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Experimental Studies of Film Cooling in Supersonic Combustors

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The current work is an experimental investigation of the dependence of film-cooling effectiveness on the injection angle, mass flux and injection temperature in supersonic combustors. The mainstream Mach number is 2.5, and the coolant was injected with sonic speed. The total temperature of the mainstream is 1500K, and for the injection it ranges from 300K to 1060K. Three injection angle is respectively $0^0, 43^0, 137^0$. The coolant mass flux ranges from 1% to 6% of the mainstream mass flux, and the mainstream mass flux is 2.5kg/s. The results show that a smaller injection angle has a better performance in film cooling effectiveness and indicate that an increase in film-cooling effectiveness with the increase of the coolant mass flux. The influence of coolant temperature is more complex. The rising of coolant temperature reduces the film-cooling effectiveness without kerosene combustion, while has not significant difference with kerosene combustion.

Nomenclature

M	=	Mach number
T_0	=	mainstream total temperature
P_0	=	mainstream total pressure
T_f	=	coolant total tempreature
Q_m	=	mainstream mass flux
q_m	=	coolant mass flux
q_0	=	heat flux without film cooling
q_f	=	heat flux with flim cooling
η_{aw}	=	adiabatic wall film cooling effectiveness
η_{iso}	=	isothermal wall film cooling effectiveness
T_w	=	wall temperature
α	=	injection angle
h	=	coefficient of heat transfer
x	=	distance to the combustor entrance

I. Introduction

THE scramjet engine has excellent performance at high Mach number, while it is also subjected to severe aerodynamic heating and combustion heating. The heating is particularly serious in the combustors. For example, the temperature of gas in scramjet combustion chamber is expected to exceed 2500K when the engine flying at Mach 6.[1] Although the hydrocarbon fuel can be used to cool the engine, it is not enough when Mach number beyond 6. So it is necessary to find other ways to protect the engine. Film cooling is a well-known method has widely used in rocket engines, aircraft, and it will be used in scramjet.[2]

Studies of supersonic film cooling begin at 1960s. Goldstein et al. experimentally studied supersonic film cooling with both air and helium as the coolant gas.[4] Hunt, M. L. et al. experimentally tested the cooling effectiveness using air and helium for a range of injection temperature and Mach numbers. The results indicate an increase in film cooling

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effectiveness as the injection rate is increased. With larger injection Mach numbers, there is slight increase in the effective cooling length per mass injection rate. The results for helium injection indicate an increase in effectiveness as compared to that for air injection.[2] Kanda et al. experimentally studied the supersonic film cooling with shockwave interaction, and found that the stronger shockwave with the pressure ratio of 1.44 decreased the effectiveness of the film cooling in the restricted region and the decrease of the effectiveness was mainly the result of the adiabatic temperature by the decrease of the local Mach number.[7] Wei Peng et al. numerically studied the effect of coolant inlet conditions on supersonic film cooling and the results indicate that, for the same coolant gas without a shock wave or with a weak shock wave, the supersonic film cooling mainly depends on the coolant gas flow rate and has little relationship to the coolant inlet height or the Mach number.[10]

All the studies above are conducted in the condition of ideal model, and not consider the shape of the combustors and the combustion in the internal of combustor. Therefore, the present experiments are conducted under the condition of a practical combustor. The direction way of the coolant, the mass flux of the coolant and the temperature of the coolant are the three key factors that can affect the cooling effectiveness. So several sets of experiment are designed to research the influence of these factors respectively.

II. Experimental Apparatus and Metheds

A. Experimental Facility

The experiments were conducted in a direct–connect test facility with exchangeable convergent-divergent nozzles of Mach 2.0, 2.5 and 3.0, which consisted of a vitiated air heater, a multi-purpose supersonic model combustor, and a kerosene delivery and heating system. The facility operation, control, and data acquisition were accomplished with a computer. The vitiated air heater, burning H_2 and air with replenishment of O_2, was used to supply heated airflows with stagnation temperatures of 700-2200 K and stagnation pressures of 0.6-4.0 MPa. The stagnation pressure and temperature of the vitiated air were measured using a CYB-10S pressure transducer and a Type-B thermocouple, respectively. The mass flow rates of the gases were controlled and measured by sonic nozzles. The uncertainty is < 1%.

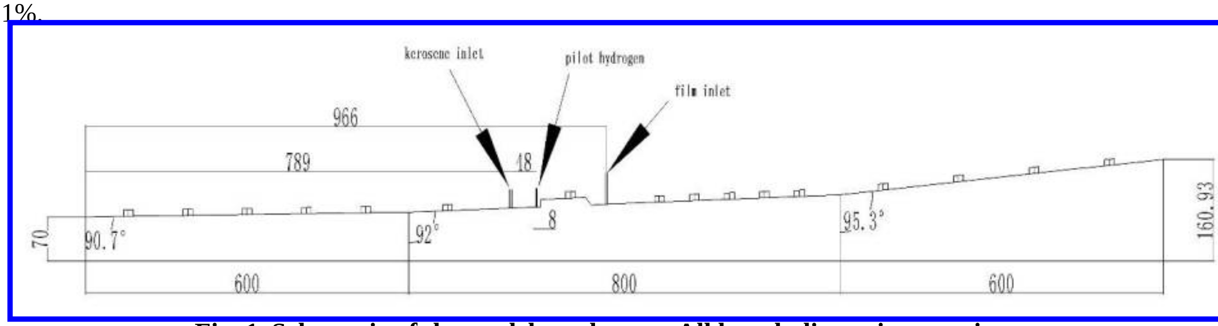


Fig. 1 Schematic of the model combustor. All length dimensions are in mm.

The model combustor is shown in Fig. 1. It has a total length of 2000 mm and consists of one isolator section of 600mm, one combustor section of 800mm and one divergent section of 600mm with the expansion angles of 0.7, 2.0 and 5.3 degrees, respectively. The entry cross section of the combustor is 70 mm in height by 150 mm in width. On the top of the combustor, there are 16 heat flux meters which position are marked up in Fig. 1. The entry of the coolant is behind the cavity. The film cooling device is detachable so it is convenient to change the direction of the coolant.

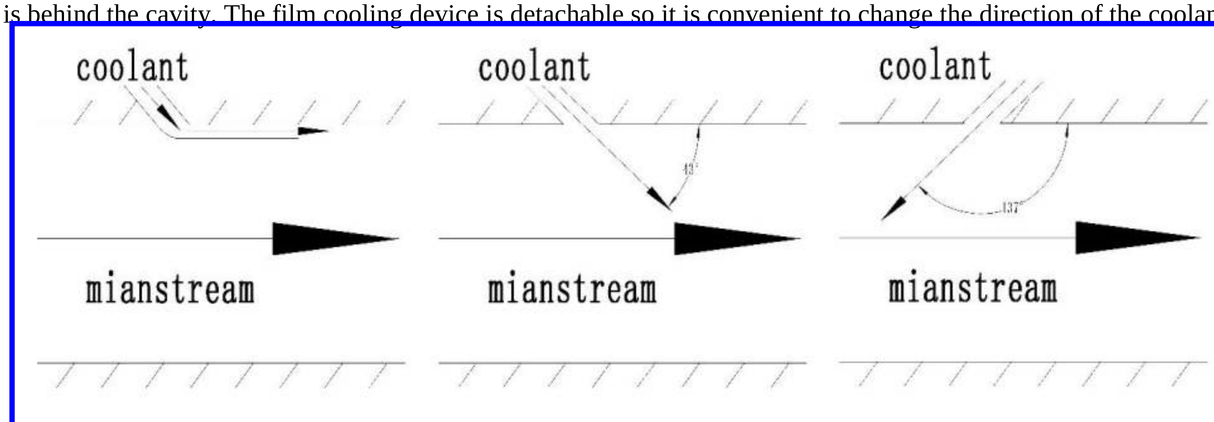


Fig. 2 schematic of the three kind of the direction of film.

B. Experimental Conditions

To resarch the influence of the direction of the coolant, three directions are set as Fig. 2. The injection angle is respectively 0°, 43°, 137°. The experimental conditions are listd in Table 1. "/" stands for experiments without film cooling. The coolant mass flux ranges from 1% to 6% of the mainstream mass flux, and the mainstream mass flux is 2.5kg/s. The coolant temperature ranges from 300K to 1060K, and for mainstream it is 1500K. The experiments are conducted on condition of both aerodynamic heating without kerosene combustion and with combustion. There are 35 experiments completed and they are divided into several sets. Each set has a changeable parameter and keep other parameters fixed. No.2-7,No.8-13,No.14-19 are conducted to explore the influence of coolant mass flux. The influence of the direction of coolant can be found by contrasting the three sets. No.20-23, No.23-26 are set to study to the influence of coolant temperature. All these experiments above are conducted on condition that without kerosene combustion. Under the actual combustion conditions, the flame and shockwave can affect the film, so No.27-35 are conducted to explore the influence of combustion.

C. Measurement Methods

The mass flux and temperature of film are controlled by the flux and ratio of air and hydrogen. The film generator are shown as Fig. 3. Distribution of the static pressure in the axial direction was determined using Motorala MPX2200 pressure transducers installed along the centerline of the model combustor sidewalls. The heat flux was measured by the Godgon heat flux meter. Supercritical kerosene used in this work was at stagnation temperatures of 750K and stagnation pressures of 3.5-6.0MPa, which was prepared using a two-stage kerosene heating and delivery system. Mass flow rate of the supercritical kerosene were controlled and measured by sonic nozzles. A small amount of polit hydrogen was used to facilitate the ignition of kerosene in the supersonic combustor, which was injected injected normal to the airflow just upstream of the cavity. It usually takes approximately 10 seconds to establish a steady signal for heat flux meter and a typical total run lasts about 17 seconds.

Table 1 Experimental conditions

	Injection angle	Coolant mass flux,g/s	Coolant temperature,K	With/Without combustion
1	/	/	/	/
2	137°	25	300	Without
3	137°	50	300	Without
4	137°	75	300	Without
5	137°	100	300	Without
6	137°	125	300	Without
7	137°	150	300	Without
8	43°	25	300	Without
9	43°	50	300	Without
10	43°	75	300	Without
11	43°	100	300	Without
12	43°	125	300	Without
13	43°	150	300	Without
14	0°	25	300	Without
15	0°	50	300	Without
16	0°	75	300	Without
17	0°	100	300	Without
18	0°	125	300	Without
19	0°	150	300	Without
20	43°	75	610	Without
21	43°	75	876	Without
22	43°	75	928	Without
23	0°	75	650	Without
24	0°	75	790	Without
25	0°	75	950	Without
26	0°	75	1060	Without
27	43°	/	/	/
28	43°	75	300	With
29	43°	75	773	With
30	0°	/	/	/
31	0°	25	300	With
32	0°	75	300	With
33	0°	125	300	With
34	0°	75	573	With
35	0°	75	908	With

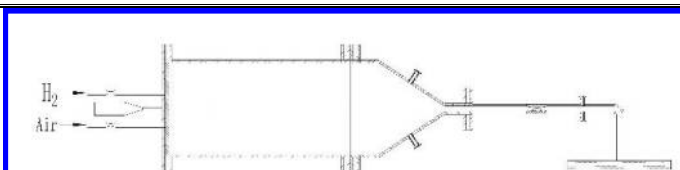


Fig. 3 Film Generator.

D. Definition of the Supersonic Film-Cooling Effectiveness

The wall of supersonic combustors are cooled by water and is almost isothermal, so the adiabatic supersonic film-cooling effectiveness is not suitable for this suitation. The isothermal supersonic film-cooling effectiveness is defined as

$$\eta_{iso} = \frac{q_0 - q_f}{q_0} \tag{1}$$

where q_0 is heat flux without film cooling, q_f is heat flux with film cooling. The effectiveness mentioned in this article refer to the isothermal supersonic film-cooling effectiveness.

III. Experimental Results and Discussion

A. The Influence of the Injetcion Angle

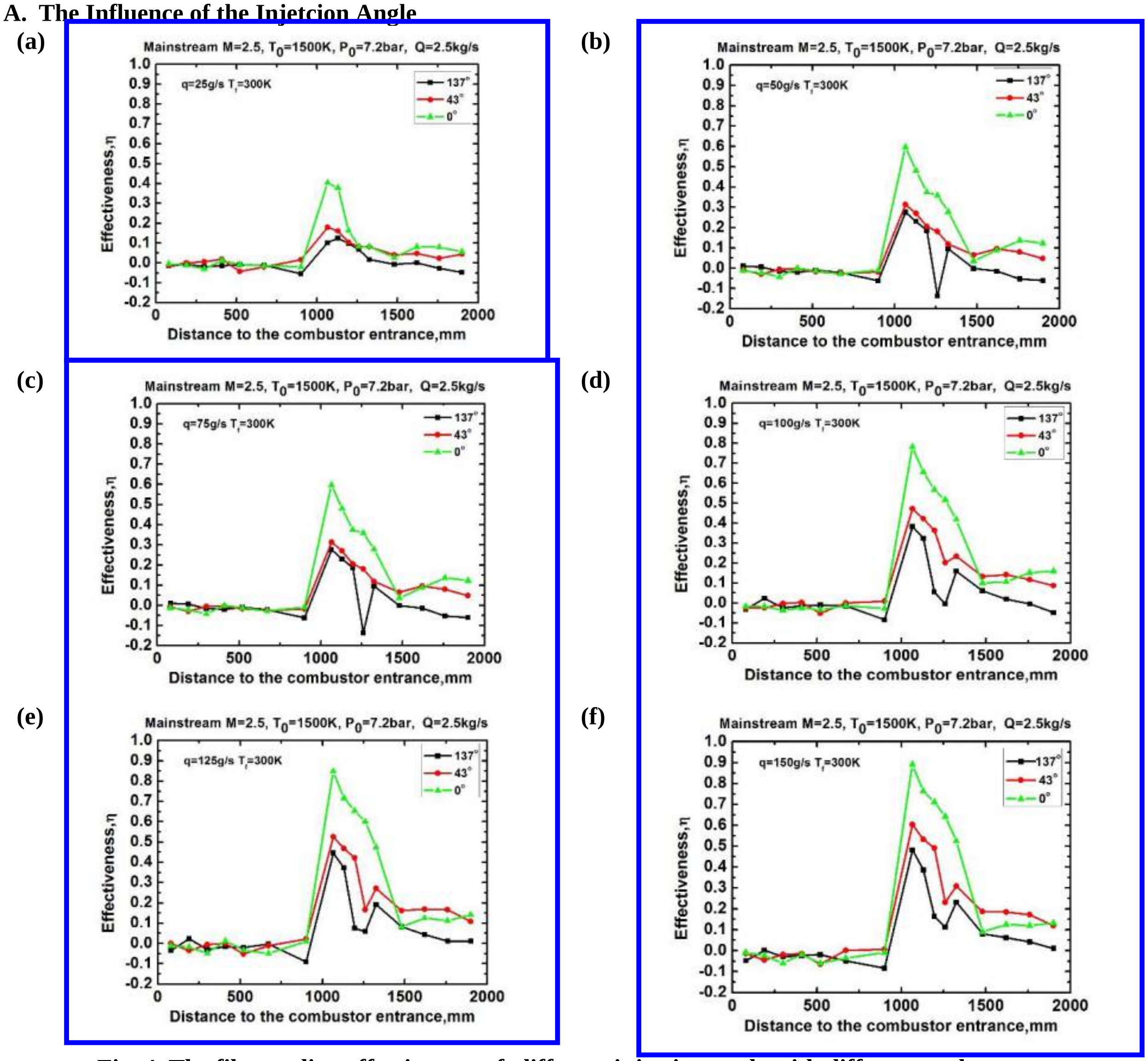


Fig. 4 The film-cooling effectiveness of different injection angle with different coolant mass flux.(a)q=25g/s, (b)q=50g/s,(c)q=75g/s,(d)q=100g/s,(e)q=125g/s,(f)q=150g/s

The film-cooling effectiveness distribution of different injection with different coolant mass flux is shown in Fig. 4. The results show that a smaller injection angle has a better performance in film cooling effectiveness regardless of the coolant flux. In the experiments, the film inlet was at 966mm distance to the entrance of the combustor. The film-cooling effectiveness is nearly 0 from the entrance to the film inlet, which indicates that the film was blown to the downstream even if to the reverse injection. When the injection angle is 137°, there is also has cooling effect even if not very good, which indicates that the film was pressure in the wall. It is a good news because the film was not be destroyed severely. The results also indicates that the film can last more than 500mm. There is a interesting phenomenon that the large angle injection can cause the film-cooling effectiveness a sudden decrease at the region of 400mm dowmstream of the film inlet, which is caused by the reflection of the shockwave that generated by interaction between film and mainstream.

B. The Influence of the Coolant Mass Flux

Fig. 5 shows that the heat flux distribution with different coolant mass flux in three injection angle. The heat flux keeps steady in the isolator section and cuts in half as a result of the existence of the cavity. A larger coolant mass flux makes a lower heat flux downstream the film inlet.

Fig. 6 shows the film-cooling effectiveness with different coolant mass flux. When the injection angle is 137º, the position 1260mm has a point which has very low effectiveness. It is caused by the reflection of the shockwave. For the smaller injection angle or parallel injection, when the coolant mass flux more than 75g/s, the increase of effectiveness is slow. When it is applied, it is wise to find a good point where can not only get good cooling effectiveness but also save the coolant. Fig. 6 also shows that the distance of film can maintain is about 500mm, which gives us information to placement the film inlet.

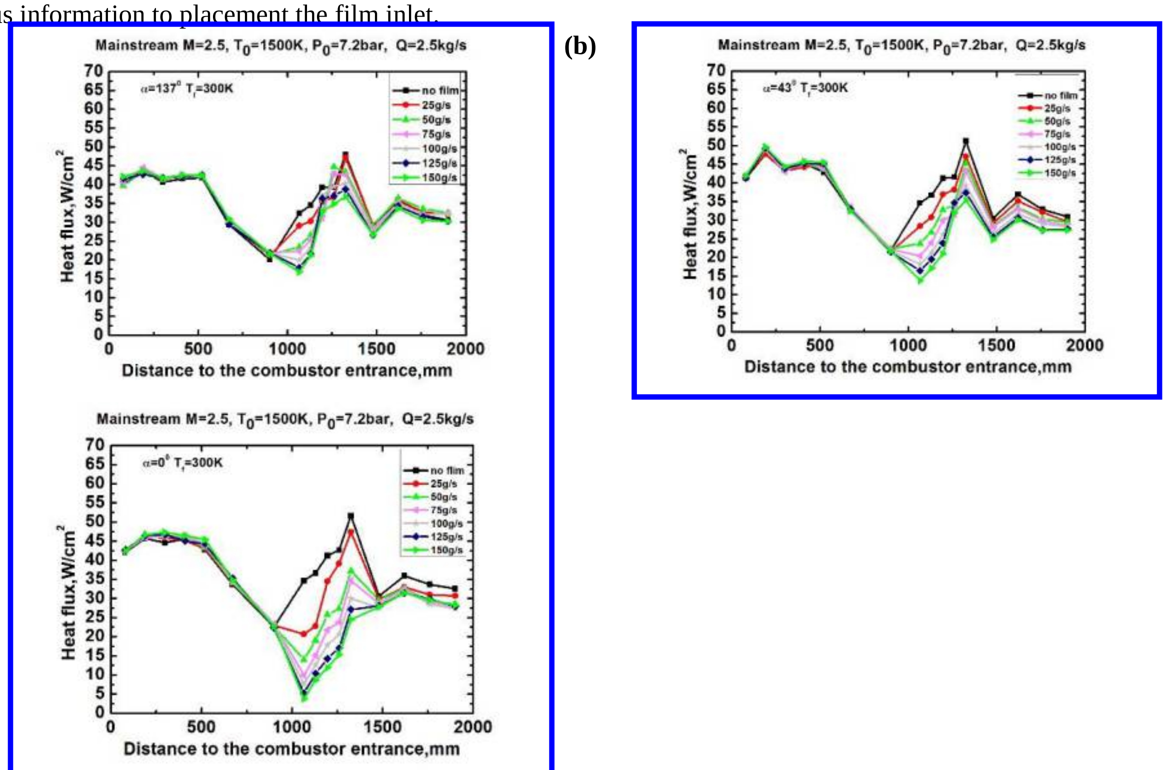
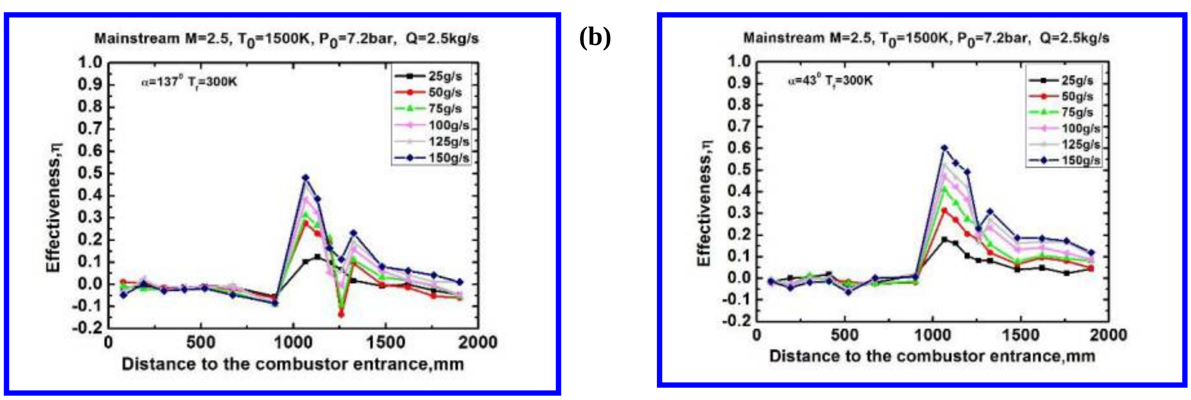


Fig. 5 The heat flux distribution of different coolant mass flux with different injection angle. (a)$\alpha = 137^{\circ}$, (b)$\alpha = 43^{\circ}$, (c)$\alpha = 0^{\circ}$.



(c)

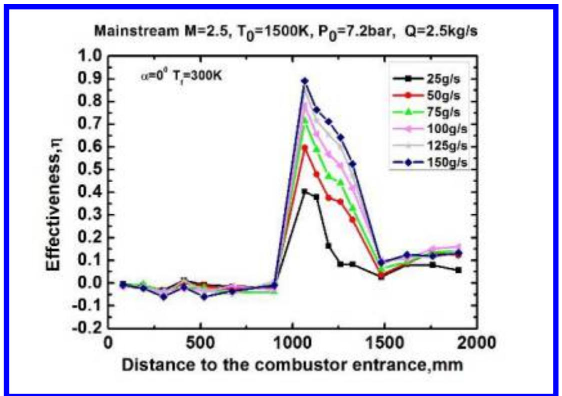


Fig. 6 The film-cooling effectiveness distribution of different coolant mass flux with different injection angle. (a)$\alpha = 137^{\circ}$, (b)$\alpha = 43^{\circ}$, (c)$\alpha = 0^{\circ}$.

C. The Influence of Coolant Temperature

Fig. 7 shows the film-cooling effectiveness under different coolant temperature. When the injection angle is 43°, the temperature of film coolant has little effect on the effectiveness. The reason is that the film prevents the heat conduction, rather than takes away heat from the wall in this condition. An interesting phenomenon is that the coolant temperature has different influence when the injection angle is different. As shown in Fig. 7, when the injection angle is 0°, a higer coolant temperature not only reduces the film-cooling effectiveness but also shortens the length of cooling distance.

(a)

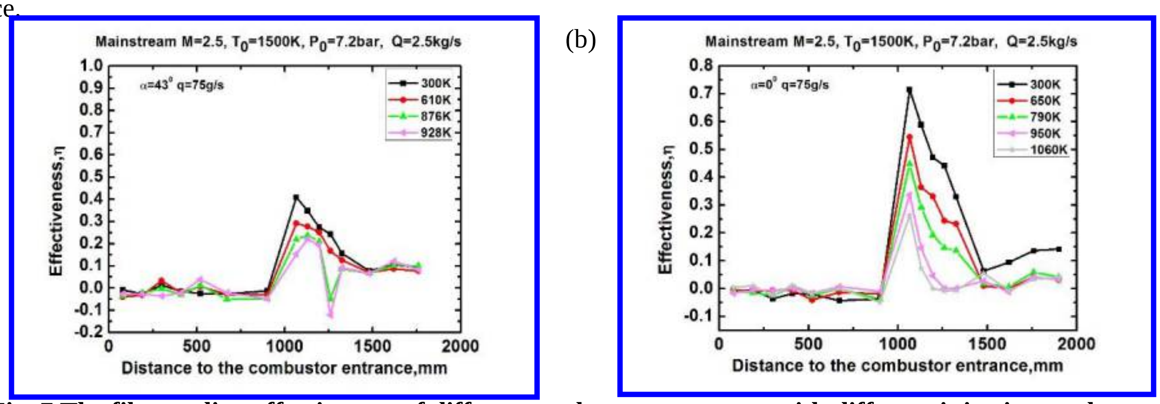


Fig. 7 The film-cooling effectiveness of different coolant temperature with different injection angle. (a)$\alpha = 43^{\circ}$, (b) $\alpha = 0^{\circ}$

D. The Influence of Kerosene Combustion

All of the experiments above are conducted in the condition of no kerosene combustion. While in actual engines, the influence of combustion can not be ingored, so it is necessary to do some researchs with combustion.

Fig. 8 is the film-cooling effectiveness with combustion in the condition injection angle is 43° and coolant flux is 75g/s. It shows that the in this injection angle the film has no effect. The reason is that the film was injected into the flame and reacts with kerosene, which destroys the film thoroughly. It means that in the large injection angle is inappropriate in the condition with combustion.

Fig. 9 shows the influence of coolant mass flux in the condition of with kerosene combustion. Compared with Fig. 8, it can be found that the injection angle is a important factor for

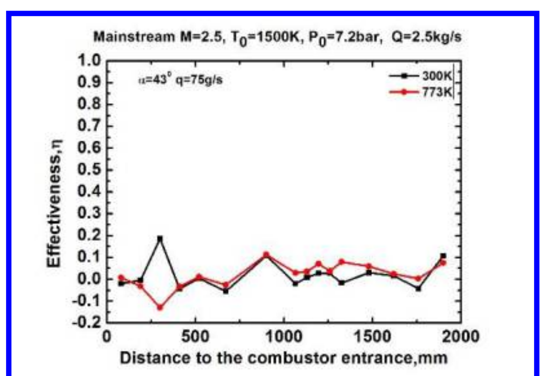


Fig.8 the film-cooling effectiveness with combustion in the condition injection angle is 43° and coolant flux is 75g/s.

the film cooling with combustion. When the injection angle is 0º, a larger coolant mass flux causes a better performance on cooling effectiveness. Especially, the effective cooling distance can last until the outlet of the combustor, which is even better than the performance without combustion.

In actual applications, the film is imported form the air inlet. As we know, the total temperature of film is very high at a high Mach number condition, therefore, if the high temperature of coolant can be used is the focus of the research. Fig. 10 shows the film-cooling effectiveness with combustion under different temperatures. It can be seen that there is a similar effectiveness no matter what the coolant temperature, which means the mechanism of film cooling is to separate the wall from the high temperature flame rather than take away heat from the wall.

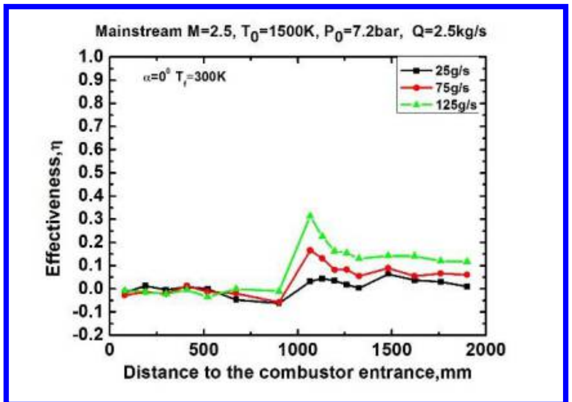


Fig. 9 The film-cooling effectiveness with combustion in the condition injection angle is 0º and coolant temperature is 300K.

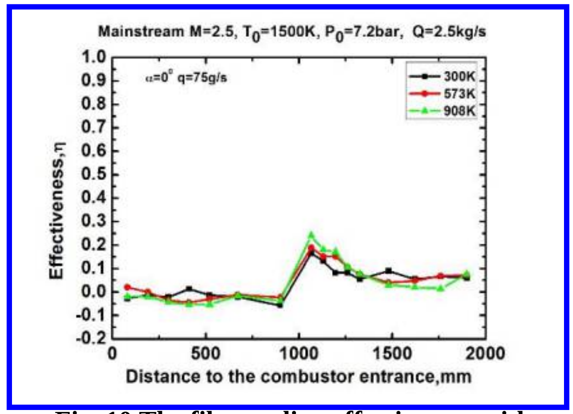


Fig. 10 The film-cooling effectiveness with combustion in the condition injection angle is 0º and coolant mass flux is 75g/s.

IV. Conclusion

The current study analyzed the effect of the injection angle, coolant mass flux, coolant temperature and combustion on film-cooling effectiveness. The mainstream was kept constant while one parameter of the coolant. The results indicate the following.

1) With the same other conditions, a smaller injection angle has better performance in film cooling, especially with the kerosene combustion.

2) The effect of coolant mass flux is that the more coolant are used, the higher film-cooling effectiveness achieved. But when the coolant mass flux more than 3% of the mainstream the incresase of effectiveness is not in proportional to the increase of mass flux.

3) The influence of coolant temperature is more complex. The higher coolant temperature reduces the cooling effectiveness without kerosene combustion, while has not significant influence with kerosene combustion.

4) For the condition of combustion, the flow fields are more complex and the big injection angle is not applicable, additional, the temperature is not any more the main factor for the film cooling.

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References

[1]Aupoix, B,Mignosi, A.Viala, S,Bouvier, F,Gaillard, R, "Experimental and Numerical Study of Supersonic Film Cooling," *AIAA Journal*, Vol.36, No.6,1998, pp.915-923.

[2] Hunt, M. Juhany, K. Sivo, " Supersonic film cooling effectiveness using air and helium for a range of injectant temperatures and Mach numbers," 1991.

[3]A Juhany, K. A. Hunt, M. L," Flowfield measurements in supersonic film cooling including the effect of shock-wave interaction,"*AIAA Journal*,Vol.32,No.3,1994,pp. 578-585.

[4]Goldstein R, Eckert E, Tsou F, Haji-Sheikh A.,"Film Cooling with Air and Helium Injection Through a Rearward-Facing Slot into a Supersonic Air Flow,". AIAA Journal, 1966, 4(6): 981-985.

[5]Juhany, K. A.,Hunt, M. L,Sivo, J. M., "Influence of injectant Mach number and temperature on supersonic film cooling," *Journal of Thermophysics and Heat Transfer* ,Vol.8,No.1,pp. 59-67.

[6]Kanda, T., et al, " Experimental studies of supersonic film cooling with shock wave interaction," *AIAA Journal*, Vol.34,No.2,1996,pp. 265-271.

[7]Kanda, Takeshi Ono, Fumiei,"Experimental Studies of Supersonic Film Cooling with Shock Wave Interaction (II)," *Journal of Thermophysics and Heat Transfer*,Vol.11,No.4, 1997,pp.590-592.

[8]Peng, W. and P.-X. Jiang,"Influence of Shock Waves on Supersonic Film Cooling," *Journal of Spacecraft and Rockets*,Vol.46,No.1,2009,pp. 67-73.

[9]Peng, W. and P.-X. Jiang,"Effect of shock waves on supersonic film cooling with a slotted wall," *Applied Thermal Engineering* ,Vol.61,No.1,2014 ,pp.187-196.

[10]Peng, W, Sun, Xiao-Kai,Jiang, Pei-xue,"Effect of Coolant Inlet Conditions on Supersonic Film Cooling," *Journal of Spacecraft and Rockets*,Vol.52,No.5,2015,pp.1456-1464.

[11]Takita, Kenichi,Masuya, Goro," Effects of Combustion and Shock Impingement on Supersonic Film Cooling by Hydrogen," *AIAA Journal*,Vol.38,No.10,2000,pp.1899-1906.

[12]Takita, Kenichi," Film Cooling Effect of Hydrogen on Cylinder in Supersonic Airflow," *Journal of Spacecraft and Rockets*,Vol.34,No.3,1997,pp.285-289.

[13]Vijayakumar, Vishnu,Pisharady, Jagadish,Balachandran, P," Computational and experimental study on supersonic film cooling for liquid rocket nozzle applications," *Thermal Science*,Vol.19,No.1,2015,pp.49-58.

[14]Goldstein,R. J., Eckert, E.R. G., Tsou, F.K., and Sheikh,A.H., "FilmCooling with Air and Helium Injection Through a Rearward-Facing Slot into a Supersonic Air Flow," AIAA Journal, Vol. 4, No. 6, 1966,pp. 981–985.