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Physical Experiments to Investigate the Effects of Street Bottom Heating and Inflow Turbulence on Urban Street-Canyon Flow

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ABSTRACT

The effects of street bottom heating and inflow turbulence on urban street-canyon flow are experimentally investigated using a circulating water channel. Three experiments are carried out for a street canyon with a street aspect ratio of 1. Results from each experiment with bottom heating or inflow turbulence are compared with those without bottom heating and appreciable inflow turbulence. It is demonstrated that street bottom heating or inflow turbulence increases the intensity of the canyon vortex. A possible explanation on how street bottom heating or inflow turbulence intensifies the canyon vortex is given from a fluid dynamical viewpoint.

Key words: urban street-canyon flow, street bottom heating, inflow turbulence, circulating water channel

1. Introduction

When wind blows nearly perpendicular to the street, characteristic flow patterns, which resemble lid-driven cavity flow patterns in many respects (Pan and Acrivos, 1967; Ramanan and Homsy, 1994; Leriche and Gavrilakis, 2000), appear within the street canyon. Urban street-canyon flow and its associated pollutant dispersion have been studied extensively during the past three decades through field observations (e.g., DePaul and Sheih, 1985, 1986), laboratory experiments (e.g., Wedding et al., 1977; Meroney et al., 1996; Brown et al., 2000), and numerical model simulations (e.g., Lee and Park, 1994; Baik and Kim, 1999). These studies have enhanced our understanding of flow regimes in street canyons, factors affecting street canyon flow, and the dispersion of pollutants emitted into the street canyon.

Wind tunnels are very useful experimental facilities because various environments similar to the atmospheric boundary layer can be produced. Laboratory studies conducted so far to investigate urban street-canyon flow and dispersion have almost exclusively utilized wind tunnels. Other useful facilities would be water tanks or channels. These have been used widely with geophysical applications (e.g., Tampieri and Hunt, 1985) but very little with urban flow and dispersion applications. Baik et al. (2000) demonstrated that a circulating water channel is useful for the study of street canyon flow.

There are many factors influencing street canyon flow, one of which is building-wall or street bottom heating caused by the absorption of solar radiation. When the heating is present, thermally induced flow due to buoyancy and mechanically induced flow coexist in the street canyon. The resultant flow field is determined by the degree of heating and the street aspect ratio (Kim and Baik, 1999). The effects of building-wall or street bottom heating on street canyon flow have been examined numerically (Sini et al., 1996; Kim and Baik, 1999, 2001) and experimentally (Uehara et al., 2000; Liu et al., 2003). Another factor influencing street canyon flow is inflow turbulence. When wind blows over buildings of various shapes and dimensions, turbulent eddies can be generated mechanically. These turbulent eddies pass over and/or stream into the street canyon and interact with existing canyon flow. There have been very limited studies examining the effects of inflow turbulence on flows in a street canyon or around a building (Zhang et al., 1993).

This study aims to experimentally investigate the effects of street bottom heating and inflow turbulence

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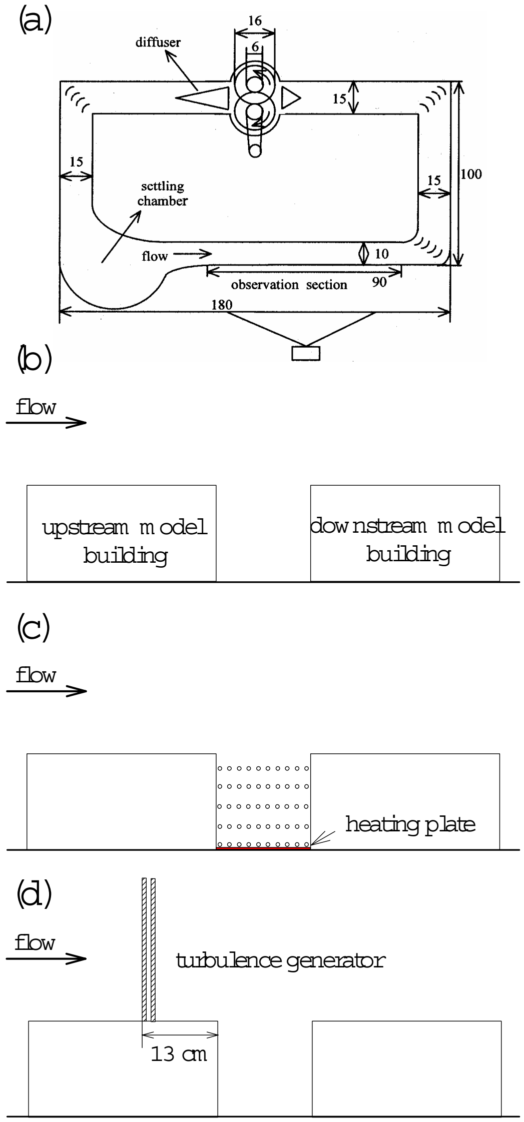

Fig. 1. The sketch of the circulating water channel: (a) top view and (b) the side view of the observation section in the control experiment, (c) street bottom heating experiment, and (d) inflow turbulence experiment. Dimensions in (a) are in cm.

on street canyon flow using a circulating water channel. In section 2, the apparatus and experimental setup are described. In section 3, results from the physical experiments are presented and discussed. In section 4, a comparison with wind-tunnel data is made. In section 5, a conclusion is given.

2. The circulating water channel and experimental setup

For this study, an Odell-Kovasznay-type circulating water channel (Odell and Kovasznay, 1971) is reconstructed following Baik et al. (2000). The circulating water channel, with its dimension of 180 cm×100 cm×50 cm, is depicted in Fig. 1. The motor rotates two vertical shafts having a stack of alternating large and small disks. A large disk on one shaft is arranged opposite a small disk on the other shaft. When the two vertical shafts rotate in opposite directions, the viscous drag of the large disks pulls water around the outside channels. Water is then ejected as horizontal jets emerging from gaps formed between the large disks (Odell and Kovasznay, 1971). To relax abrupt changes in water flow in the circulating water channel, diffusers are placed downstream and upstream of the pump and a settling chamber is made upstream of the observation section. The water channel has turning vanes at three corners. In the setting shown in Fig. 1a, water circulates counterclockwise.

Two model buildings with equal height (10 cm) and width (40 cm) are mounted on the bottom of the observation section. This building width is purposely expanded to make the approach flow nearly parallel to the bottom (corresponding to the urban roughness case in Meroney et al., 1996). The two model buildings are 10 cm apart, giving a street aspect ratio of 1. Therefore, it is expected that a skimming flow in the canyon will be observed. The channel water is 30 cm deep. To determine flow velocity in the model street canyon, neutrally buoyant particles made up of polyamide and oil paint are released in the canyon and traced using a digital camcorder (Sony DCR-TRV520). The horizontal and vertical flow velocities are obtained by measuring particle displacements for 0.5 s. Objective analysis is performed using the Barnes (1964) method to convert irregularly-distributed experimental data to evenly-spaced data.

Three experiments are carried out in this study. The first is a control experiment in which there is neither bottom heating nor a turbulence generator (Fig. 1b). In the second experiment (Fig. 1c), bottom heating is applied without a turbulence generator. For this, a thin copper plate (10 cm×10 cm) is placed on the model street bottom and electrically heated. Using digital thermocouples, water temperature is measured at five different levels (z/H = 0.05, 0.25, 0.5, 0.75, and 0.95, where H is the model building height) and ten horizontal locations (x/H = 0.05, 0.15, 0.25, 0.35, 0.45, 0.55, 0.65, 0.75, 0.85, and 0.95). The first and second experiments enable us to investigate the effects of street bottom heating on street canyon flow. In the third experiment (Fig. 1d), there is a turbulence generator but no bottom heating. For this, turbulence is generated by two rows of five long, rectangular acrylic rods attached to the top surface of the upstream model building. Each rectangular rod is placed at 45° to the

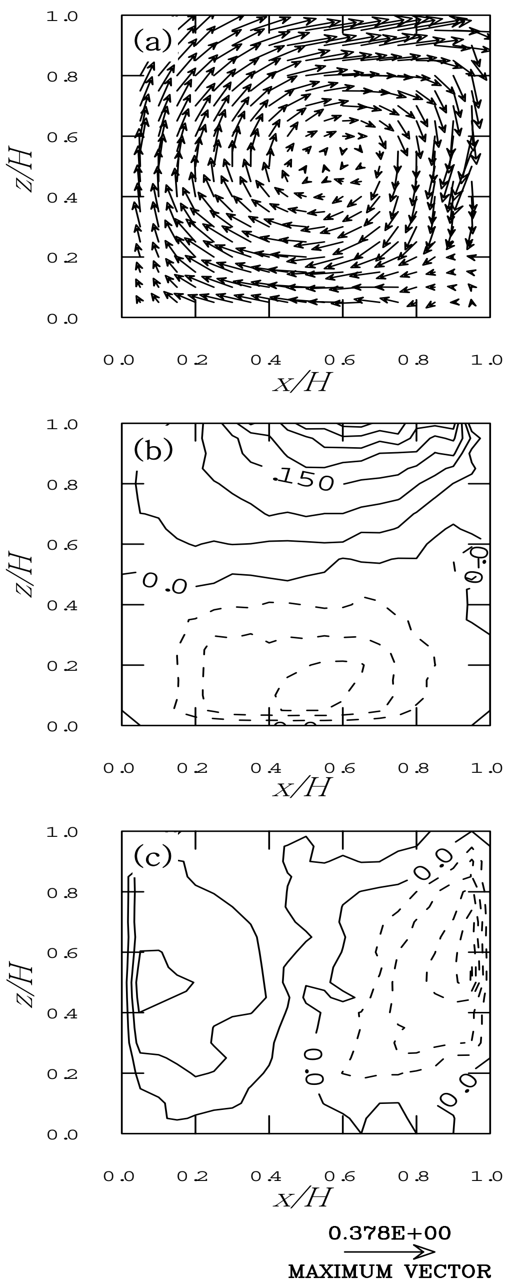

Fig. 2. The fields of normalized (a) velocity vector, (b) horizontal velocity, and (c) vertical velocity in the control experiment. The velocity components are normalized by the horizontal velocity at $z = 2H$, where H is the height of the model building. The contour interval in (b) and (c) is 0.05.

approach flow. The first and third experiments enable us to investigate the effects of inflow turbulence on street canyon flow. The approach flow speed is specified by the transformer which controls revolutions of the motor so that the computed Reynolds number exceeds a critical Reynolds number for turbulence generation.

3. Results and discussion

3.1 *Control experiment*

In the control experiment with no street bottom heating and no turbulence generator, the free stream velocity averaged from $x/H = 0$ (horizontal location of the upstream building edge) to x/H=1 (horizontal location of the downstream building edge) at z=20 cm (that is, z/H=2) is 12 cm s^{-1}. With this velocity scale and a depth scale of $2H$, the computed Reynolds number is 20870. This value exceeds a critical Reynolds number for turbulence generation in the water channel.

Figure 2 shows the fields of normalized velocity vector, horizontal velocity, and vertical velocity in the control experiment. The velocity components are normalized by the horizontal velocity at z/H=2. Note that the street aspect ratio is 1 and the ambient flow approaches from the left. As expected, a clockwise-rotating, stable vortex is formed in the canyon (Fig. 2a). This is consistent with many wind-tunnel (e.g., Brown et al., 2000) and numerical (e.g., Lee and Park, 1994) studies. This vortex is produced and maintained by the downward transfer of the ambient-flow momentum from the above-canyon region into the street canyon. The reversed horizontal flow is observed below $z/H \sim 0.5$ and its maximum is located close to the bottom (z/H=0.1) (Fig. 2b). The region with updraft in the canyon is wider than that with downdraft and the downdraft near the downstream building is stronger than the updraft near the upstream building (Fig. 2c). The magnitude of the maximum downdraft is 1.3 times larger than that of the maximum updraft.

3.2 *Experiment with street bottom heating*

Figure 3 shows the vertical profile of normalized average horizontal velocity above the canyon top in the experiment with street bottom heating (denoted as the EXH experiment hereafter). The horizontal velocity is horizontally averaged from $x/H = 0$ to 1 and then normalized by U_{2H}. The horizontal velocity increases with height up to $z/H \sim 1.8$ and is almost uniform above it. The horizontal velocity in the EXH experiment is slightly weaker than that in the control experiment in the region of $1.25 < z/H < 1.70$. However, the magnitude and vertical shape of the horizontal velocity in the two experiments are very similar to each other. This implies that the amount of the downward transfer of the ambient-flow momentum into the street canyon in the EXH experiment would be similar to that in the control experiment. Therefore, if some

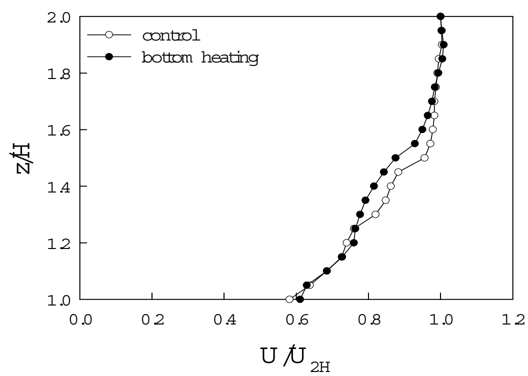

Fig. 3. The vertical profile of normalized average horizontal velocity above the canyon top in the experiment with street bottom heating. The horizontal velocity is horizontally averaged from $x/H = 0$ to 1 and then normalized by U_{2H}. For comparison, the vertical profile in the control experiment is also shown.

differences occur in the field of street canyon flow between the two experiments, it may be expected that these are due to the bottom heating.

When there is bottom heating, the flow pattern in the canyon is generally similar to that in the experiment without bottom heating (Fig. 4). However, some differences are observed in the flow field as well. The reversed flow is stronger with bottom heating and the maximum reversed flow is displaced slightly upstream from the center of the canyon (Figs. 2b and 4b). Near the upstream building, the strong updraft region becomes wider (Figs. 2c and 4c). The vertical profiles of the normalized velocity components at upstream, canyon center, and downstream locations are plotted in Fig. 5. The reversed flow at x/H=0.5 is stronger with bottom heating (Fig. 5a). At x/H=0.15, stronger updraft is observed everywhere except at the canyon top (Fig. 5b). At x/H=0.85, in most regions, the downdraft is stronger than that in the control experiment (Fig. 5c).

Figure 6 shows the normalized temperature field in the EXH experiment. The temperature T is normalized by $(T–T_{\min})/(T_{\max} - T_{\min})$, where $T_{\max}$ and $T_{\min}$ are the maximum and minimum temperatures, respectively. A region with relatively high temperature is observed near the upstream building in the lower region of the canyon. This is because the reversed horizontal flow advects heated water toward the upstream building. On the other hand, a region with relatively low temperature is observed near the downstream building in the middle and upper region of the canyon. This is due to the intrusion of relatively cold water into the canyon near the downstream building.

Based on the experimental results described above, we present how street bottom heating affects urban street-canyon flow as follows. When there is street

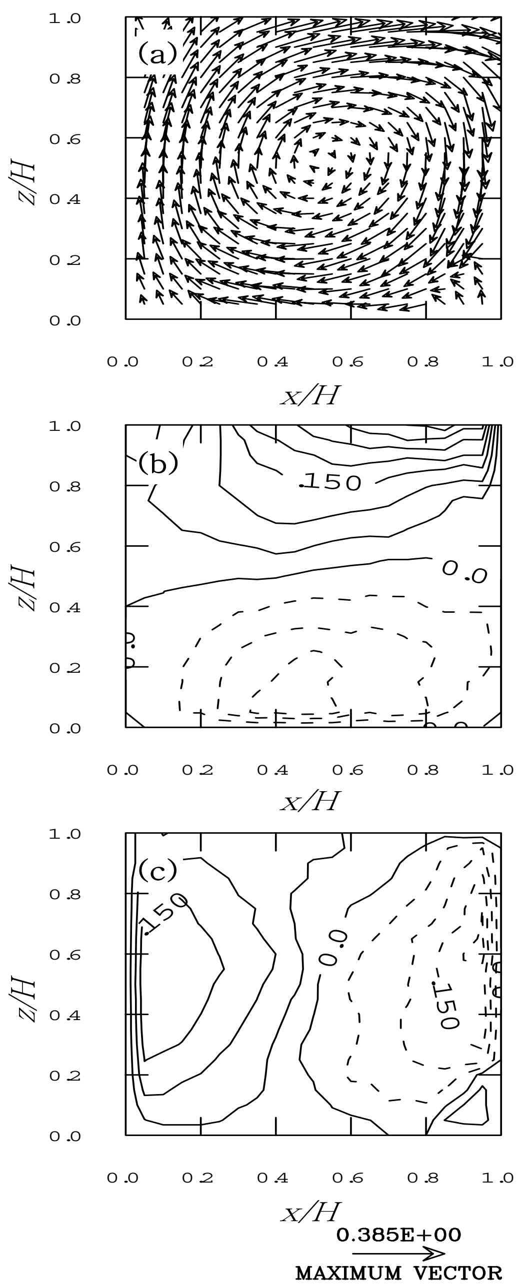

Fig. 4. The same as Fig. 2 except for the experiment with street bottom heating.

bottom heating, the reversed flow associated with the canyon vortex advects heated air toward the upstream building. Hence, at any height of the lower street canyon region, the air temperature is relatively high near the upstream building. Then, a thermal updraft is induced there due to the positive temperature excess (positive buoyancy force). This thermally induced updraft is constructively combined with the mechanically induced updraft that appears when there is no street

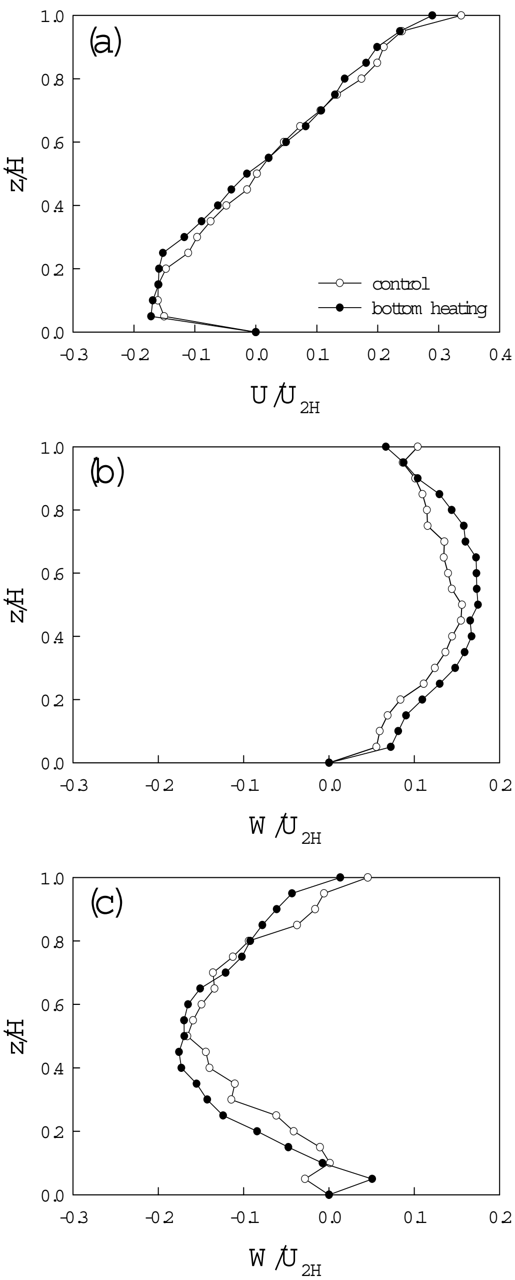

Fig. 5. The vertical profiles of normalized (a) horizontal velocity at the canyon center ($x/H = 0.5$), (b) vertical velocity at an upstream location ($x/H = 0.15$), and (c) vertical velocity at a downstream location ($x/H = 0.85$) in the experiment with street bottom heating. The velocity components are normalized by U_{2H}. For comparison, the vertical profiles in the control experiment are also shown.

bottom heating, thus producing a stronger updraft. This intensified updraft near the upstream building induces, by mass conservation, stronger reversed flow in the lower canyon and thereby stronger downdraft near the downstream building. By this process, the canyon vortex intensifies with street bottom heating.

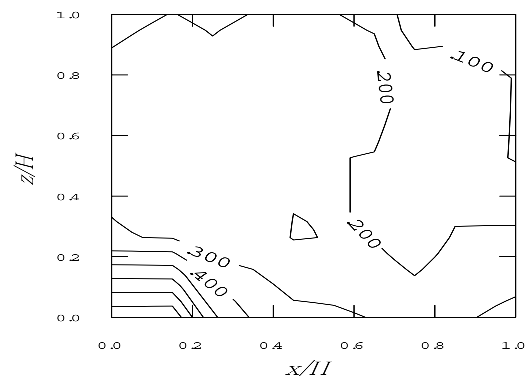

Fig. 6. The field of normalized temperature in the experiment with street bottom heating. The temperature T is normalized by $(T - T_{\min})/(T_{\max} - T_{\min})$, where $T_{\max}$ and $T_{\min}$ are the maximum and minimum temperatures, respectively. The contour interval is 0.1.

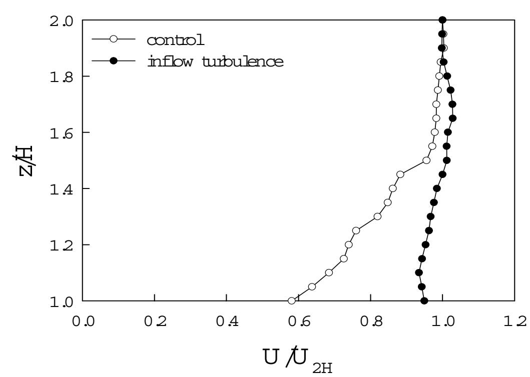

Fig. 7. The same as Fig. 3 except for the experiment with inflow turbulence.

When street bottom heating is present, thermally induced flow is combined with mechanically induced flow in a street canyon depending on the degree of bottom heating and the street aspect ratio. Through extensive two-dimensional numerical simulations, Kim and Baik (2001) identified five flow regimes according to the street aspect ratio and bottom heating. Following their study, the present experimental case can be categorized into regime II, which is mainly observed when the street aspect ratio is relatively small or the bottom heating is weak. In this flow regime, the vortex intensity increases with increasing heating intensity. The results from the present water-channel experiment with bottom heating and their interpretation support the physical realism of the numerical model results presented by Kim and Baik (2001). Further physical experiments with various street bottom heatings and aspect ratios, using a circulating water channel or

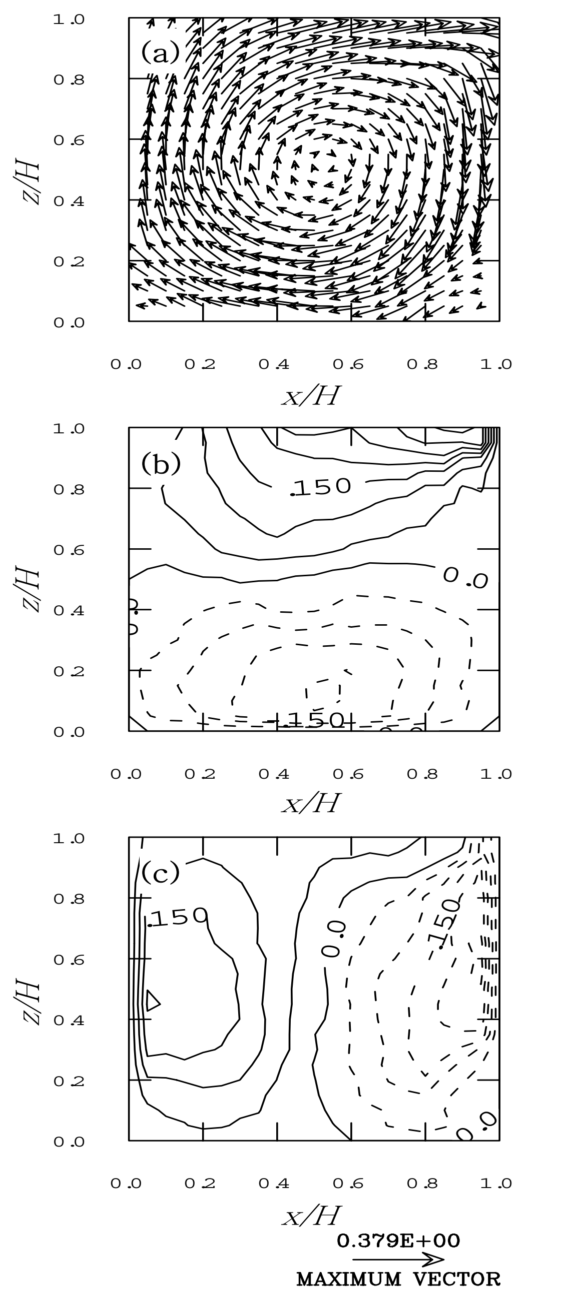

Fig. 8. The same as Fig. 2 except for the experiment with inflow turbulence.

a wind tunnel, are needed for a better understanding of street canyon flow.

3.3 *Experiment with inflow turbulence*

The vertical profile of normalized average horizontal velocity above the canyon top in the experiment with inflow turbulence (denoted as the EXT experiment hereafter) is shown in Fig. 7. In this experiment, the horizontal velocity changes very little with height above z/H=1. The horizontal velocity at any height is larger in the EXT experiment than in the control experiment with no appreciable inflow turbulence. The difference in the horizontal velocity between the two experiments becomes large when going downward from $z/H \sim 1.6$. The largest difference is observed at the canyon top (z/H=1), where the horizontal velocity in the EXT experiment is 1.6 times larger than that in the control experiment. This suggests that the amount of the downward momentum transfer of the ambient flow into the street canyon is larger in the EXT experiment than in the control experiment. This is expected to strengthen the canyon vortex.

The flow field in the canyon in the EXT experiment is generally similar to that in the control experiment (Fig. 8), mainly except for the intensity of the canyon vortex. The reversed flow below $z/H \sim 0.5$ intensifies when there is inflow turbulence (Figs. 2b and 8b). The strong updraft region near the upstream building widens in the EXT experiment (Figs. 2c and 8c) and so does the strong downdraft region near the downstream building (Figs. 2c and 8c). These features are well reflected in the vertical profiles of the normalized velocity components at upstream, canyon center, and downstream locations (Fig. 9). The reversed flow at $x/H = 0.5$ strengthens with inflow turbulence (Fig. 9a). At x/H=0.15, stronger updraft is observed everywhere except at the canyon top (Fig. 9b). At x/H=0.85, the downdraft in the EXT experiment is stronger than that in the control experiment (Fig. 9c).

Based on the above results (Figs. 7, 8, and 9), we speculate how inflow turbulence affects urban street-canyon flow as follows. Some portion of inflow turbulent eddies interact with horizontal flow near the canyon top as they cross along the canyon top. This interaction appears to result in intensified horizontal flow, which then strengthens downdraft near the downstream building by mass conservation. Some portion of inflow turbulent eddies intrude into the street canyon by downdraft on the downstream side of the canyon. This intrusion might act to enhance downdraft. Then, by mass conservation, the reversed flow in the lower canyon and updraft near the upstream building intensify. This further intensifies horizontal flow near the canyon top. Therefore, the horizontal velocity at the canyon top is larger in the EXT experiment than in the control experiment and the vertical shear of the horizontal velocity above the canyon top becomes very small (Fig. 7).

Despite some speculations, it is not very clear how inflow turbulence affects street canyon flow because of the velocity measurement limit. In this study, measured velocities, including turbulent parts and mean parts, are averaged temporally and spatially. A partition of measured velocities into mean and turbulent

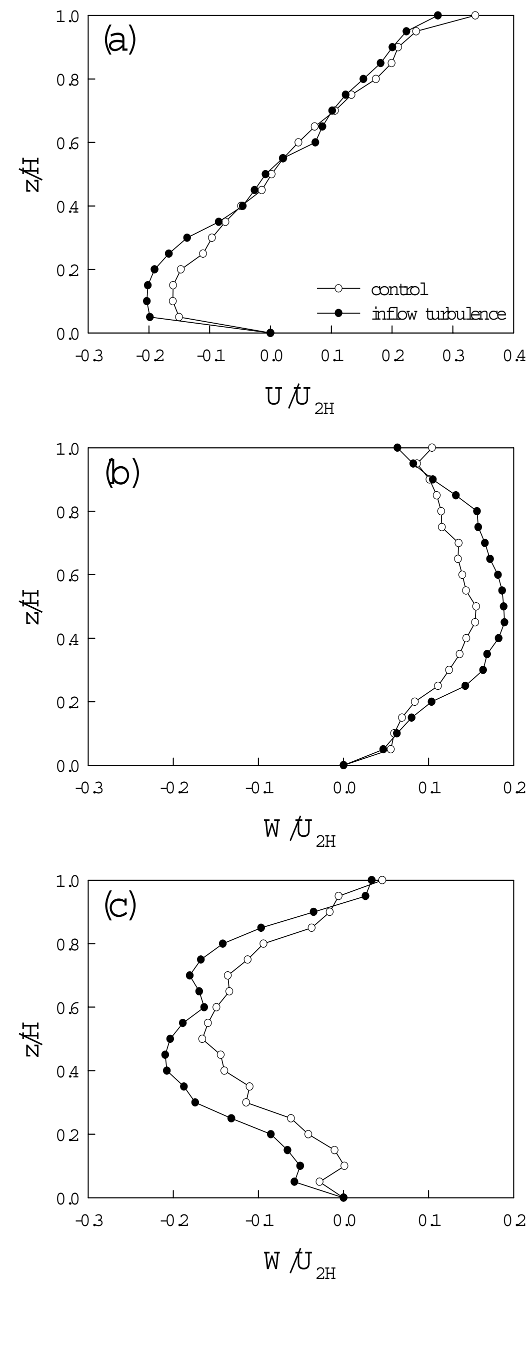

Fig. 9. The same as Fig. 5 except for the experiment with inflow turbulence.

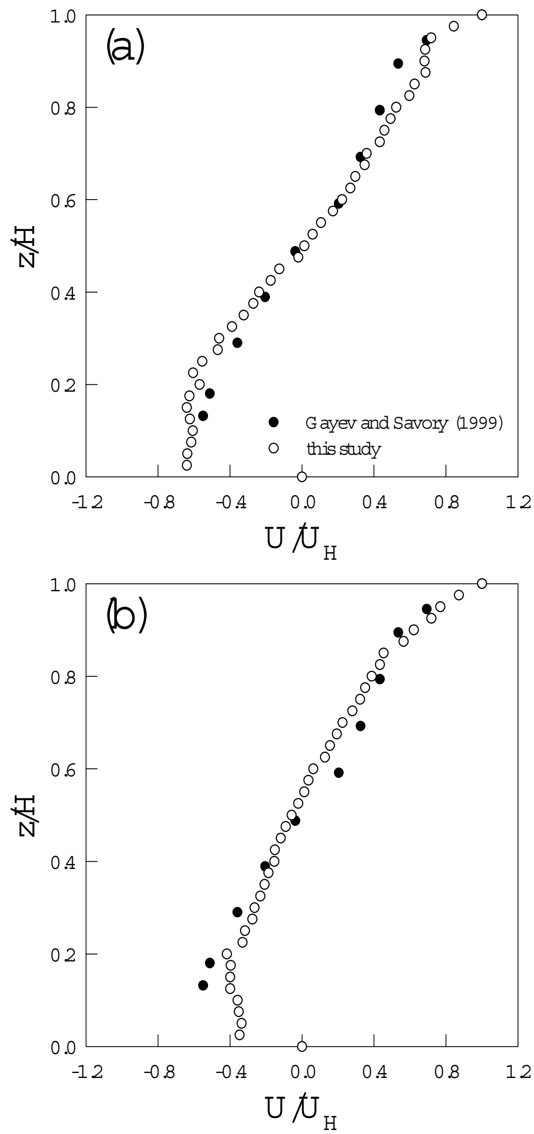

Fig. 10. The vertical profiles of the normalized horizontal velocity at (a) $x/H = 0.33$ and (b) $x/H = 0.67$ in the present water-channel experiment and the wind-tunnel experiment of Gayev and Savory (1999).

parts is not reasonably possible in this study. To overcome this, the circulating water channel needs to be equipped with an advanced velocity measurement facility. However, in spite of the measurement limit, our experimental results indicate that inflow turbulence increases the intensity of the canyon vortex.

4. Comparison with wind-tunnel data

The water-channel experimental result (control experiment) is compared with the wind-tunnel result of Gayev and Savory (1999), noting that their experimental setup is similar to the one in this study. Given sufficiently long model buildings, the flow in the street canyon can be characterized as the flow in the urban roughness (Gayev and Savory, 1999). Figure 10 shows the vertical profiles of the normalized horizontal velocity at x/H=0.33 and 0.67. In this figure, the horizontal velocity is normalized by the horizontal velocity at z/H=1 for comparison because the wind-tunnel result is expressed with U_H. At the upstream location (Fig. 10a), the horizontal velocity profile in the water-channel experiment is very similar to that in the wind-tunnel experiment. At the downstream location (Fig. 10b), the magnitude of the horizontal velocity near the street-canyon bottom seems to be slightly smaller in the water-channel experiment than in the wind-tunnel experiment, although there are not enough wind-tunnel data there. However, above z/H=0.2, the two velocity profiles are very similar. Overall, the velocity profiles in both the experiments closely resemble each other, implying that the circulating water channel can be a good experimental tool to investigate urban street-canyon flow because of its relatively low cost and easy tractability.

5. Conclusion

This study was undertaken to experimentally investigate the effects of street bottom heating and inflow turbulence on street canyon flow using a circulating water channel. It was shown that street bottom heating increases the intensity of the canyon vortex. The process involved was presented in terms of the combined effect of thermally induced flow and mechanically induced flow, and the mass conservation principle. It was shown that inflow turbulence also increases the intensity of the canyon vortex. However, no affirmative conclusion was reached to explain how inflow turbulence affects street canyon flow, requiring further investigation. This study demonstrates that the circulation water channel is very useful for investigating street canyon flow. The present apparatus will be more reliable for urban street-canyon flow and dispersion research if it is equipped with advanced velocity and concentration measurement facilities.

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