A Laboratory Model of Urban Street-Canyon Flows

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ABSTRACT

A circulating water channel is constructed to examine urban street-canyon flow. In the cases of an even-notch street canyon in which model buildings on both sides of the street have equal heights, one vortex is observed in model canyons with aspect ratios of 1 and 1.5, and two counterrotating vortices are observed in canyons with aspect ratios of 2, 2.4, and 3. In all of the even-notch cases, the center of the vortex (or the upper vortex) is located slightly downstream of the canyon center, and the downward motion downstream is stronger than the upward motion upstream. The magnitudes of the maximum updraft and downdraft are almost independent of the aspect ratio. In the case of a stepup notch, one vortex is observed in the canyon. In the case of a stepdown notch, two counterrotating vortices are observed. The upper vortex resembles to some extent an isolated roughness flow, and the lower vortex is characterized by a skimming flow. It is shown that the results of the water-channel experiments are generally in good agreement with those simulated using a numerical model with a turbulent kinetic energy–dissipation (k–ε) turbulence closure scheme, although there is a noticeable difference in the relative strengths of the upper and lower vortices in the two-vortex regime. This study demonstrates that the circulating water channel is useful for the study of street-canyon flow.

1. Introduction

An urban street canyon is the space surrounded by a city road and its flanking buildings. Because pollutants emitted into a street canyon tend to disperse less than those emitted in an open area, air quality becomes a serious problem in most large cities, especially because of the emissions from motor vehicles. To understand pollutant dispersion in urban street canyons, and to help urban planners to take further into account urban geometry with optimal dispersion, an essential first step is to investigate street-canyon flows.

There have been observational, numerical, and wind-tunnel studies to characterize flow and dispersion in urban canyons. DePaul and Sheih (1985, 1986) conducted a field experiment in an urban street canyon with an aspect ratio (ratio of the building height to the width between buildings) of about 1.4. They found that the pollutant retention time becomes shorter as the ambient wind speed increases and that a primary vortex cell in the canyon is present when the ambient wind speed exceeds 1.5–2.0 m s^{-1}. Observations in an urban canyon with an aspect ratio of about 1 by Nakamura and Oke (1988) showed an approximately linear relationship between wind speeds above the roof and above the center of the canyon floor, with a diminution factor of approximately two-thirds for wind speeds up to 5 m s^{-1}.

Many numerical modeling studies (e.g., Hunter et al. 1990/91, 1992; Sini et al. 1996; Baik and Kim 1999) have examined how street-canyon flows vary with aspect ratio. These studies indicated that a transition from the wake interference flow regime to the skimming flow regime occurs when the aspect ratio exceeds a threshold value [e.g., ~0.7 in Sini et al. (1996)] and that in the skimming flow regime the number of vortices in canyons increases with increasing aspect ratio. The pollutant dispersion in canyons was shown to be linked closely with the vortex circulation (e.g., Lee and Park 1994). Sini et al. (1996) and Kim and Baik (1999) pointed out the importance of thermal effects in determining the number and intensity of vortices and hence pollutant dispersion.

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Wedding et al. (1977) performed a wind-tunnel study of gaseous pollutants in urban street canyons and concluded that the mean flow rather than turbulent diffusion controls pollutant dilution. Flow visualization and tracer concentration measurements in a wind tunnel (Hoydysh and Dabberdt 1988) showed that dispersion patterns are strongly dependent upon the canyon asymmetry and less dependent upon the canyon orientation to the prevailing flow. A subsequent wind-tunnel study by Dabberdt and Hoydysh (1991) revealed significant sensitivities of street-canyon concentrations to the block shape and emissions from adjacent avenues. These studies and others suggest that favorable urban geometry and meteorological conditions can reduce pollutant concentration levels.

An alternative tool to a wind tunnel in a study of flow and dispersion in urban street canyons can be a water tank or water channel. Water tanks have been used extensively in a wide range of applications in geophysical fluid dynamics. The purpose of this paper is to examine street-canyon flow using a circulating water channel. Experimental data will be analyzed to characterize canyon flow in the water channel, and fluid-experiment results will be compared with numerical-model results.

2. Experimental apparatus and design

The apparatus constructed for this experimental study is a circulating water channel originally developed by Odell and Kovasznay (1971) to make density-stratified flows. Figure 1 depicts the top view and side view of the observation section of the water channel with a dimension of 180 cm × 100 cm × 50 cm. In this study, the working fluid is water, and the density stratification is not considered.

Two vertical shafts have a stack of alternating large and small disks. A large disk on one shaft is arranged to be opposite to a small disk on the other shaft. A motor drives the two counterrotating shafts. When the two shafts rotate in opposite directions, the viscous drag of large disks pulls water around the outside channels. As a result, water is ejected as horizontal jets emerging from the gaps formed between large disks (Odell and Kovasznay 1971). To relax abrupt changes in water flows in the circulating channel, diffusers are placed downstream and upstream of the pump, and a settling chamber is constructed upstream of the observation section. The water channel has turning vanes at three corners, and a vorticity generator is placed upstream of model buildings to produce shear. In the setting shown in Fig. 1, water flows counterclockwise.

Three configurations of two surface-mounted model buildings are considered to characterize canyon flow in the water channel (Fig. 2). For an even-notch configuration (heights of two model buildings are equal), five cases with different aspect ratios are examined in which the height of the model building is fixed at 24 cm, but the width between the two buildings varies. The widths considered here are 24, 16, 12, 10, and 8 cm, giving aspect ratios of 1, 1.5, 2, 2.4, and 3, respectively. In the case of a stepup notch, the height of the upstream (downstream) building is set to 16 cm (24 cm). In the case of a stepdown notch, the height of the upstream (downstream) building is set to 24 cm (16 cm). In both the stepup- and stepdown-notch cases, the width between the two buildings is fixed at 10 cm. In the direction perpendicular to the approach flow, the width of the observation section of the water channel is 10 cm (Fig. 1), and the model buildings are also 10-cm wide and hence entirely spanning the observation section. The water channel has a uniform depth of 34 cm. The flow speed just above the height of the model canyon top (24 cm) is controlled at 13 cm s^{-1}.

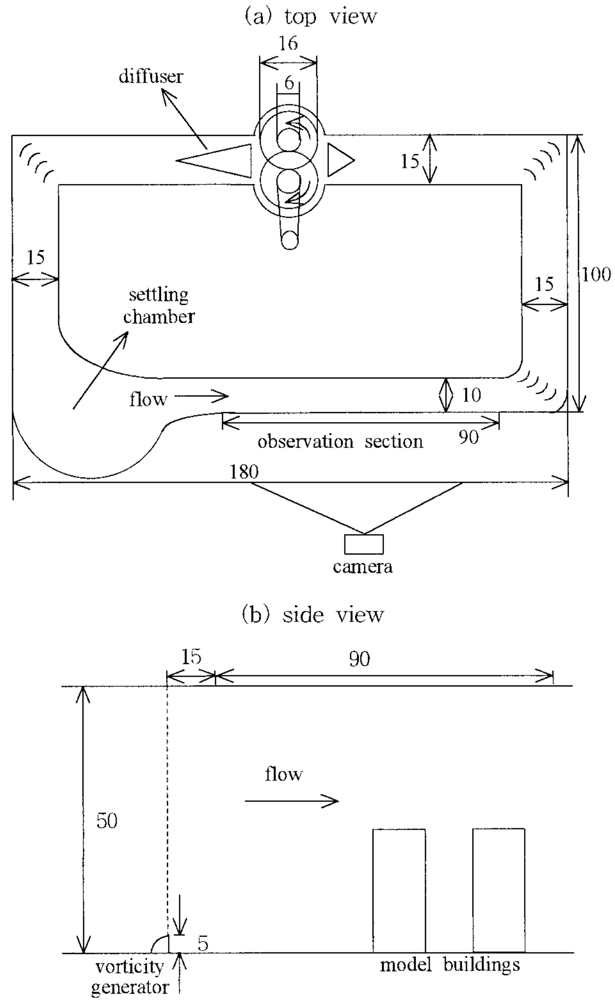

FIG. 1. The schematics of the circulating water channel constructed for this study: (a) top view and (b) side view of observation section. All dimensions are in centimeters.

To visualize water flows and to determine flow velocities in model canyons, neutrally buoyant particles consisting of oil and aluminum powder are released in canyons. Particles are traced using a camera (Nikon

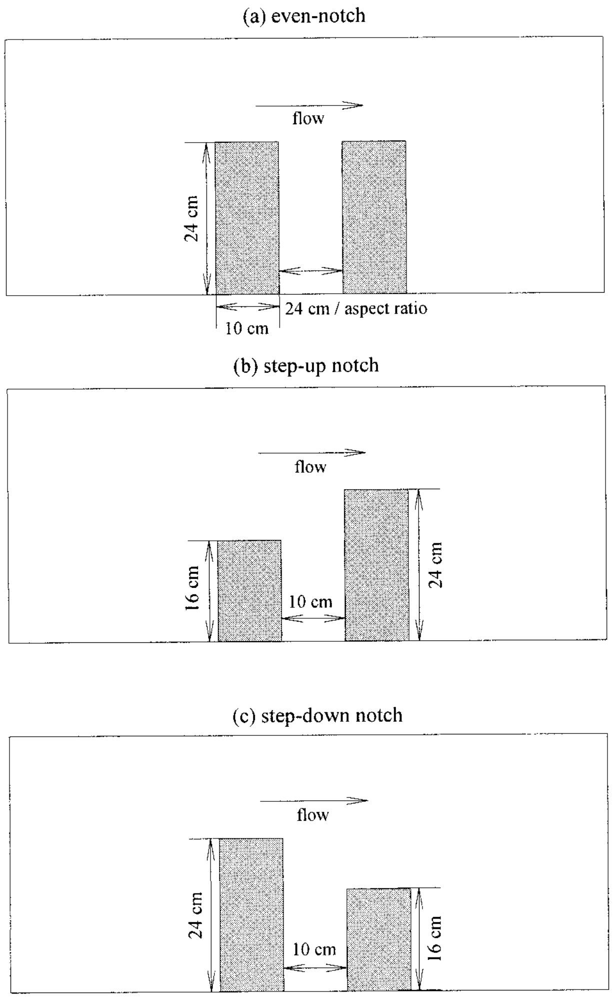

FIG. 2. Three configurations of two model buildings in the water channel experiments: (a) even-notch, (b) stepup-notch, and (c) stepdown-notch cases.

F-801s) with an exposure time of 0.5 s. The horizontal and vertical flow velocities are obtained by measuring particle displacements during the period of 0.5 s. Numerous particles are released into canyons, and numerous consecutive pictures are taken to represent better the canyon flow. We tried to minimize sidewall effect by releasing particles at the central transverse cross section of the canyon. Objective analysis for the irregularly distributed experimental data is performed using the Barnes (1964) method to facilitate comparisons between laboratory and numerical-model results.

An experiment in a situation without model buildings is performed to determine an undisturbed vertical profile of horizontal velocity. A regression analysis reveals a power-law profile of $U = U_r(z/z_r)^{0.224}$, where speed $U_r = 3.2$ cm s^{-1} and height $z_r = 20$ cm. The exponent value of 0.224 in the velocity profile is similar to that in the wind tunnel study by Castro (1979). The computed Reynolds number for the undisturbed flow is ~10 000, which exceeds a critical Reynolds number for turbulence generation.

3. Numerical model

The numerical model used in this study is the same as that described by Baik and Kim (1999). The model solves two momentum equations, a mass continuity equation, and turbulent kinetic energy and dissipation equations (k–ε turbulence closure scheme) on a staggered grid system using the finite volume method. For details of the numerical model, see Baik and Kim (1999). Two isolated buildings are placed in the model. In the even-notch cases, the building height is fixed at 96 m and the width between the two buildings varies to give aspect ratios of 1, 1.5, 2, 2.4, and 3. In the stepup- and stepdown-notch cases, the height of the taller (shorter) building is 96 m (64 m), and the width between the two buildings is 40 m. In terms of geometrical scaling, these settings in the numerical experiments are in accordance with those in the fluid experiments. The horizontal and vertical domain sizes are 400 and 240 m, respectively. The grid size is 2 m in both the x (horizontal) and z (vertical) directions, and the time step is 0.2 s. The model is integrated up to time $t = 4800$ s. The inflow horizontal velocity profile is specified as $U_i = U_r(z/z_r)^{0.224}$, where $U_r = 4$ m s^{-1} and $z_r = 96$ m. The same exponent value determined from the fluid experiment is used in the inflow velocity profile.

4. Results and discussion

Figure 3 shows the velocity vector field in the water-channel experiment and the streamline field at $t = 4800$ s in the numerical-model experiment in a model urban street canyon with an aspect ratio of 1. Because this aspect ratio and the four other aspect ratios examined in this study (1.5, 2, 2.4, and 3) exceed a threshold value for a transition from the wake interference flow regime to the skimming flow regime [e.g., ~0.7 in Sini et al. (1996)], the street-canyon flow is expected to be characterized by a skimming flow. In both the experiments, one vortex is generated in the canyon, and the vortex center is located slightly downstream of the canyon center.

Figure 4 shows the vertical profile of the normalized vertical velocity at upstream, center, and downstream locations of a street canyon with an aspect ratio of 1. To compare fluid and numerical experiment results, the vertical velocity is normalized by the horizontal velocity just above the top of the model canyon, and the height is normalized by the model building height with an aspect ratio of 1. Both the experiments exhibit downward motion downstream of the canyon and upward motion upstream, which are connected with the one-vortex circulation (Fig. 3). At the canyon center, weak upward motion is observed because of a slight downstream shift of the vortex center. The magnitude of the downward

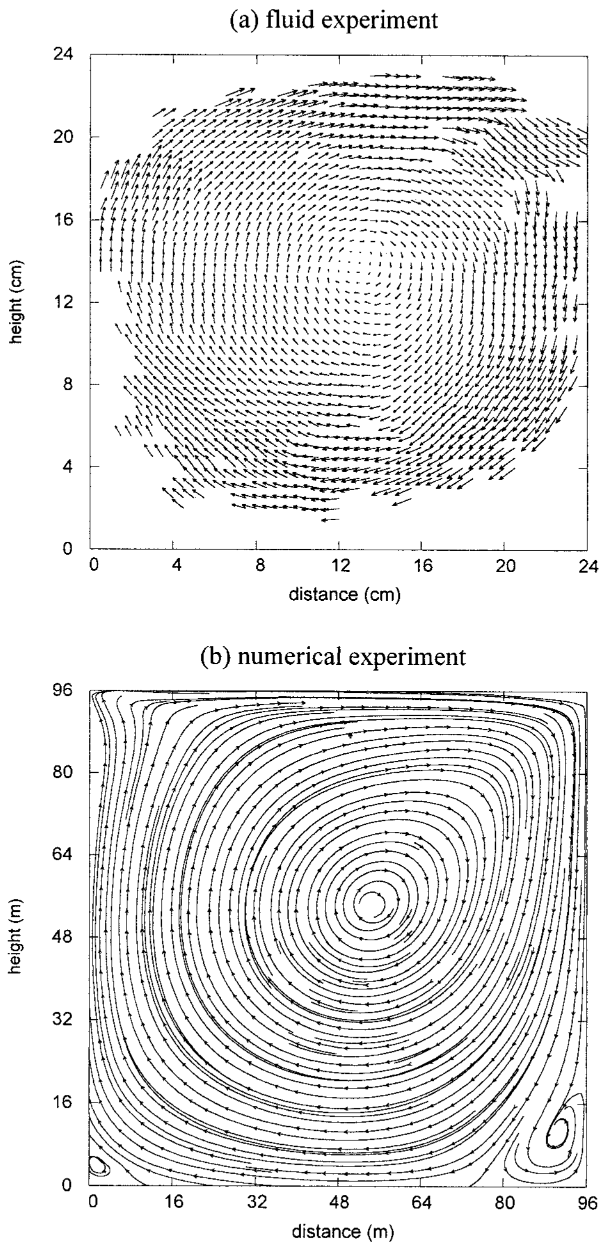

FIG. 3. (a) Velocity vector field in the water-channel experiment and (b) streamline field at t = 4800 s in the numerical-model experiment in a model urban street canyon with an aspect ratio of 1. The maximum velocity vector length in the water-channel experiment corresponds to 4.04 cm s^{-1}.

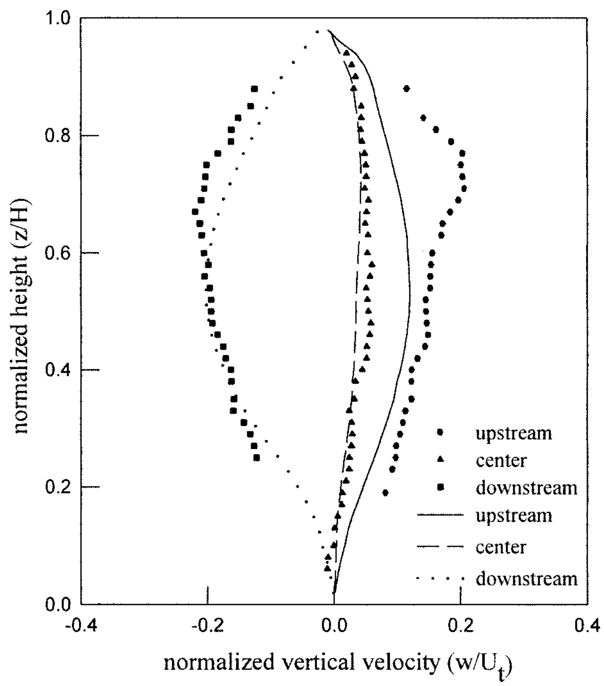

FIG. 4. The vertical profile of the normalized vertical velocity at an upstream position (x/W = 0.125, where x is the horizontal distance from the upstream building, and W is the width between two buildings), a center position (x/W = 0.5), and a downstream position (x/W = 0.875) in a model urban street canyon with an aspect ratio of 1. The vertical velocity is normalized by the horizontal velocity just above the top of the model canyon (U_t), and the height is normalized by the model building height with an aspect ratio of 1 (H). The dots represent water-channel results, and the lines represent numerical-model results.

motion downstream is larger than that of the upward motion upstream. At the upstream location, the normalized vertical velocity in the fluid experiment is stronger than that in the numerical experiment. At the center and downstream locations, however, the vertical profile of the normalized vertical velocity in the fluid experiment closely resembles that in the numerical experiment.

In the numerical experiment with an aspect ratio of 1.5 (Fig. 5b), two counterrotating vortices are generated in the canyon. The vertical size of the upper vortex is larger than that of the lower vortex, and the center of the lower vortex is shifted farther downstream than that of the upper vortex. In the fluid experiment with an aspect ratio of 1.5 (Fig. 5a), only one vortex is observed in the canyon, with a slight downstream shift of its center. The observed flow velocities near the corner of the downstream model building and near the bottom around the canyon center have comparable velocity components in both downward and upstream directions, however. This result is somewhat indicative of a possibility of the presence of another vortex, with its center close to the corner of the downstream building. If a vortex does exist there, its size will be much smaller than the main vortex size. With the method of measuring flow velocity described in section 2, however, it was difficult to obtain velocity data in regions close to the model building corners.

When the aspect ratio is 2 (Fig. 6), both the experiments show that two counterrotating vortices are generated in the canyon, and that the vertical size of the upper vortex is larger than that of the lower vortex. Also, the center of the upper vortex is shifted downstream.

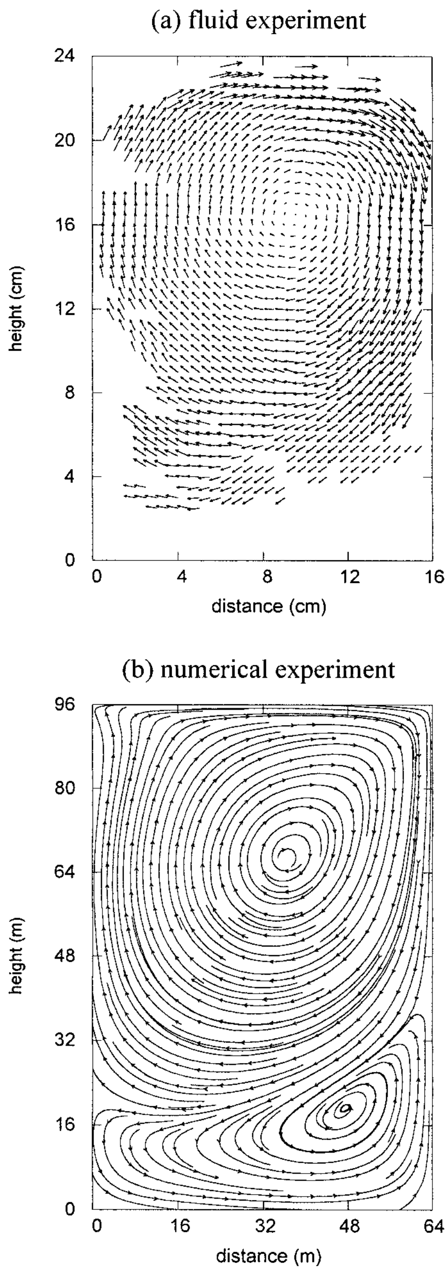

FIG. 5. The same as Fig. 3 but for an aspect ratio of 1.5. The maximum velocity vector length in the water-channel experiment corresponds to 4.73 cm s^{-1}.

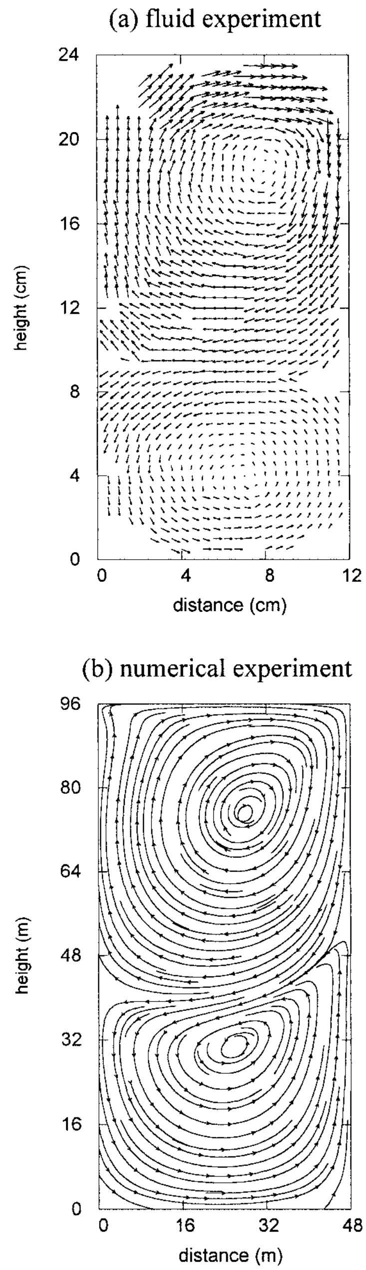

FIG. 6. The same as Fig. 3 but for an aspect ratio of 2. The maximum velocity vector length in the water-channel experiment corresponds to 4.30 cm s^{-1}.

Note that the center of the lower vortex in the numerical experiment is closer to the upper vortex. This feature also is observed in the cases with aspect ratios of 2.4 and 3 (see Figs. 8b and 9b below).

Figure 7 shows the vertical profile of the normalized vertical velocity at upstream, center, and downstream locations of the canyon with an aspect ratio of 2. Observed upward and downward motions are connected with the two-vortex circulation shown in Fig. 6. That is, downward (upward) motion exists downstream (upstream) of the upper canyon, and upward (downward) motion exists downstream (upstream) of the lower canyon. As in the one-vortex circulation (Fig. 4), the magnitude of the downward motion downstream of the upper canyon is larger than that of the upward motion upstream of the upper canyon in both the experiments. The normalized vertical velocity profile for the upper vortex in the fluid experiment is somewhat similar to that in the numerical experiment. For the lower vortex, however, there is a distinctive difference between the fluid

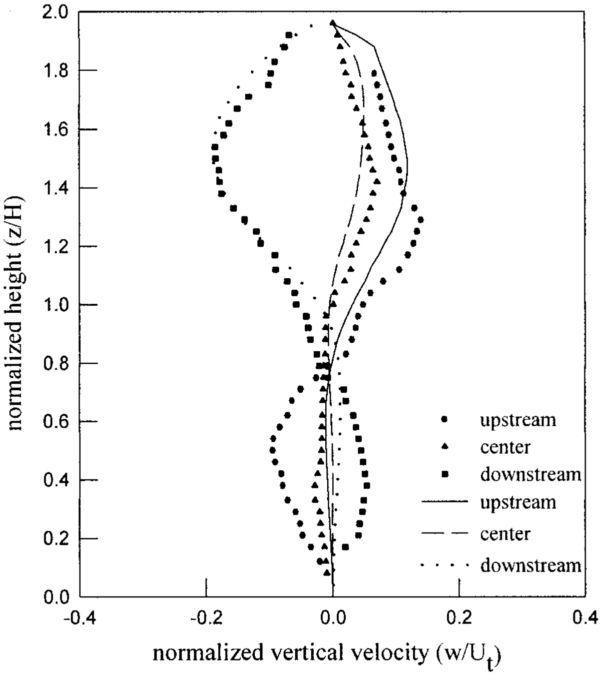

FIG. 7. The same as Fig. 4 but for an aspect ratio of 2.

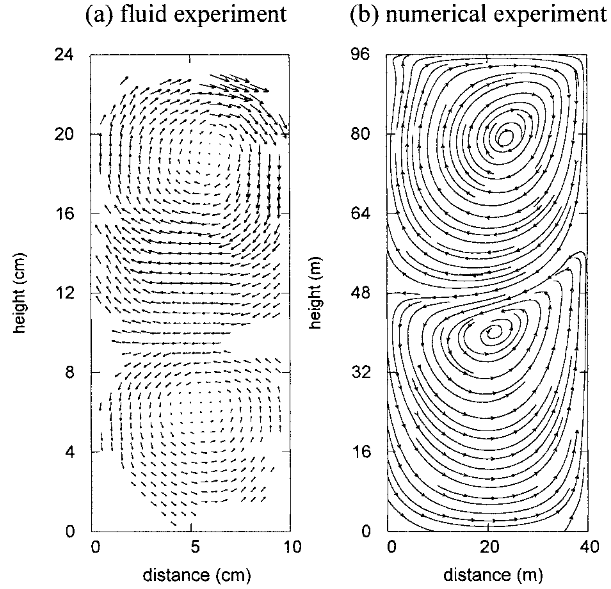

FIG. 8. The same as Fig. 3 but for an aspect ratio of 2.4. The maximum velocity vector length in the water-channel experiment corresponds to 4.37 cm s^{-1}.

and numerical experiments in that the normalized vertical velocities at the upstream and downstream locations in the fluid experiment are much stronger than those in the numerical experiment.

Figure 7 indicates that in the numerical experiment the upper vortex is much stronger than the lower vortex in comparison with the fluid experiment. Baik and Kim (1999) suggested that the upper vortex is maintained by momentum transfer from the ambient flow into the street canyon and the lower vortex is maintained by momentum transfer from the upper vortex into the lower vortex. Therefore, it is thought from Fig. 7 that the ratio of the amount of the momentum transfer from the upper vortex into the lower vortex to that from the ambient flow into the street canyon is much larger in the fluid experiment than in the numerical experiment.

Because the turbulent diffusion process plays an important role in the momentum transfer, the turbulence closure method employed in a numerical model can influence the result (strength of the lower vortex in Fig. 7). To examine this aspect, a numerical experiment was performed in which a first-order closure scheme (Deardorff 1973; Sommeria 1976) was used to parameterize the turbulent process. Results indicated that the lower vortex in the model with the first-order closure scheme is stronger than that in the model with the k–ε closure (1.5 order) scheme used in this study. The upper vortex in the fluid experiment more closely resembled the upper vortex in the model with the k–ε closure scheme than that in the model with the first-order scheme, however. Thus, the result may be somewhat sensitive to the turbulence closure scheme. In the k–ε turbulence closure scheme used in this study, five empirical constants must be specified. Although this study uses constant values typically employed in numerical models for simulating canyon flow or flow around obstacles (e.g., Zhang et al. 1996; Sini et al. 1996), it is not clear whether these values are universal for this kind of flow system. There might be some sensitivity of the result to the empirical constants. Therefore, a systematic study of the sensitivity of street-canyon flow to turbulence closure schemes (also free parameters in a given scheme) is needed. In addition to the turbulence closure scheme and free parameters in it, it is believed that the bottom boundary condition (exactly no-slip condition in the numerical experiment but not exactly no-slip condition in the fluid experiment) made a minor contribution to the strength difference of the lower vortex in Fig. 7.

In both the fluid and numerical experiments with an aspect ratio of 2.4 (Fig. 8), two counterrotating vortices are generated in the canyon, and the center of the upper vortex is located slightly downstream of the canyon center. In the fluid experiment, the vertical size of the upper vortex is larger than that of the lower vortex. In contrast, in the numerical experiment, the vertical sizes of the vortices are similar.

When the aspect ratio is 3 (Fig. 9), both the experiments show that two counterrotating vortices are generated in the canyon and that the center of the upper vortex is shifted slightly downstream.

Figure 10 shows the normalized maximum updraft upstream of the canyon and maximum downdraft downstream of the canyon, as a function of the aspect ratio. In both the fluid and numerical experiments, the maximum downdraft downstream of the canyon is stronger

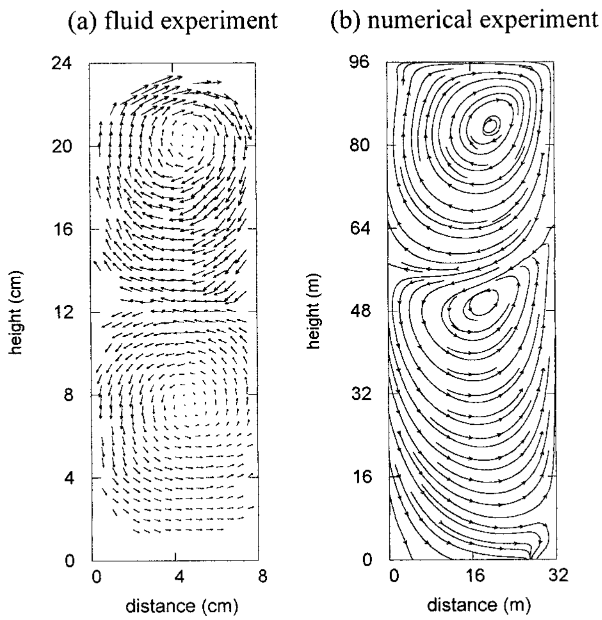

FIG. 9. The same as Fig. 3 but for an aspect ratio of 3. The maximum velocity vector length in the water-channel experiment corresponds to 4.06 cm s^{-1}.

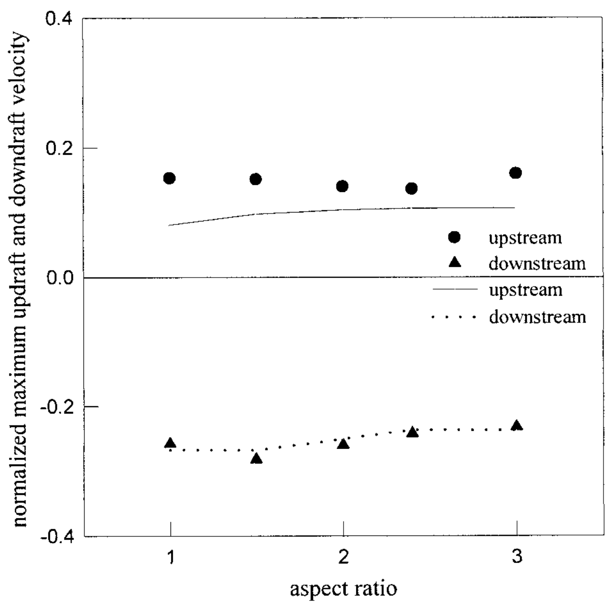

FIG. 10. The normalized maximum updraft and downdraft upstream and downstream of the canyon, respectively, as a function of the aspect ratio. The dots represent water-channel results and the lines represent numerical-model results.

than the maximum updraft upstream of the canyon for all aspect ratios. Also, both the experiments show that the magnitudes of the maximum updraft and downdraft are almost uniform over the range of aspect ratios, that is, almost independent of the aspect ratio. This finding is related to the fact that the velocity profile above the canyon is almost the same in each of the fluid or numerical experiments. Note that, in this study, the model building height is fixed in all the cases with different aspect ratios. Figure 10 indicates that the normalized maximum downdraft downstream of the canyon in the fluid experiment is almost the same as that in the corresponding numerical experiment. In contrast, the normalized maximum updraft upstream of the canyon in the fluid experiment is stronger than that in the corresponding numerical experiment. In the fluid experiment with an aspect ratio of 1.5, the ratio of the maximum downdraft to the maximum updraft is 1.87. This value is close to the value ($\sim$1.7) calculated from the field observations in a street canyon with an aspect ratio of about 1.4 by DePaul and Sheih (1986).

Thus far, we investigated flow fields in street canyons with different aspect ratios in even-notch configurations. Most numerical or wind-tunnel studies conducted so far have focused on even-notch configurations. Next, we will examine street-canyon flows when the building heights are unequal by using both fluid and numerical experiments. Figure 11 shows the velocity vector field in the water-channel experiment and the streamline field at t = 4800 s in the numerical-model experiment in a canyon with a stepup-notch configuration. In this case, the downstream building is higher than the upstream building. In the current setting (stepup or stepdown notch), the height of the taller building is 1.5 times that of the shorter building. In both the experiments, one vortex is generated in the canyon. The vortex center in the numerical experiment is closer to the height of the upstream building top than is that in the fluid experiment. In the numerical experiment, two small vortices are observed near the corners of the upstream and downstream buildings. If the two buildings become higher and higher, the two small vortices eventually would combine to produce a vortex in the lower canyon with its horizontal size equal to the width of the street canyon.

Figure 12 shows the velocity vector field in the water-channel experiment and the streamline field in the numerical-model experiment in a canyon with a stepdown-notch configuration. In this case, the upstream building is higher than the downstream building. Both the experiments exhibit two counterrotating vortices in the canyon. In the upper canyon, the upstream building can be considered to act as an isolated obstacle with an effective height equivalent to the height difference between the two buildings, thus producing a vortex circulation behind the obstacle that resembles an isolated roughness flow. The lower vortex is characterized as a skimming flow. If the inflow direction is opposite to that of Fig. 12, the situation becomes a stepup-notch case, and only one vortex is generated in the canyon as shown in Fig. 11.

The pathway and travel time of pollutants released near the street level depend on the number and intensity of vortices generated in the street canyon (Kim and Baik 1999; Baik and Kim 1999). The results from Figs. 11

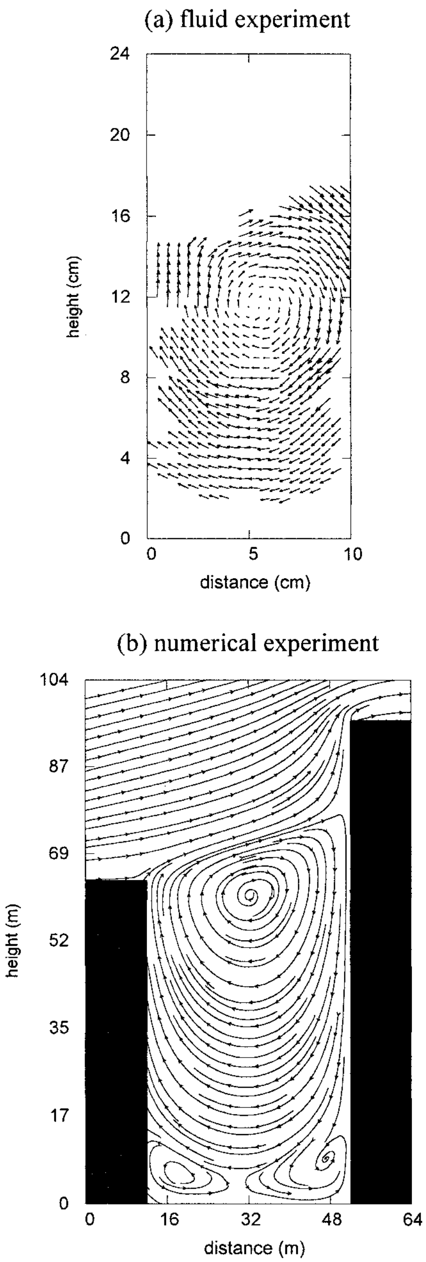

FIG. 11. (a) Velocity vector field in the water-channel experiment and (b) streamline field at $t = 4800$ s in the numerical-model experiment in the case of stepup notch. Note that the height of the upstream building in the water-channel (numerical model) experiment is 16 cm (64 m), the height of the downstream building is 24 cm (96 m), and the width between the two buildings is 10 cm (40 m). The maximum velocity vector length in the water-channel experiment corresponds to 3.89 cm s^{-1}.

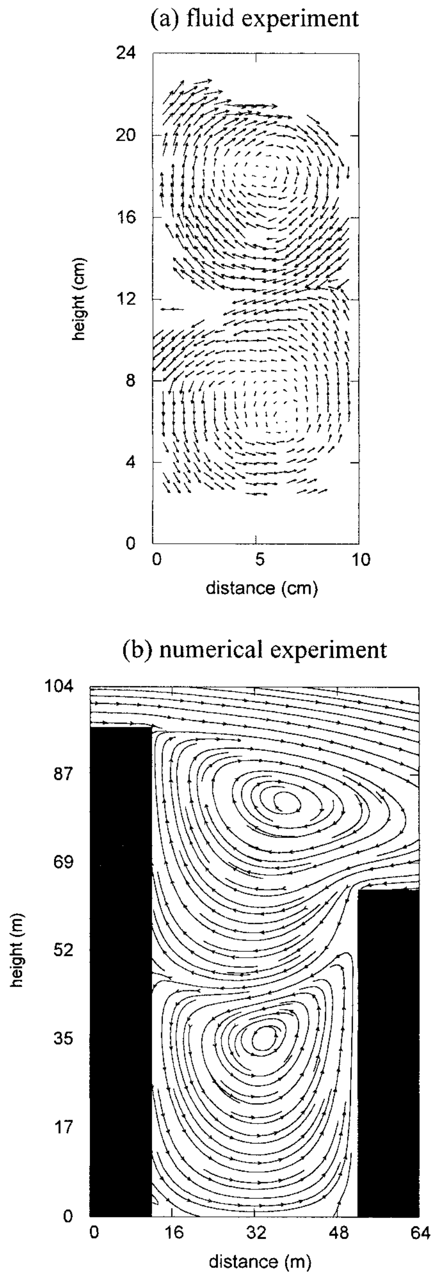

FIG. 12. (a) Velocity vector field in the water-channel experiment and (b) streamline field at $t = 4800$ s in the numerical-model experiment in the case of stepdown notch. Note that the height of the upstream building in the water-channel (numerical model) experiment is 24 cm (96 m), the height of the downstream building is 16 cm (64 m), and the width between the two buildings is 10 cm (40 m). The maximum velocity vector length in the water-channel experiment corresponds to 3.37 cm s^{-1}.

and 12 suggest that wind direction plays a crucial role in the determination of the pollutant pathway and travel time in stepup- and stepdown-notch situations.

5. Conclusions

A circulating water channel was constructed to investigate urban street-canyon flows in even-notch, stepup-notch, and stepdown-notch configurations. Results of fluid experiments were compared with those simulated using a two-dimensional numerical model with a k–ε turbulence closure scheme. It was shown that fluid-experiment results are generally in good agreement with numerical-model results, thus demonstrating that the circulating water channel is a useful tool for the study of street-canyon flow. In addition to the street-canyon flow study, this water channel can be used effectively to study flow past an obstacle. This work is under way to characterize the recirculation region behind an obstacle as a function of the flow speed and obstacle slope. Also, the water channel can be used effectively to study topographic effects in stratified flows (Tampieri and Hunt 1985).

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