Turbulent near-wakes of periodic array of square blocks on a plate

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This paper describes the experimental study of the flow structure past square blocks located on a ground plate with various spacings. The experiment was carried out in a circuit type wind tunnel of a 200 × 200 mm working section and 2000 mm in length at a Reynolds number of 990, which is based on the free-stream velocity and the height of block. The test blocks, side length $D = 23$ mm and height $H = 5$ mm, were aligned at a regular spacing S in a square array on the lower wall of the test section, and the spacing was systematically varied to provide $S/H = 2$, 3, 5, 7, 10, and 13. The mean velocity and turbulence intensities were measured by a laser Doppler velocimeter (LDV). It was found that the spacing ratio $S/H = 7$ is optimum to augment the turbulence intensity near the ground plate when the repeated blocks are aligned in a square array.

Keywords: laser Doppler velocimeter (LDV); turbulent flow; turbulence; velocity distribution; reattachment; square block

Introduction

As electronic components become evermore powerful, their internal heat generation increases accordingly. The dissipation of this heat becomes paramount if high levels of electronic reliability and lifetime are expected; therefore, control of the air flow around the outer casing is an important design criterion. The development and understanding of air-cooling techniques must be undertaken if the working quality of the equipment is to improve. Therefore, control of the air flow around electronic modules becomes an important design item in air cooling, and development of the cooling technique will ensure quality on electronic equipment. In connection with the problem of forced convection cooling on an electronic package, Sparrow et al. (1982) reported the correlation between heat transfer and pressure drop using a full-scale model. Ashiwake et al. (1983) obtained the heat transfer coefficient around a package, and Yanagida et al. (1984) predicted the heat transfer coefficient on the surface of IC packages using the heat transfer equation for a two-dimensional (2-D) obstacle. Flow structure past repeated 2-D ribs on a ground plate, such as the IC packages on the electronic circuit board, have been investigated by Hijikata et al. (1984), Mori et al. (1985), Ichimiya et al. (1983) and Okamoto et al. (1993). Hijikata et al. and Mori et al. studied the flow pattern between two adjoining ribs among repeated 2-D ribs on a ground plate for a single case of $S/H = 14$. Ichimiya et al. measured the flow over repeated ribs on the lower insulated wall of a duct, whose upper wall was heated for cases of $S/H = 4$, 6, and 14. Okamoto et al. reported the detailed study of the flow structure over repeated 2-D square ribs on a ground plate for spacing ratios and found its optimum value to augment turbulence in the free stream. As mentioned above, most of the existing studies are limited to 2-D ribs on a ground plate, which are used to simulate IC packages on the board. However, the turbulent near-wake behind a three-dimensional (3-D) block has a vastly different complex flow structure, as reported by Okamoto. In the references mentioned thus far, no information is presented on detailed flow structure past arrayed 3-D blocks, such as in electronic components. Furthermore, for the further development of air-cooling techniques, knowledge of the flow's properties past repeated 3-D blocks at relatively low velocities is indispensable. The present paper describes an experimental study of such a flow strucutre past repeated 3-D blocks of a square section for various spacing ratios S/H.

Apparatus and measurement procedures

The experiment was carried out in a circuit-type wind tunnel of a 200 × 200 mm working section and 2000 mm in length. X, Y, and Z are coordinates with their origin at the center of the base of the central block, located 400 mm from the leading edge of the ground plate, as shown in Figure 1. The X-coordiante was chosen to be in a direction along the ground plate, the Y- and Z-coordinates are for the horizontal and vertical directions, respectively. Test blocks of square section, with side length $D = 23$ mm and height $H = 5$ mm, were placed at the origin of the coordinate system, and aligned at a regular pitch S in a square array on the lower wall of the test section. Their position could be varied to provide $S/H = 2$, 3, 5, 7, 10, and 13. The trough created between two blocks is referred to as a groove. The time-mean velocity and turbulence intensity were measured by laser Doppler velocimeter (LDV). The LDV used in this experiment is as follows (forward-scattering dual beams mode, 2 colors, 4 beams, power: 4 Watt argon-ion, operating power: 300 mW, wave length: green 514.5 nm, blue 488 nm, beam spacing: 50 mm, focal distance: 500 mm, measurement region:

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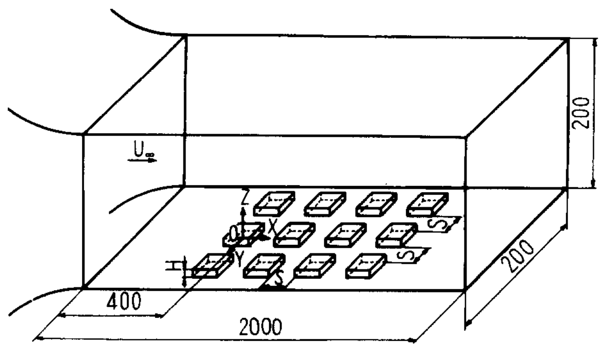

Figure 1 Apparatus and nomenclature

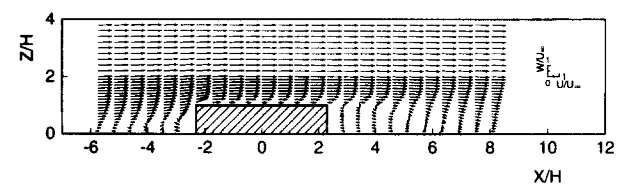

Figure 2 Mean velocity vectors in the flow past a single block at $Y/H = 0$

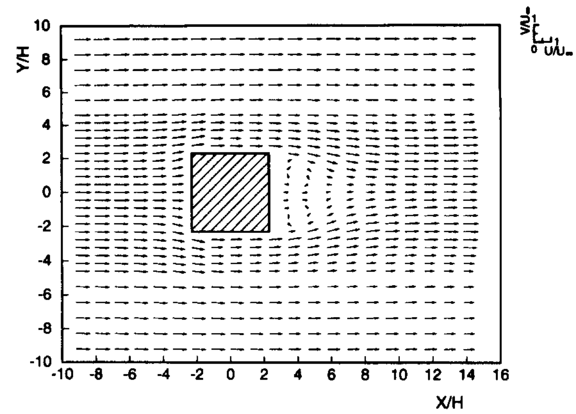

Figure 3 Mean velocity vectors in the flow past a single block at $Z/H = 0.5$

diameter 0.16 mm, length 3.2 mm). Smoke from a joss stick was use for seeding the air flow. Measurements were made at several streamwise locations corresponding to the midpoint of the groove between two streamwise blocks and the centre of grooves among four blocks and at other locations in the groove, between two streamwise blocks for a free-stream velocity of $U_\infty = 3$ m/s corresponding to $\mathrm{Re} = U_\infty H/\nu = 990$. Uncertainty is estimated by the method of ANSI/ASME PTC 19.1 (1986) and summarized as

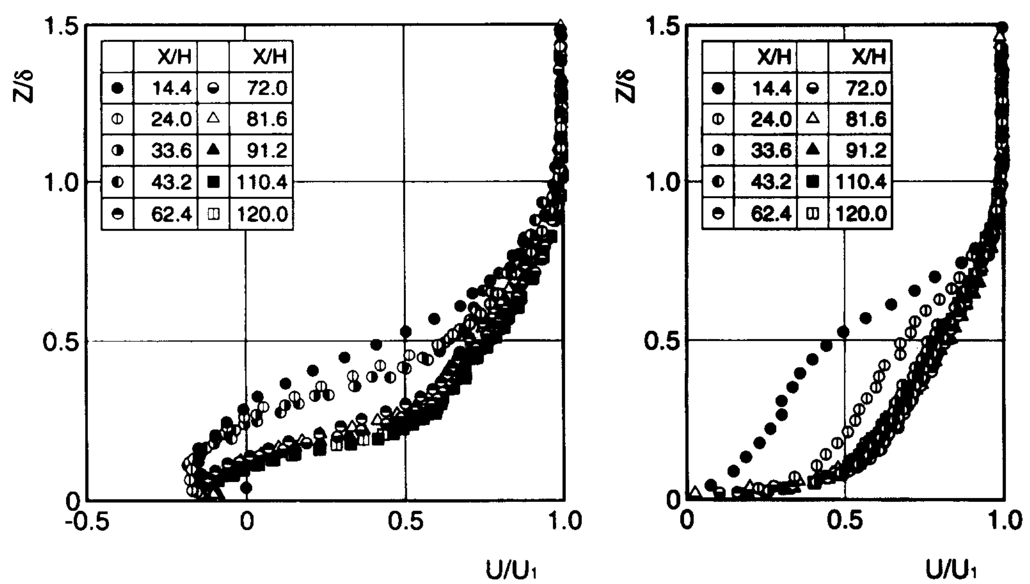

Figure 4 Mean velocity profile at midpoint of groove in $Y/H = 0$(a) and $Y/H = -4.8$(b) for $S/H = 5$

Notation

D	side length of square block
H	height of block
Re	Reynolds number, $= U_\infty H/\nu$
S	spacing between two adjoining blocks
U	time-mean velocity
U_1	velocity at outer edge of shear layer
U_∞	free-stream velocity
u'	X-component of fluctuating velocity
$\bar{X}$	distance in X-direction from the rear face of the block

Greek

δ	turbulent shear layer thickness
ψ	stream function
ν	kinematic viscosity of air
ρ	density of air

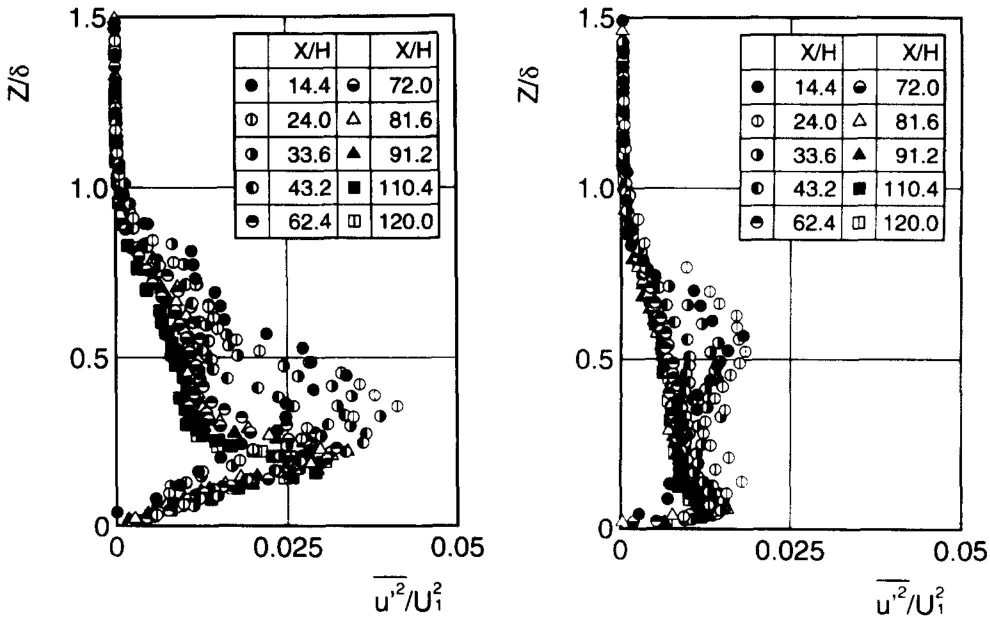

Figure 5 Turbulence intensity at midpoint of groove in $Y/H = 0$(a) and $Y/H = -4.8$(b) for $S/H = 5$

follows (uncertainty in H and D are 0.05 mm, in δ is 0.1 mm, in X, Y, and Z are 0.1 mm, in U/U_∞, V/U_∞ and W/U_∞ are 2.1%, in $\overline{u'^2}/U_\infty^2$ is 4.1%, and in $\psi/U_\infty \cdot H$ is 2.9%, respectively).

Experimental results and discussions

Flow pattern past a single block on ground plate

Figures 2 and 3 show the mean velocity vectors of the flow past a single block in the case of vertical centre section at $Y/H = 0$ and horizontal centre section at $Z/H = 0.5$ respectively. The flow, having separated from the block reattaches to the ground plate at a downstream location, generating a recirculation region behind a block. The length of the recirculation region; namely, the distance from the rear face of a block to the reattachment point is nearly $4.2H$, and after reattachment, a turbulent shear layer is developed along the ground plate. Furthermore, the approaching flow separates from the ground plate in front of a block, forming a small recirculation region. The distance from the frontal face of a block to the separation line is nearly $3.0H$. The flow past the frontal corner goes downstream in parallel with the side face, which means that no vortices are shed from the frontal corner for the case of a block of small aspect ratio ($H/D = 0.21$), as shown in Figure 3. The maximum length of the recirculation region is nearly $3.2H$ at the line of $Y/H = 0$ in the plane of $Z/H = 0.5$. Okamoto et al. (1993) reported the detailed study of the flow structure over repeated 2-D square ribs on a ground plate for various values of S/H and pointed out that the flow's properties over the square ribs is dependent on the flow pattern in the groove between two adjoining square ribs, thus, the flow pattern past repeated ribs can be divided into two groups. In the first case, a large stable recirculation region in the groove without reattachment of the separation streamline on the floor in the groove exists; whereas, in the second case, a smaller recirculation region in the groove behind a rib with subsequent reattachment of the separation streamline can be seen to exist. In the present experiment, two parameters of $S/H = 5$ and $S/H = 10$ were selected to investigate the detailed flow structure.

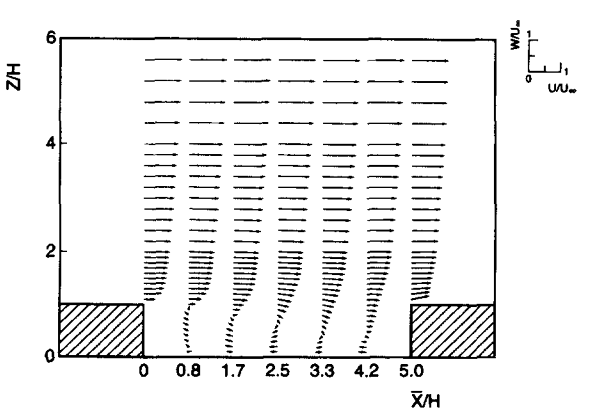

Figure 6 Mean velocity vectors of the flow in the groove at $Y/H = 0$ for $S/H = 5$

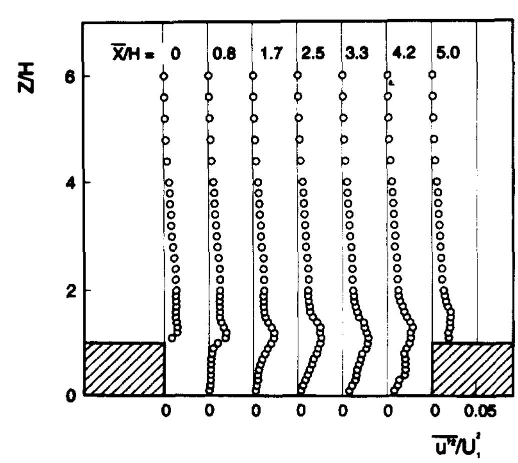

Figure 7 Turbulence intensity in the groove at $Y/H = 0$ for $S/H = 5$

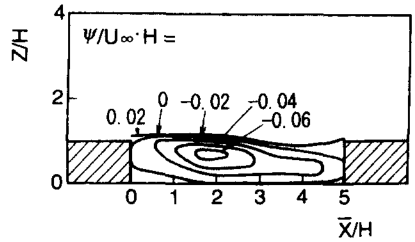

Figure 8 Streamlines in the groove at $Y/H = 0$ for $S/H = 5$

Flow pattern past repeated blocks for S/H = 5

To examine the development of the similarity in the shear layer, Figure 4 shows the mean velocity profiles in sections at the midpoints of grooves between two streamwise blocks in $Y/H = 0$, and the centre of groove among four blocks in $Y/H = -4.8$ for the case of $S/H = 5$. The thickness δ of the turbulent shear layer was defined by the value of Z where U is equal to $0.99U_i$. The velocity profiles are similar at the downstream distance from $X/H = 72$ at $Y/H = 0$, and $X/H = 33.6$ at $Y/H = -4.8$. Figure 5 shows the turbulence intensity in the shear layer at $Y/H = 0$, and $Y/H = -4.8$ for $S/H = 5$, and it can be seen to decay with increasing downstream distance and accomplish a self-preserving profile in the region of $X/H \geq 110.4$ at $Y/H = 0$ and $X/H \geq 62.4$ at $Y/H = -4.8$.

Figure 6 shows the mean velocity vectors of the flow in the groove between two streamwise blocks at $Y/H = 0$ for $S/H = 5$. It is seen in the figure that there is a reverse flow region in the groove. The midpoint of the groove is $X/H \approx 110$ and the velocity profile does not take the similar profile in the groove due to the existence of the recirculation region.

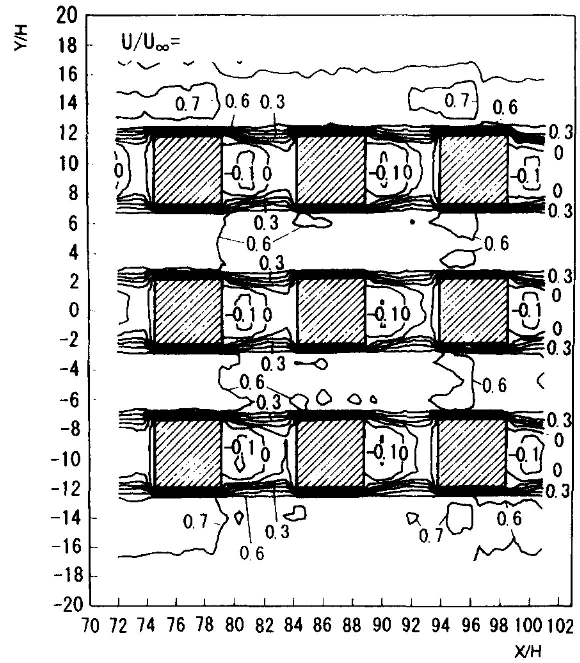

Figure 9 Isovelocity lines around the repeated blocks in $Z/H = 0.5$ for $S/H = 5$

Figure 7 shows the turbulence intensity in the groove between two streamwise blocks at $Y/H = 0$ for $S/H = 5$. The turbulence intensity is almost the same profile as in the downstream stations with a peak at $Z/H = 1.2$ in the groove for $S/H = 5$. However the turbulence intensity does not attain the self-preserving profile in the groove.

Figure 8 shows the streamline given by $\psi/U_\infty \cdot H = \text{const}$ in the groove between two streamwise blocks at $Y/H = 0$ for

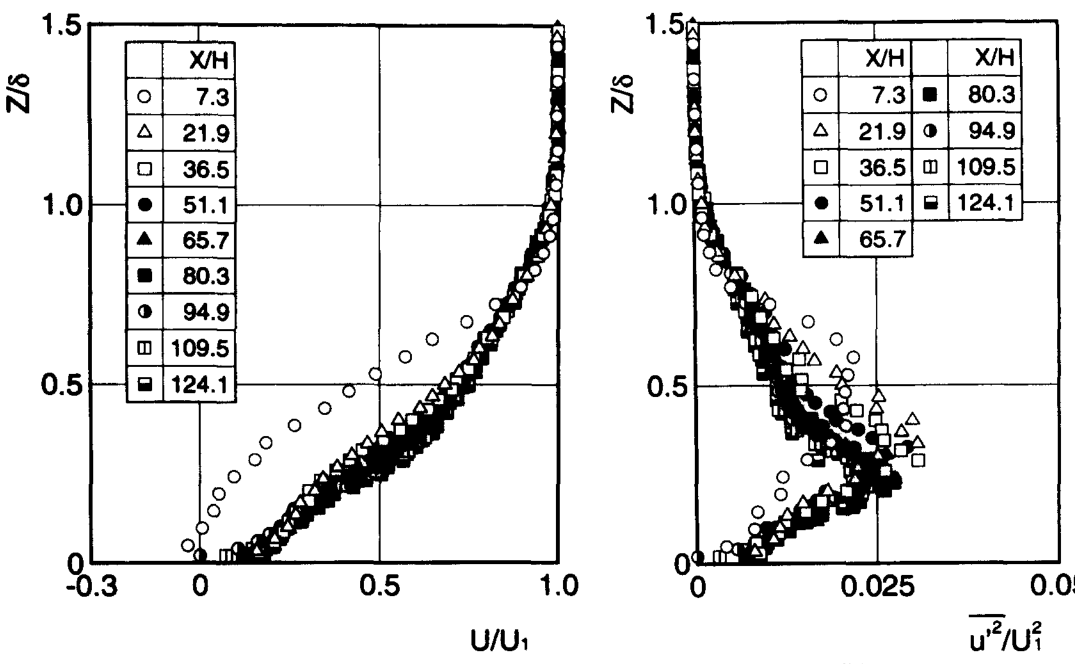

Figure 10 Mean velocity profile (a) and turbulence intensity (b) at midpoint of groove in $\bar{X}/S = 0.5$ and $Y/H = 0$ for $S/H = 10$

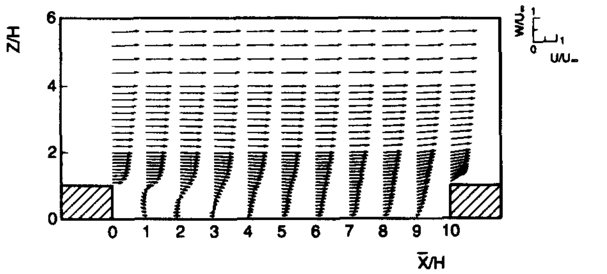

Figure 11 Mean velocity vectors of the flow in the groove at $Y/H=0$ for $S/H=10$

$S/H=5$, where ψ is the stream function obtained by integrating the X-component of the local mean velocity with respect to Z. A large recirculation region occupies the entire groove between two blocks without reattachment. Figure 9 shows the iso-velocity lines of the flowfield around the repeated blocks in the plane of $Z/H=0.5$ for $S/H=5$. The large variation in the iso-velocity lines is concentrated in the groove between two streamwise blocks, while the iso-velocity lines are almost unchanged in the groove between two transverse blocks. Consequently, the effect of the blocks on the flowfield past repeated blocks is mainly confined to the space within the groove between two streamwise blocks.

Flow pattern past repeated blocks for S/H = 10

Figure 10 shows the mean velocity profiles and turbulence intensity at the midpoints of groove in $\bar{X}/S=0.5$ and $Y/H=0$ for $S/H=10$. The mean velocity profiles tend to be similar in the region of $X/H \geq 21.9$, while the turbulence intensity tends to be a self-preserving profile in the region of $X/H \geq 65.7$. Figure 11 shows the mean velocity vectors of the flow in the groove at $Y/H=0$ for $S/H=10$. It shows that there is reverse flow in the region of $\bar{X}/H \leq 3$ behind the upstream block and a favorable flow in the region of $4 \leq \bar{X}/H \leq 10$. Hence, the free streamline leaving the upstream block encloses the recirculation region and reattaches to the ground plate at $\bar{X}/H \approx 3 \sim 4$.

Figure 12 shows the streamlines in the groove at $Y/H=0$ for $S/H=10$. A recirculation region exists behind the upstream-block, and its length is approximately $3.3H$ with the reattached flow leading downstream from it. Figure 13 shows the turbulence intensity in the groove at $Y/H=0$ for $S/H=10$. The peak turbulence at $Z/H \approx 1.1$ attains a maximum near the reattachment point ($\bar{X}/H=3 \sim 4$) and decays with increasing distance from the reattachment point. Figure 14 shows the iso-velocity lines of the flowfield around the repeated blocks in the plane of $Z/H=0.5$ for $S/H=10$. The dense lines concentrate in the groove between two streamwise blocks in similar manner to those in Figure 9 for $S/H=5$.

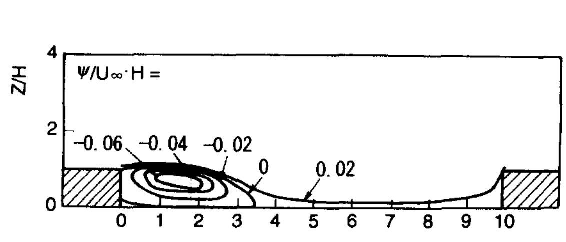

Figure 12 Streamlines in the groove at $Y/H=0$ for $S/H=10$

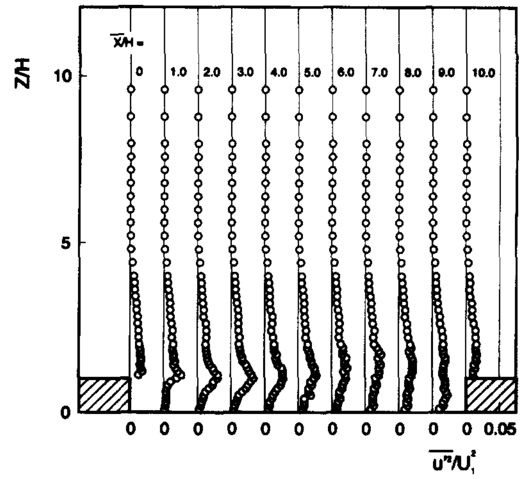

Figure 13 Turbulence intensity in the groove at $Y/H=0$ for $S/H=10$

Effect of spacing ratio S/H on flow pattern past repeated blocks

Figure 15 shows the mean velocity profiles at the midpoint of groove in $\bar{X}/S=0.5$ and $Y/H=0$ between the two streamwise blocks for $S/H=2$ and 13, in order to examine the similarity of velocity profiles in the shear layer at the downstream distance. The velocity profiles tend to be similar in the region of $X/H \geq 82.5$ for $S/H=2$ and $X/H \geq 26.4$ for $S/H=13$. The location where the similar profile first begins shifts downstream for $S/H=2$ and 5, as compared with those of $S/H=10$ and 13, because the midpoint of the groove is located inside the recirculation region behind the upstream block for $S/H=2$ and $S/H=5$.

Figure 16 shows the variation of the mean velocity profile at the groove midpoint for $\bar{X}/S=0.5$ and $Y/H=0$ near $X/H=110$ with the spacing ratio S/H. The mean velocity profiles concentrate in a narrow range, and are almost the same in the region of $Z/H \geq 1$, independent of spacing ratio S/H, except for $S/H=2$. The reverse flow region appears near the ground plate for $S/H \leq 7$. The variation in turbulence intensity at the midpoint of groove in $\bar{X}/S=0.5$ and $Y/H=0$ near $X/H \approx 110$ with spacing

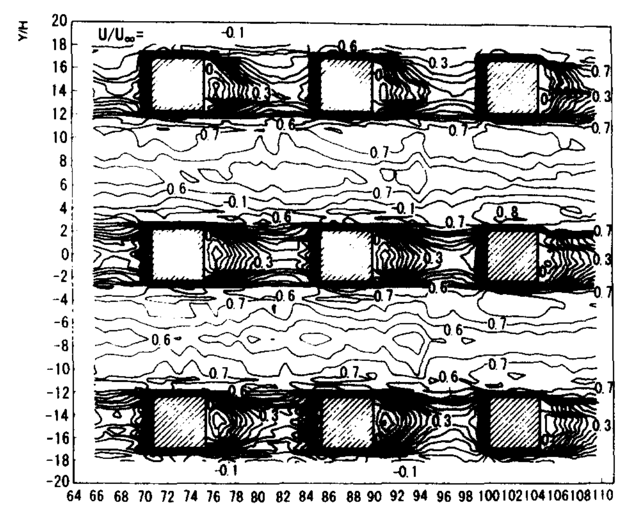

Figure 14 Isovelocity lines around the repeated blocks in $Z/H=0.5$ for $S/H=10$

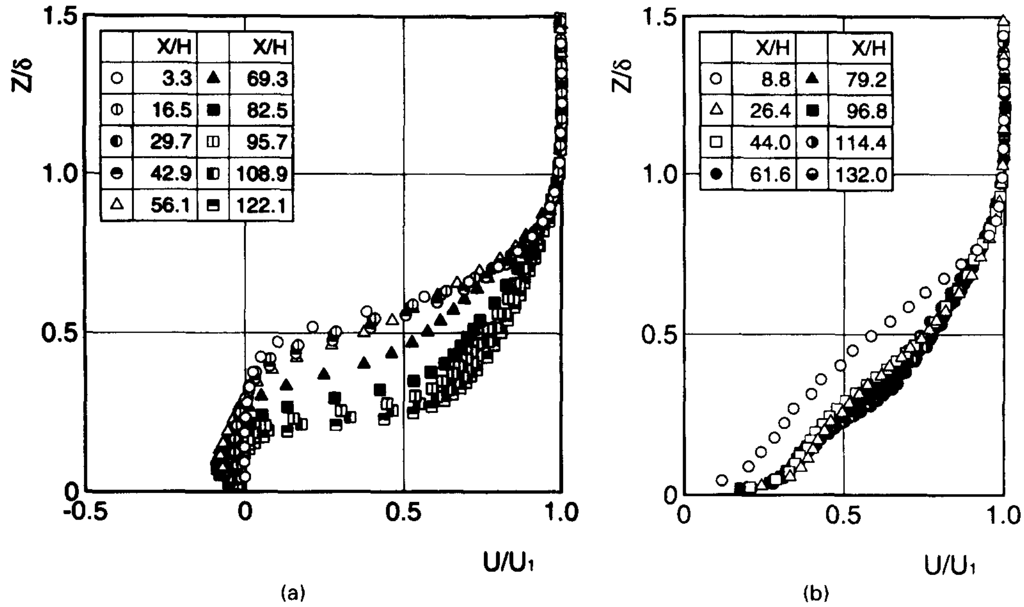

Figure 15 Mean velocity profile at midpoint of groove in $Y/H = 0$ for $S/H = 2$(a) and $S/H = 13$(b)

ratio S/H, is shown in Figure 17. It is obvious from the figure that the turbulence intensity increases for $S/H \leq 7$ and then decreases for $S/H > 7$ as the value of S/H increases. Hence, it is noteworthy that the spacing ratio $S/H = 7$ is optimum to augment the turbulence intensity near the ground plate, when repeated blocks are aligned on a ground plate.

Figure 18 shows the mean velocity vectors of the flowfield in the groove at $Y/H = 0$ for $S/H = 3$ and $S/H = 7$. It is found from this figure that the reverse flow region occupies the entire groove for $S/H = 3$, and the reverse flow exists in the region of $\bar{X}/H \leq 3.5$ behind the upstream blocks and favorable flow in the region of $4.2 \leq \bar{X}/H \leq 7$ for $S/H = 7$ is similar to that for $S/H = 10$. Figure 19 shows the streamlines in the groove between the two streamwise blocks at $Y/H = 0$ for $S/H = 3$ and $S/H = 7$. The small stable recirculation region occupies the entire groove without reattachment for $S/H = 3$. For $S/H = 7$, a recirculation region exists behind the upstream block, the length of which approximately $3.6H$, and the reattached flow goes downstream from it. Hence, the free streamline leaving the upstream block does not reattach in the groove for the case of $S/H \leq 5$ and encloses the recirculation region and reattaches to the ground plate for the case of $S/H \geq 7$.

Figure 20 shows the turbulence intensity in the groove between the two streamwise blocks at $Y/H = 0$ for $S/H = 3$ and $S/H = 7$. The turbulence intensity has almost the same low value in the groove for $S/H = 3$ in Figure 20a. For the case of

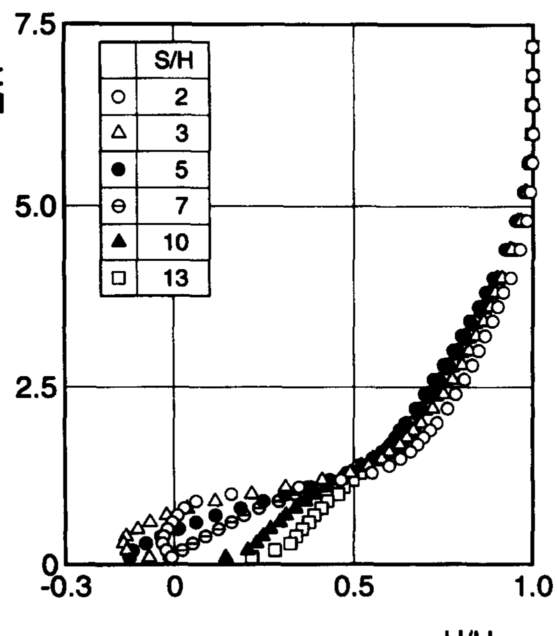

Figure 16 Mean velocity profile in $\bar{X}/S = 0.5$ and $Y/H = 0$ near $X/H = 110$

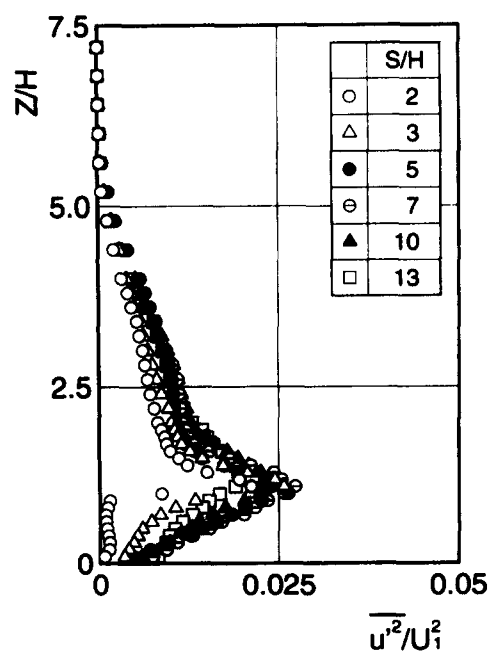

Figure 17 Turbulence intensity in $\bar{X}/S = 0.5$ and $Y/H = 0$ near $X/H = 110$

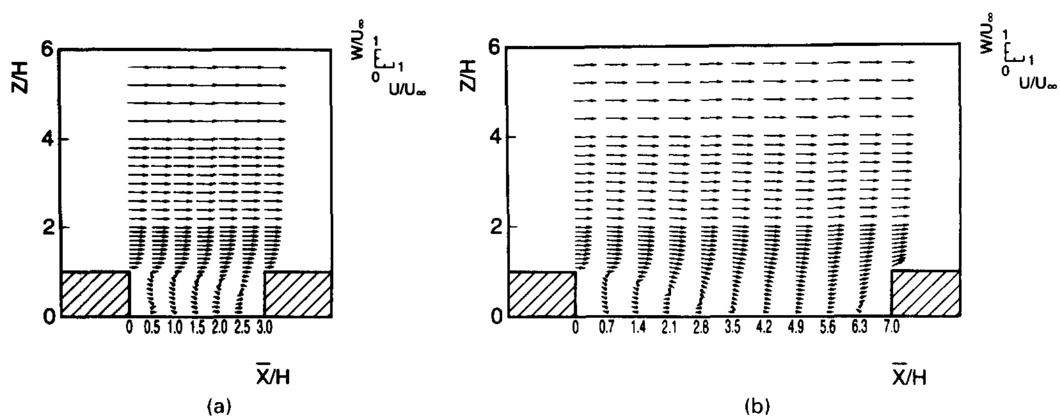

Figure 18 Mean velocity vectors of the flow in the groove at $Y/H = 0$ for $S/H = 3$(a) and $S/H = 7$(b)

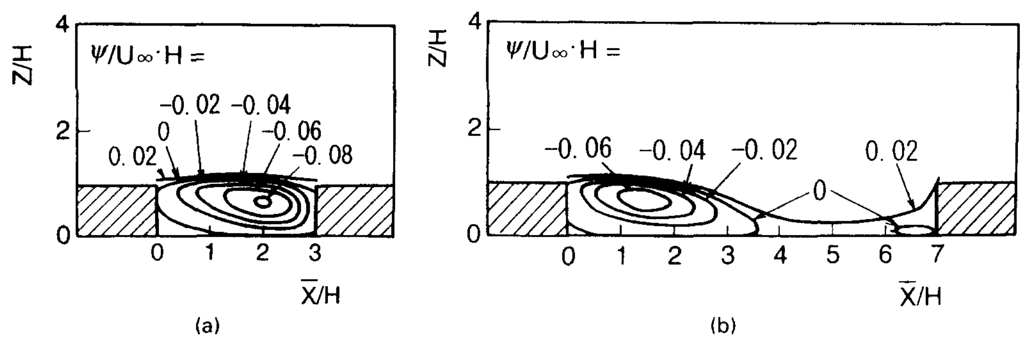

Figure 19 Streamlines in the groove at $Y/H = 0$ for $S/H = 3$(a) and $S/H = 7$(b)

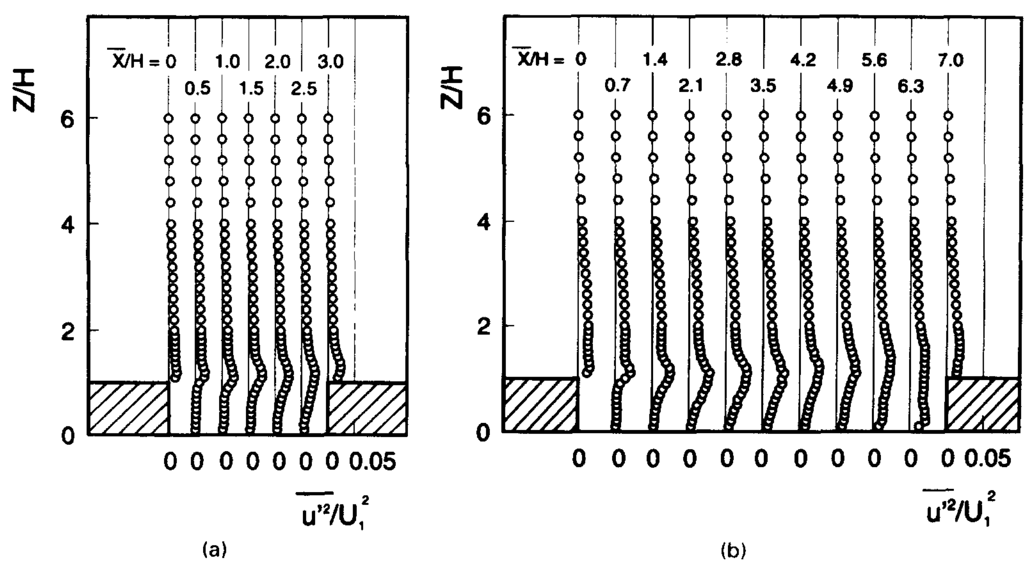

Figure 20 Turbulence intensity in the groove at $Y/H = 0$ for $S/H = 3$(a) and $S/H = 7$(b)

$S/H = 3$, the blocks are closely placed, and the stable vortices are set up in the grooves; therefore the recirculation region occupies the whole groove between the blocks without reattachment, because the length of recirculation region is nearly $4.2H$ for a single block. Hence, the turbulence intensity becomes low as compared with that of $S/H = 7$. However, the turbulence intensity attains a maximum near the reattachment point for the case of $S/H = 7$ in Figure 20b is similar to that for $S/H = 10$, as shown in Figure 13. For the case of $S/H \geq 7$, there is the recirculation region behind the upstream blocks, and the reattached flow goes downstream from the reattachment point. The reattachment point corresponds to the position of the maximum turbulent intensity near the ground plane and is near the midpoint in the groove for the case of $S/H = 7$. Furthermore, for the case of $S/H = 10$ and 13, the turbulence intensity decreases as compared with that of $S/H = 7$. The distance from the reattachment point to the next downstream block is longer for the cases of $S/H = 10$ and 13 than for $S/H = 7$, hence, the turbulence intensity decays with increasing downstream distance behind the recirculation region to become the largest for $S/H = 7$.

Conclusion

This paper presented the experimental study of the flow structure past repeated 3-D blocks of square section on a ground plate for various values of spacing ratio S/H. The results of the present study are summarized as follows:

(1) The effect of the blocks on the flow field past the repeated blocks is mainly limited to within the groove between two streamwise blocks.

(2) A large recirculation region occupies the entire groove between two blocks without reattachment for $S/H \leq 5$. However, the free streamline leaving the upstream block encloses the recirculation region and reattaches to the ground plate for $S/H \geq 7$.

(3) The turbulence intensity increases for $S/H \leq 7$ and then decreases for $S/H > 7$ as the value of S/H increases. Hence, the spacing ratio $S/H = 7$ is optimum to augment the turbulence intensity near the ground plate when repeated blocks are aligned on the ground plate.

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