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An experimental approach to turbulent heat transfer using a symmetric expanded plane channel †

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Abstract

The flow in a symmetric expansion plane channel is known to deflect to one side of a channel even at a low Reynolds number due to the Coanda effect. Details of flow structure have been investigated by various authors; however, there have been a few works conducted in the area of on heat transfer. This paper presents experimental results of turbulent heat transfer in separated and reattached flows in a symmetric expansion plane channel. Experiments were conducted using a low-speed open-circuit wind tunnel. The step H was 20 mm high and 200 mm wide, with an expansion ratio of 2.0. The Reynolds number based on the uniform flow velocity at step and H was varied from 5,000 to 35,000, respectively. The mean and turbulent fluctuating velocities were measured using mainly two types of split film probe. A cold single wire probe was used for measuring the mean and turbulent fluctuating temperatures. It was found that the local Nusselt number profile was considerably different on the upper and lower walls due to the Coanda effect, which is was caused by instability between the upper and lower separated shear layers. Empirical formulae for the maximum Nusselt number in the reattachment region are hereby proposed for the upper and lower walls, respectively. The two formulae are well correlated with the previous general formula proposed. The location of maximum Nusselt number is found to be very close to the flow reattachment point. Details of the velocity and temperature fields were clarified and their correlations with the heat transfer characteristics described above investigated. Furthermore, the wavelet transformation methodology was employed to study instantaneous flow and temperature behaviors, which exhibited its usefulness in the study of the present complicated flow and temperature fields.

Keywords: Double step; Separated and reattachment flow; Turbulent heat transfer

1. Introduction

The importance of the prediction of heat transfer in the separated, reattached, and redeveloping regions of incompressible or compressible flow is recognized in relation to many types of heat exchangers. Thus, numerous experimental and numerical works have been conducted on this area.

These previous papers have been reviewed by several authors [1-5]. It has been noticed that the flow structure in the separated and reattached regions is extremely complicated; this means that the details of the turbulent heat transfer mechanism are presently not yet fully understood.

A symmetric expansion plan channel consists of a basic geometrical configuration in which the separation and reattachment of flow occurs. There have been several experimental and numerical studies concerning the flow in the channel. Studies have clarified that the flow in the channel deflected to one side of the wall even at a low Reynolds number due to the instabilities of the separated shear layer (i.e., the so-called the Coanda effect). On the other hand, only a few studies have been conducted on turbulent heat transfer in the channel [6-8] even though several numerical results at low Reynolds numbers have already been reported [9-12]. These previous works have been extensively reviewed by Ota [5].

The purpose of the present study is to experimentally investigate the turbulent heat transfer in the separated, reattached, and redeveloping regions in a symmetric expansion plane channel. Details of the flow and temperature fields are clarified to study their correlations with heat transfer characteristics.

2. Experimental apparatus and procedures

The experiments were carried out in a low-speed open- circuit wind tunnel driven by an axial blower at inlet [13]. Fig. 1 illustrates the experimental apparatus and test section.

It is a rectangle with a height of 500 mm, a width of 200 mm and length of 1,500 mm, which is similar to those used in

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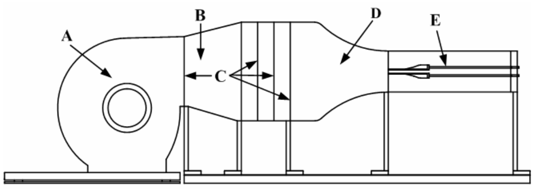
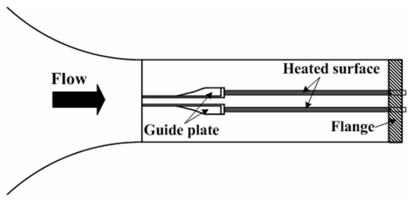


A : Blower b : Diffuser C : Screen D : Nozzle E : Test section

(a) A low speed wind tunnel



(b) Test section

Fig. 1. Experimental apparatus and test section.

previous studies [14, 15]. In the present experiments, a symmetric expansion plane channel was constructed in the central part of the test section. The height of the upstream channel W_0 was 40 mm, while that of the downstream W_1 was 80 mm, producing a step height H=20 mm. The expansion ratio E.R. (=W_1/W_0) was equal to 2.0 in the present study. Furthermore, the channel width W_2 was 200 mm as described above, resulting in an aspect ratio of A,R. (W_2/H) of 10.0.

Fig. 2 illustrates the test configuration, several important parameters, and coordinates employed. In the present study, both the upper and lower surfaces downstream of the step were heated, while conducting electric current to a stainless steel foil of 0.03 mm thick and 200 mm wide stuck onto both steps of the plate. The heat transfer experiments were conducted under a condition of constant heat flux q_w, which varied from 50 to 1,000 w/m^2, depending on the free stream velocity U_{ref} to avoid increasing the wall temperature.

The wall temperature T_w was measured using 0.05 copper-constantan thermocouples embedded onto the plate surface inside the foil.

During the temperature measurements T and t' in the flow field, a tungsten cold wire of 5 μm was used. The mean and turbulent fluctuating velocities U, V, u', and υ' were measured using two types of split-film probes of 150 μm heating the walls. A single hot wire probe of 5 μm was also used in the flow along with constant temperature anemometers.

Buoyancy was considered, and the difference between the mainstream and wall temperature was established in a small size to reduce the effect of buoyancy.

The wavelet transformation method [16, 17] was employed to investigate instantaneous flow and temperature behaviors, because of the method's usefulness in the study of the present complicated flow and temperature fields. The Gabor function was utilized as a wavelet function in the present study. The present experiments were conducted in a range of free stream velocity U_{ref} from 3.5 to 18.8 m/s, and the corresponding Reynolds number being based on H and U_{ref} from 5,000 to 35,000,

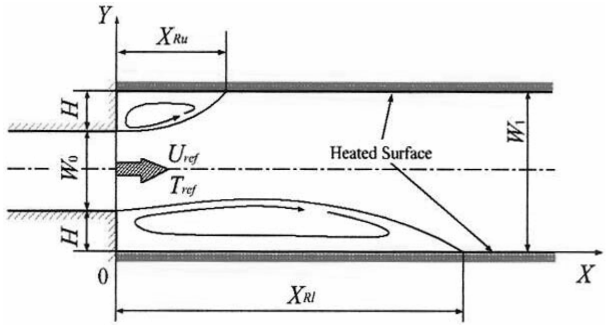


Fig. 2. Flow configuration and coordinates.

the velocity profile at the step was found to be symmetrical to the center line of channel although it had a rather parabolic shape. The turbulence intensity in the central section was about 2% of the free stream velocity. These results suggested that the free stream in the present experiments was under a developing state.

Detailed measurements of the velocity and temperature characteristics in the flow were carried out at *Re*=15,000, since the experimental condition was very stable.

3. Experimental results and discussion

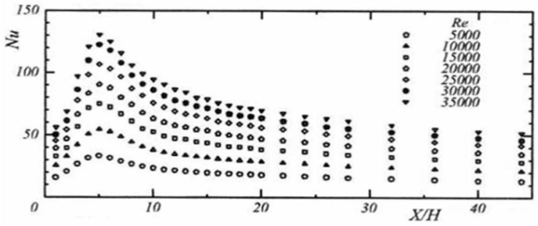
Fig. 3 presents the local Nusselt number (Nu) distributions both on the upper and lower walls in the Reynolds number range examined. The main flow entering into the downstream channel deflected upward, forming a short recirculation region along the upper wall and another along the lower wall. The separated shear layer developed to the downstream and was diffused by the high shear stress. Accordingly, a thin shear layer reattached onto the upper wall, resulting in a higher heat transfer coefficient and a thick shear layer reattached onto the lower wall produced a lower heat transfer coefficient. As can be clearly seen from the figure, Nu increased steeply to the downstream on the upper wall, attained a maximum, and subsequently decreased monotonically.

On the other hand, Nu on the lower wall varied slowly compared to the upper wall. Fig. 3(c) directly compares the local Nu distributions at Re=15,000 on both the upper and lower walls. As can be seen, Nu is very different in the separated and reattached regions but its difference quickly disappeared to the downstream, suggesting an early development of the thermal boundary layers on both walls.

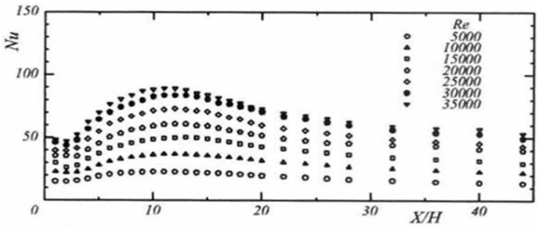
Fig. 4 shows a variation of the maximum Nu with Re both on the upper and lower walls. Included in the figure are the empirical formulae analyzed in the present study. It is very clear that a difference between those on the upper and lower walls increased with an increase in Re, which reached up to about 45%.

$$Nu_{max} = 0.079\ (U_{ref}H/\upsilon)^{0.071}\ \text{(upper wall)} \quad (1)$$

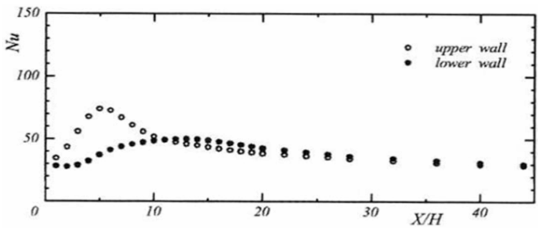
$$Nu_{max} = 0.053\ (U_{ref}H/\upsilon)^{0.712}\ \text{(lower wall)} \quad (2)$$



(a) Upper wall



(b) Lower wall



(c) Re=15000

Fig. 3. Local Nusselt number.

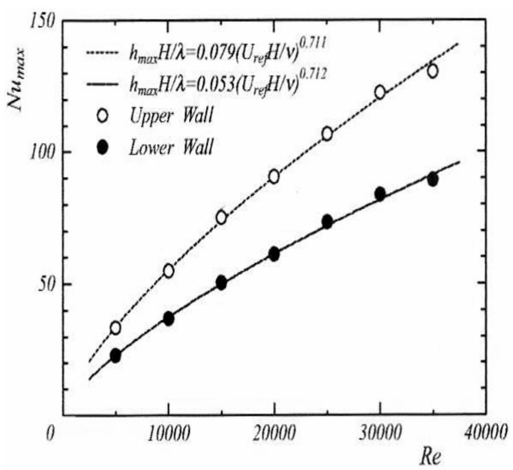
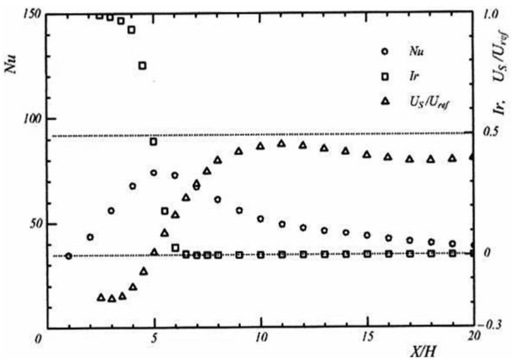


Fig. 4. Maximum Nusselt number.

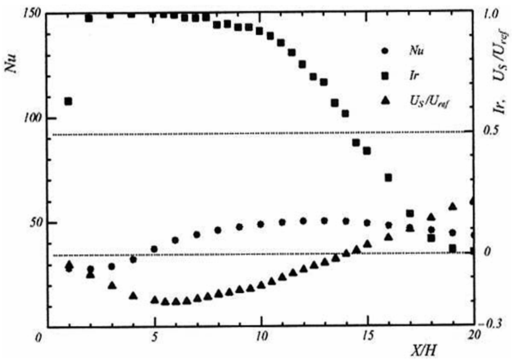
It is interesting to note that the power of Re is almost equal to the other, both on the upper and lower walls.

Fig. 5 shows the surface velocity Us and the reverse flow rate Ir near the wall (3υ above the wall surface) along with the Nu at Re=15,000.

In the present study, the reverse flow rate was measured with a split film probe. It may be reasonable to define a reattachment region as a stream-wise distance between Ir=0.1 to 0.9, which extends from about 4 to 6H along the upper wall, and from about 10.5 to 17.5H along the lower wall, respectively. Such a large difference results in a great variation of Nu distribution shown in Fig. 3. It can also be detected that the surface velocity becomes nearly equal to zero in the neighborhood of a stream-wise location at Ir=0.5. Thus, it is reasonable to define a time-averaged flow reattachment point as the point of Ir =0.5.



(a) Upper wall



(b) Lower wall

Fig. 5. Reverse flow rate, surface velocity (y=3 mm), and local Nusselt number at Re=15,000.

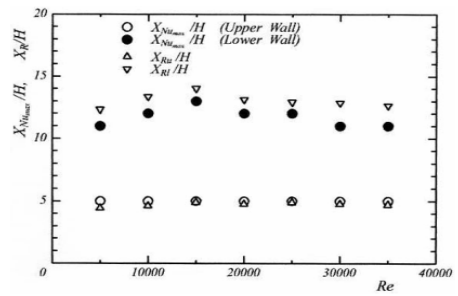


Fig. 6. Reattachment length and point of Nu_{max}.

Fig. 6 presents the reattachment length X_R along with the point of the maximum Nu X_{Numax}. On the upper wall, X_{Numax} is almost equal to X_R, and its variation with Re is very small. However, on the lower wall, X_{Numax} appeared to be smaller than X_R, suggesting that Nu attained its maximum upstream flow reattachment point, although it is not easy to determine it accurately because of the slow variation of Nu, as shown in Fig. 3.

Fig. 7 illustrates the maximum Nu based on the reattachment length as a function of the Reynolds number based on X_R. An empirical formula proposed previously by Ota et al.

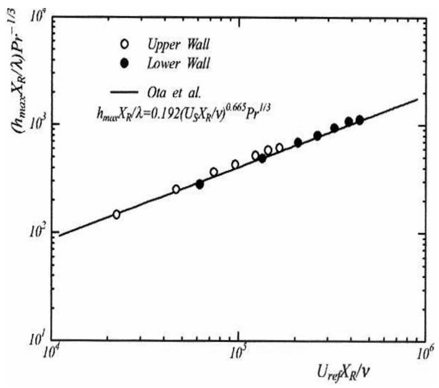


Fig. 7. Correlation of maximum Nusselt number.

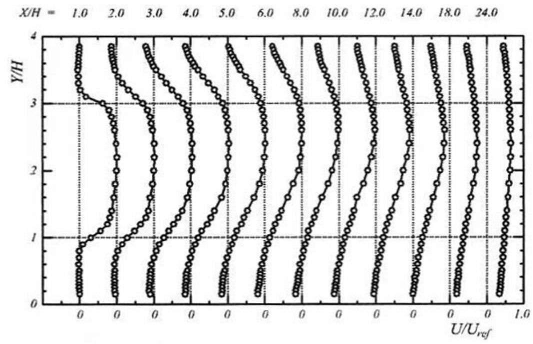


Fig. 8. Mean velocity in the X-direction.

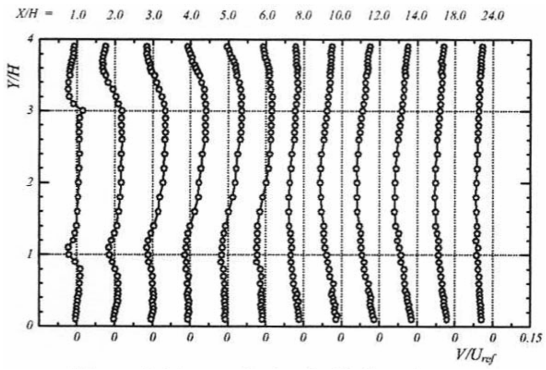


Fig. 9. Mean velocity in the Y-direction.

[3] is included for comparison in Fig. 7. They presented this formula by thoroughly surveying numerous published data.

In the present study, the free stream velocity at the step was assumed to be nearly equal to the velocity along the separated shear layer. From the results, it is clearly shown that the empirical formula proposed by Ota et al. correlated well with the present experimental data. These results illustrated that the diffusion of the separated shear layer strongly dominated the heat transfer characteristics in the reattachment flow region.

Figs. 8-14 illustrate the mean and turbulent fluctuating velocities and temperatures along with the turbulent shear stress at Re=15,000. The velocity profile U at X/H=1.0 just downstream of the step is symmetrical to the channel center line, with the main flow deflecting upward and subsequently shifting downward in the downstream region.

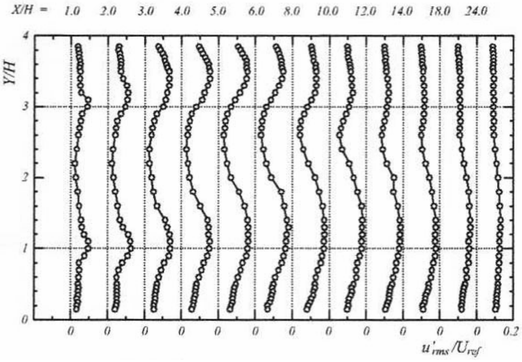


Fig. 10. Turbulent fluctuating velocity in the X-direction.

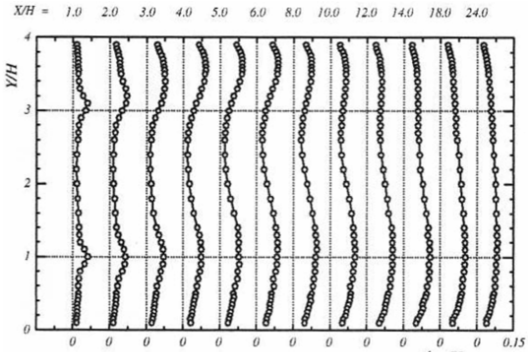


Fig. 11. Turbulent fluctuating velocity in the Y-direction.

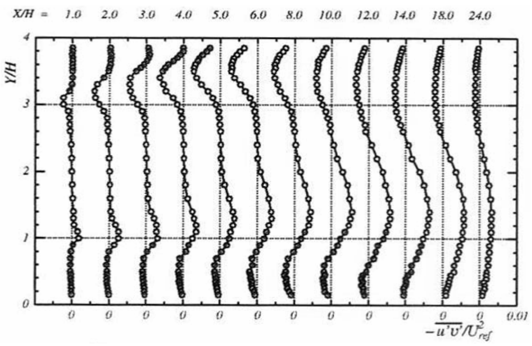


Fig. 12. Turbulent shear stress.

The maximum value of the reverse flow was attained at about $0.20U_{ref}$ and $0.17U_{ref}$ near the upper and lower walls in the recirculation regions, respectively. The main flow retained U_{ref} until about X=6H and subsequently decreased to the downstream due to the diffusion of the separated shear layer, as shown in Fig. 8. The velocity V was first observed to be positive in the main flow region because of the upward deflection of the lower; however it became negative while exhibiting the downward deflection (Fig. 9). The maximum positive value of V is about 0.06 U_{ref}, while its negative value is about 0.08 U_{ref}.

Figs. 10 and 11 show two components of turbulence intensity; it is clear that both profiles are very similar in shape although their values are different. Peaks were detected along two separated shear layers, which developed to the downstream as interference for each other. It was found that the

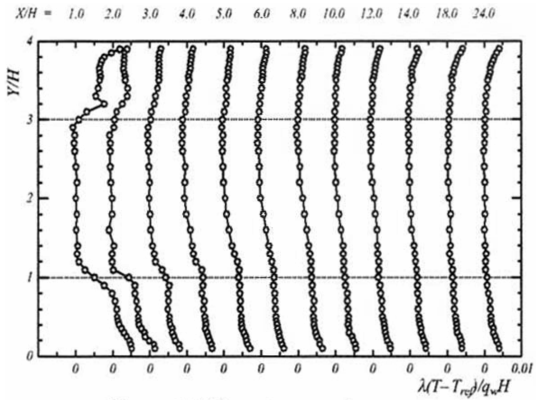


Fig. 13. Mean temperature.

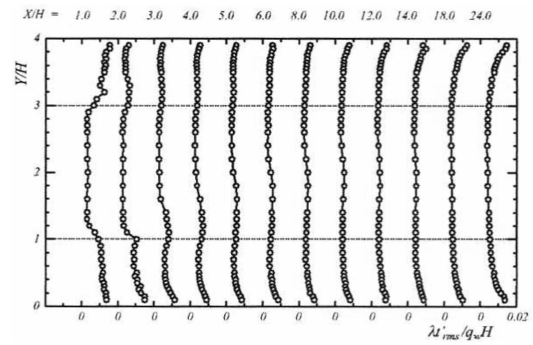


Fig. 14. Turbulent fluctuating temperature.

order of magnitude of υ'_{rms} was roughly equal to that of V and its maximum exceeded 0.08 U_{ref}. On the other hand, u'_{rms} attained a maximum of 0.19 U_{ref} in the reattachment flow region.

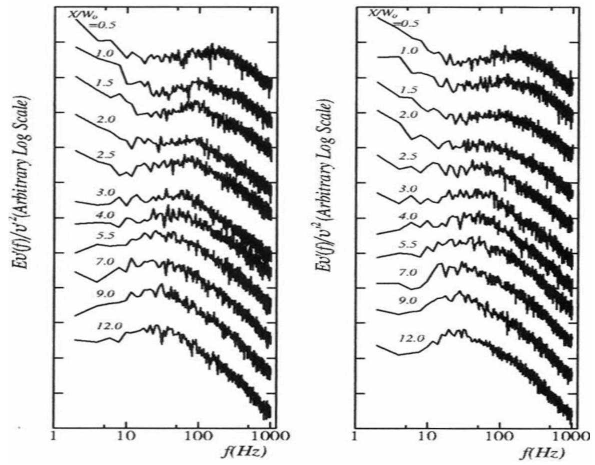
Fig. 12 presents the turbulent shear stress at several streamwise cross sections. In the present experiments, the measurements of $\overline{-u'v'}$ with low uncertainty were not made in the flow region of Ir>0.1 due to the difficulty of simultaneous measurements of u′ and v′ with high reliability.

However, such discriminating data are included in the figure since they may be useful in investigating the turbulence characteristics, at least on a qualitative basis. The turbulent shear stress increased its magnitude along with the development of separated shear layer, after which it reached a maximum in the reattachment flow region on both the upper and lower walls.

Figs. 13 and 14 show the mean and turbulent fluctuating temperature distributions. In the recirculation region, the mean temperature rises rather steeply near the wall surface and also in the separated shear layer, suggesting the existence of two thermal resistance layers.

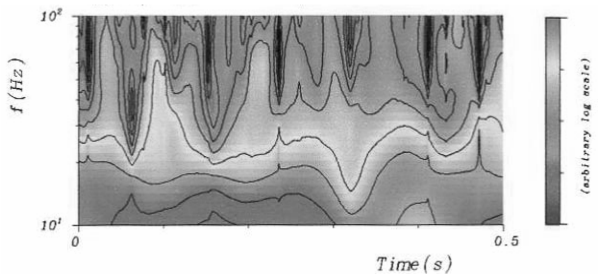
The turbulent fluctuating temperature profile is rather similar in shape to that of the mean temperature presented in Fig. 12 in the entire temperature field examined in the present study. These mean and turbulent fluctuating velocity and temperature results characterize the heat transfer behaviors described previously.

Fig. 15 shows representative results of the power spectrum of v′ at points of the outer edge of the separated shear layer

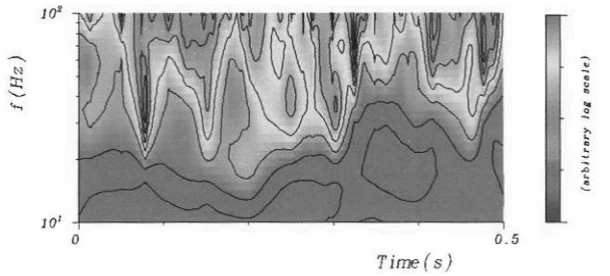


(a) Upper wall (b) Lower wall

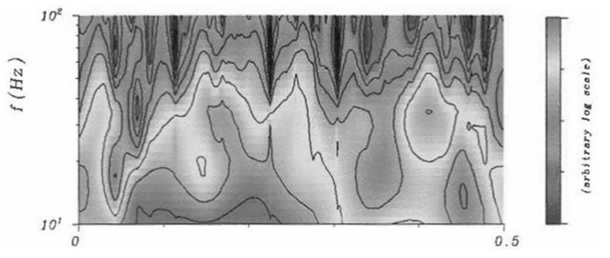
Fig. 15. Power spectrum of v′.



(a) X/X_{Ru}=0.2 Y/H=2.2



(b) X/X_{Ru}=1.0 Y/H=2.6



(c) X/X_{Ru}=5.0 Y/H=2.8

Fig. 16. Wavelet power spectrum of υ′.

(U/U_{max} ≅ 0.99). It is clearly shown that two dominant frequencies have been observed at about f≦10Hz (fH/U_{ref} <0.02) and f≦170Hz (fH/U_{ref}<0.32). The former corresponds to a low frequency flapping motion of the separated shear layer, while the latter corresponds to a high frequency of small vortices formed by the Kelvin-Helmholtz instability.

A clear dominant frequency was found at f=30Hz (fH/U_{ref}= 0.55) in the downstream, indicating a development of vortices and their shedding from the reattachment flow region. Profile shapes of the power spectrum and the dominant frequency were nearly the same on both the upper and lower walls. This phenomenon may have been brought about by the unification of two shear layers separated at the upper and lower corners of the step. Large-scale vortices were shed frequently to the downstream from the reattachment region. The main flow at low temperature was entrained into the reattachment region, resulting in a high heat transfer coefficient therein. It has been recently been noticed that there are several unsteady features in large-scale organized structures that randomly deformed and broke off with time (Ishikawa [18]. The wavelet transformation method is useful in investigating the instantaneous characteristics of the flow.

Fig. 16 illustrates typical results of the wavelet transformation of υ′. It was found that a low frequency region originating from the low frequency flapping motion of the separated shear layer was dominant just downstream of the separation point (Fig. 16(a)).

In the reattachment flow region shown in Fig. 16(b), the energy was dispersed in a wide frequency range, while a low frequency region, including the vortex-shedding frequency, was dominant in the redeveloping region downstream of the reattachment point (Fig. 16(c)).

4. Concluding remarks

Experimental investigations were conducted to clarify the details of turbulent heat transfer in asymmetric expansion plane channel of expansion ratio 2.0. According to the results, the distribution of the local Nu was exhibited extremely differently on the upper and lower walls. This originated from the Coanda effect, which was caused by the instability between the upper and lower separated shear layers. The stream-wise variation of Nu was great on the upper wall, accompanying a short recirculation region, while it was rather gentle on the lower wall accompanying a long recirculation region.

Empirical formulae were proposed for the maximum Nu in the reattachment flow region on both walls. It was found that the stream-wise point of Nu_{max} was located very close to the flow reattachment point. Furthermore, the present results of the maximum heat transfer coefficient correlated well with the previous formula proposed by Ota et al. [10, 11, 15], in which the reattachment length was employed as a reference length. Meanwhile, the mean and fluctuating velocities and temperatures were measured at Re=15,000 in a wide stream-wise range. Mean velocity profiles clarified the general flow structure deflected by the Coanda effect, and the turbulence profiles reflected the development of the separated shear layer and its correlation with the heat transfer characteristics. The power spectrum of the velocity fluctuation revealed that the dominant frequency of large scale vortices shed from the reattachment region was nearly equal to $0.70U_{ref}/X_r$ on both the upper and lower walls.

The wavelet transformation of the velocity fluctuation was found to be useful in investigating the instantaneous features of the complicated separated and reattached flow.

Acknowledgement

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Nomenclature

A.R.	:	Aspect Ratio (W_2/W_0)
E_{fx}	:	Power spectrum of X
E.R.	:	Expansion Ratio (W_1/W_0)
f	:	Frequency
H	:	Step Height
h	:	Heat transfer coefficient ($q_w/(T_w-T_{ref})$)
I_r	:	Reverse flow rate
Nu	:	Nusselt number (hH/λ)
Pr	:	Prandtl number
q_w	:	Heat flux per unit area and unit time
Re	:	Reynolds number (U_{ref}/Y)
T,t′	:	Mean and fluctuating temperatures
U,u′	:	Mean and fluctuating velocities in X-direction
V,v ′	:	Mean and fluctuating velocities in Y-direction
W_0,W_1	:	Upstream and down stream channel, heights
X,Y	:	Coordinates
X_{Numax}	:	Stream-wise distance step to a point of maximum Nu
X_R	:	Time averaged reattachment length
λ ,υ	:	Thermal conductivity and kinematic viscosity

Subscripts

l	:	Lower wall
max	:	Maximum
rms	:	Root mean square
s	:	Near wall
u	:	Upper wall

Superscripts

‾	:	Time averaged

References

[1] L. S. Fletcher, D. G. Briggs and R. H. Page, Heat Transfer in Separated and Reattached Flows: An Annotated Review, *Israiel J. Tech.*, 12 (1974) 236-261.

[2] W. Aung, Separated Forced Convection, *Proc. ASME-JSME Thermal Eng. Conf.*, 2 (1983) 499-515.

[3] T. Ota and H. Nishiyama, A Correlation of Maximum Turbulent Heat Transfer Coefficient in Reattachment Flow Region, *Int. J. Heat Mass Transfer*, 30 (1983) 1193-1200.

[4] W. Merzkirch, R. H. Page and L. S. Fletcher, A Survey of

Heat Transfer in Compressible Separated and Reattached Flows, *AIAA J.*, 26 (1988) 144-150.
[5] T. Ota, A Survey of Heat Transfer in Separated and Reattached Flows, *Appl. Mech. Rev*., 53 (2000) 219-235.
[6] E. G. Filetti and W. M. Kays, Heat Transfer in Separated, Reattached and Redevelopment Regions behind a Double Step at Entrance to a Flat Duct, *ASME J. Heat Transfer,* 89 (1967) 163-168.
[7] N. Seki, S. Fukusako and T. Hirata, Effect of Stall Length on Heat Transfer in Reattachment Region Behind a Double Step at Entrance to an Enlarged Flat Duct, *Int. J. Heat Mass Transfer*, 19 (1976) 700-702.
[8] N. Seki, S. Fukusako and T. Hirata, Turbulent Fluctuations and Heat Transfer for Separated Flow Associated with a Double Step at Entrance to an Enlarged Flat Duct, *ASME J. Heat Transfer*, 98 (1976) 588-593.
[9] N. Seki, S. Fukusako and T. Hirata, Laminar Heat Transfer Downstream of a Sudden Enlargement of a Duct, *Bull. JSME*, 2l (1978) 254-257.
[10] T. Ota and T. Toda, Prediction of Laminar Heat Transfer and Flow in a Plane Enlarged Channels, *Proc. 9th IHTC*, 6, 20 MSCl1, (1990) 305-311.
[11] T. Ota and T. Hata, Numerical Analysis of Laminar Heat Transfer and Flow in a Plane Enlarged Channel, *Proc. 2nd JSME-KSME Thermal Eng. Conf*., 1 (1992) 63-65.
[12] T. Ota, H. Yanaoka and T. Hata, Numerical Analysis of Laminar Flow and Heat Transfer in a Two-Dimensional Symmetrically Enlarged Channel, *Trans. JSME*, 60B, (1994) 3930-3936.
[13] T. Ota and H. Kato, Turbulent Heat Transfer in a Separated and Reattached Flow over a Blunt Flat Plate, *Proc. ASME/ JSME. Thermal Eng. Joint Conf.,* 3 (1991) 191-196.
[14] T. Ota and Y. Sugawara, Turbulent Heat Transfer in the Separated and Reattached Flow around an Inclined Downward Step, *Proc. l0th IHTC*, 4 (1994) 113-118.
[15] T. Ota, H.G. Fu and H. Yoshikawa, Effects of Aspect Ratio on Turbulent Heat Transfer around a Downward Facing Step, *Proc. 12th IHTC*, 2 (2002) 723-728.
[16] G. Beylkin, R. Coifman, I. Daubechies, S. Mallat, Y. Meyer, L. Raphael and B. Ruskai,, Eds., *Wavelets and Their Applications*, Jones & Bertlett, Cambridge, MA (1992).
[17] C. K. Chui, Ed., Wavelet: A Tutorial in Theory and Applications, *Academic Press*, Boston (1992).
[18] H. Ishikawa, M. Kiya, O. Mochizuki and R. Maekawa, POD and Wavelet Analysis of Coherent Structures in a Turbulent Mixing Layer, *Trans. JSME*, 63B (1997) 2001-2008

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