Effect of a Coaxial Jet on the Film-Cooling Performance Downstream of a Suddenly Expanded Swirling Flow

C. Gau* and T. M. Huang†
National Cheng Kung University, Tainan, Taiwan, Republic of China

The effect of a coaxial jet on the film-cooling performance downstream of a suddenly expanded swirling flow in a film-cooled pipe is studied. A flat-vane swirler situated upstream before expansion is used to produce the swirling flow. Both the radial temperature distributions and the film-cooling effectiveness are measured, and the results are presented and discussed. In the experiment, the jet/mainstream velocity ratio ranged from 0–1.5, the swirl number from 0–0.6, and the blowing parameter from 0.5–2.0.

Nomenclature

M = blowing parameter, U_j/U_m
S = swirl number
U = velocity
x = axial distance from slot exit
y = radial distance from pipe wall
y_c = slot height
η = film cooling effectiveness, $(T_{aw} - T_m)/(T_j - T_m)$

Subscripts
aw = adiabatic wall
c = coaxial jet
j = film jet at slot exit
m = mainstream

Introduction

THE problem of film-cooling heat transfer has wide applications in high-temperature systems and, therefore, has generated much research interest. Film-cooling performance can be significantly affected by the mainstream conditions. It has been shown in the previous work[1] that, in a film-cooled pipe downstream of an abrupt 2.4:1 expansion, the suddenly expanded swirling flow can have a significant effect on the film-cooling performance. This is attributed to the complex flow structure, which is significantly affected by both the swirl and the film jet velocity.

For the case of film cooling without swirl, the flow passing through a sudden expansion can separate, recirculate, and reattach to the wall. A recirculation zone is formed. The recirculation zone has a direct contact with the film jet and, therefore, can have a significant effect on the film jet structure. The reattachment of flow can impinge and severely destroy the film jet structure and reduce significantly the film-cooling performance. For the case with the presence of swirl, it has been shown[1] that as the swirl increases the size of the recirculation zone decreases, and the reattachment point moves upstream, which can cause an earlier destruction of film jet structure. On the other hand, the increase in film jet velocity can reduce the size of the recirculation zone and move the reattachment point downstream. In addition, the increase in film jet velocity can make the film jet structure stronger. Therefore, the increase in blowing parameter can increase the film-cooling effectiveness.

However, in the previous studies,[1] the swirl hub was blocked with a guide cone and no air could pass through the swirl hub. In a practical combustor, a fuel nozzle is usually placed in the center of the swirler and air is allowed to pass through the swirl hub to atomize the fuel jet. Therefore, the swirling flow entering a combustor is always accompanied by a coaxial jet. So et al.[2] studied the jet characteristics in a confined swirling flow without expansion and found that the jet, even with a small amount of axial momentum, is strong enough to eliminate completely the recirculation zone behind the hub and change the flow structure. It can be expected that, for suddenly expanded swirling flow, the coaxial jet velocity can have a significant effect on the film-cooling performance on the wall. Therefore, the objective of the present work is to study the effect of the coaxial jet on the film-cooling performance for a swirling flow through a film-cooled pipe downstream of an abrupt expansion.

Instrumentation and Equipment

Experiments are performed in the same test facilities and pipe expansion of 2.4:1 as described in Ref. 1, and they are shown in Fig. 1. The same sets of flat-vaned swirlers are used to generate swirling flow except that the guide cone in front of the hub is removed and replaced with a coaxial tube, having an inside diameter of 4.5 cm, that can inject a coaxial jet. The coaxial jet is made with a different air system. The coaxial tube is led normally to the wind tunnel before the settling chamber and is turned 90 deg toward the flow direction in the center of the wind tunnel. The flow disturbance caused by the presence of the coaxial tube is reduced with honeycombs and screens in the settling chamber. Inside the coaxial tube, two

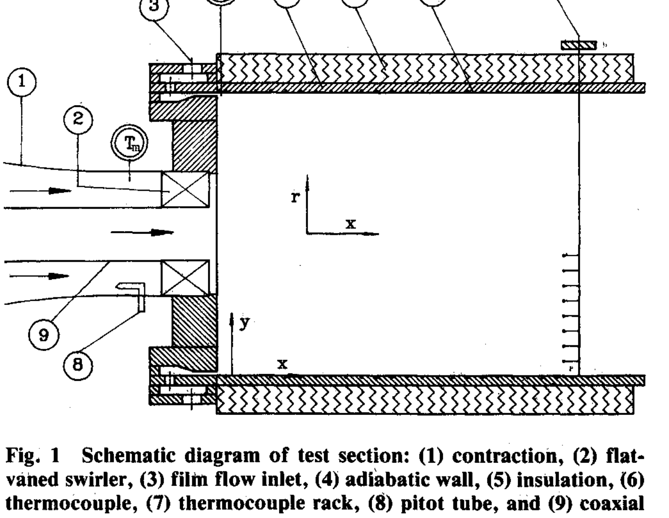


Fig. 1 Schematic diagram of test section: (1) contraction, (2) flat-vaned swirler, (3) film flow inlet, (4) adiabatic wall, (5) insulation, (6) thermocouple, (7) thermocouple rack, (8) pitot tube, and (9) coaxial tube.

Received Aug. 28, 1989; revision received Jan. 23, 1990.

*Associate Professor, Institute of Aeronautics and Astronautics.
†Graduate Student, Institute of Aeronautics and Astronautics.

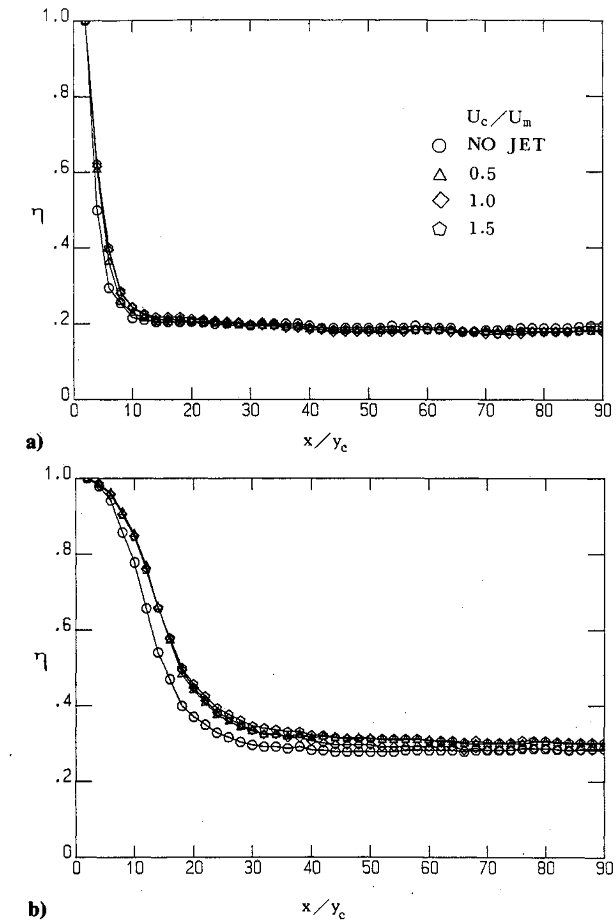


Fig. 2 Effect of jet velocity ratio on film-cooling effectiveness for $S = 0.6$: a) $M = 0.5$; b) $M = 1.7$.

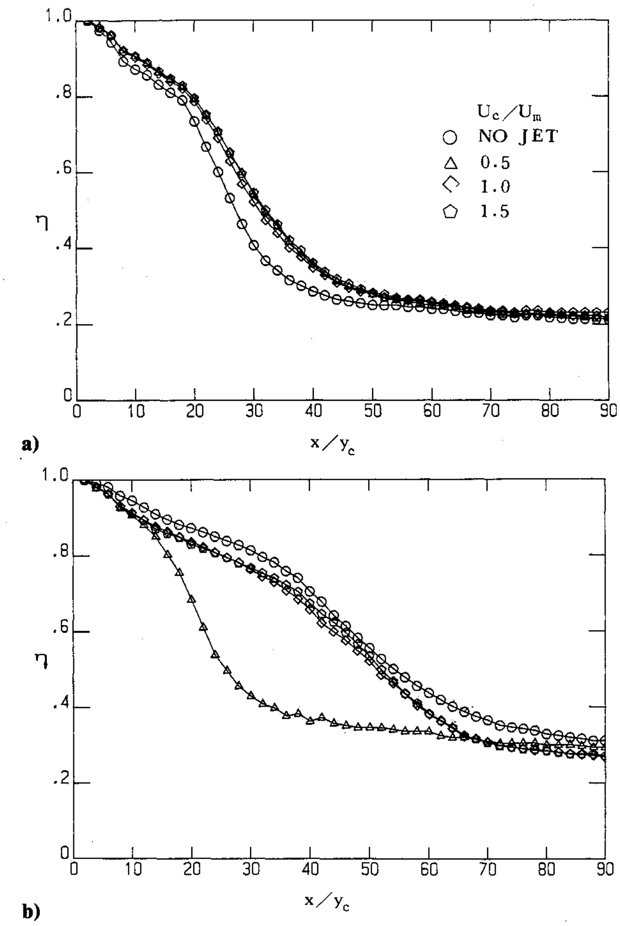


Fig. 3 Effect of jet velocity ratio on film-cooling effectiveness for $S = 0.2$: a) $M = 1.0$; b) $M = 1.5$.

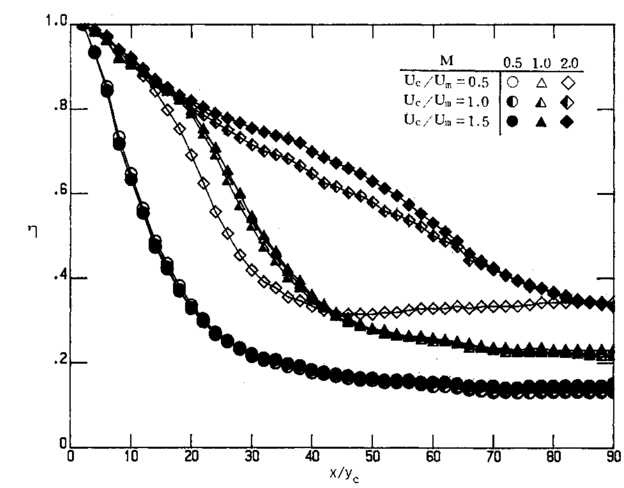


Fig. 4 Effect of jet velocity ratio on film-cooling effectiveness for $S = 0.2$ at different blowing parameters.

different honeycombs at different locations are used to eliminate large eddies generated by the blower and the 90-deg elbow. The distance from the last honeycomb to the tube exit is more than 2 m to insure that the flow at the tube exit is fully developed and turbulent.

A total of 45 thermocouples, equally spaced, are embedded in the pipe wall to measure the adiabatic wall temperature in the axial direction. The outside pipe wall is well-insulated. A total of another 24 thermocouples, having a wire diameter of 0.05 in., are made into a rack, which can be inserted into the pipe to measure the radial temperature distributions. The pitch between adjacent thermocouples near the wall is 2 mm. Farther away from the wall the pitches are 4, 6, and 8 mm, respectively, increasing in the direction toward the pipe center.

Results and Discussion

The effect of a coaxial jet at four different velocity ratios $U_c/U_m = 0$, 0.5, 1.0, and 1.5 on the film cooling effectiveness are studied, and the typical results for the case at low blowing parameter and at high blowing parameter range are presented in the following figures. The effect of the coaxial jet on the film-cooling effectiveness is small when the swirl number is high ($S = 0.6$), as shown in Fig. 2. For a high swirl ($S = 0.6$), a corner recirculation zone (CRZ) forms upstream in a relatively small region as described in Ref. 1. The central coaxial jet moves rapidly downstream, and the chance for the jet to be entrained into the CRZ is small. Therefore, the variation of the coaxial jet velocity has a negligible effect on the structure of CRZ, which has a direct contact with the film jet, and the rate of mixing of film jet with CRZ. However, the coaxial jet may be entrained downstream, and impinge on and destroy the film jet structure. Since the film jet has been destroyed completely upstream of the jet entrainment, the reduction of film-cooling effectiveness due to the entrainment of the coaxial jet is negligible.

For a swirl number of $S = 0.2$, the effect of the coaxial jet on film-cooling effectiveness may become significant at some blowing parameter, as shown in Fig. 3. When the swirl number is small ($S = 0.2$), the CRZ that appears is relatively large. On the other hand, it has been shown[3-5] that the relatively low degree of swirl ($S < 0.4$) has the effect of increasing the width of jet flow and causing the entrainment and the decay of the coaxial jet. Therefore, the coaxial jet can be readily entrained into the CRZ. The entrainment of the coaxial jet into the CRZ may change the entire flow structure inside and significantly affect the film-cooling effectiveness. The entrainment of the coaxial jet can result in a severe destruction of the film jet structure at $U_c/U_m = 0.5$ as shown in Figs. 3b and 4. However, a large reduction of film-cooling effectiveness occurs only at relatively high blowing parameters ($M \geq 1.5$). At low blowing parameters, the expanded coaxial jet entrains and impinges on the film jet at the downstream location where the film jet has almost completely mixed with the mainstream. Therefore, no further reduction in film-cooling effectiveness at low blowing parameters can be

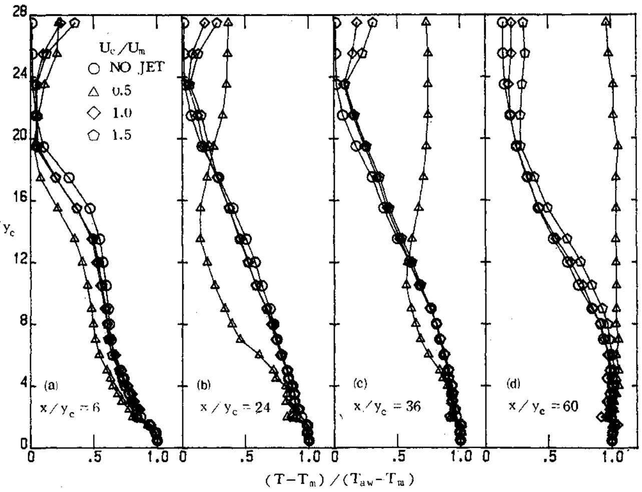


Fig. 5 Effect of jet velocity ratio on temperature distributions for $S = 0.2$ and $M = 1.5$: a) $x/y_c = 6$; b) $x/y_c = 24$; c) $x/y_c = 36$; d) $x/y_c = 60$.

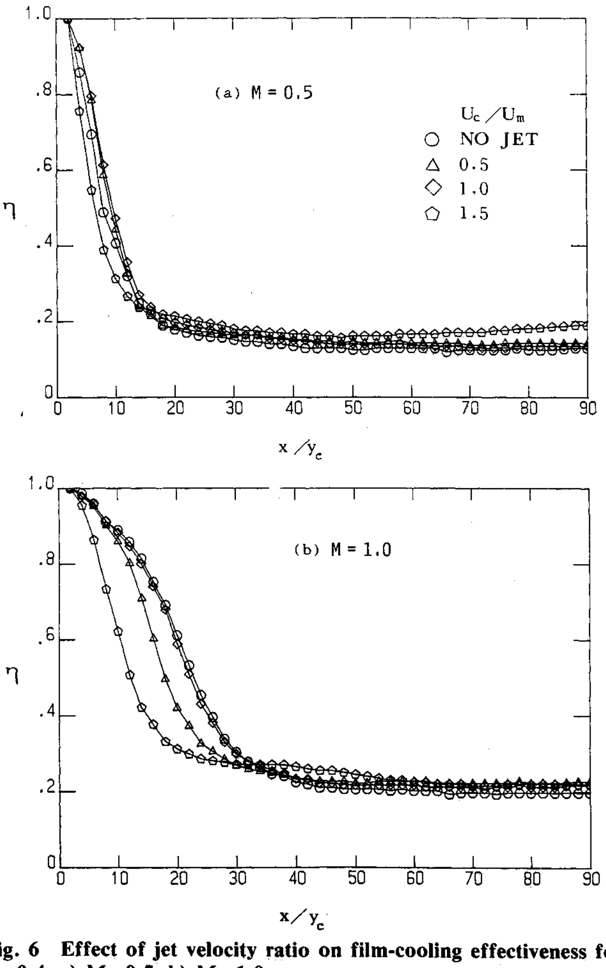


Fig. 6 Effect of jet velocity ratio on film-cooling effectiveness for $S = 0.4$: a) $M = 0.5$; b) $M = 1.0$.

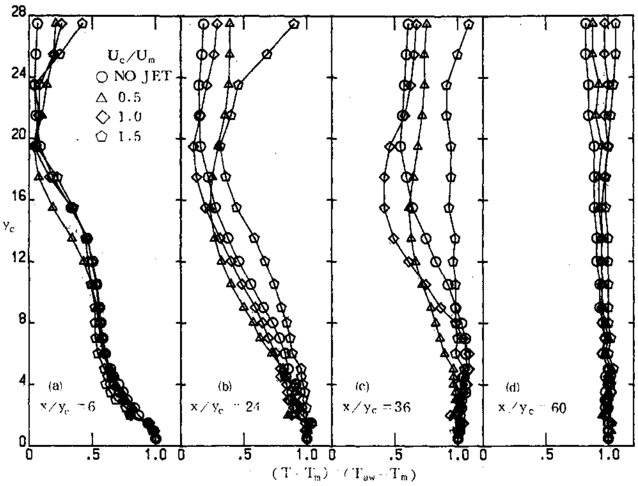
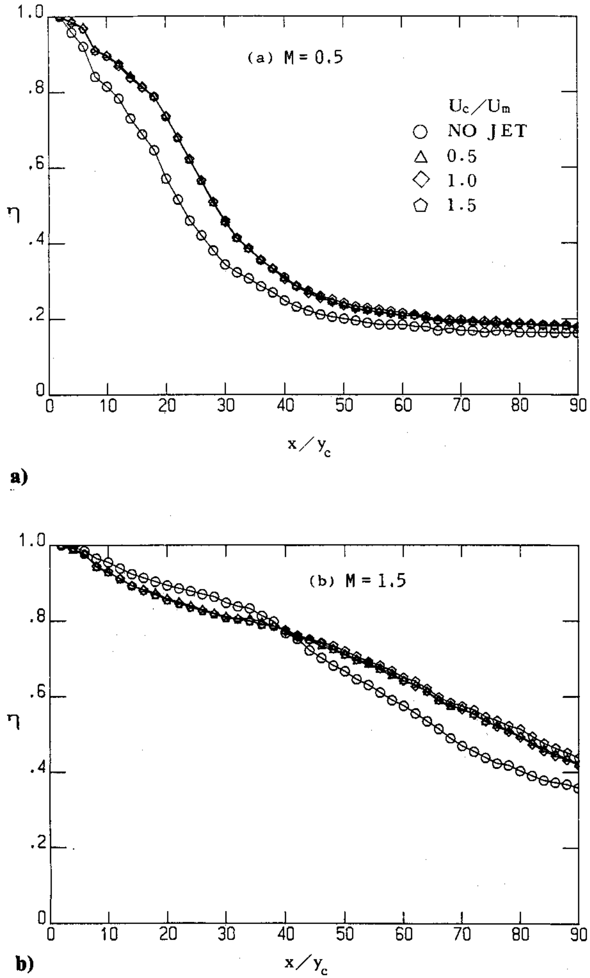


Fig. 7 Effect of jet velocity ratio on temperature distributions for $S = 0.4$ and $M = 1.0$: a) $x/y_c = 6$; b) $x/y_c = 24$; c) $x/y_c = 36$; d) $x/y_c = 60$.

observed. The situation for the case when the velocity ratio is high and the blowing parameter is large is very similar. The higher axial momentum of the jet makes the entrainment with and the impingement on the film jet layer occur farther downstream, where film jet structure is relatively weak. Therefore, the effect of jet velocity on the film-cooling effectiveness is small. The change of flow structure at $U_c/U_m = 0.5$ can be inferred from the temperature measurements, as shown in Fig. 5. Because of the entrainment of the coaxial jet, the dimensionless temperature distribution at locations $x/y_c = 24$ and 36 for $U_c/U_m = 0.5$ deviates significantly from that for other velocity ratios, as shown in Figs. 5b and 5c. No significant difference in dimensionless temperature is found when the velocity ratio is high, i.e., $U_c/U_m = 1.0$ or 1.5, at the same locations. Note that the higher temperature at the pipe center ($y/y_c = 37.5$) is due to the frictional heating of the blower blade, not the formation of central toroidal recirculation zone that occurs when coaxial jet velocity is zero and the swirl number is relatively high, i.e., $S \geq 0.4$. It appears that the heated coaxial jet does not have a significant effect on the flow structure except when $U_c/U_m = 0.5$.

However, the effect of jet velocity on the film-cooling effectiveness is very complicated. The film-cooling effectiveness for the case of $S = 0.2$ and $M = 1.5$ is not affected significantly except when $U_c/U_m = 0.5$. For the case of $S = 0.4$, the film-cooling effectiveness does not monotonically decrease or increase with the jet velocity ratio, as shown in Fig. 6b. Moderate reduction in film-cooling effectiveness in the near slot region can be observed. However, in the downstream region where the film structure may be destroyed completely, the film-cooling effectiveness at different velocity ratios approaches esentially the same value. When the swirl increases ($S = 0.4$), the growth of the jet width and decay of the jet may not be as rapid as that for $S = 0.2$. On the other hand, the size of the recirculation zone decreases. Therefore, the coaxial jet is not readily entrained into the recirculation zone and changes the entire flow structure inside, which causes a significant reduction in the film-cooling effectiveness. At low blowing parameters, the effect of velocity ratios on the film-cooling effectiveness becomes smaller, as shown in Fig. 6a, because the film jet structure has been completely destroyed. The temperature distributions, as shown in Fig. 7, indicate the change of flow structure as a function of the jet velocity ratio. However, the consequent change of film-cooling effectiveness by the jet velocity ratio is not large. It appears that the change of flow structure is insignificant, which does not significantly affect the film-cooling performance. More detailed understanding of the flow structure is needed.

For the case when the swirl number $S = 0$, the recirculation zone is very large and the growth of the width of the jet flow is



a)

b)

Fig. 8 Effect of jet velocity ratio on film-cooling effectiveness for $S=0$: a) $M=0.5$; b) $M=1.5$.

very slow. The coaxial jet entrains and impinges on the film jet layer at a far downstream location where the film jet structure is very weak. The structure of the recirculation zone is hardly affected by the jet flow. Therefore, the variation of jet velocity ratio does not have a significant effect on the film-cooling effectiveness, as shown in Fig. 8, except when the velocity ratio is zero. Without the coaxial jet, a weak recirculation zone behind the swirl hub appears, which can change the flow structure of the recirculation zone in the corner of the expansion and affect the film-cooling effectiveness. This is also true when the mainstream is swirled, as shown in the preceding figures. However, the effect is very complicated and a more detailed flow-visualization experiment is needed.

Conclusions

The coaxial jet flow can significantly reduce the film-cooling effectiveness when the jet is entrained into the recirculation zone in the corner of an abrupt pipe expansion and changes the flow structure inside. For the case when the coaxial jet entrains the film jet downstream of the reattachment point, the coaxial jet velocity has a negligible effect on the film-cooling performance. Because of the complicated effect of jet velocity on the film-cooling performance, correlations for film-cooling effectiveness in terms of relevant parameters is not possible.

References

[1]Gau, C., Yih, K. A., and Chang, S. S., "Effect of Swirling Flow on Film-Cooling Performance Downstream of a Sudden Expansion," *Journal of Thermophysics and Heat Transfer*, Vol. 5, No. 1, 1991, pp. 89–95.

[2]So, R. M. C., Ahmed, S. A., and Mongia, H. C., "Jet Characteristics in Confined Swirling Flow Flow," *Experiments in Fluids*, Vol. 3, No. 4, 1985, pp. 221–230.

[3]Beer, J. M., and Chigier, N. A., *Combustion Aerodynamics*, Robert E. Krieger Publishing, FL, 1983, pp. 100–146.

[4]Lilley, D. G., "Swirl Flow in Combustion: A Review," *AIAA Journal*, Vol. 15, No. 8, 1977, pp. 1063–1078.

[5]Gupta, A. K., Lilley, D. G., and Syred, N., *Swirl Flow*, Abacus Press, Tunbridge Wells, England, UK, 1984, pp. 1–16 and 119–218.