Fluid Flow and Local Heat Transfer around Two Cubes Arranged in Tandem on a Flat Plate Turbulent Boundary Layer*

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Experimental studies were performed to investigate the fluid flow and local heat transfer around two cubes arranged in tandem on a flat plate turbulent boundary layer. The Reynolds number, based on the cube height d , ranged from 4.0×10^3 to 3.2×10^4 . The thickness of the turbulent boundary layer δ was $\delta/d \geq 2.17$. The surface temperature distribution around the cubes was measured with thermocouples under conditions of constant heat flux. The effect of spacing b between two cubes was clarified in the range of $0.33 \leq b/d \leq 1.33$. In the case of $b/d \geq 0.67$, the horseshoe vortex is formed in front of each cube. However, at $b/d = 0.33$, it does not form in front of the 2nd cube. The local heat transfer is high in the horseshoe vortex regions and the flow reattaching regions. The average Nusselt numbers of 1st cube, $\overline{Nu}_1$, and 2nd cube, $\overline{Nu}_2$, are expressed as $\overline{Nu}_1 = 0.24 Re^{0.66}$ and $Nu_2 = 0.27 Re^{0.64}$, respectively. They are virtually unaffected by the spacing. However, that of base plate between two cubes, $\overline{Nu}_{p12}$, has a maximum value of $\overline{Nu}_{p12} = 0.47 Re^{0.60}$ at about $b/d = 0.67$.

Key Words: Forced Convection, Heat Transfer, Pressure Distribution, Flow Visualization, Separation, Turbulent Boundary Layer, Two Cubes, Horseshoe Vortex

1. Introduction

The flow around three-dimensional blocks is extremely complex because it is dominated by the horseshoe vortex, flow separation, and flow reattachment. Recently, studies on the cooling design of highly integrated electronic equipment are increasingly important. As such, it is necessary to investigate the characteristic of the local heat transfer around three-dimensional blocks. Chyu & Natarajan⁽¹⁾ measured the local mass transfer around a wall mounted cube by the naphthalene sublimation technique. The Reynolds number ranged from 3.1×10^4 to 1.04×10^5 , and the thickness of the turbulent boundary layer δ was significantly lower than cube height d ($\delta/d = 0.2 \sim 0.25$). Natarajan & Chyu⁽²⁾ investigated the effect of the flow angle-of-attack of a wall-mounted cube on

the local mass transfer under the same experimental conditions as Ref. (1). The present authors^{(3),(4)} investigated the local heat transfer around a wall-mounted cube by thermocouples under conditions of constant heat flux. The Reynolds number ranged from 4.2×10^3 to 3.3×10^4 , and the thickness of the turbulent boundary layer was greater than the cube height ($\delta/d = 1.5 \sim 1.83$). The correlation between the flow and the heat transfer was clarified by the visualization of surface flow and the measurement of pressure distribution.

To clear the flow around an array of blocks, Igarashi & Takasaki⁽⁵⁾ investigated the flow around three two-dimensional rectangular blocks in the laminar boundary layer. The ratio of height to side length of each block ranged from $H/d = 0.1 \sim 0.33$, the ratio of spacing to side length ranged from $b/d = 0.33 \sim 1.0$, and the Reynolds number based on the side length of the block ranged from $Re = 3.8 \times 10^3 \sim 1.15 \times 10^4$. They cleared the effect of the ratio of boundary layer thickness and the height of the block on the flow characteristics. Igarashi & Takasaki⁽⁶⁾ measured the local heat transfer of the second block and clarified the correlation between the fluid flow and heat transfer. Meinders et al.⁽⁷⁾ investigated the local and face-

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averaged heat transfer of an array of cubes in the rectangular channel by infrared thermography. The Reynolds number ranged from $Re=795\sim 5\,066$, and the thickness of laminar boundary layer was $\delta/d \approx 0.5$. The spacing of the cubes was fixed to $b/d=1.0$. Therefore, the effect of spacing on the flow and heat transfer was not clarified.

In our present study, we investigated the effects of the spacing of two cubes arranged in tandem on the characteristic of local heat transfer. The ratio of spacing and side length ranged from $b/d=0.33\sim 1.33$, the Reynolds number based on d ranged from $Re=4.0\times 10^3\sim 3.2\times 10^4$, and the thickness of turbulent boundary layer was $\delta/d \geq 2.17$. From the flow visualization around the cubes, and the measurement of the surface pressure, the correlation between the fluid flow and the heat transfer was clarified.

Nomenclature

C_P : pressure coefficient $= (p-p_0)/0.5\rho u_0^2$

b : spacing between blocks

d : side length of block

H : height of block

h : local heat transfer coefficient $= \dot{q}/(\theta_w - \theta_0)$

$\bar{h}$: face-averaged heat transfer coefficient
 $= \iint_S [\dot{q}/(\theta_w - \theta_0)] dS/S$

Nu : Nusselt number $= hd/\lambda$

Nu_1, Nu_2 : average Nusselt number of 1st and 2nd cube $= \bar{h}d/\lambda$

Nu_{p12} : average Nusselt number on base plate between two cubes (area B-E-H-C)

p_0, p : free stream static pressure and wall pressure

$\dot{q}$: heat flux

Re : Reynolds number $= u_0 d/\nu$

u_0 : free stream velocity

δ : boundary layer thickness

θ_0, θ_w : free stream temperature and wall temperature

λ : thermal conductivity of fluid

ν, ρ : kinematic viscosity and density of fluid

2. Experimental Apparatus and Procedure

Figure 1 shows a schematic view of two cubes. Experiments were conducted in a low speed wind tunnel with a working section 400 mm high, 300 mm wide and 800 mm long. Two cubes, with height d of 30 mm, were arranged in tandem on a flat plate. The spacing between the two cubes, b , ranged from 10 mm to 40 mm. The free-stream velocity, u_0 , ranged from 2 to 16 m/s. Therefore, the Reynolds number based on the cube height ranged from $Re=4.0\times 10^3$ to 3.2×10^4 . The turbulent intensity of the free-stream in this range was about 0.5%. The turbulent boundary layer

Fig. 1 Coordinate system and symbols

Fig. 2 Experimental model for heat transfer measurement

was achieved by attaching a circular cylinder of 10 mm in diameter on the base plate at 500 mm upstream of the cubes. The boundary layer thickness, δ , ranged from 65 mm ($u_0=16$ m/s) to 200 mm ($u_0=2$ m/s) at the position of the leading edge of the 1st cube. Therefore the ratio δ/d was from 2.17 to 6.7. The visualization of the flow in the streamwise direction of $y=0$ was made by a smoke-wire method, and the visualization of the surface flow of the cubes and the base plate was made by an oil-film method. The surface pressures on the cubes and the base plate were measured by an inclined multi-tube manometer connected with pressure taps of 0.6 mm in diameter. The experimental uncertainties of pressure coefficient C_P was within ± 0.01 at $u_0=16$ m/s. The pressure was measured at 1 100 points, 4 mm intervals on each cube surface, and 2.5~10 mm intervals on the base plate.

Figure 2 shows the test model for the local heat transfer measurement. One cube was heated while the other was unheated. Each cube was fabricated from acrylic resin, and the thickness of each face of the heated cube was 3 mm. The thickness of the base plate around the test model was 5 mm. The faces of the heated cube and the plate were covered with five stainless steel sheets that were 0.02 mm thick and 30 mm wide. One sheet covered three faces of the cube and the plate, and the other sheets covered the plate. They were connected in an electrical series and heated by applying an alternating current under conditions of constant heat flux. The temperature difference between the heated surface and the free-stream was about 10°C. The radiant energy can be neglected in the estimation of the heat transfer. Copper-constantan thermocouples of 0.1 mm in diameter were attached underneath the stainless steel sheets in one-fourth of the entire surface area. In order to obtain

the temperature distribution over the entire area, measurements were performed eight times under the same experimental conditions, i.e., four times by rotating the heated cube and the base plate around the test model every 90 degrees along the axis parallel to the vertical coordinate, and four times again by changing the position of heated and unheated cubes. The surface temperature was measured at about 2000 points, at 3 mm intervals on each cube surface, and 4~8 mm intervals on the plate. To estimate the heat loss by conduction from the heater to the acrylic resin, the thermocouples were also attached on interior surfaces of the heated cube, unheated faces of the heated cube, and under the surface of the base plate. The heat transfer coefficient was calculated taking the above loss into account. The heat loss to two unheated faces of the heated cube on the heat transfer coefficient was estimated to be about 10%. The experimental uncertainties of the heat transfer coefficient was within $\pm 5\%$ except for the area around side edges of the cube. The heat transfer coefficient of the base plate around the unheated cube was not adopted because it was affected by the heat loss from the plate to the unheated cube.

3. Flow Characteristics

3.1 Flow visualization

Figures 3(a)~(d) show the flow visualization by the smoke-wire method in the streamwise direction of $y=0$. The spacing between two cubes ranges from $b/d=0.33\sim 1.33$. The Reynolds number based on the cube height is $Re=3.2\times 10^4$. In each case, the inner shear layer, which separated from the front corner of the 1st cube, reattaches to the area around the back edge of the top face. The separation bubble is observed on the top face of the 1st cube. The outer shear layer, which separated from the front corner of the 1st cube, reattaches around the front corner of the 2nd cube. It is divided into two flows: the flow over the 2nd cube, and the circulating flow between the 1st and 2nd cubes. In cases of $b/d\geq 0.67$, this circulating flow reattaches on the base plate and then reaches the rear face of the 1st cube. But in case of $b/d=0.33$, the downward flow on the front face of the 2nd cube separates before it reaches the base plate, and a closed vortex is formed between the two cubes.

The surface oil-flow pattern for $b/d=0.67$ is shown in Figs. 4(a)~(c), as follows: top view, unfolding view of the 1st cube, and the unfolding view of the 2nd cube, respectively. On the base plate, a horseshoe pattern is formed in the front and side regions of the 1st cube. A horseshoe pattern is also seen in front of the 2nd cube, although not as clearly. In the case of narrow spacing ($b/d=0.33$), this pattern

(a) $b/d=0.33$

(b) $b/d=0.67$

(c) $b/d=1.0$

(d) $b/d=1.33$

Fig. 3 Flow visualization by the smoke-wire method ($y=0$, $Re=3.2\times 10^4$)

is not seen in front of the 2nd cube. On the front face of the 1st cube, the stagnation point exists at $y=0$, $z=0.6d$ and the flow spreads radially. The inner shear layer, which separated from the upper and side edges of the front face, reattach to the area around the back edges of the top and side faces, respectively. The reverse flows are formed on the top and side faces. They separate near the front edges, indicated by white lines of the oil accumulation, as seen in Fig. 4(b). The outer shear layer separated from the front face of the 1st cube reattaches around the upper and side edges on the front face of the 2nd cube, and it flows downward, and then it separates near the center of this face. The flow, which separated from the front face of the 2nd cube reattaches on the base plate between the two cubes and reaches the bottom part of the rear face of the 1st cube. The upward flow is seen on the rear face of the 1st cube. On the top and the

(a) Top view

(b) 1st cube

(c) 2nd cube

Fig. 4 Flow visualization by the oil-film method
($b/d=0.67$, $Re=3.2 \times 10^4$)

side faces of the 2nd cube, there is no reverse flow region.

3.2 Pressure distribution

Figures 5(a)~(c) show the contours of the mean pressure coefficient on the base plate, 1st cube, and 2nd cube, respectively, for $b/d=0.67$. On the base plate, the maximum pressure region is formed in front of the 1st cube ($x=-0.15d$, $y=0$), that is the flow reattaching point of the downward flow from the front face. The minimum values of C_P exist in the side regions of the 1st cube ($x=0.2d$, $y=\pm 0.6d$) resulting from the flow separation at the corners A and D. On the front face of the 1st cube, the stagnation point has a maximum value of C_P . On the top, both side and rear faces of the 1st cube, the values of C_P are nega-

(a) Flat plate

(b) 1st cube

(c) 2nd cube

Fig. 5 Contours of pressure coefficient ($b/d=0.67$,
 $Re=3.2 \times 10^4$)

tive, because these faces are in the separated and reattaching flow regions. On the top and side faces, the value of C_P is high in the flow reattaching regions, and low in the reverse flow regions formed in front of the reattaching regions. On the 2nd cube, the value of C_P is in the range of $-0.3 \sim 0$ except for the flow reattaching regions of upper and side edges of the front face.

Figures 6(a) and (b) show the pressure coefficient in the streamwise direction of $y=0$ for $b/d=0.33 \sim 1.33$. On the front and top faces of the 1st cube, there is no effect of the spacing on the pressure coefficient. On the top face of the 1st cube, the flow

(a) 1st cube

(b) 2nd cube

Fig. 6 Pressure distributions in the streamwise direction ($y=0$)

reattaching point, as indicated by notation R, has a maximum value of C_P . On the rear face of the 1st cube, the value of C_P in the case of narrow spacing ($b/d=0.33$) is slightly higher than it was for $b/d \geq 0.67$ resulting from the flow reattachment by the closed vortex between the two cubes. On the front face of the 2nd cube, the distribution of C_P is almost flat except for the upper edge O. Negative pressure tends to recover to zero with an increase in spacing. In the case of narrow spacing of $b/d=0.33$, the value of C_P in the flat region is almost the same as that on the rear face of the 1st cube. This is caused by the formation of the closed flow between the two cubes. On the top face of the 2nd cube, the value of C_P decreases in the upstream region in the case of $b/d \geq 1.0$ because of the formation of a separation bubble at the upstream edge.

4. Heat Transfer Characteristics

4.1 Local heat transfer

Figures 7(a)~(c) represent the contours of the local Nusselt number on the base plate, 1st cube, and 2nd cube, respectively, for $b/d=0.67$ and $Re=4.0 \times 10^3$. On the base plate, the Nusselt number for the front and sides of each cube is high due to the formation of the horseshoe vortex. In particular, the Nusselt number for the front of the 1st cube is remarkably high,

(a) Flat plate

(b) 1st cube

(c) 2nd cube

Fig. 7 Contours of local Nusselt number ($b/d=0.67$, $Re=4.0 \times 10^3$)

the value is more than two times that of the plate farthest from the cube ($Nu=35 \sim 40$). However, a low Nusselt number region is located behind the 2nd cube. On the front and side faces of the 1st cube, the value of Nu in the bottom part is high due to the formation of the horseshoe vortex. On the top face, the value of Nu has a maximum value in the flow reattaching region near the back edge, and decreases along the direction of reverse flow. On the rear face, the Nusselt number decreases along the upward flow from the bottom. For the 2nd cube, the Nusselt number is high around the upper and side edges on the front face and around the front edges on the top and side faces, which are the flow reattaching regions. On the top and side faces, the Nusselt number decreases along the flow toward the back edge. The Nusselt number on the rear face is considerably lower than on the other faces.

Fig. 8 Local Nusselt number line plots in the streamwise direction ($y=0$, $Re=4.0 \times 10^3 \sim 3.2 \times 10^4$)

Figures 8(a)~(c) show the Nusselt number line plots in the streamwise direction of $y=0$ for $b/d=0.33$, 0.67 , and 1.33 , respectively. In each case, there is a maximum of the Nusselt number on the top face of the 1st cube (K-L). This corresponds to the reattaching point of the flow separated from the front edge K. In case of $b/d=0.33$, the maximum value of the Nusselt number on the rear face of the 1st cube (L-M) corresponds to the flow reattachment of the vortex between two cubes. On the front face of the 2nd cube (N-O), the maximum value of the Nusselt number exists around the upper edge O in the case of $b/d=0.33$. However, in the case of $b/d \geq 0.67$, the position of the maximum value exists slightly lower than the upper edge O corresponding the shift of the reattaching point. On the base plate between two cubes (M-N), there is a sharp increase in the Nusselt number in front of the 2nd cube corresponding to the formation of the horseshoe vortex in case of $b/d \geq 0.67$. However, the Nusselt number in front of the horseshoe vortex region is considerably lower. The high Nusselt number regions formed by the horseshoe vortex and the reattaching flow located almost the same position independent of the Reynolds number.

Figures 9(a) and (b) show the Nusselt number distribution on each face of the 1st and 2nd cubes at a given height of $z/d=0.5$ for $Re=4.0 \times 10^3$. The Nusselt number distribution of the single cube is also

Fig. 9 Local Nusselt number line plots around each cube ($z/d=0.5$, $Re=4.0 \times 10^3$)

shown in Fig. 9(a). On the front and side faces of the 1st cube, the Nusselt number is not affected by the spacing, and the value is almost equal to that for the single cube. On the rear face of the 1st cube, the value

Fig. 10 Comparison of local Nusselt number distribution in the streamwise direction ($y=0$)

of Nu is higher than it is for the single cube because of the circulating flow between two cubes. The value of Nu increases with a decrease in spacing. For example, the value for $b/d=0.33$ is 20% higher than it is for the single cube. On the front face of the 2nd cube, the value of for $b/d=0.33$ is lower than it is for $b/d \geq 0.67$, because the horseshoe vortex is not formed at $b/d=0.33$. On both the side and rear faces of the 2nd cube, spacing has little effect on the Nusselt number distribution. As a whole, the effect of the spacing on the Nusselt number of the two cubes is insignificant, since difference in the values of the Nusselt numbers is within $\pm 10\%$.

The Nusselt number distributions in the streamwise direction of $y=0$ for $b/d=1.0$ are presented in Figs. 10(a) and (b), compared with those obtained by Meinders et al.⁽⁷⁾. On each face of the 1st and 2nd cubes, the value of Nu obtained in the present study is higher than those of Meinders et al. This difference is due to the turbulent intensity of the boundary layer. The experiment by Meinders et al. was performed under the condition of laminar boundary layer with a thickness of $\delta/d \approx 0.5$. However, the present experiment was performed under the condition of turbulent boundary layer with a thickness of $\delta/d > 1$.

4.2 Average Nusselt number

The individual average Nusselt numbers of the 1st and 2nd cubes, and the base plate between two cubes [area B-E-H-C, see Fig. 7(a)] are shown in

Fig. 11 Average Nusselt number

Figs. 11(a), (b), and (c), respectively. For the 1st cube, the average Nusselt number, $\overline{Nu}_1$, increases with the decrease in the spacing between two cubes. This corresponds to enhancement of heat transfer on the rear face. For example, the value of $\overline{Nu}_1$ for $b/d=0.33$ is 5~10% higher than it is for $b/d=1.33$. Consequently, the effect of the spacing on Nu_1 is negligible. The correlation of $\overline{Nu}_1$ can be expressed within $\pm 5\%$ as

$$\overline{Nu}_1 = 0.24 Re^{0.66} \quad (1)$$

For the 2nd cube, the average Nusselt number, $\overline{Nu}_2$, is not affected by the spacing. The correlation of $\overline{Nu}_2$ can be expressed as

$$\overline{Nu}_2 = 0.27 Re^{0.64} \quad (2)$$

The value $\overline{Nu}_2$ is about 10% lower than that of $\overline{Nu}_1$ in the range of the present Reynolds number. According to Meinders et al.⁽⁷⁾, the average Nusselt number of the 1st cube had a minimum value and that of the 2nd cube had a maximum value among an array of cubes. The discrepancy to the present result can be expressed as follows. The 1st cube for the Meinders et al. was situated in the laminar boundary layer of $\delta/d \approx 0.5$ which result in a lower Nusselt number. However, the turbulent flow was formed behind the 1st cube, and thus, the heat transfer was enhanced at the position of the 2nd cube.

The average Nusselt number on the base plate between two cubes, $\overline{Nu}_{p12}$, is higher for $b/d = 0.67$ than that for $b/d = 0.33$. This is due to the formation of the horseshoe vortex for $b/d \geq 0.67$. The difference of both values decreases with the increase in the Reynolds number. However, $\overline{Nu}_{p12}$ gradually decreases with an increase in spacing in the range of $b/d \geq 0.67$. This is related to the increase in the low heat transfer region in front of the horseshoe vortex. From above, it is indicated that the value of $\overline{Nu}_{p12}$ has a maximum at about $b/d = 0.67$, which is the minimum spacing for the formation of the horseshoe vortex. The correlation of the maximum value of $\overline{Nu}_{p12}$ can be expressed as follows;

$$\overline{Nu}_{p12} = 0.47 Re^{0.60} \quad (3)$$

5. Conclusion

The flow and local heat transfer around two cubes arranged in tandem on a flat plate turbulent boundary layer were investigated. The spacing between two cubes ranged from $b/d = 0.33 \sim 1.33$. The Reynolds number based on the cube height ranged from $Re = 4.0 \times 10^3 \sim 3.2 \times 10^4$, and the thickness of the turbulent boundary layer was $\delta/d \geq 2.17$.

(1) For the spacing $b/d \geq 0.67$, the horseshoe vortex forms in front of the 2nd cube as well as in front of the 1st cube, and heat transfer in these regions are enhanced. However, in the case of narrow spacing of $b/d = 0.33$, there is no formation of the horseshoe vortex in front of the 2nd cube.

(2) The inner shear layer, which separates from the front face of the 1st cube, reattaches in an area around the back edges on the top and side faces. The outer shear layer reattaches in an area around the upper and side edges of the front face of the 2nd cube. On the rear face of the 1st cube, there is a flow reattachment in case of $b/d = 0.33$ by a closed vortex formed between two cubes. Each reattaching point presents maximum values of pressure and heat transfer.

(3) The characteristics of the local heat transfer

of the 1st cube, with the exception of the rear face, are almost same as those of a single cube. The heat transfer on the rear face of the 1st cube increases with a decrease in spacing. For the 2nd cube, the characteristics of the local heat transfer are not affected by the spacing.

(4) The high Nusselt number regions formed by the horseshoe vortex and the reattaching flow locate in almost the same position independent of the Reynolds number.

(5) The average Nusselt numbers of 1st cube, $\overline{Nu}_1$, and 2nd cube, $\overline{Nu}_2$, are virtually unaffected by the spacing between two cubes. The values of $\overline{Nu}_1$ and $\overline{Nu}_2$ can be expressed within $\pm 5\%$ as

$$\begin{aligned} \text{1st cube} \quad \overline{Nu}_1 &= 0.24 Re^{0.66} \\ \text{2nd cube} \quad \overline{Nu}_2 &= 0.27 Re^{0.64} \end{aligned}$$

The value of $\overline{Nu}_2$ is about 10% lower than that of $\overline{Nu}_1$ in the range of the present Reynolds number.

(6) The average Nusselt number on the base plate between two cubes, $\overline{Nu}_{p12}$, has a maximum value at about $b/d = 0.67$, which is the minimum spacing for the formation of the horseshoe vortex. The maximum value of $\overline{Nu}_{p12}$ can be expressed as $\overline{Nu}_{p12} = 0.47 Re^{0.60}$.

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