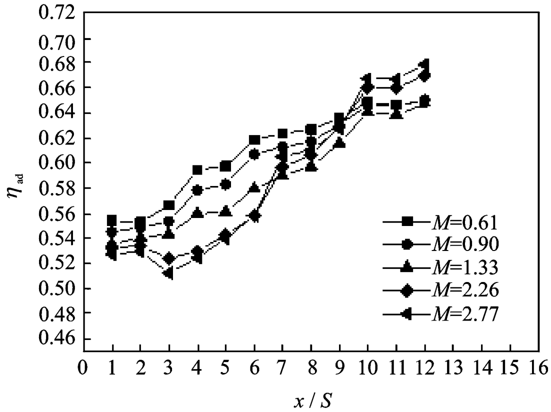
For either the staggered mode or inline mode, the film flow displays an obvious "developing" feature in the front zone of effusion cooling configuration. The film outflows injected from the front rows do not merge together to form a uniform film layer, therefore the laterally-averaged adiabatic cooling effectiveness increases or the adiabatic temperature decreases rapidly along the streamwise direction. By comparison, the varying gradient of the laterally-averaged adiabatic cooling effectiveness along the streamwise direction is greater in the staggered mode than that in the inline mode. This means that the staggered mode will benefit the development of film flow and is capable of achieving full film coverage by fewer number of effusion cooling-holes rows.

For the staggered arrangement, the laterally-averaged adiabatic film cooling effectiveness originated from the first few rows is higher under the lower blowing ratio, which agrees well with the results of discrete film cooling from early studies[24, 25]. Under a lower blowing ratio, the coolant jet has the lower penetration capacity, which is helpful to make the coolant jet covering the downstream surface of the holes. But for multi-rows of film cooling holes, the maintainance capacity of jet spreading along streamwise direction under lower blowing ratio is also lower, thus leading to a slower growth of film layer. Also, the vigorous film layer is provided with the ability of suppressing coolant jet penetration. Therefore, the laterally-averaged adiabatic film cooling effectiveness originated from the last few rows is higher under a bigger blowing ratio.

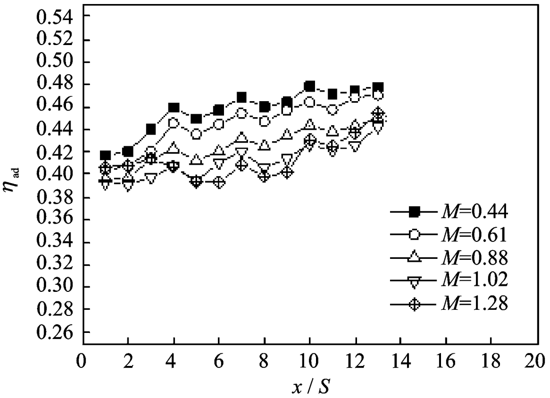
For the inline arrangement, the film coverage in the lateral direction is seriously weaker than that of the staggered mode. The inline mode thus needs longer developing stage to realize the full film coverage. The laterally-averaged adiabatic film cooling effectiveness in the front zone of effusion cooling configuration decreases with the increase of blowing ratio.



(a) Staggered arrangement, S/d=3, P/d=3, α=90°



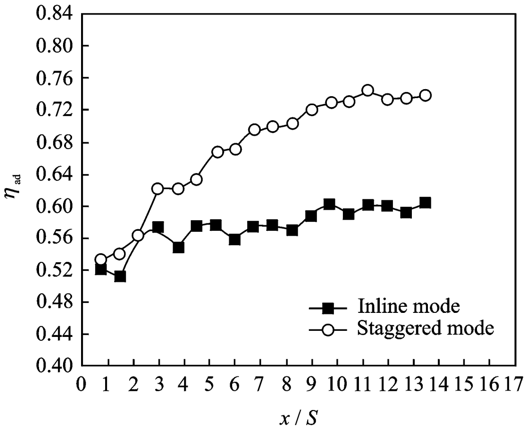
(b) Staggered arrangement, S/d=4, P/d=4, α=35°



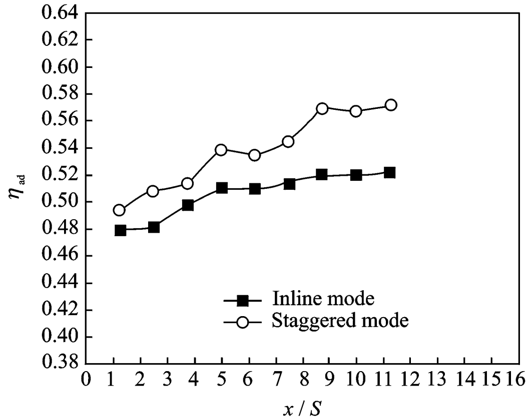
(c) Inline arrangement, S/d=4, P/d=4, α=90°

Fig. 3 Laterally-averaged adiabatic cooling effectiveness distributions at different blowing ratios

Fig. 4 presents the laterally-averaged adiabatic cooling effectiveness distributions along the streamwise direction under different multi-hole arrangements. As discussed in the above, the varying gradient of the laterally-averaged adiabatic cooling effectiveness along the streamwise direction is obviously lower for the inline arrangement than that for the corresponding staggered ar-

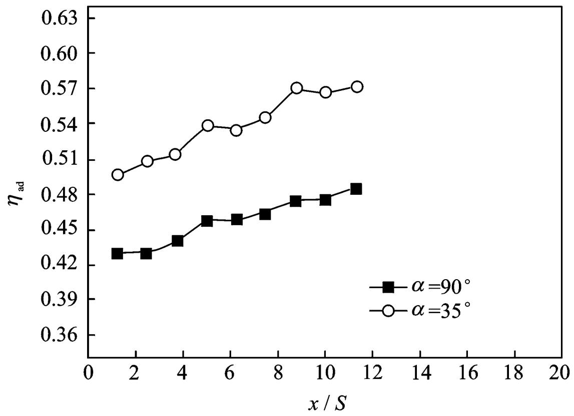


(a) M=0.58, S/d=3, P/d=3, α=90°

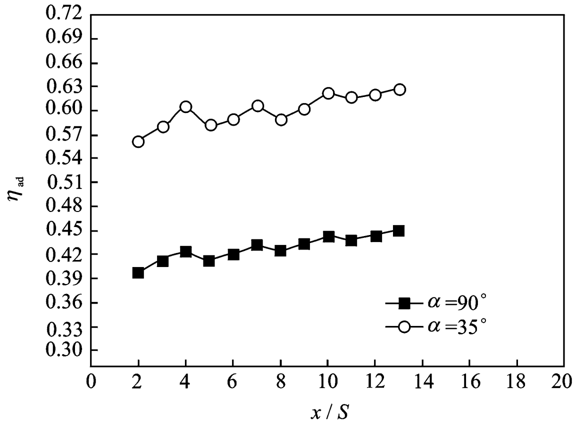


(b) M=0.8, S/d=5, P/d=5, α=35°

Fig. 4 Laterally-averaged adiabatic cooling effectiveness distributions under different hole arrangements



(a) Staggered arrangement, S/d=5, P/d=5, M=0.83



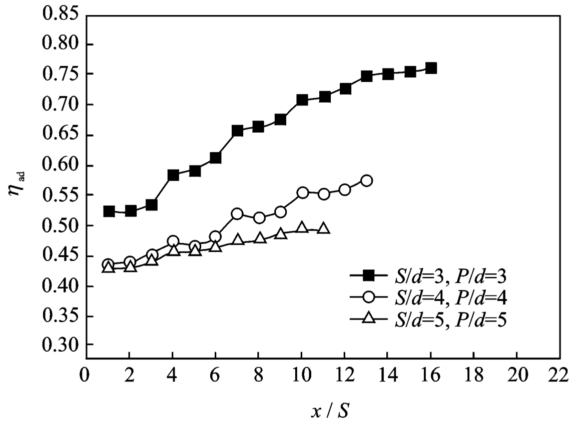
(b) Inline arrangement, S/d=4, P/d=4, M=0.86

Fig. 5 Laterally-averaged adiabatic cooling effectiveness distributions under different jet orientation angles

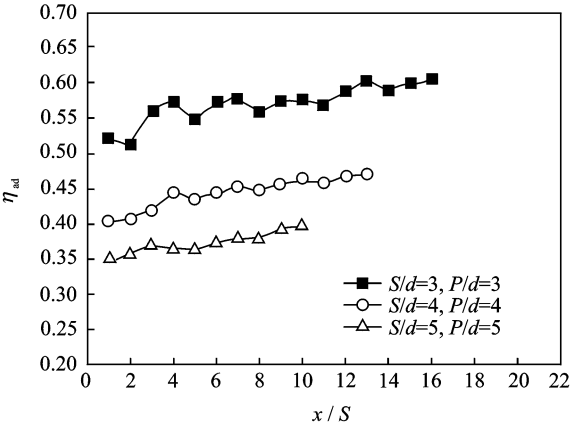
rangement. The laterally-averaged adiabatic cooling effectiveness for the staggered mode is also higher than that for the corresponding value of inline mode at the same blowing ratio.

Fig. 5 shows the laterally-averaged adiabatic cooling effectiveness distributions along the streamwise direction under different jet orientation angles. Either for the staggered mode or the inline mode, the laterally-averaged adiabatic cooling effectiveness with jet orientation angle of 35° is greater than that of 90° angle. As the coolant is discharged with a certain inclined angle, the coolant flow velocity components from effusion holes can be divided into two parts, i. e. , the tangent velocity and the normal velocity. In the tangential direction, the coolant is forced to flow downstream the film hole, which is also called as wall jet. From the view of enhancing film cooling effectiveness, the greater tangent velocity is expected to maintain wall jet momentum along the streamwise direction. While in the normal direction, it is the opposite case. The coolant flow penetrates the primary flow and lifts off the surface. As expected, the lower coolant jet penetration along normal direction and the higher spread along streamwise direction with the inclined discharge are to benefit the film cooling effectiveness.

Fig. 6 presents the laterally-averaged adiabatic cooling effectiveness distributions along the streamwise direction under different hole-to-hole pitches. According to the work of Yang and Zhang[19] on the cooling film development of staggered arrangement, the development of film layer of the effusion cooling scheme could be divided into three stages. Firstly, the film cooling effec-



(a) Staggered arrangement, M=0.81, α=90°



(b) Inline arrangement, M=0.6, α=90°

Fig. 6 Laterally-averaged adiabatic cooling effectiveness distributions under different hole-to-hole pitches

tiveness increases rapidly along streamwise direction in the front rows of multi-holes where the film layer is undergoing a developing stage. Then the laterally averaged adiabatic film cooling effectiveness increases tardily in the middle rows of multi-hole where the film layer is undergoing a transition stage. Finally, once the effusion film layer is developed, the laterally averaged adiabatic film cooling effectiveness should trend to be constant. Generally, the transition stage is accomplished in the 17th row. For the small pitches (such as $S/d = P/d = 3$), this feature is well demonstrated. While for the large pitches, film layer is undergoing the developing stage. The holes array arranged with small pitches is in favor of obtaining a developed film layer.

According to the varying trend of the laterally-averaged adiabatic film cooling effectiveness along streamwise direction for the inline arrangement, it is deduced that the film layer development will be very slower than that for the staggered arrangement. The reason has been discussed in the above.

4 Conclusions

(1) The varying gradient of the laterally-averaged adiabatic cooling effectiveness along the streamwise direction in the front zone of effusion cooling configuration is greater for the staggered mode than that of the inline mode. The laterally-averaged adiabatic cooling effectiveness for the staggered mode is higher than the corresponding value of inline mode at the same blowing ratio. (2) For the staggered multi-holes mode, the laterally-averaged adiabatic film cooling effectiveness originated from the first few rows is higher under the lower blowing ratio. While for the last few rows, the higher film cooling effectiveness is achieved under a bigger blowing ratio. The holes array arranged with small hole-to-hole pitches is in favor of obtaining developed film coverage layer rapidly. (3) Either for the staggered arrangement or the inline arrangement, the laterally-averaged adiabatic cooling effectiveness with inclined jet orientation angle of 35° is greater than the corresponding value of normal orientation angle at the same blowing ratio. The lower coolant jet penetration along the normal direction and higher spread along the streamwise direction with the inclined discharge is benefit to the film cooling effectiveness.

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