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Micro film cooling performance

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ABSTRACT

A novel idea for micro film cooling experiment is proposed and conducted. Both fabrication of a micro film-cooled device and evaluation of its performance are presented. The film cooling device is placed in a wind tunnel system for evaluation with the blowing parameter (M) ranging from 1 to 12.5 and the film jet slot heights of 25 μm, 45 μm and 50 μm, respectively. The micro film cooling performance obtained is found much higher, and the amount of cooling air used is much less, approximately two or three order magnitude lower, than that in the large-scale film cooling system. This means much saving of power consumption and more engine efficiency.

1. Introduction

Film cooling process has been widely adopted on the walls of a high temperature system, such as on gas turbine blade, the wall of a combustion chamber and nozzle of a gas turbine engine, to protect the wall surface from being over heated [1,2]. Cooling air is usually designed to inject from or along the hot surfaces and form an insulation layer to protect surfaces from being overheated. Film cooling performance is a measure of the effectiveness of a film that can protect the surface, which is the degree of a film that has preserved its structure and has not been destroyed by mixing with the freestream and is defined as the temperature difference between the adiabatic wall temperature under the film and the freestream temperature, divided by the temperature difference between the film jet at the slot exit and the freestream. Extensive review on both analytical and experimental studies on film cooling performance is available [1–5].

However, in the past the film jet used in the film cooling process is so thick that the amount of cooling air used is so large that it can effectively reduce the performance of a gas turbine engine. In addition, the relatively thick film jet is expected to rapidly mix with the hot gas in the freestream and reduce its protection effectiveness [6–10]. The current paper presents a design and fabrication procedure by micro-electro-mechanical system (MEMS) techniques that can make a micro film-cooled device which can inject a micro air jet for film cooling purpose. Fabrication of such micro device is motivated by the findings [11] in our laboratory that a micro jet exiting from a micro slot can have a much deeper penetration without breakdown and mixing with the ambient air. When this micro jet is used for film cooling protection, this jet or film flow along the wall is expected to maintain its structure without rapid mixing with the freestream air until at very later stage. Therefore, film cooling performance of this micro device is expected to be much better than the large-scale film-cooled system. In this paper, the micro film cooling concept is for a cooling film injected from a slot with a height of tens of micron regime while the large-scale film cooling system is for a cooling film injected from a slot with a height of several millimeters regime. In addition, the use of micro film-cooled concept can save much of the cooling air in a gas turbine engine, and generate more power. This means a higher power efficiency engine.

2. Fabrication of the film-cooled device

A top view for the design of a micro slot film cooling device with temperature sensor array is shown in Fig. 1(a). The temperature sensors are aligned parallel to each other on the film-cooled surface and are more concentrated in the region close to the film slot exit and sparse afterward. This is due to the fact that large variation of film cooling effectiveness usually occurs in the upstream and small variation in the downstream. In the very upstream region in a distance less than 4000 μm from the slot exit, there a total of 16 sensors and the gap between neighboring sensors is 250 μm. In the next region of 4000–12,000 μm, there are total of 16 sensors and the gap between neighboring sensors is 500 μm. In the region of 12,000–20,000 μm, there are a total of 8 sensors and the gap is 1000 μm. In the region of 20,000–40,000 μm, there are a total of 10 sensors and the gap is 2000 μm. In the final region of 40,000–60,000 μm, there are a total of 5 sensors and the gap is 4000 μm.

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Nomenclature

K	thermal conductivity
M	blowing ratio, $\rho_j U_j/\rho_\infty U_\infty$
T	temperature
t	cover plate or slot lip thickness
Uj	average velocity of the film jet
U_∞	average velocity of the mainstream
x	axial distance from slot
y_c	slot height
η	film cooling effectiveness

Greek symbol

ρ	density

Subscripts

aw	adiabatic wall
j	film jet at slot exit
∞	mainstream

The dimension of all the temperature sensors is the same, and is 0.3 μm in thickness, 10 μm in width and 30 μm in length. A detailed design of the 3-D structure of the film-cooled device is shown in Fig. 1(b).

The temperature sensor array is used to measure the film cooling effectiveness, which can be made by depositing and patterning a metal film on a glass substrate that has a very low thermal conductivity, k. However, the metal line has very low temperature coefficient of resistance (TCR) that amplification of the temperature signals are required. This requires more effort to achieve since each sensor requires one amplification circuit system. A total of 55 amplification systems are required to incorporate into the measurement system. In addition, the metal sensor we made has a very short life time which prohibits the use of this type of sensors. On the other hand, one can also fabricate doped polysilicon as temperature sensor array on a silicon substrate. Since silicon substrate has a very high value of thermal conductivity, the polysilicon sensor array fabricated has to be moved to a glass substrate, which has a much lower thermal conductivity, to avoid heat loss from the substrate to the ambient during the film cooling experiments. Despite that the use of polysilicon as temperature sensor will complicate the fabrication process, the doped polysilicon sensor has a very high TCR which does not require the use of amplification system. In addition, the doped polysilicon sensor has a much longer life time. Therefore, polysilicon material is selected to make into temperature sensor array and the material used for doping is boron.

Before deposition of the sensor layer, a tetraethylorthosilicate (TEOS) oxide layer is deposited as an etching stop when silicon substrate is removed by wet etch. Metallization is made after completion for sensor fabrication. After completed sensor and metal lines fabrication, the silicon substrate is bonded with a glass substrate by epoxy. After removing the silicon substrate by wet etch, both the sensor array and metal lines are moved to a glass substrate, as shown in Fig. 2(a). Detailed fabrication techniques are very similar to the reports [12,13] and will not be repeated here. Finally, a film slot was made on the top by forming a convergent channel in a layer of an epoxy-based photoresist (SU-8) and enclosing with a thin cover plate made of poly(methylmethacrylate) (PMMA), as shown in Figs. 2(c) and (d). In addition, a relatively large hole is drilled in the glass substrate to allow heated or cooled air flow to enter into the film slot, as shown in Fig. 2c. For a better insulation, the glass substrate is ground to a much thinner size,

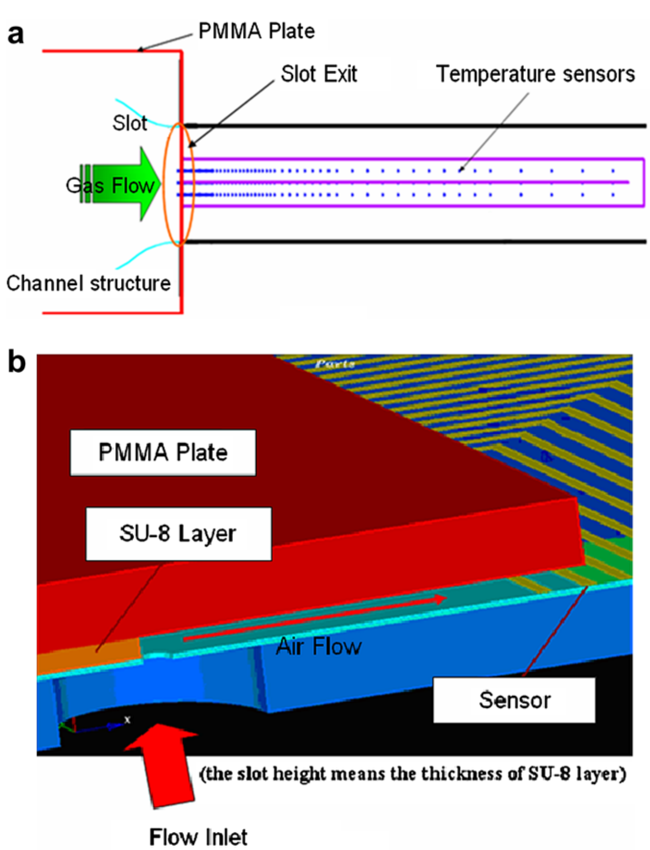

Fig. 1. (a) The design of a micro slot film cooling device with temperature sensor array under the film-cooled surface and (b) schematic diagram of a 3D micro film-cooled device.

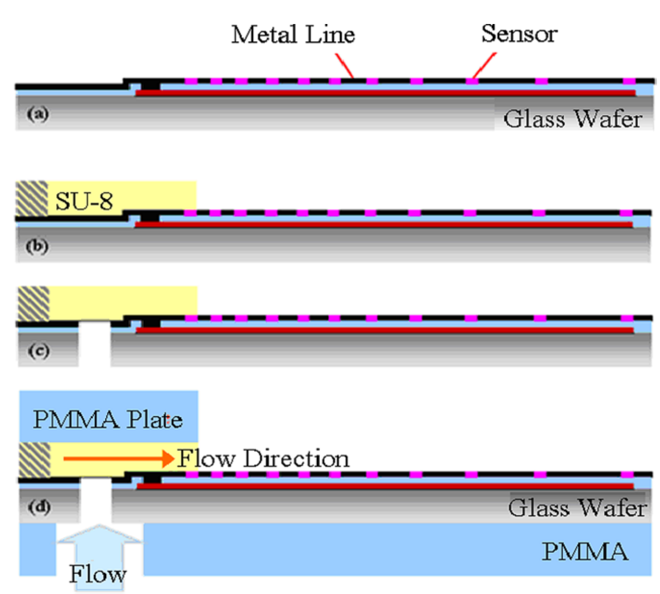

Fig. 2. Fabrication process: (a) deposition of heater, temperature sensors and metal lines, (b) air slot formation by coating SU-8 layer and lithography, (c) hole opening for entrance of cooling flow and (d) bonding of the PMMA plate.

around 200 μm in thickness, and bonded with a PMMA plate in below, as shown in Fig. 2(d), to further reduce the heat loss since the PMMA plate has a thermal conductivity an order of magnitude smaller than the glass. The completed film-cooled device is shown in Fig. 3.

3. Experimental apparatus and procedures

The film-cooled device is placed into a wind tunnel system, as shown in Fig. 4, where film cooling performance is measured and determined. The test section at the outlet of contraction in the wind tunnel is rectangular, as shown in Fig. 4, and has inside dimensions of 100 mm in height and 152 mm in width and 664 mm in length. Mainstream air is supplied from and discharged into the environment by an open type of wind tunnel. The turbulence intensity at the entrance of the test section is 1%, which was measured with TSI hot wire anemometer. The injection air is supplied by a different air system that can be heated at desired temperatures. Therefore, instead of film cooling method, the film heating method is adopted to measure the film cooling effectiveness. In fact, both the film cooling and the film heating methods have been adopted in the past [2,7,8–10]. The only difference between the film heating method and the film cooling method is the direction of the heat transfer. For film heating method, the heat transfer is from the heated film to the mainstream. For the film cooling method, the heat transfer is from the mainstream to the cooled film. Reversing the direction of the heat transfer does not affect the mixing process of film jet with the mainstream and the film cooling effectiveness defined in the paper. In addition, film heating method has more advantages than the film cooling method. In the film cooling method, the entire air in the wind tunnel has to be heated and the entire wall of the wind tunnel needs well insulation. However, in the film heating method, the film jet air is required to be heated and the piping for the film jet air needs well insulation. However, the amount of the film jet air flow and the insulation material used in the film heating method is much less. Therefore, the experimental facilities required and energy consumed for film heating method is much less than that for the film cooling method.

The air flow is supplied by a high pressure tank that can furnish a very clean and steady flow for at least 10 h. The flow is then regulated and controlled by a mass flow controller (Brooks 5850E) that is made by Brooks Co and has a measurement accuracy of ±6 ml/h. The flow velocity at the film slot exit can be readily found from the mass flow rate, the slot exit area and the temperature or the density of the exit flow. The turbulence intensity of the injection air measured at the exit is 4.5%.

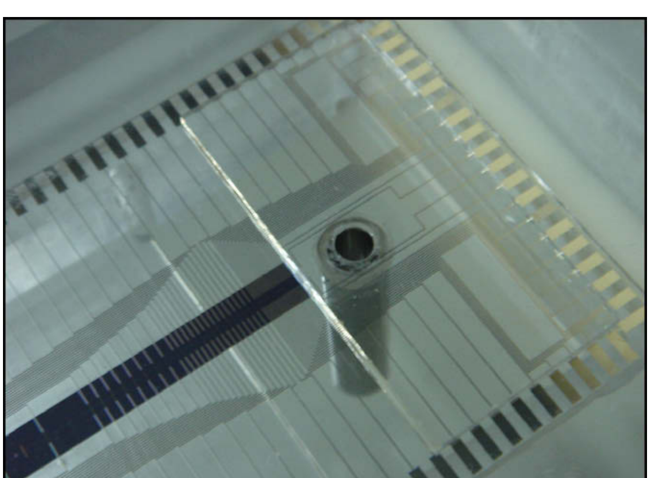

Fig. 3. Completed film-cooled device.

In order to validate the current fabrication techniques of the temperature sensors, the resistivity of the temperature sensors along the film-cooled surface were measured and compared with the results in the literature. The agreement with the literature data [14] confirms the current techniques of doping process. Secondly, the completed film-cooled device is then placed in an oven with controlled temperature to measure its resistivity at different temperatures. Typical resistivity variations with temperatures for some of the sensors are shown in Fig. 5. For the sensors with boron concentration of 10^{19} atms/cm^3, the resistivity varies indeed very linearly with temperature. All other temperature sensors exhibit similar trend and these curves are used as calibration. It was estimated that all the temperature sensors have a measurement accuracy of ± 0.1 °C.

With well thermal insulation outside the wall, the adiabatic wall temperatures under the film flow can be measured. With temperature measurements in the mainstream and at the exit of the film slot, the film cooling effectiveness can be obtained by substituting all the temperatures into the film cooling effectiveness equation as follows:

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

where T_∞ is the mainstream temperature and T_j is the film jet temperature at slot exit. The injection air is heated 15–25 °C higher than the ambient. The error analysis is performed by following the method reported in Kline and McClintock [15]. The maximum uncertainty of the measured film cooling effectiveness is ±7%.

4. Results and discussion

The film cooling effectiveness can be used as an indication of the film jet structure. A higher film cooling effectiveness means a nearly complete structure of film jet is preserved, and mixing of film jet with the mainstream is very weak; while a lower film cooling effectiveness means a poor structure of film jet, and mixing of film jet with the mainstream is very intense. Therefore, one can infer the film jet structure from the film cooling effectiveness measurements. When the film slot in the micro film-cooled device is 50 μm and covered with an 800 μm thick cover plate, the cooling effectiveness is very poor, as shown in Fig. 6. A significant reduction in the film cooling effectiveness occurs right after the film jet exits from the slot. It appears that the film jet could not maintain its structure and mix rapidly with the mainstream right after coming out from the slot exit. The rapid mixing of film jet with the mainstream right after the slot exit is attributed to the relatively thick cover plate used in comparison with the film slot thickness. The ratio of cover plate thickness versus the film slot height, t/y_c, is 16 which is very large as compared with the case used in the large-scale film cooling system where the cover plate thickness versus the film slot thickness varies from 0.1 to 2.0 [1]. In the large-scale film system, the film cooling effectiveness for the case of t/y_c equal to 2.0 can be less than half of the case for t/y_c equal to 0.126. This is attributed to the vortex induced in the back of the thick cover plate, as explained in Fig. 7, which expedite and enhance mixing of the film jet with the mainstream. In the case of micro film cooling process, the PMMA cover plate we used is 0.8 mm in thickness and is very thick. To compare the film cooling effectiveness of the current micro film-cooled device with the one in the large-scale film cooling system [7], the film cooling effectiveness is significantly lower, as shown in Fig. 8. The film slot made in the large-scale film cooling system has 3 mm in height. It appears that even at these high blowing ratios (M = 2.5 or 5), the film

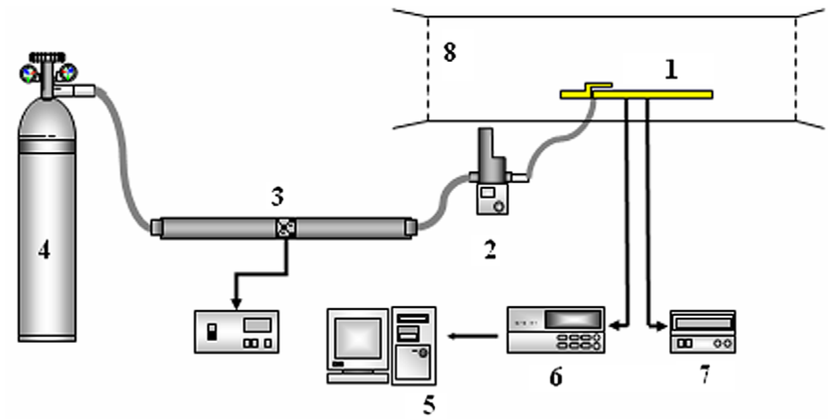

Fig. 4. Schematic diagram of experimental apparatus: (1) micro film-cooled device, (2) air flow controller for the micro jet, (3) film air flow heating system with controlled temperature, (4) gas storage tank, (5) personal computer, (6) data acquisition system, (7) power supply system and (8) wind tunnel system.

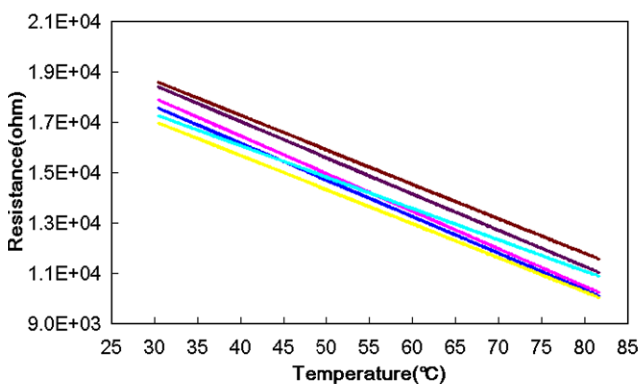

Fig. 5. Typical resistivity variations with temperatures for different sensors.

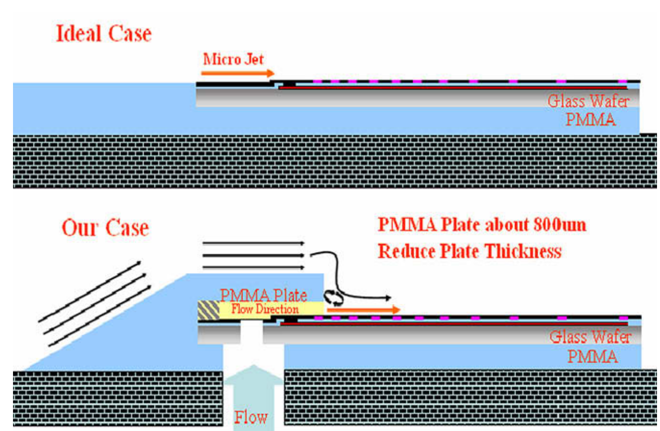

Fig. 7. Schematic diagram to show the occurrence of vortex flow in the back of a thick cover plate.

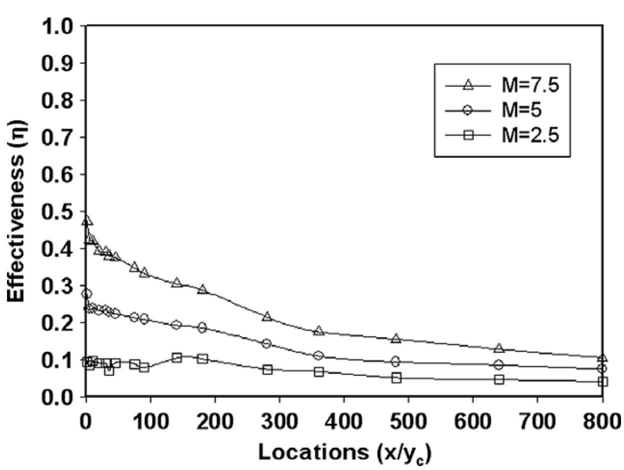

Fig. 6. Variation of film cooling effectiveness η on different blowing ratios when the film slot height is 50 μm with a 800 μm thick cover plate.

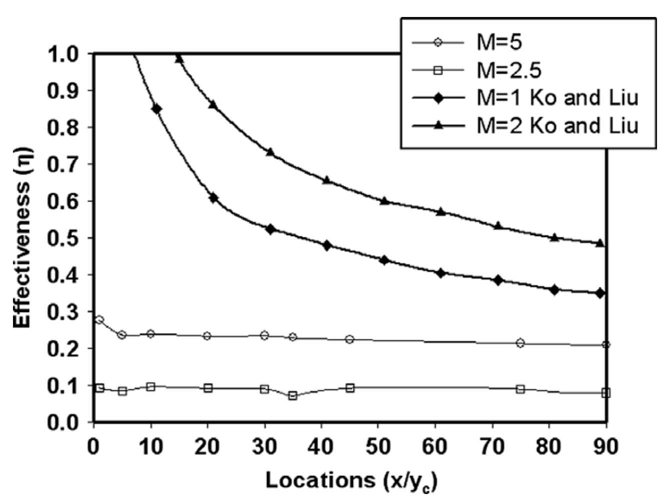

Fig. 8. Comparison of the micro film cooling effectiveness with the large-scale film cooling effectiveness. In the micro film-cooled device, the film slot has 50 μm in height and the cover plate has 800 μm in thickness ($t/y_c = 16$).

jet structure has already been destroyed completely once the film jet exits from the slot. The destruction of the film jet is apparently due to the vortex flow induced in the back of the cover plate. Therefore, in the next experiments we would like to use much thinner cover plate. The thin cover plate used is the one used for transparency, which has a thickness of 100 μm. It is expected that a much thinner cover plate can significantly increase the film cooling performance.

When the slot height is 45 μm with a 100 μm thick cover plate on the top, the film cooling performance can be significantly improved, as shown in Fig. 9 even when the blowing ratio is not very high. It appears that the vortex generated in the back of the thin cover plate is not so large and intense which can promote mixing of the film jet with the mainstream. Therefore, film jet can maintain its structure until at very later stage. This can lead to a significant increase in the film cooling performance. When the blowing ratio becomes higher, the film jet structure becomes stronger which could not be readily destroyed by mixing with the mainstream. This leads to a significant increase in the film cooling performance.

When the slot height is 25 μm with a 100 μm thick cover plate on the top, the film cooling effectiveness may not be lower than the case when the slot height is 45 μm with a cover plate thickness of 100 μm on the top if one compares the results shown in Figs. 9 and 10. In fact, the ratio of the cover plate thickness versus the film slot height, t/y_c, for Fig. 9 is 2.22 and is smaller than the one (which is 4) for Fig. 10. Therefore, one can expect that the film cooling effectiveness for the case of $t/y_c = 2.22$ is higher than the case of $t/y_c = 4$. In fact, the film cooling effectiveness for the case of $t/y_c = 2.2$ is much lower than the case of $t/y_c = 4$. It can be inferred from the film cooling effectiveness that at $x/y_c = 300$ with $M = 5$, the film jet structure for the case of $t/y_c = 2.22$ has been completely destroyed while the film jet structure for the case of 4 still maintain some of its structure. One possible reason can be explained by the experimental finding in [11] that a micro jet issued from a smaller slot can penetrate much deeper into a stagnant environment without destruction. Therefore, it is expected that the micro film jet from a smaller slot can penetrate deeper along the surface without rapidly mixing with the mainstream and causing complete destruction of its structure. For the case of $t/y_c = 4$, the film flow is injected from a much narrower slot. Therefore, the film jet for the case of $t/y_c = 4$ can penetrate much deeper without rapid mixing with the mainstream than the film jet for the case of $t/y_c = 2.22$. In fact, the film cooling effectiveness does not decay very much for x/y_c greater than 300, as shown in Fig. 10. The film jet maintains its structure until at very later stage when x/y_c is greater than 1200. This micro film jet which can maintain its structure at this later stage on the film-cooled surface without destruction has not been found in large-scale film jet [1–5].

When the slot height is 25 μm with a 200 μm thick cover plate on the top ($t/y_c = 8$), the film cooling effectiveness indeed is lower than the case for slot height of 25 μm with a 100 μm thick cover plate on the top ($t/y_c = 4$) if one compares the results shown in Figs. 10 and 11. Apparently, this is attributed to a greater t/y_c in Fig. 11. A greater t/y_c can lead to the occurrence of larger vortex flow in the back of the cover plate which results in enhanced mixing of film jet with the mainstream and significantly reduces the film cooling effectiveness. The film cooling effectiveness for the case of $t/y_c = 8$ is so low after $x/y_c = 300$, as shown in Fig. 11, that the film jet could no longer maintain its structure as the case for $t/y_c = 4$. On the other hand, as one compares the film cooling effectiveness for the case of slot height of 45 μm with a 100 μm thick cover plate ($t/y_c = 2.22$) and the case of slot height of 25 μm with a 200 μm thick cover plate ($t/y_c = 8$), the film cooling effectiveness for $t/y_c = 8$ is still higher than the case of $t/y_c = 2.22$. The reason is still the one explained previously, i.e. the film jet from a smaller slot can penetrate deeper along the surface with better preservation of its structure without rapid and enhanced mixing with the mainstream. It appears that the vortex generated in the back of the cover plate in the micro film-cooled system does not play such an important role as the slot height to affect the film jet mixing with the mainstream and reduce the film cooling performance.

Comparison is also made between the current micro film cooling effectiveness with the large-scale film cooling effectiveness reported by others [7], as shown in Fig. 12. For $M = 1$, the micro film cooling performance is much better than the case for large-scale film cooling performance. However, for $M = 2$, the micro film cooling effectiveness for slot height of 45 μm is smaller than, and for slot height of 25 μm is almost equal to, the large-scale film cooling performance. It appears that the increase of the blowing ratio to in-

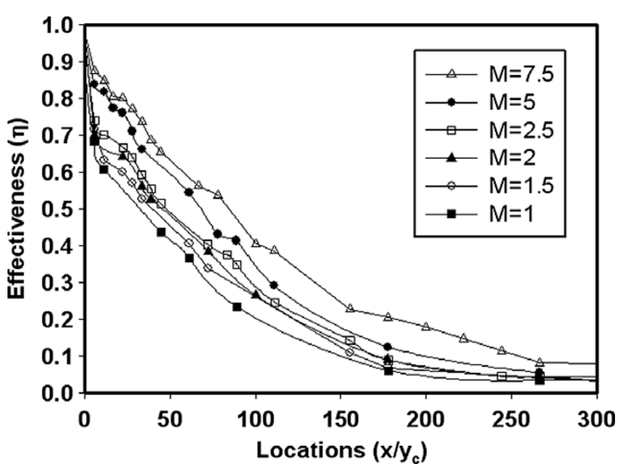

Fig. 9. Variation of film cooling effectiveness η at different blowing ratios when the film slot height is 45 μm and the cover plate thickness is 100 μm ($t/y_c = 2.22$).

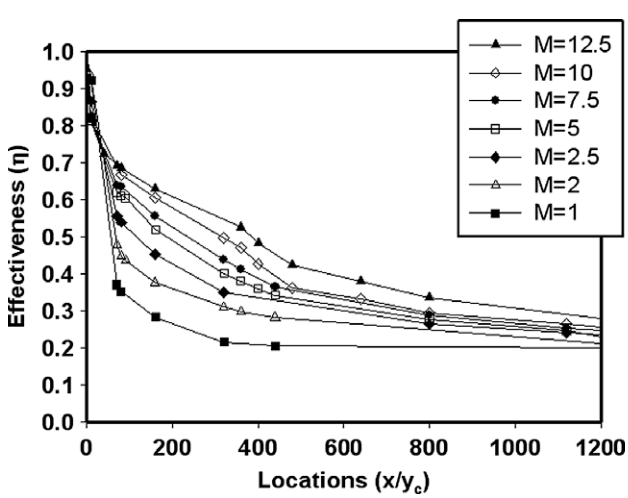

Fig. 10. Variation of film cooling effectiveness η at different blowing ratios when the film slot height is 25 μm with a 100 μm thick cover plate ($t/y_c = 4$).

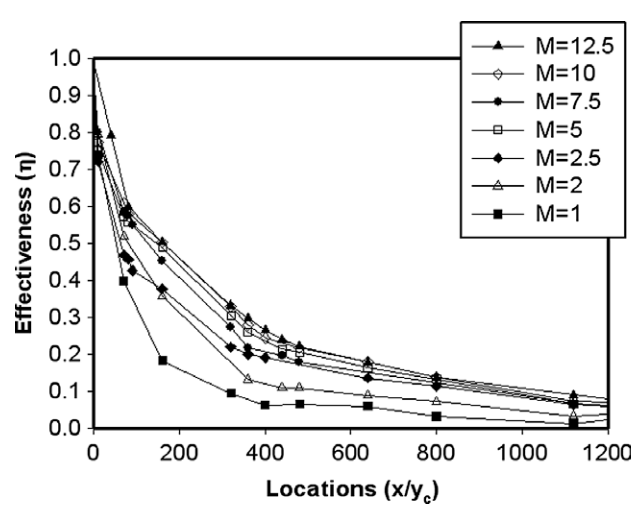

Fig. 11. Variation of film cooling effectiveness η at different blowing ratios when the film slot height is 25 μm with a 200 μm thick cover plate.

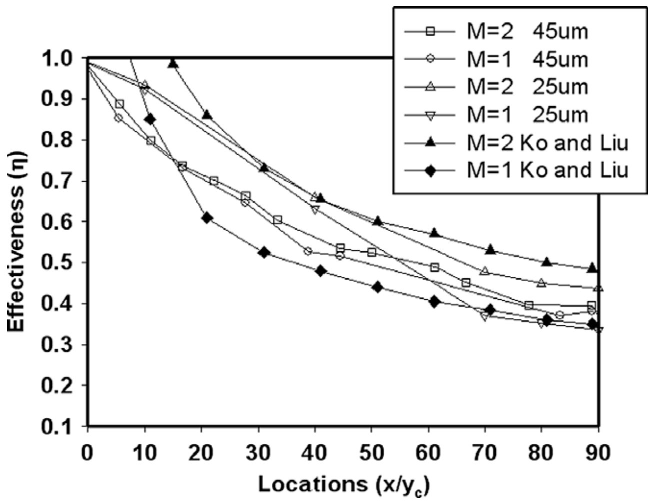

Fig. 12. Comparison of the micro film cooling effectiveness (with cover plate thickness of 100 μm) with the large scale film cooling effectiveness.

crease the film cooling effectiveness in the micro scale system is not so effective as in the large-scale film cooling system. This is attributed to the fact [11] that increase of the micro jet velocity can lead to enhanced mixing of film jet with the ambient or the mainstream.

The most important advantage of the micro film process is that the amount of cooling air used in the micro film system is two or even three order of magnitude lower than that used in the large-scale film cooling system. This can significantly increase power efficiency of a gas turbine engine. However, the location at which the effectiveness is measured is scaled to the slot width, as shown in Fig. 12. The scaled location for 40 means 1 mm for a 25 μm-wide slot and 80 mm for 2 mm-wide slot. Physically, the penetration depth for a cooling jet emerged from a micro slot is much shorter than that emerged from a large-scale slot. As a result, much more micro slots are required for cooling a certain length of a liner or blade than large slots. This can reduce the advantage of lower amount of cooling air needed for production of the micro jet.

5. Conclusions

Experiments have been performed to study and obtain the micro film cooling effectiveness. It has been found that the micro film cooling performance can be much higher than the case of large-scale film performance if one can properly control the film slot height and cover plate thickness. A film jet from much smaller height of slot can better preserve its structure and leads to much higher film cooling performance. However, one should ensure that cover plate thickness is thin enough and is within an acceptable range. From the current study, one can conclude that the cover plate thickness in micro film cooling system is relatively not so sensitive to affect the film cooling performance as in the case of large-scale film cooling system.

The slot height for large-scale film cooling system is usually a couple of millimeters while the slot height for the micro film system may be more than a few of micrometers. Therefore, in addition to the better film cooling performance in the micro film cooling system, the most important advantage is that the amount of cooling air used in the micro film system is much lower which can significantly increase power efficiency of a gas turbine engine. However, this advantage may be offset by the requirement of use of more micro slots.

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