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Effects of injection type on slot film cooling for a ramjet combustor†

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Abstract

A slot film cooling technique has been used to protect a combustor liner from hot combustion gas. This method has been developed for gas turbine combustors. A ramjet combustor exposed to high temperature can be protected properly with a multi-slot film cooling method. An experimental study has been conducted to investigate the change of the first slot angle under recirculation flow and the influence of wiggle strip within a slot, which affects the film cooling effectiveness. The first slot angle has been changed to understand the effect of the injection angle on the film cooling effectiveness in a recirculation zone. The distribution of dimensionless temperature was obtained by a thermocouple rake to investigate the wiggle strip effect, and the adiabatic film cooling effectiveness on downstream wall was measured by a thermochromic liquid crystal (TLC) method. At the first slot position, the film cooling effectiveness decreases significantly because of the effects of recirculation flow. The lip angle of the first slot affects slightly on the film cooling effectiveness. The wiggle strip reinforces the structure of slot and keeps the uniform open area of slot. However, it induces three dimensional flows and enhances the flow mixing between the main flow and the injected slot flow. Therefore, the wiggle strip decreases slightly the overall film cooling effectiveness.

Keywords: Ramjet combustor; Slot film cooling; Recirculation flow; Heat transfer; Thermochromic liquid crystal (TLC)

1. Introduction

A ramjet engine is used for supersonic jet planes and strategic guided weapons due to its several merits. The performance and effectiveness of ramjet engines depend highly on the temperature and pressure in combustor. Therefore, the thermal design of combustor in ramjet engines is the core technology to effectively protect the combustor wall and to keep the wall temperature under an allowable limit [1].

Nowadays, two kinds of thermal cooling design are applicable to the ramjet combustor. One is the ablation cooling method, of which the ablator layer coated on the wall is cut by the injected heat. The other is the film cooling method. The coolant through holes or slots on the wall makes an isolated film between the hot combustion gas and the exposed wall, and the coolant film protects the combustor liner from the hot combustion gas [2].

The ramjet system is classified by the location of air induction system, such as the front dump typed ramjet and the side dump typed ramjet. This study modeled the slot film cooling on a front dump typed ramjet combustor which is applicable to a long distance missile. Generally, the front dump typed ramjet combustor has a sudden-expansion step or an expanded duct generating a recirculation-flow zone just after the inlet. The recirculation zone appears at the position of the flame holder after the expansion zone. Therefore, the reattachment of hot gas flow induces the high thermal load and the resulting high wall temperature over the allowable material temperature reduces the life of

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ramjet combustor [3].

The studies of slot film cooling on a flat plate had been conducted for a long time. There are three possible approaches for correlating the slot film cooling data. First, it is assumed that the coolant film is not mixed with the mainstream. The film between the hot combustion gas and the coolant is assumed to be in uniform average temperature at any downstream position from the injection point. Heat is conducted into the film at the same rate as to the wall in the absence of the film cooling [4]. The second model is that the mixing occurs and the effectiveness is decreased by the influx of hot gas. It is an alternative approach to assume some models for the mixing process between the mainstream and coolant film [5, 6]. One is the Hatch-Papell equation which tends to give better correlations at close to the injection slot, and the second model is better for further downstream [7].

The objective of this study is to obtain an information of the heat transfer characteristic in combustor with slots, when the coolant is injected through the wiggle strip slot in a recirculation flow.

2. Experimental apparatus and procedures

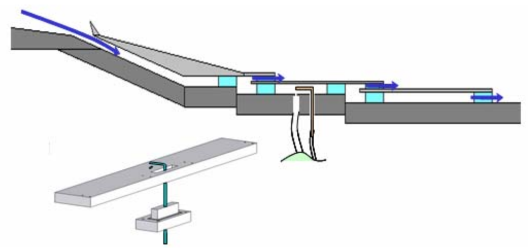
2.1 Flow experimental apparatus

The experimental apparatus consists of the flow experiment for measuring the coolant flow rate from each exit, and the heat transfer experiment for measuring the adiabatic wall film cooling effectiveness and the dimensionless temperature to obtain the heat transfer characteristic in the combustor [8].

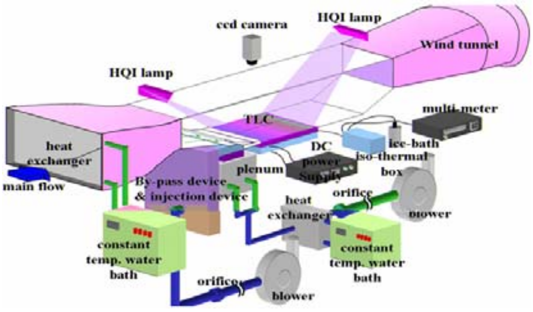
Fig. 1 shows the schematic diagram of experimental apparatus. Fig. 1(a) is the flow experimental apparatus for measuring the flow rate of injection from the slot. The wind tunnel used for this experiment is an open and suction type for the mainstream flow.

2.2 Heat transfer experimental apparatus

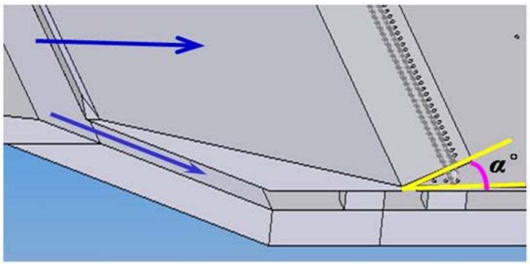
The heat transfer experimental setup consists of five parts such as contraction part, test section, diffuser part, suction section and the secondary injection flow section as shown in Fig. 1(b). The mainstream temperature is controlled by the heat exchanger, which is connected to a constant temperature reservoir. The secondary flow injection system consists of 3.75 kW blower, orifice flow meter, heat exchanger and plenum. The heat exchanger is connected to a constant temperature reservoir to control the temperature of secondary flow.



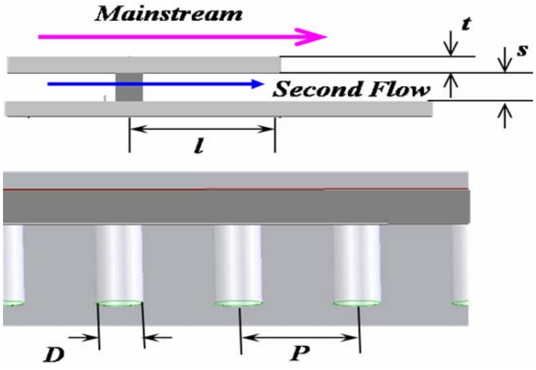
(a) Flow experimental setup



(b) Heat transfer experimental setup



(c) Slot injection angle



(d) Geometry of pins inside slot

Fig. 1. Schematic diagram of experimental apparatus.

Blowers used for the suction and the secondary injection system are continuously controlled by inverters [8].

The temperature field is measured by a thermocouple rake with J-type thermocouples. Distributions of

Table 1. Dimensions of slot geometry.

Unit : mm

Slot injection angle (α)	0°	15°	20°
Lip thickness (t)	2		
Height of slot tip (s)	5	7.5	10.5
Slot length (l)	6.8		
Pin diameter (D)	2		
Pin gap (P)	5		

film cooling effectiveness and heat transfer coefficient are measured in the test plate attached with TLC sheet (R20C20W HALLCREST Ltd., 300 mm×300 mm). It can be used from 20°C to 40°C. The calibrations were conducted under the same condition of main experiments and repeated with various temperature ranges. Fig. 1(c) is the slot injection angle to confirm slot angle effect and Fig. 1(d) is the geometry of pins inside the slot to confirm wiggle strip within the slot. Table 1 presents the dimensions of tested slot geometry.

2.3 Test section

Geometry of the test section is 400 mm wide by 150 mm high by 1500 mm long and the area ratio of the contraction section is 9:1. A trip wire of 3 mm diameter is attached at the beginning of test section to ensure fully developed turbulent boundary layer in the test section.

The mainstream velocity is 15 m/s which it was measured by a Pitot tube at the upstream region of the test section during the present experiments.

2.4 Experimental parameters

Dimensionless temperature field is determined as Eq. (1).

$$\theta = \frac{T_{air} - T_\infty}{T_2 - T_\infty} \tag{1}$$

The film cooling effectiveness is used as a dimensionless form of the adiabatic wall temperature, and defined as Eq. (2);

$$\eta = \frac{T_{aw} - T_\infty}{T_2 - T_\infty} \tag{2}$$

Heat transfer coefficient is ratio of temperature and heat flux which is defined as Eq. (3);

$$h = \frac{q}{\Delta T} = \frac{q}{T_\infty - T_{aw}} \tag{3}$$

Blowing rate is the mass flow rate of the second flow to the mainstream flow;

$$M = \frac{\rho_2 U_2}{\rho_\infty U_\infty} \tag{4}$$

The uncertainty analysis was performed using the method described by Kline and McClintock [11]. The uncertainty of film cooling effectiveness is 6.7% and the dimensionless temperature is 4.6% over the entire operation range of the measurement, based on 95% confidence level.

3. Results and discussions

In this study, the velocity and the temperature of main flow are 15 m/s and 20°C, respectively. The main objectives of present experiment are the effect of injection angle of the slot in a recirculation flow zone and the effect of the wiggle strip in a slot on the wall cooling performance. For using dimensionless length, we represented relations between height of slot tip and x-coordinate. Mass flow rate at the slot is increased with the large injection angle of slot exit, but the parallel component of injection velocity decreases comparing with the parallel injection.

Fig. 2 presents the distribution of laterally averaged dimensionless temperature at the blowing rate of 0.3. Near the exit of slot (x/s=1.0), the dimensionless temperature is about 1.0 for z/s<1.0 (under the slot lip) resulting high film cooling effectiveness. However, the dimensionless temperature decreases quickly as moving toward the downstream position due to mixing of the injected coolant with the mainstream. Such quick mixing of the coolant and mainstream is caused by the large recirculation flow of mainstream.

Fig. 3 shows the local distribution of dimensionless temperature at two downstream positions of x/s=1.0 and 10.0. At x/s=1.0 (near the slot exit), the dimensionless temperature changes slightly in lateral direction (y-coordinate) having on a periodic pattern. It is noted that the vertical lines indicate the positions of pins (a model of wiggle strip) inside the slot. The wakes behind the pins influence the mixing of coolant flow. Therefore, the flow is mixed well in lateral direction at x/s=10.0 as shown in Fig. 3(b).

We compare the film cooling effectiveness values

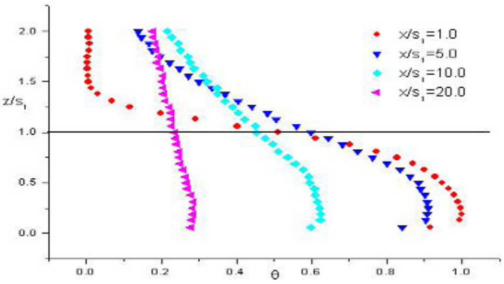
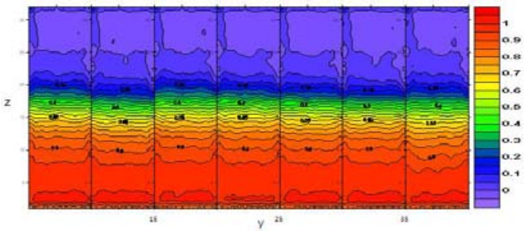
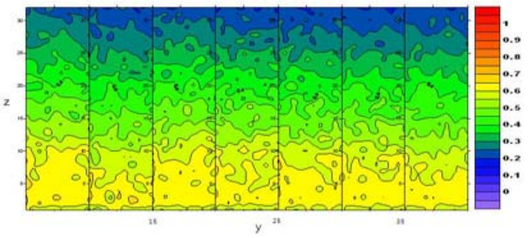


Fig. 2. Lateral averaged dimensionless temperature distribution at M=0.3 for injection angle of 0°.



(a) x/s$_l$ = 1.0



(b) x/s$_l$ = 10.0

Fig. 3. Contours of dimensionless temperature at M=0.3 for injection angle of 0°.

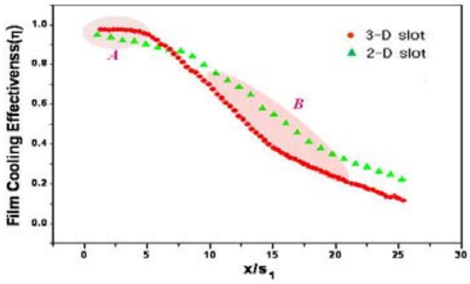


Fig. 4. Comparison of film cooling effectiveness of 2-D slot and 3-D slot at M=0.3 for injection angle of 0°.

of 2-D slot and 3-D slot to obtain the effect of pins inside the slot in Fig. 4. The 2-D slot indicates the coolant flow ejected from a slot without any obstacles having a two dimensional slot flow, but the 3-D slot has pins within the slot (Fig. 1(d)) simulating a wiggle strip which is used to support the slot lip and to keep the slot clearance. Thus, the 3-D slot shows a three dimensional flow pattern including wakes behind pins as shown in Fig. 3(a). The film cooling effectiveness values of 3-D slot are slightly higher near the exit of slot (x/s < 7, region A) because the slot flow has a slightly higher velocity due to the reduced exit flow area by pins. However, the values are much lower than those of 2-D slot at the downstream region (region B). This large decrement for the 3-D slot is caused by the enhanced flow mixing due to wakes generated by pins inside the slot.

Fig. 5 presents the distributions of film cooling effectiveness for different injection angles of slot lip (15° and 20°) and compares those with a theoretical values suggested by Stollery and El-Ehwany [3]. The film cooling effectiveness values for the 20° injection slot are slightly higher than those for the 15° injection slot, because the amount of coolant mass flow for the 20° injection slot is larger than that for the 15° injection slot. It is noted that the blowing rate is defined by the velocity at slot exit, not the total mass flow rate, so the larger open area for the 20° injection slot has more mass flow through the slot exit at the same blowing rate. However, the difference is a little due to the slight change of injection angle of slot lip. Comparing film cooling effectiveness values are compared to the theoretical values, experimental values decrease sharply and are much less than the theoretical values [3, 10].

Such low values are caused by the large flow mixing with the hot mainstream due to a strong recirculation flow which was separated at the duct inlet [8]. The theoretical value is obtained by a condition of 2-D parallel slot flow and 2-D boundary layer mainstream [8]. This result indicates that the disturbed mainstream, such as a recirculation flow, influences significantly the slot film cooling effectiveness due to vigorous flow mixing of coolant and hot mainstream.

Fig. 6 shows the streamwise distributions of film cooling effectiveness for various blowing rates from M=0.15 to 0.65 at the injection angle of 20°. The values decrease sharply and reach the value less than 0.1 for x/s ≥ 10 at the lower blowing rates (M ≤ 0.21). This is due to the strong flow mixing with the hot mainstream for low momentum of the injected coolant flow. Therefore, the coolant flow injected to a recirculation flow zone requires a certain momentum (blowing rate) to overcome the flow mixing and to protect the combustor liner surface for a targeted area.

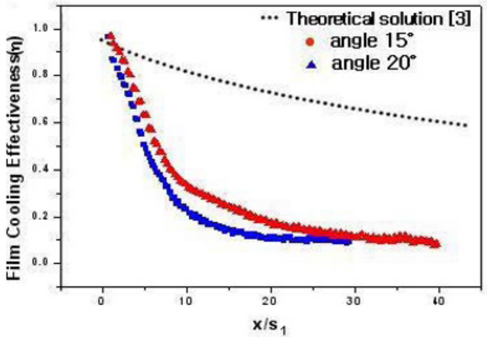


Fig. 5. Comparison of film cooling effectiveness at M=0.5 for injection angles of 15°and 20°.

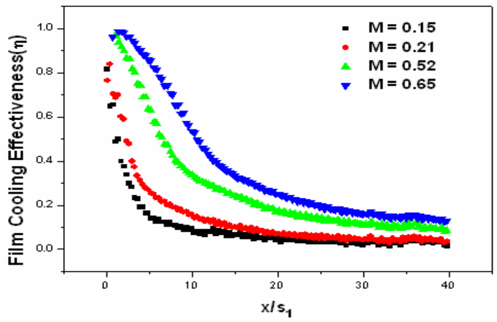


Fig. 6. Streamwise distributions of film cooling effectiveness for various blow rates at injection angle of 15°.

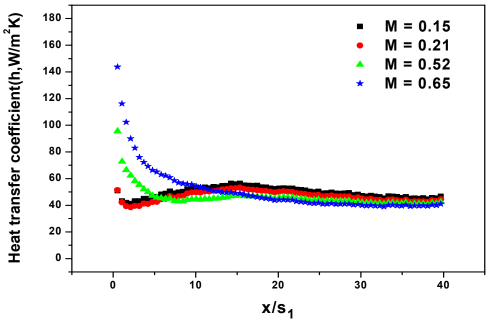


Fig. 7. Distributions of heat transfer coefficient for the various blowing rates at the injection angle of 15°.

Fig. 7 presents the distributions of heat transfer coefficient for various blowing rates at the injection angle of 20°. Effect of recirculation flow for the slot downstream makes rapidly decreasing tendency of the heat transfer coefficient distributions. However, the heat transfer coefficients are affected slightly by the blowing rate (injection velocity) and the affected region is near the slot exit (x/s ≤ 10). The cooling performance can be obtained from the measured data in Figs. 6 and 7 for various blowing rates.

4. Conclusion

The wiggle strip reinforces the weak structure of the slot film cooling, and prevents the reverse flows into the upstream slot. However, it produces 3-D flows, and the mixing between the main flow and the secondary flows are promoted by the wiggle strip. As a result, the total film cooling effectiveness is decreased by the effect of the wiggle strip. Film cooling effectiveness is decreased by increasing the slot injection angle in downstream region, even though the total cooling flow increases with increasing the slot injection angle. The recirculation flow in mainstream disturbed the coolant flow resulting significant decrease of film cooling effectiveness, especially for low blowing rates. Therefore, the flow momentum (blowing rate) of coolant should be a certain value to overcome the disturbance of recirculation flow.

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