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## IMPROVEMENT OF FILM COOLING EFFECTIVENESS IN THIN RECTANGULAR CHANNEL BY USING RIBLETS

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### ABSTRACT

Film cooling behavior in a thin rectangular channel was experimentally studied by using water and the film cooling effectiveness was compared with previous correlations for a wide space. The flow pattern and the wall temperature distribution were visualized with hydrogen bubbles and liquid crystal sheet, respectively. The wavy temperature distribution was observed on the wall just after the injection slit. The temperature wave slowly moved and oscillated in the streamwise direction. The wave propagation in the spanwise direction was relatively small, but the wave pattern was randomly different in each experimental condition. The low and high temperature regions of the wave corresponded to the high and low speed regions near the wall, respectively. It was suggested that the temperature wave was generated with the several longitudinal vortexes developed downstream of the injection in the thin channel. As thinning the channel, the size of vortexes corresponding to the wave length became smaller and the cooling effectiveness was decreased. The riblets were tentatively used to depress the vortexes and increase the film cooling effectiveness. By using the appropriate riblets, the inrushes of high speed main flow into the film due to the vortexes was reduced and approximately 30 % increase of the cooling effectiveness was obtained.

### EXPERIMENTAL APPARATUS AND MAJOR RESULT

A primary fluid(cold water) was flowing in the thin rectangular channel and a secondary fluid(hot water) was injected from the slit of the width s= 5 mm. The duct width was W= 50 mm and the height can be changed from h= 20mm to 5 mm. The thin-plate-type riblets were mounted on the upper plate of the duct just after the injection slit. The parametric studies about the riblets size for the height $h_R$ and the lateral pitch $\lambda_R$ were conducted.

Shown in Fig. A-1 is the relation of the cooling effectiveness and the non-dimensional distance from the injection slit with or without the riblets of $\lambda_R/W= 0.05$ . The mass blowing ratio m was 0.26. The experimental effectiveness data were calculated from the average temperature during 90 s measured with thermocouples intruded at the center wall. The lines are calculated with the empirical correlation by Seban et al.(1957) and Obata(1971) for a wide space. The improvement of the effectiveness can be observed with the installation of the riblets. The improvement is significant at x/s=5~10.

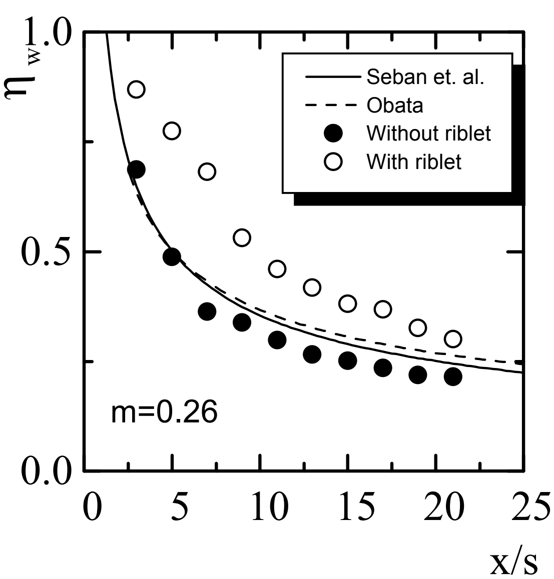


**Fig. A-1 Film cooling effectiveness with or without riblets**

## NOMENCLATURE

$D_h$: hydraulic diameter of channel
g: acceleration due to gravity
h: channel height
L: distance from channel inlet
m: mass blowing ratio $[=\rho_2 v_2/(\rho_1 u_1)]$
Pr: Prandtle number
$Re_1$: Reynolds number of primary fluid $(=u_1 D_h/\nu_1)$
s: slit width
T: temperature
u: velocity in x direction
$v_2$: injection velocity
W: channel span
x: distance from injection slit
y: spanwise distance
$\eta_w$: film cooling effectiveness $[=(T_w-T_1)/(T_2-T_1)]$
$\lambda$: wave length
$\nu$: kinematic viscosity
$\rho$: density
subscript 1: primary fluid, 2: secondary fluid, w: wall

## INTRODUCTION

Thermal efficiency of gas turbines can be improved by increasing the gas temperature. With higher gas temperature a reasonable lifetime of turbine components can be ensured only by protecting them from the hot gas stream. Film cooling is a commonly-used technique for protecting component walls against the hot gas stream. Previous basic studies were focused on the film cooling behavior in a low turbulence freestream by using a large wind tunnel (Goldstein, 1971). Film cooling in a turbulent narrow space is sometimes necessary for the actual industrial components. To understand the basic behavior of the film cooling in the turbulent narrow space, the film cooling behavior in thin rectangular channel was investigated experimentally by using water.

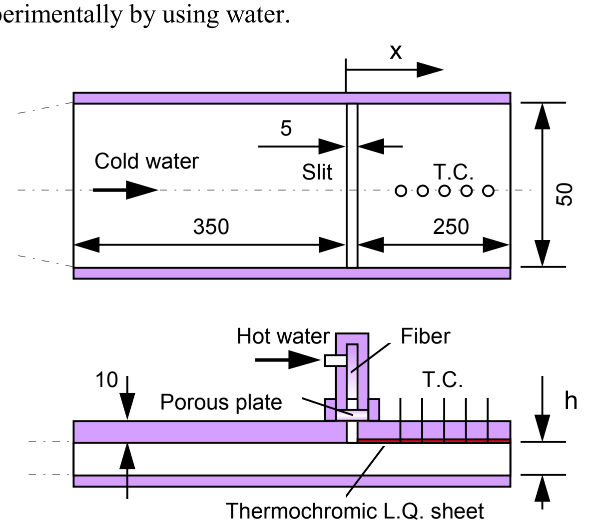


**Fig. 1 Schematics of experimental apparatus**

The riblets have been developed in the NASA/Langley research center and considered to be effective to reduce the wall shear stress when they reduce the inrushes of high speed main flow to the wall region due to the sweep and ejection. The reduction of the shear stress is summarized by Clark(1990) and Lazos & Wilkinson(1988). It is believed that the lateral pitch of the riblets should be less than 1/3 of the average lateral span of the streaks for the effective reduction of wall shear. The temperature wave observed in the thin rectangular channel is considered to be generated with the several longitudinal vortexes and would be an important indicator of turbulence penetrated into the film. Though the vortexes were relatively stationary rather than spatially and temporally dependent like the sweep and ejection, the riblets were tentatively used to reduce the inrushes of high speed main flow into the film due to the vortexes developed in the thin rectangular channel.

## EXPERIMENTAL APPARATUS

Shown Fig.2 is a schematic of the experimental apparatus by using water. A primary fluid (approximately 20°C water) was flowing in the thin rectangular channel and a secondary fluid (approximately 60°C water)was injected from the slit of 5mm width. It was possible to adjust the duct height h between 20 and 5 mm to investigate the effect of a narrow space. The flow distribution of the injection was eliminated with the porous plate (mesh 20μm) upstream of the slit. The injection slit located at L= 350mm(L / $D_h$ is greater than 10.5) from the duct inlet to ensure a fully turbulent condition in the duct. Flow rates of the main and the secondary flow were measured with the turbine flow meters. The measurement error was within ±2% of the measured values. The temperature of mainflow was measured at the entrance of the duct and that of the secondary flow was measured at the just upstream of the porous plate by T-type thermocouples.

The wall temperatures were measured with thermocouples intruded in the center of the upper plate at intervals of 10mm from the rear end of the slit. The thickness of upper plate was 10 mm to ensure an adiabatic wall condition. The thermocouples of 0.3mm diameter were penetrated to the inner surface and fixed with an adhesive acrylic glue. These data were transferred to the personal computer through GPIB and analyzed. The measurement error of the thermocouple was ±0.1°C. Flow behavior and wall temperature distribution were visualized with hydrogen bubbles and a thermochromic liquid crystal sheet, respectively. The hydrogen bubbles were generated from a platinum wire of 50 μm diameter at the distance 20 mm(x/s=4) downstream of the injection slit. The liquid crystal sheet initiated to change to red at 45°C(40°C for riblets surface) and the color band was 5°C(1°C for riblets surface). The experiments were conducted at the primary velocity of 0.4 to 1.07 m/s. The corresponding $Re_1$ was 12000~32000 at h= 20 mm, 11000~20500 at h= 15 mm, 10000~18000 at h= 10 mm and 4500~8500 at h= 5 mm.

## CORRELATION OF FILM COOLING EFFECTIVENESS FOR A WIDE SPACE

The general correlation of film cooling effectiveness for a narrow space has not been proposed and the previous correlations for a wide space may be applicable even for the narrow space when the film exists near the wall. For the slit-film cooling effectiveness $\eta_w$, Seban et al.(1957) proposed the following correlation.

$$\eta_w = 2.2A^{-0.5} \quad \textbf{(1)}$$

where A is non-dimensional parameter which is often used in an analysis of a two-dimensional jet(Humber et al., 1993) and defined as,

$$A = \frac{x}{ms} \quad \textbf{(2)}$$

where m is a mass blowing ratio as,

$$m = \frac{\rho_2 v_2}{\rho_1 u_1} \quad \textbf{(3)}$$

where $u_1$ is a mainstream velocity. In the present study, the average duct velocity is used as $u_1$. On the other hand, Obata(1971) proposed the following correlation by using the same non-dimensional parameter.

$$\eta_w = 1.9A^{-0.45} \qquad 10 \le A \le 100$$
$$\eta_w = 9.6A^{-0.8} \qquad 100 \le A \quad \textbf{(4)}$$

## EXPERIMENTAL RESULTS AND DISCUSSIONS

### Film cooling effectiveness on plain surface

Shown in Figs. 2 to 5 are relations of the mass blowing ratio m and the cooling effectiveness $\eta_w$ at the different channel heights. The experimental effectiveness data were calculated from the average temperature during 90 s measured with thermocouples intruded at the center wall. The solid lines and dashed lines are the predictions by the correlations of cooling effectiveness for a wide space. The scattering of the data is larger just after the injection slit due to the temperature waving mentioned below. The correlations predict the larger effectiveness with an increasing mass blowing ratio but the experimental data approach an asymptotic value. The film cooling effectiveness at the isothermal condition where the primary and secondary fluids are completely mixed should be proportional to the mass blowing ratio. So the asymptotic value does not mean the well-mixed condition in the thin rectangular channel. It is considered that this asymptotic behavior is special feature of the film cooling in the narrow space. The asymptotic behavior could be successfully predicted with the low Reynolds k-ε turbulent model assuming a separation bubble model just after the injection (Osakabe, 1995&1998).

Shown in Fig.2 is the relation of the mass blowing ratio m and the film cooling effectiveness $\eta_w$ at x/s=3. The effectiveness decreases with a decreasing channel height h and this tendency is significant at the smaller m. It is interesting that the smaller effectiveness is obtained suggesting the stronger mixing at the smaller h in spite of the smaller $Re_1$.

Shown in Fig.3 is the relation of m and $\eta_w$ at x/s=5. Though the difference of effectiveness due to the channel height h is smaller than that at x/s=3, the effectiveness decreases with a decreasing h.

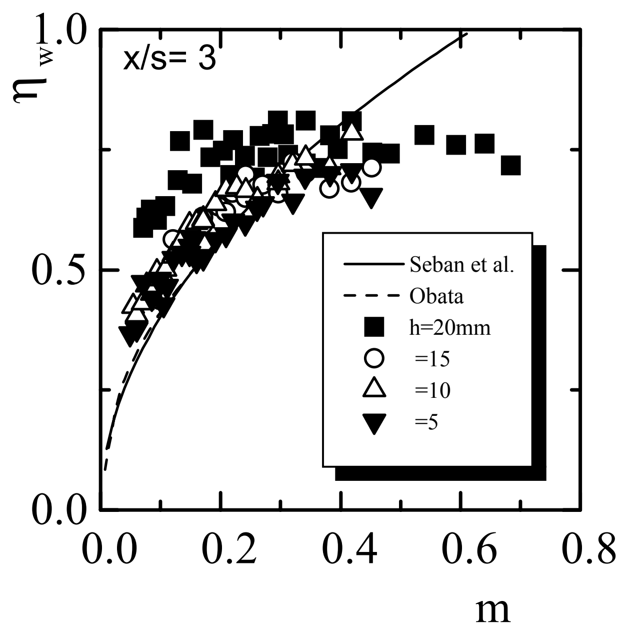


**Fig. 2 Film cooling effectiveness at x/s= 3**

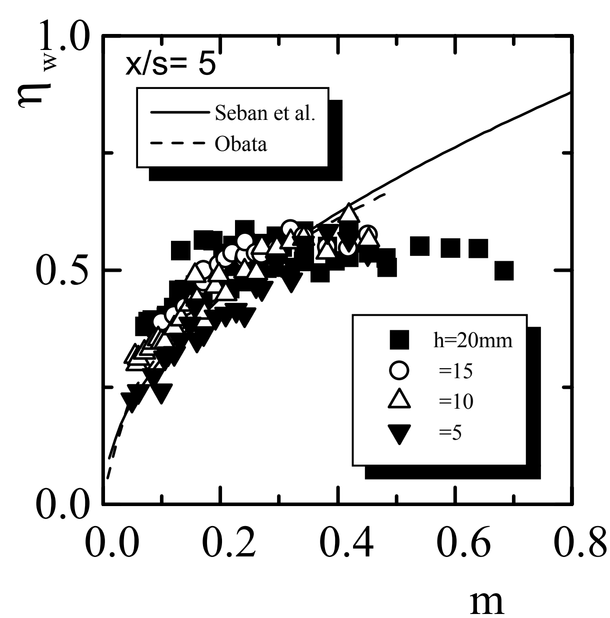


**Fig. 3 Film cooling effectiveness at x/s= 5**

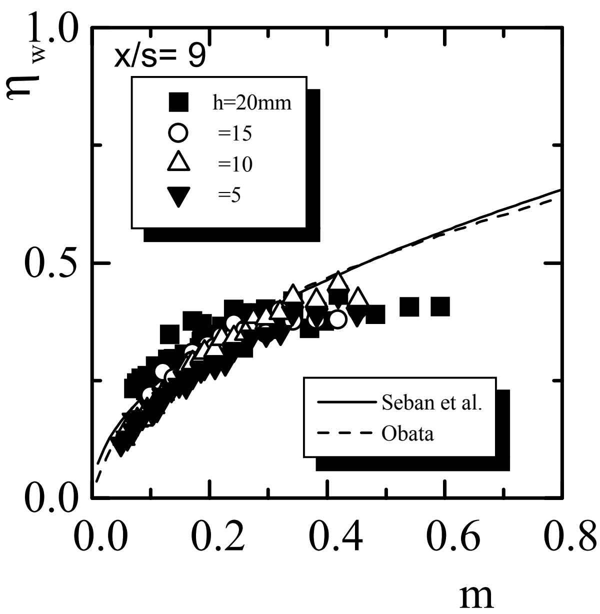


**Fig. 4 Film cooling effectiveness at x/s= 9**

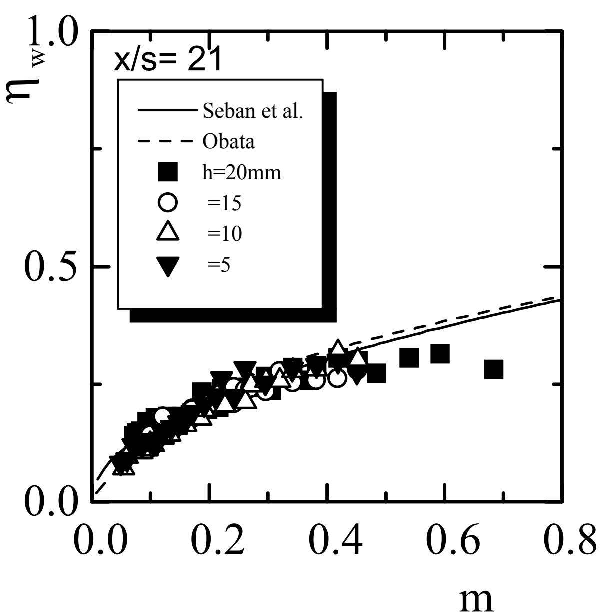


**Fig. 5 Film cooling effectiveness at x/s= 21**

Shown in Fig.4 is the relation of m and $\eta_w$ at x/s=9. Though the difference of effectiveness due to the channel height h is much smaller than that at x/s=3, the effectiveness decreases as h decreases. The previous correlations for a wide space give good prediction at x/s=9.

Shown in Fig.5 is the relation of m and $\eta_w$ at x/s=21. The effectiveness is small due to the well mixing of the primary and secondary fluids at the far downstream of the injection. The effectiveness difference due to the channel heights is vanishingly small and the effectiveness is well predicted with previous correlations. It is interesting that the correlations for a wide space and the experimental data at the far downstream of the injection agree well in spite of the different channel heights.

**Temperature wave on plain surface just after injection**

The wavy temperature distributions on the wall just after the injection slit were observed in spite of the two-dimensional injection as shown in Fig.6. The temperature wave slowly moved and oscillated in the streamwise direction. The wave propagation in the spanwise direction was relatively small, but the wave pattern was randomly different in each experimental condition. So the measured temperature at the center line of the channel showed the scattering due to the different wave pattern. Movies for hydrogen bubbles generated with a platinum wire (50 μm diameter) attached on the wall showed the following flow structure near the wall. The high speed flow region was corresponding to the low temperature region indicating the invasion of the cold mainstream. At the high temperature region, the low speed flow or the flow reversal was observed. The reverse flow was possible at the positive pressure gradient region just after the injection slit. These flow structure was confirmed only near the wall and it was difficult to visualize the turbulent flow far from the wall.

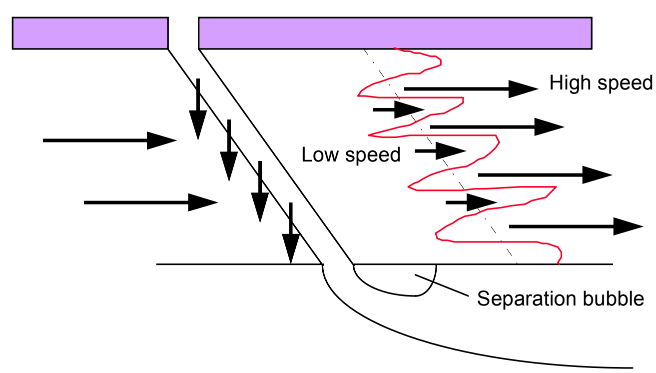


**Fig. 6 Temperature wave and corresponding flow behavior**

Photographs of the temperature wave at the different channel heights are shown in Fig.7. The mass blowing ratio was 0.45. As thinning the channel, the wave length of the temperature pattern becomes smaller. It is expected that the smaller wave length indicates the well-mixing in the film. The temperature wave length observed in the narrow space is considered as an important parameter for the mixing in the film. As thinning the channel, the wave length of the temperature pattern became smaller indicating the stronger invasion of cold fluid and resulted as the decrease of film cooling effectiveness.

Shown in Fig.8 is the relation of the non-dimensional wave length divided by the channel width W(=50 mm) and the mass blowing ratio m. The temperature wave indicated with the isothermal yellow line of 55°C at x/s=2~5 was measured. The wave length was the average of about 50 sampling data at the same experimental conditions. It has the tendency that the wave length decreases as the channel height decreases. The wave length becomes approximately the same as the channel height at h=5 mm . It is considered that the temperature wave is generated with the several longitudinal vortexes which size is affected with the channel height.

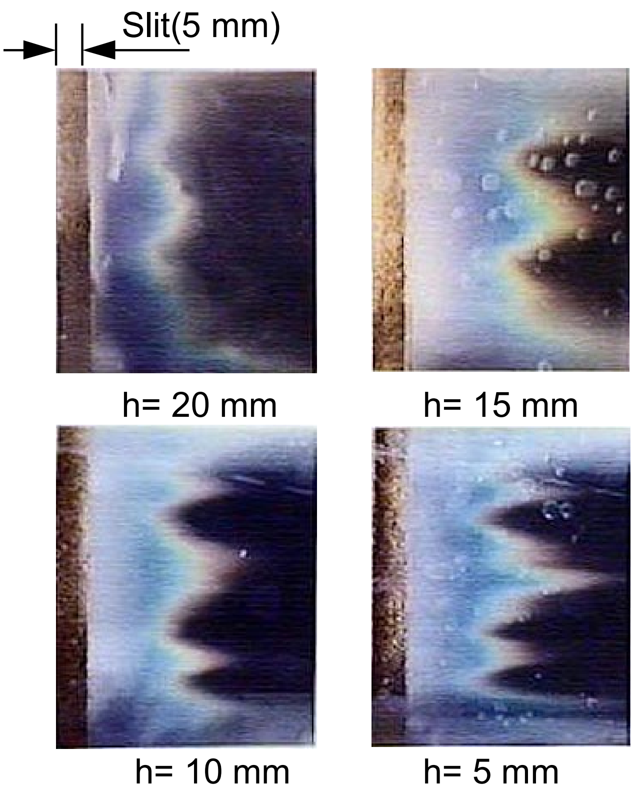


**Fig. 7 Temperature wave at the different channel heights at m=0.45**

**Table 1 Configuration of riblets**

| | Riblet1 | Riblet2 | Riblet3 |
|---|---|---|---|
| $\lambda_R$ /W | 0.2 | 0.1 | 0.05 |
| $h_R$ /h | 0.25 | 0.25 | 0.15 |

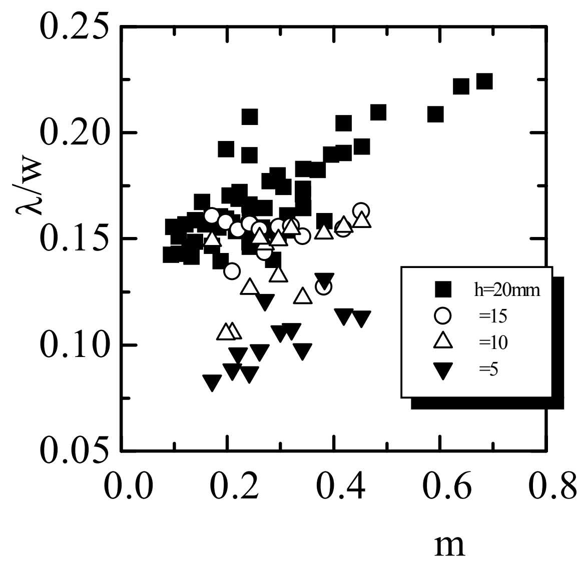


**Fig. 8 Temperature wave length**

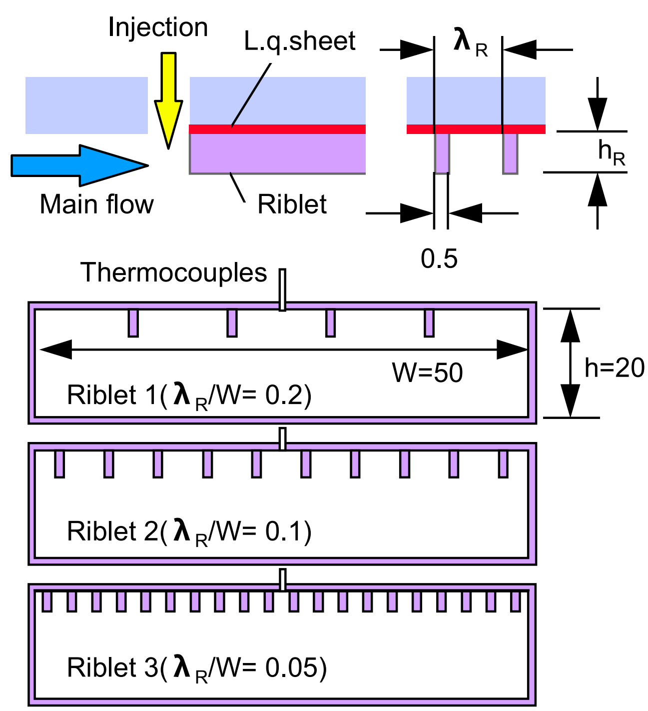


**Fig. 9 Cross-sectional and end view of riblets**

**Film cooling on plain surface with riblets**

The riblets were attached on the liquid crystal sheet as shown in Fig.9 in the channel of h= 20 mm. The riblets were arranged to become symmetry at the center line of the channel where the thermocouples were intruded. In this study, experiments by using three kinds of riblets as shown in Table 1 were conducted. The lateral pitch of the riblets are defined as $\lambda_R$ and the riblets heights are defined as $h_R$. It is considered that the riblets of the lateral span $\lambda_R$/W= 0.2 is too large to prevent the inrushes of high speed mainflow due to the vortexes because the pitch is larger than the temperature wave length. The riblets of the $\lambda_R$/w=0.1 and 0.05 is expected to reduce the invasion of mainflow due to the vortexes.

The profiles of the wavy temperature on the wall with the riblets of the different span are shown in Fig.10. The mass blowing ratio was 0.26. The temperature wave was defined as the isothermal yellow line of 42°C. The coordinates x and y are the distances in the spanwise and flow direction, respectively. As these experiments were conducted at constant temperatures of the primary and secondary fluids, the isothermal line of 42°C shows the line where the effectiveness is approximately 0.5. The advance of the isothermal line in the flow direction indicates the increase of the film cooling effectiveness. The riblets of the lateral pitch $\lambda_R$/W= 0.1 and 0.2 enhance the temperature wave amplitude and fail to improve the effectiveness. This indicates the local inrushes of the high-speed mainflow between the riblets. The riblets of the lateral pitch $\lambda_R$/W= 0.05 significantly improve the film cooling effectiveness. So the riblets with the lateral span of approximately 1/3 of the temperature wave was effective to prevent the inrushes of the high-speed mainflow and improve the film cooling effectiveness. It is interesting that the lateral span of the riblets for the effective reduction of wall shear is also less than 1/3 of the average lateral span of the streaks (Lazos & Wilkinson, 1988).

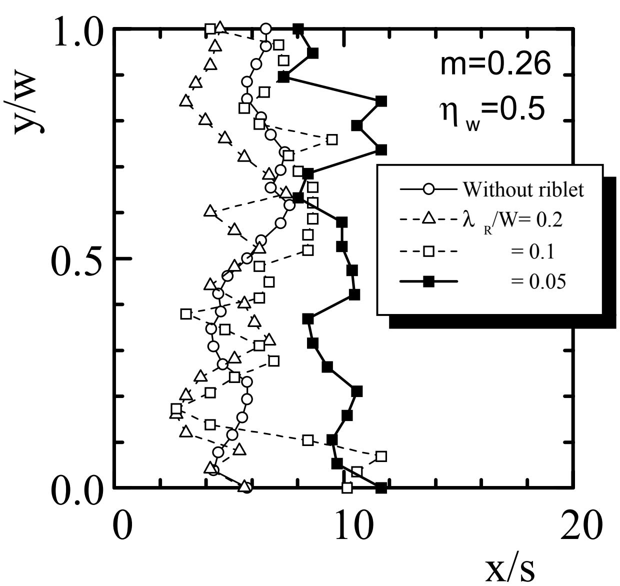


**Fig. 10 Temperature wave at different riblets**

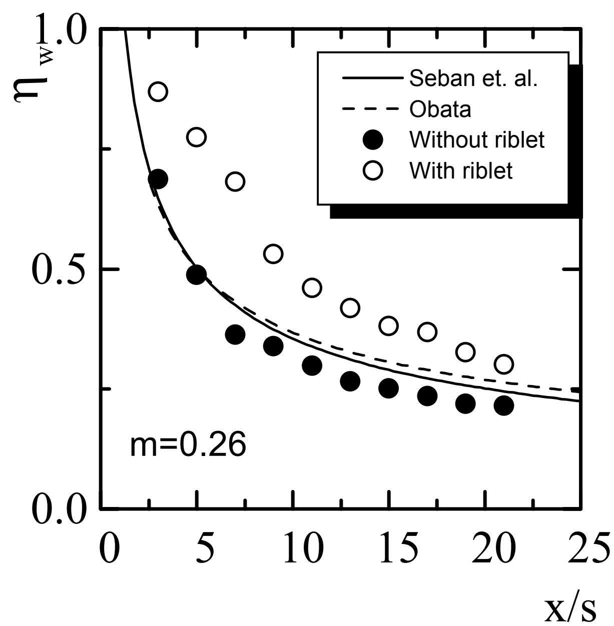


**Fig. 11 Improvement of film cooling effectiveness**

Shown in Fig.11 is the relation of the cooling effectiveness and the non-dimensional distance from the injection slit with or without the riblets of $\lambda_R$/W= 0.05 . The mass blowing ratio m was 0.26 as same as Fig.10. The experimental effectiveness data were calculated from the average temperature during 90 s measured with thermocouples intruded at the center wall. The lines were calculated with the empirical correlation by Seban et al.(1957) and Obata(1971) for a wide space. The experimental data without the riblets agree well with the empirical correlations for a wide space. The improvement of the effectiveness can be observed with the installation of the riblets. The improvement is significant at x/s=5~10.

Shown in Figs. 12 to 15 are relations of the mass blowing ratio m and the cooling effectiveness $\eta_w$ with or without the riblets of $\lambda_R$/W= 0.05. The solid lines and dashed lines are the predictions by the correlations of cooling effectiveness for a wide space.

Shown in Fig.12 is the relation of the mass blowing ratio and the film cooling effectiveness at x/s=3. The improvement of the effectiveness can be observed with the installation of the riblets. The 15% increase of the effectiveness is achieved at x/s=3.

Shown in Fig.13 is the relation of the mass blowing ratio and the film cooling effectiveness at x/s=5. The improvement of the effectiveness also can be observed with the installation of the riblets. The improvement is more significant than that at x/s=3. The increase of the effectiveness is approximately 30%.

Shown in Fig.14 is the relation of the mass blowing ratio and the film cooling effectiveness at x/s=9. The improvement of the effectiveness can be observed with the installation of the riblets. The 15% increase of the effectiveness is achieved at x/s=9.

Shown in Fig.15 is the relation of the mass blowing ratio and the film cooling effectiveness at x/s=21. The effectiveness becomes small due to the mixing of the primary and secondary fluids at the far downstream of the injection. The improvement of the effectiveness can be observed with the installation of the riblets. The 8% increase of the effectiveness is achieved at x/s=21.

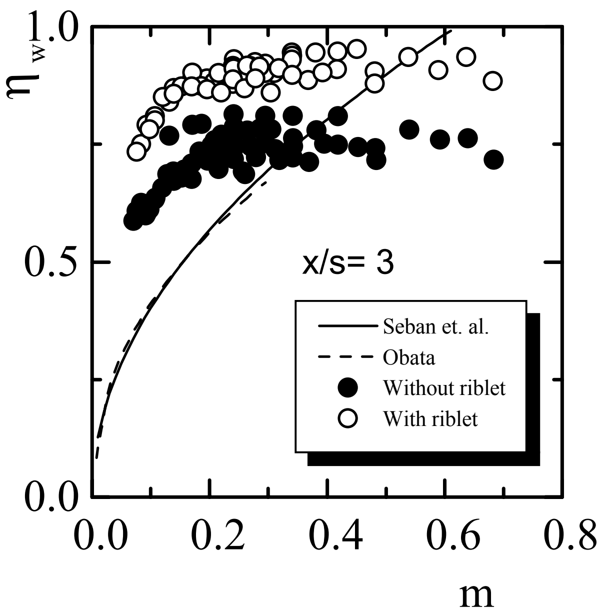


**Fig. 12 Film cooling effectiveness at x/s=3**

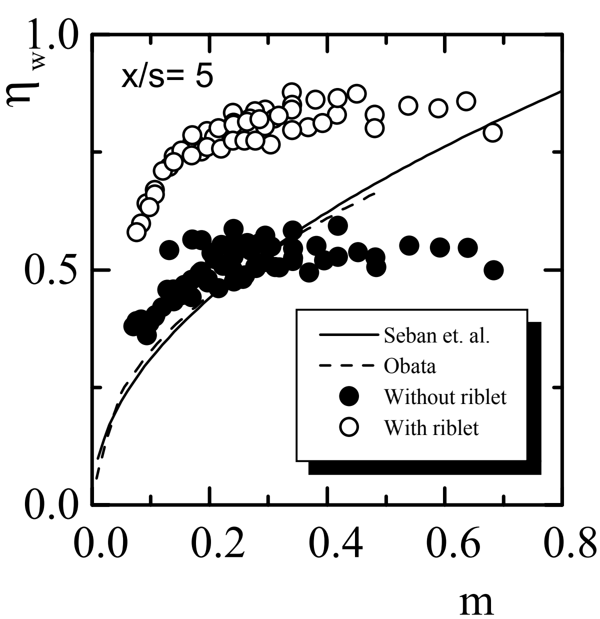


**Fig. 13 Film cooling effectiveness at x/s=5**

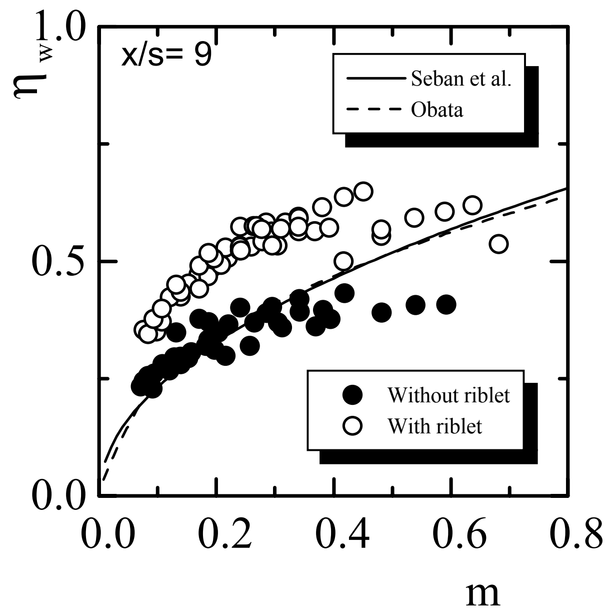


**Fig. 14 Film cooling effectiveness at x/s=9**

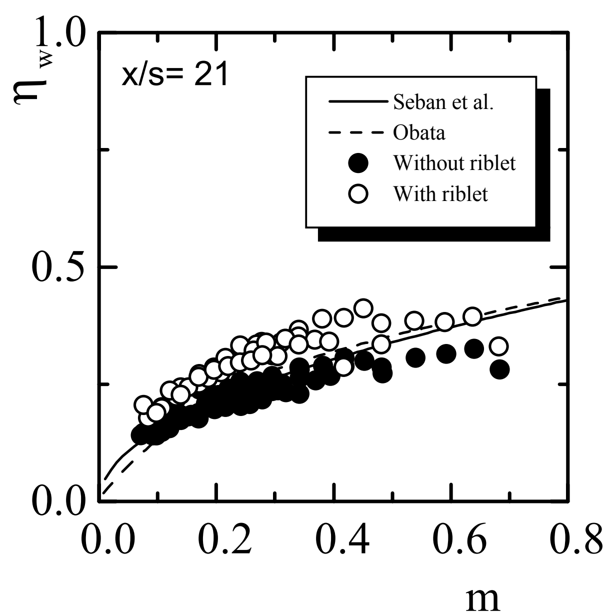


**Fig. 15 Film cooling effectiveness at x/s=21**

## CONCLUSION

The film cooling experiments were conducted in the thin rectangular channel with or without the riblets. The following main results were obtained in the present experiment.

1. The correlations for a wide space predict the larger effectiveness with an increasing mass blowing ratio but the experimental data approached to an asymptotic value.
2. The temperature wave was observed on the plain surface at x/s =2 to 5 just after the injection slit. The temperature wave slowly moved and oscillated in the streamwise direction. The wave propagation in the spanwise direction was relatively small. The high speed flow region was corresponding to the low temperature region indicating the invasion of the cold mainstream. At the high temperature region, the low speed flow or the flow reversal was observed. It was suggested that the temperature wave was generated with the several longitudinal vortexes developed in the thin channel.
3. The temperature wave length was considered as an important parameter for the mixing in the film. As thinning the channel, the wave length of the temperature pattern on the plain surface became smaller indicating the stronger invasion of cold fluid and resulted as the decrease of film cooling effectiveness.
4. Significant improvement of film cooling effectiveness was obtained with the installation of the appropriate riblets. This also suggests the existence of the longitudinal vortexes which can be effectively reduced with the riblets.
5. The riblets with the lateral span of approximately 1/3 of the temperature wave were effective to reduce the inrushes of the high-speed mainflow due to the vortexes and improve the film cooling effectiveness. It is interesting that the lateral span of the riblets for the effective reduction of wall shear is also less than 1/3 of the average lateral span of the streaks in the turbulent boundary layer.

## REFERENCES

Clark, D. G., 1990, Turbulence control by passive means, Kluwer Academic Publishers

Goldstein, R.J., 1971, “Advances in heat transfer”, Vol.7, Academic Press,321-377

Humber,A.J., Grandmaison,E.W. and Pollard,A., 1993, “Mixing between a sharp-edged rectangular jet and a transverse cross flow”, Int. J. Heat Mass Transfer, 36(18), 4307-4316

Lazos, B. and Wilkinson, S.P., 1988, “Turbulent viscous drag reduction with thin-element riblet”, AIAA J.,26(4), 496

Obata,M., “ Experimental study for slit film cooling with large injection angle”, (in Japanese), Proc. of JSME, No.710-14, (1971), 213-216

Osakabe,M. Miyazawa,T., Horiki,S., Mikawa,D. and Obata,M., 1995, “Film cooling in thin rectangular channel (Comparison of experimental results with previous correlation and k-ε model)”, (in Japanese), J. of MESJ, 30(5), 397-404

Osakabe, M., Miyazawa, T., Motoda, T., Wu, Y.W. and Nakashima, K., 1995, “Film cooling behavior in thin rectangular channel(Quick prediction with k-ε turbulent model)”, Proc. of Int. Gas Turbine Congress, Ⅱ-223

Seban, R. A., Chan, H.W., and Scesa, S., 1957, “Heat transfer to a turbulent boundary layer downstream of an injection slot”, ASME Paper 57-A-36,