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Thermal Effect on Pollutant Dispersion in an Urban Street Canyon

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ABSTRACT: This investigation was carried out to reveal the impact of solar radiation on wind flow structure and pollutant dispersion in an urban street canyon of aspect ratio of one using the computational fluid dynamic (CFD) technique. The simulation results (velocity and concentration data) show that heating from building wall surfaces and ground lead to strong buoyancy forces as the air is heated by the wall surface when receiving direct solar radiation. This thermally induced buoyancy plays a significant role in determining flow fields within street canyon. When the sun shines on the leeward side of the building and the ground, the airflow structure and pollutant dispersion patterns are similar to that without solar radiation, the buoyancy flux adds to the upward advection flux along the wall strengthening the original vortex. When the windward wall is warmer than the air, an upward buoyancy flux opposes the downward advection flux along the wall, and divides the flow structure into two counter-rotating vortices indicating a clockwise top vortex and a reverse lower vortex within the canyon. Further, the impact of various temperature differences on the windward heating and different velocities for inlet velocity has been examined. The relative influence of the thermal effect can be estimated by bulk Richardson number (R_b).

Key words: Urban Street Canyon, CFD, Buoyancy Flux, Thermal Effect, Pollutant Dispersion

INTRODUCTION

Urban street canyon has been an active area of study in air quality modeling for many years, both in terms of predicting actual roadside exposure to pollution and as a more theoretical test-case for using different numerical models (Garmory, 2009). Several important parameters that influence the pollutant dispersion process in street canyons have been the subject of these investigations. These parameters are ambient conditions (wind speed and direction), building geometry (height, width and roof shape), street dimensions (breadth and width), thermal stratification (solar insulation and orientation, building and street thermal capacitance), vehicular movement (size, number, and frequency), plume buoyancy, etc (Xie, 2005a).

In the past two decades, numerous investigations have been devoted to elucidate wind flow and pollutant transport in urban street canyons using wind tunnel experiments (Meroney and Pavageau,1996; Ohya,1996; Kastner-Klein and Plate, 1999; Halek,2010), numerical models (Huang *et al.,* 2000;Chan and Dong,2002; Li,2006; Cheng,2009), and occasionally deploying full-scale experiments (Rotach 1995;Johnson and Hunter,1999; Pourahmad,2007). Oke(1988) ,Sini (1996) and Xie (2006a) have studied the flows and the pollutant dispersion within a street, and summarized the flow regimes according to the ratio of the building height and the street width. Ahmadi (2002) have simulated the flow and particulate pollutant transport near an isolated building using a Lagrangian particle tracking method. Chan et al.(2003) studied the flow field and pollutant dispersion characteristics in a three-dimensional urban street canyon formed by a multi canopy building using computational fluid dynamics (CFD) in conjunction with k-e turbulence model. Baker et al.(2004) introduced the simple photochemistry of NO-O_3-NO_2 into a large-eddy simulation model and examined reactive pollutant dispersion in a street canyon with a street aspect ratio of one. Baik et al.(2007) examined reactive pollutant dispersion in an urban street with a street aspect ratio of one using a CFD model incorporating simple NO-NO_2-O_3 photochemistry.

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Thermal effect, which is often neglected in the studies of urban-scale environmental fluid mechanics, is another important factor affecting street canyon wind flow and pollutant transport. A temperature measurement in a street canyon with an aspect ratio of 1.06 and a sky view factor of 0.43 by Nakamura and Oke (1988) Showed that the maximum temperature difference between the building surface and the air temperature is as large as 12-14 ! . Thermal forcing such as building surface or street canyon bottom heating is mainly induced by direct daytime solar radiation on building facades and ground surface that in turn heats up the air in the vicinity, which causes strong upward motion of the air.

Numerical studies of buoyant flow in urban street canyon are few in literatures compared with those under isothermal conditions. Sini et al.(1996) have studied the mechanical-buoyant induced flow in a street canyon with a aspect ratio of w/h=0.89 and demonstrated that wall temperature can largely influence the flow structure and vertical transport distribution. Kim and Baik (2001, 2003) investigated the impact of street bottom heating on the flow regimes with different aspect ratios and various temperature differences using a two dimensional numerical k-ε turbulence model. Uehara (2000) used wind tunnel experiment investigating the thermal stratification effects with different Rb numbers on the wind flow using a stratified wind tunnel with various temperature gradients. Xie (2005a,b;2006a;2007) examined the mechanical-buoyant induced wind flow in an street canyon considering different aspect ratios, temperature difference, wind velocity and symmetrical and asymmetrical canyons on vortex structure and pollutant dispersion. These studies concerned about the thermal effect on flow structure and the impact of different bulk Richardson numbers were not comprehensive enough to demonstrate the effects of solar radiation of different building facades (due to different zenith angles) on the wind flow and pollutant dispersion within the street canyon (Ahmad,2009).

This object of this paper is developing a RNG turbulent model to investigate the impact of heating building facades and ground surfaces on the flow structure and pollutant distribution with different wind velocities, different temperature difference in different time of the day. To examine the effects of the thermal effect on the flow field and pollutant dispersion in urban street canyons, eleven numerical experiments are performed with the different building façade heating and different wind speeds.

MATERIALS & METHODS

The wind direction is perpendicular to street canyon that the geometry is unchanged along the direction of the canyon, a 2D computational domain included three street canyons is considered, simulating a built-up urban environment. The schematic diagram of the computational domain and boundary conditions is shown in Fig. 1. The mathematical model was based on the numerical solution to the governing fluid flow and transport equations, which were derived from the basic conservation and transport principles in incompressible flows. Buoyancy forces are added in momentum conservation adopting the Boussinesq approximation. It is assumed that the density and the other physical parameters do not change except for the density in the buoyancy forces term. The turbulence production due to the buoyancy effect is included when the thermal effect in the street canyon is taken into consideration (Xie,2005a).

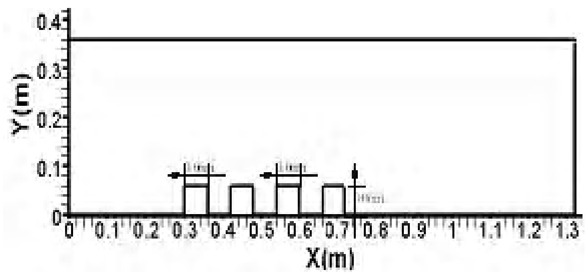

Fig. 1. Sketch of the street canyon model domain (H/W=1)

The Fluent CFD package was used to solve the Navier-Stokes equations for the mean flow in street canyons with the RNG turbulent model. The constants for the studied RNG k-ε turbulence model are summarized in Table1.The spatial domain was divided into 65,908 structured rectangular cells, 132,873 faces and 66,966 nodes.

Table 1. Coefficient of k-ε model equation

K-ε	C_μ	$C_{\varepsilon 1}$	$C_{\varepsilon 2}$	$\sigma_k, \sigma_\varepsilon$
RNG	0.0845	1.42	1.68	Analytical formula

Velocity inlet boundary profiles were used in the main inlet wind flow and the vehicle exhaust. A user-defined subroutine for including the power exponent 0.28 the power law inlet velocity profile into FLUENT code was developed and used in the present model. At the outlet boundary, outflow conditions were applied and zero gradient boundary conditions are prescribed. At the upper boundary, symmetry boundary conditions were applied and zero vertical velocity conditions were applied as well as zero normal derivatives for all the other variables. The ground and building surfaces were defined as walls with no slip boundary conditions. The governing equations were discretized using the finite volume method and the SIMPLE algorithm was used to solve the equations.

The accuracy of the CFD model was validated using the extensive experimental database collected from the atmospheric diffusion wind tunnel at the Japanese National Institute for Environmental Studies (Uehara *et al.*, 2000). The bulk Richardson number is defined by $R_b = \dfrac{gL(\theta_n - \theta)}{\theta_n u_0^2}$. The simulated results with h/w=1, U_h=0.14m/s, $\Delta\theta = 2°C$ and R_b=-0.21 are compared with the wind tunnel results with a bulk Richardson number R_b=-0.21. Figure 2 and 3 compares the experimental and calculated temperature and horizontal velocity along the vertical centerline of the street canyon. Above the roof level, the temperature in the numerical simulation is larger than in the experiment (Fig. 2). In the core of the street canyon, the numerical temperature is slightly lower than the experimental values measured by Uehara et al. (2000). Fig. 3 compares the normalized horizontal velocity along the vertical centerline of the street canyon with the experimental results. The current CFD results agreed well with the wind tunnel measurements inside the street canyon, but lower than the experimental results above the street canyon. This difference was attributed mainly to the different inflow boundary velocity and turbulent intensities adopted. Besides, the surface roughness of the solid boundaries in the wind tunnel experiment was unknown that imposed additional uncertainty in present CFD model. (Xie , 2006b). In spite of these differences, both profiles of temperature and horizontal velocity are similar to the experimental results. The validation suggested that the present CFD model may be used for simulating airflow and pollutant dispersion in an urban street canyon with the solar heating.

RESULTS & DISCUSSION

In this simulation, the temperature of the ground, the leeward wall or the windward wall is set to 37 °C, while the ambient air temperature in the domain is 27 °C. For the three sunlit wall configurations as Sini (1996) and Xie (2005a,b), including the isothermal reference case, the wind flow streamlines are shown in Fig.3. Fig.3 displays the airflows profiles when the wind speed of the top height is 0.065 m/s and the temperature difference is 10 °C.

In the reference case of no heating, one primary vortex is formed and there are two vortices in the corner

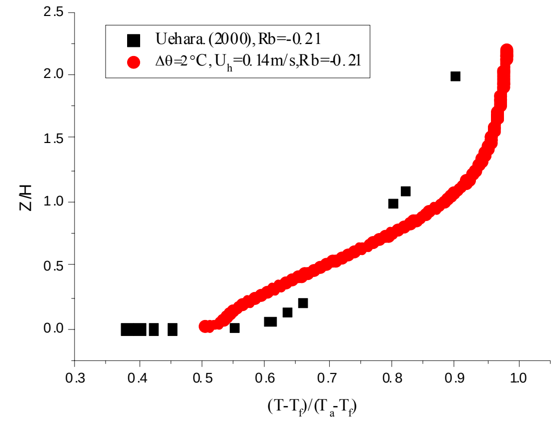

Fig. 2. Vertical profiles of temperature $(T-T_f)/(T_a-T_f)$

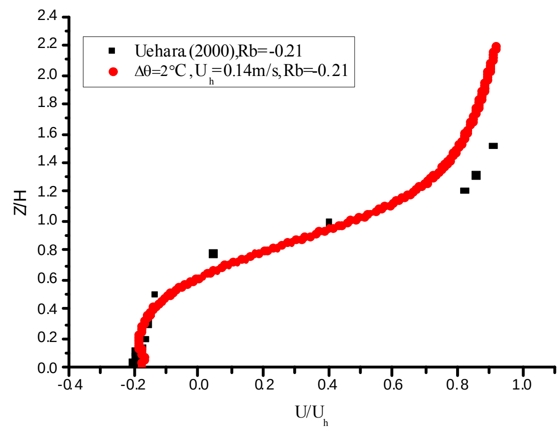

Fig. 3. horizontal velocity U/U_h along the center line

of leeward and windward separately and the primary vortex center is located above the street canyon (Fig. 4). In the case of leeward heating, the primal vortex moves slightly toward the leeward side and the left small vortex disappears and right vortex shrinks as the interaction of buoyancy force (Fig. 5). In the case of floor heating, the primary vortex is well centred within the street canyon and bottom part is largely influenced by the upward velocity induced by buoyancy force (Fig. 6). In the case of windward side of building heating, two counter-rotating vortices are developed that different from the above three cases in the same aspect ratio of h/w=1 (Fig. 7). Since the windward wall is warmer than the air, an upward buoyancy flux opposes the downward advection flux along the wall, and divides the flow structure into two counter-rotating vortices forming a clockwise top vortex and a reverse lower vortex in the street canyon.

Figs 8 & 11displays the pollutant concentration profiles when the wind speed of the top height is 0.065 m/s and the temperature difference is 10°C. A clockwise vortex within the street canyon and higher

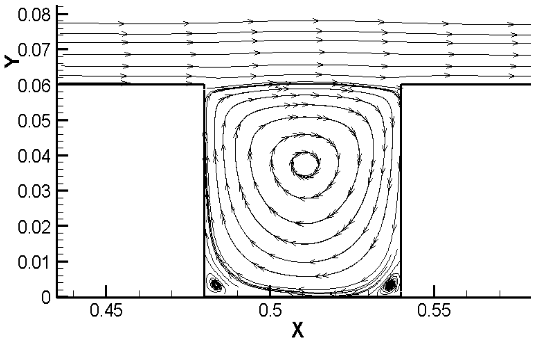

Fig. 4. Air flow with no heating

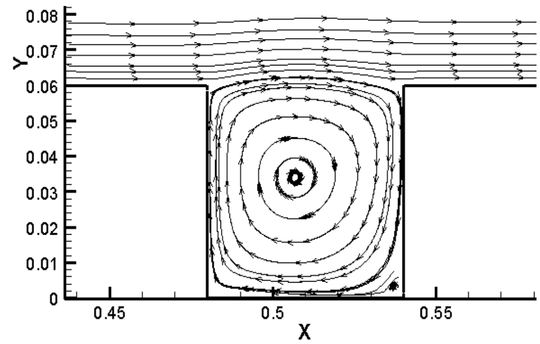

Fig. 5. Air flow with leeward heating

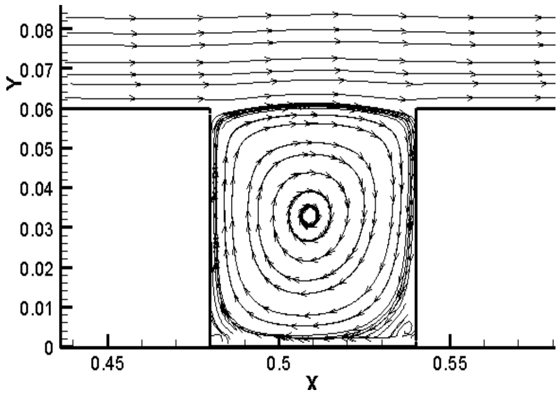

Fig. 6. Air flow with floor heating

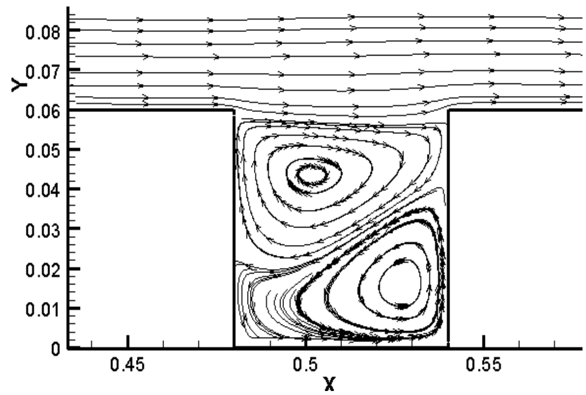

Fig. 7. Air flow with windward heating

concentration at leeward side of building has been found in previous studies when there is no sunlight heating on any solid surface (Fig. 8). As the air close to the leeward side of the building is heated when the sun shines directly on this side of the building, the buoyancy flux adds to the upward advection flux along this wall, and the air will rise vertically and strengthen the original vortex and pollutant transport compared to the isothermal case (Xie,2005a). When the windward wall is heated, an upward buoyancy flux opposes the downward advection flux along this wall, and divides the flow structure into two counter-rotating cells: a clockwise top vortex and a reverse lower vortex within the canyon. As a result, pollutants are accumulated at the windward side of the building, and the pollutant concentrations in the street canyon increase. The maximum pollutant concentration are 0.0625 kmol/m^3 in isothermal case (Fig. 8) and 0.0261 kmol/m^3 in leeward side heating (Fig. 9) and 0.0215 kmol/m^3 in floor side heating (Fig. 10) and 0.0588 kmol/m^3 in windward side heating (Fig. 11).

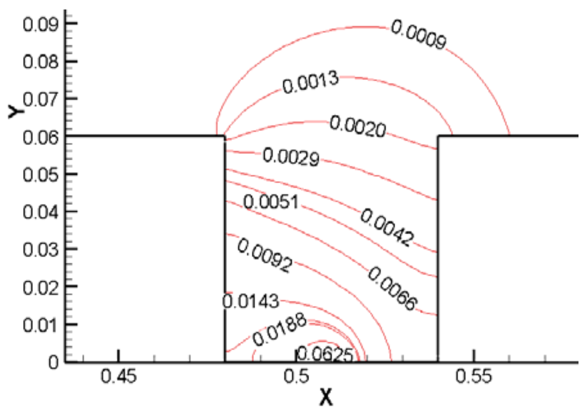

Fig. 8. Pollutant concentration with no heating

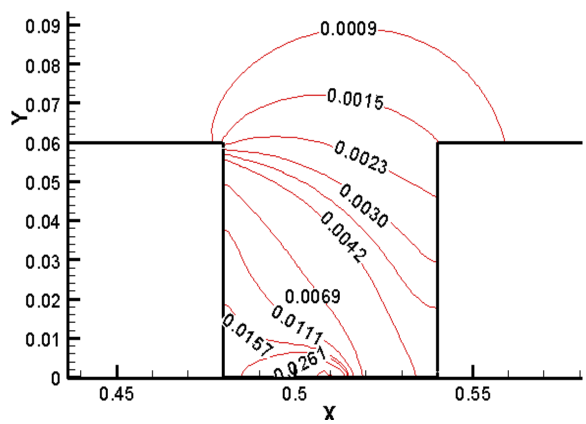

Fig. 9. Pollutant concentrations with leeward heating

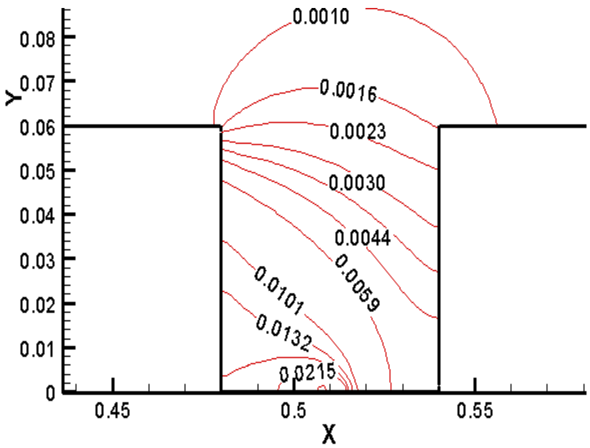

Fig. 10. Pollutant concentrations with floor heating

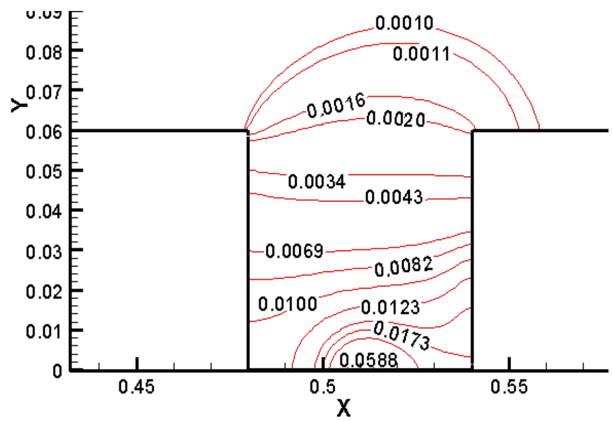

Fig. 11. Pollutant concentrations with windward heating

When the windward wall is warmer than the air, the buoyancy induced by the heated windward wall tends to oppose the downward flow and form an upward buoyancy flux to oppose the downward advection flux along the windward wall.

Fig. 12-15 shows the flows streamlines in the street canyon with windward heating and different temperature range in the same free-stream flow (U_h=0.065m/s). For a temperature range of $\Delta\theta = 2°C$, there are two small vortices at the corner of the street canyon, and the vortex at the windward side is slightly larger than those on the leeward compared with isothermal case (Fig. 12). When the temperature difference increases the flow structure changes and there are two vortices with a clockwise top vortex and a reverse ground vortex in the street canyon. The upward buoyancy flux creates a distinctive effect on the downward flow along the windward side, thereby dividing the flow structure into two counter-rotating cells, with one vortex center near the leeward wall side and the other near the windward side (Fig. 13-15). When the temperature range increases from 2 °C to 20°C, the vortex near the windward side expands and the clockwise vortex close to the leeward side shrinks duo to the increase in buoyancy force. As a result, the pollutant accumulates at the windward side but the concentration in the street canyon decreases with increasing temperature difference.

Pollutant accumulations appear on both sides of the street and the pollutant diffusion is influenced by the small vortex at the corner of the canyon, and the pollutant concentration in the street canyon increases (Figs 16-19). From the maximum concentration in the floor of street canyon, the concentration of the temperature difference of 10°C is the highest (0.0588 kmol/m^3), the temperature difference of 5°C is 0.0357 kmol/m^3 (Fig. 17), the temperature difference of 15 ! is 0.0385 kmol/m^3 (Fig.19) and the temperature difference of 2 ! is 0.0625 kmol/m^3 (Fig. 16). When the temperature difference of $\Delta\theta = 10°C$, the lower counter-clockwise vortex circulation carries the pollutant to the windward side from the line source and leads to more pollutants on the windward side than on the leeward side at the lower region of street canyon (Fig. 18). Because the lower vortex is weak, thus some of the emission pollutants may move to the leeward and some move to the windward side in two directions and it is difficult for the pollutant to disperse and the pollutant concentration is high.

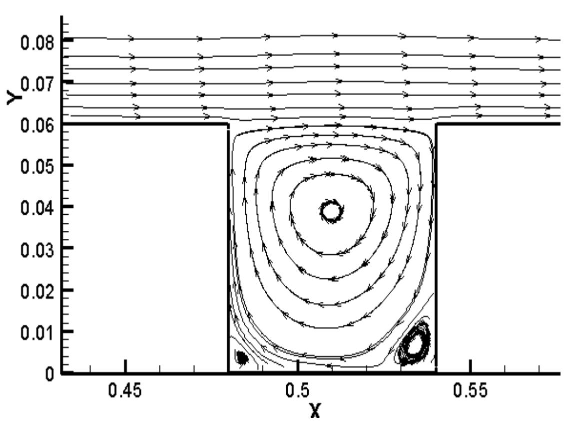

Fig.12. Streamlines with windward heating in different temperature ($\Delta\theta = 2°C$, R_b=-0.91)

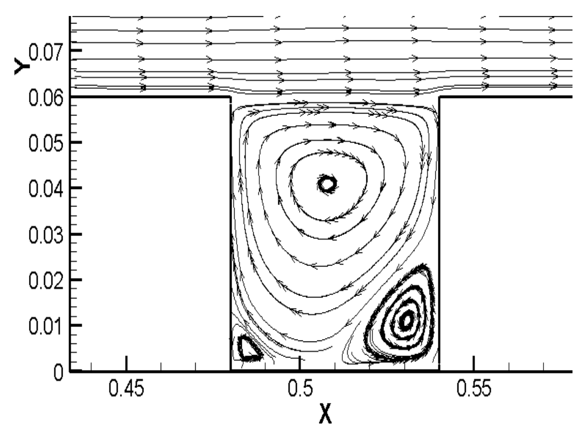

Fig.13. Streamlines with windward heating in different temperature ($\Delta\theta = 5°C$, R_b=-2.29)

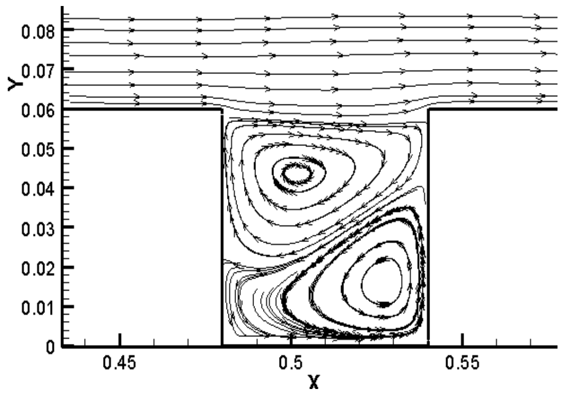

Fig.14. Streamlines with windward heating in different temperature ($\Delta\theta = 10°C$,Rb= -4.57)

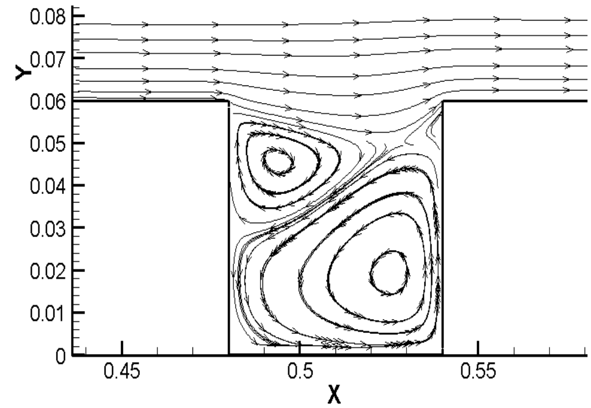

Fig.15. Streamlines with windward heating in different temperature ($\Delta\theta = 15°C$, Rb= -6.86)

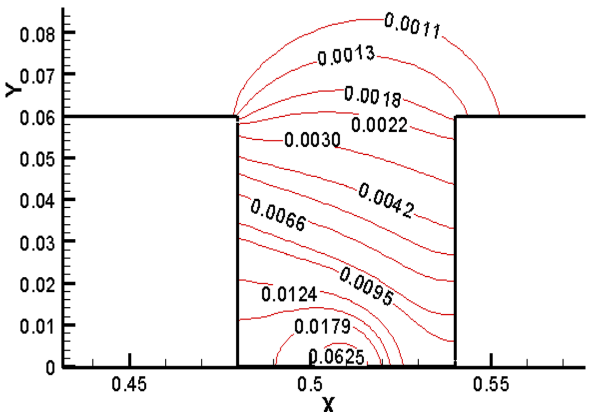

Fig. 16. Pollutant concentration with windward heating in different temperature ($\Delta\theta = 2°C$, Rb=-0.91)

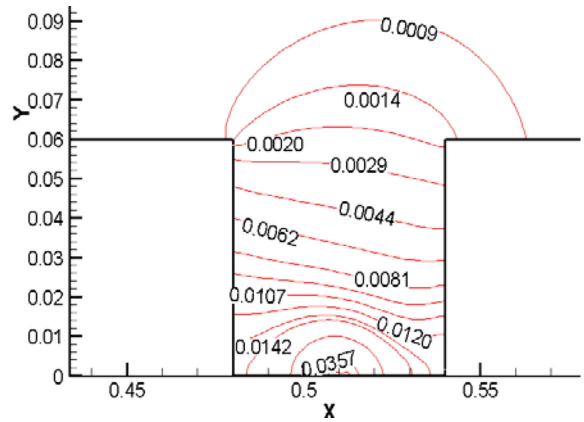

Fig. 17. Pollutant concentration with windward heating in different temperature ($\Delta\theta = 5°C$, Rb=-2.29)

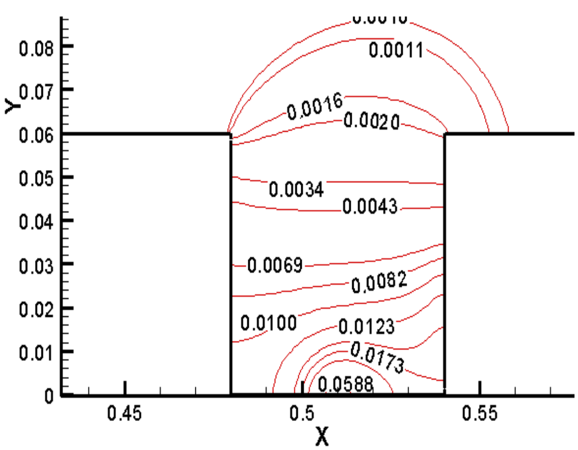

Fig. 18. Pollutant concentration with windward heating in different temperature ($\Delta\theta = 10°C$,Rb= -4.57)

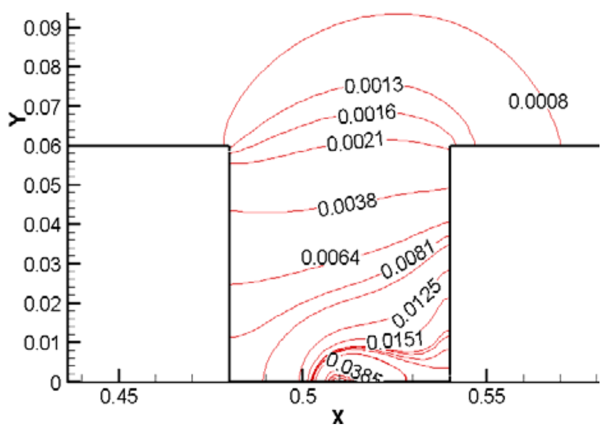

Fig. 19. Pollutant concentration with windward heating in different temperature ($\Delta\theta = 15°C$, Rb= -6.86)

CONCLUSION

A CFD model based on the RANS equations coupled with RNG turbulence model was used to study the impact of solar radiation on the airflow structure and pollutant concentration distribution when the different building surfaces and ground were heated. This numerical model was evaluated by an experimental database obtained from the Japanese National Institute for Environmental Studies using an atmospheric diffusion wind tunnel experiment (Uehara *et al.*, 2000). The normalized temperature and horizontal velocity calculated by the CFD model and wind tunnel measurements agreed reasonably well with each other. It was found that this model validation exercise demonstrated the reliability of the current CFD model in handling stratified street canyon flow and pollutant transport.

In the present model of street aspect ratio of h/w=1 configuration, solar heating has an important effect on the air flow structure when the windward side is heated. An upward buoyancy flux opposes the downward advection flux along the wall, and divides the flow structure into two counter-rotating cells with a clockwise top vortex and a reverse lower vortex within the canyon. As a result, the pollutants are accumulated at the windward side of the building, and the pollutant concentrations in the canyon increase. When the sun shines on the leeward side of the building and ground level, the airflow structure and pollutant dispersion pattern are similar to the case of that without solar radiation. Because the air close to the leeward side and the ground level is heated when the sun shines on these sides, the buoyancy flux adds to the upward advection flux along the leeward wall, and the air goes up vertically and strengthens the vertical movement and the intensity of the vortex is increased. This effect intensifies the pollutant transport and causes the pollutant concentration in the street canyon to decrease.

The results reported in this paper would be interesting to urban planners and engineers working on urban vehicle emission control and city air quality improvement as well as city street planning. Further research on the air quality of the urban street canyon is expected to focus on the different street configurations which are warmed on different façade, the impact of moving vehicles and the chemical reaction of the pollutant in urban canyons.

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