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The improvement of outdoor thermal-wind environment and indoor energy consumption by the harmony of the shape and the material of building for designing the block scale of the city

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1. Introduction

On the countermeasures of urban heat island, improvement of the material covering urban surface and improvement of these physical shapes are studied independently. The application as an appropriate combination of these two in consideration to location (climate) and weather condition (season and time) etc. is one of key issue. About the radiation and the energy balance on the urban surface, no similarity theories like the one for the flow field exist and its control is also difficult. Therefore, there are few experimental cases using a scale model like Spronken-Smith and Oke (1999) (on urban green park) etc. Solar radiation heats the surface of the urban canopy and it is resulted that characteristic air flow pattern is formed by the strong buoyancy inside the street canyon. In a general wind tunnel experiment, scale model surface is heated by electric wires and this approach doesn't express the radiation balance on the scale model surface explicitly. In this study, the authors tried to minimize the influence of roughness to flow field and to settle halogen lamps in close position. This is a challenging approach to reproduce the similar condition of radiation balance to the summer sunny day's in the wind tunnel. When the wind velocity is small, the effect of the surface material is obviously shown in the thermal-wind environment at the vicinity of the roof top part (increase of the wind velocity and decrease of the turbulent energy).

2. Review on the effect of aspect ratio and different approaching wind on wind flow

Air exchange between outside and inside of the canopy relies on the momentum of the air flow. Therefore, understanding of the complexity of flow field taking street configuration, UHI effects, solar radiation, et al. into consideration could effectively assist to guide urban design (Oke, 1988). The meteorological conditions are mainly controlled by canopy geometry and climatic characteristics. However, when wind velocity in the street canyon is very low, the impacts of buoyancy and vehicle-induced turbulence are also crucial (Ahmad et al., 2005).

The uniform canyon was used to represent the urban structure in most of the experimental and simulation researches. But non-uniform canyon is believed to have better ventilation and could enhance pollutant dispersion (Chan et al., 2001). A simulation showed that non-uniform urban structure with the separation of step-up and step-down notch along the street canyon increased the wind velocities in the vicinity of high buildings (Gu et al., 2011). The roof shape and building height has strong influence on the vortex dynamics inside of the canyon (Xie et al., 2005). Another simulation results showed that the wind velocity increased in the conditions of flat, slanted and trapezoid-shaped roof, while decreases in the conditions of downwind and upwind wedge-shaped roofs. On the contrary, the pollutant concentration increases in the conditions of flat-shaped roof, while decreases in the conditions of slanted and trapezoid-shaped roofs, due to the change of turbulent kinetic energy (Yassin, 2011).

2.1 Aspect ratio

Aspect ratio is a widely used parameter in simplifying geometrical features of street canyon. 0.67 is considered to be the optimized aspect ratio for energy consumption considering the shading effect from nearby buildings (Lei et al., 2011). Due to the different aspect ratio, when approaching wind direction is perpendicular to the street canyon, the flow pattern can be described by three regimes, isolated roughness flow, wake interference flow, and skimming flow (Oke, 1988). Chan et al. (2001) concluded that in order to achieve better air quality in street canyon, the aspect ratio should be restricted to the threshold value of skimming flow. Yassin compared the velocity of different aspect ratio conditions and found that the lowest velocity appeared near the ground surface (Yassin and Ohba, 2012; Yassin, 2013). In deep canyon, thermal conductance has been decreased significantly, and it is easy to maintain heat inside (Oliveira Panão et al., 2009). Many researches have been conducted to clarify the flow field inside of canopy with different aspect ratio. Baik et al. (1999) conducted water channel experiments. Stepped canopy was also studied and one vortex in step-up case and two vortices in step-down case were observed. They pointed that the aspect ratio has no impact on the maximum updraft and downdraft.

Many researches combined the effect of heating wall and canopy structure. The heat transfer mainly depends on the flow pattern inside of the canyon (Sugawara and Kawahara, 2011). Li et al. (2011) used a validated large-eddy simulation model to investigate the ground heating effect in canyon. Some researches indicated that only in the deep street canyon with windward wall heating, a significant effect of buoyancy force on the vortex was found. A secondary counter rotating vortex forms due to buoyancy force and the direction of the flow near the windward wall changes from downward to upward. The velocity is reduced by around 50 % (Kovar-Panskus et al., 2002; Allegrini et al., 2013). This suppression on the main vortex is also proved by a LES simulation, with the temperature of heating wall higher than air temperature. In the meantime, the results of simulation also showed that the leeward wall heating accelerated the vortex (Cai, 2011). Under windward wall heating condition, the air temperature is higher than that under leeward heating condition (Memon and Leung, 2010). Xie et al. (2007) compared the flow regime in street canyon with different aspect ratio and found that windward wall intends to accumulate more heat and pollutant. Baik et al. (2012) used CFD model to simulate the effect of building roof greening on thermal environment in the street canyon, and found that the cool air generated from roof greening flew into the canyon and improve the air quality near roads.

The previous work has discussed the effect of different aspect ratio with different surface heating. But for experimental research, only the condition with aspect ratio equals to 1 was conducted in wind tunnel. Our concerns are to conduct wind tunnel experiments using different aspect ratios setup under different surface heating conditions.

2.2 Approaching wind direction

For the flow field in canopy, different approaching wind direction has difference of flow pattern in the street canyon. For perpendicular flow, a vortex forms in the center of the regular canopy. For parallel flow, the wind flows along the canyon axis with possible updraft near the canyon wall, due to the friction of wall surface. This friction retards the approaching wind flow (Nakamura, 1988). But the vertical velocity is very low (Ghiaus et al., 2006). And in the deep canyon, parallel flow intends to increase personal exposures of pollutant (Ng and Chau, 2014).

Few studies focused on oblique flow. Eliasson et al. (2006) conducted a long-term measurement in a canyon, and found a helical vortex in canyon when the included angle between flow and canyon is within 60°, and a counter rotating secondary vortex formed in the lower portion of the canyon under low wind velocity and weak turbulence conditions. An empirical model was developed by Ghiaus et al. (2006) and achieve 5°C lower temperature inside the canyon than that of the canopy layer under oblique flow. Another simulation investigation also showed that the oblique flow produced better ventilation than perpendicular flow in a uniform building block (Hang et al., 2013). Yassin (2013) used a CFD model to simulate a three-dimensional flow and pollutants dispersion, and found that when the wind direction is oblique, the minimum concentration was near the windward wall, and the concentration decreased with the included angle decreasing and aspect ratio increasing. In the leeward corner, the pollutant concentration is lower in oblique flow conditions than that in perpendicular flow condition.

Niachou et al. (2008) conducted field experiments to clarify the effect of approaching wind direction. For perpendicular flow, a clockwise vortex formed in the center of the canyon, with uplifts along the leeward wall, and down-lifts long the windward wall, and was influenced by ground heating. For parallel flow, the flow showed a downward movement along the side wall. And for oblique flow, the flow pattern is the joint action of vortex and channeling.

The flow patterns due to different wind orientations under surface heating conditions have not been well discussed.

3. Review on the influence of building materials on the thermal environment

The surface of the building, including roof and vertical facade materials and windows, is considered to have huge impacts on both indoor and outdoor thermal environment. The emitted heat generates a strong buoyancy force near the buildings and ground surfaces. This thermally induced flow influences the flow field, and thus influences the outdoor thermal environment (Xie et al., 2005). Approaches to mitigate this thermal effect of urban surfaces include using high-albedo materials, cool colored materials, and phase change materials (which exchange energy in the transition between solid and liquid phases) (Santamouris et al., 2011). Most of these materials owe their effectiveness to high solar reflectance and high infrared emittance, which lead to less absorption of solar radiation and faster release of absorbed energy as heat.

3.1 Review on the high-albedo and cool colored materials

Cool roof coatings made of high-albedo materials is an effective, economy and easily operable technique that contributes to the reduction of energy consumption and the improvement of thermal comfort both inside and outside of buildings (Synnefa et al., 2007). Rough-textured and dark surfaces intend to absorb more solar radiation than smooth and light-colored ones (Doulos et al., 2004). One study of 14 types of reflective coatings found that white coatings had better performance than aluminum-pigmented coatings did because the lower infrared emittance of the metallic coatings tended to leave them hotter (Synnefa et al., 2006). That study also demonstrated that under hot summer conditions, highly reflective coatings can reduce the surface temperature of white concrete tile by 4°C during daytime and by 2°C at night. An investigation of 87 predominantly single-pigment paint films with thicknesses ranging from 10 to 37 mm recommended against using certain pearlescent pigments, such as blue/purple, red/orange, and brown/black, in cool coatings as their near-infrared absorption exceeded 0.5 (Levinson et al., 2005). Akbari et al. (2005) collaborated with roofing material manufacturers to produce cool colored products, such as asphalt shingles, concrete, clay tiles, metal roof, wood shakes, and coatings. Synnefa et al. (2011) developed five different colors of asphalt for application to pavements and demonstrated that they had higher solar reflectance and lower surface temperatures as compared to conventional black asphalt. Radhi et al. (2014) compared 32 common surface materials and suggested that white and light color materials could assist on mitigating UHI in highly productive solar regions. Coutts et al. (2013) conducted a comparative experiment on green and cool roof, and suggested that cool materials coated with insulated paint can give best performance on mitigating urban heat.

Heat storage of various pavement materials like asphalt, concrete, and bare soil, and its effects on the boundary layer has also been well discussed. The low reflectance and moderate heat conductivity and of asphalt is concluded to be the main reason for the unique thermal performance of asphalt pavements. The surface temperature of bare soil is lower than that of pavement because of the evaporation effects (Asaeda and Ca, 1996). A special paving material “Katsuren travertine” was found to have high reflectance and specific heat capacity and low thermal conductivity compared to concrete, and a promising potential on mitigate urban heat island (Lin and Ichinose, 2014).

3.2 Review on other materials and parameters

Phase change and thermochromic materials generally can maintain lower surface temperatures than common materials. Karlessi et al. (2011) investigated the performance of phase change materials (PCM) doped cool colored coatings in different melting point and concentrations and found that coatings containing PCMs can store heat so that surface temperature could be maintained at a relatively low level and help improve thermal inertia. Karlessi et al. (2009) compared thermochromic, highly reflective and common coatings and found that the reflectance of thermalchromic coatings were higher than the other two, achieving lower surface temperature, which made it a better material to improve human comfort.

Yesilata et al. (2011) found that the application of the scrap-tire pieces on building walls can reduce the heat transfer from outdoor to indoor by increasing the wall’s thermal resistance. Asaeda and Ca (2000) found that evaporation from the ceramic porous pavement surface could make the surface temperature lower than that of the non-porous or the normal porous pavement because of the less absorption of radiation. Yamazaki et al. (2011) conducted experiment on a developed porous ceramics with high water retention and evaporation capacity, and concluded that temperature of concrete with ceramic pellets laying above maintained 15 °C lower than that without ceramic pellets. Pisello and Cotana (2014) applied cool clay tile on a traditional residential building, and the results showed that the peak indoor temperature decreased by 4.7 °C in summer, and 1.2 °C in winter, which is relatively less negative impact compared to the significant positive impact in summer. Anak Guntor et al. (2014) investigated a developed coating material made from waste tile and confirmed its potential to decrease the surface temperature to 4.4 °C compared to asphalt.

The roughness of surface materials and orientation of buildings can also influence the performance of materials, due to different incident angle of the solar radiation and the insolation duration (Bougiatioti et al., 2009). Takebayashi et al. (2011) analyzed the relations between solar reflectance of uneven surfaces and surface shapes and found that the flat surface can reduce solar reflectance and remain relatively higher surface temperature. Synnefa et al. (2006; 2007) found that the building’s facade surface materials facing east and west could reach to very high surface temperatures. In a field experiment in Athens, the temperature difference between east and west wall surface can reach 19°C (Santamouris et al., 1999).

3.3 Review on the impact of materials on UHI using numerical simulation

Some studies have used simulations to investigate the thermal performance of different urban surface materials. Using meteorological simulations, Taha (1997) found that increases in urban albedo can achieve decreases in air temperature as great as 4°C. Santamouris et al. (2012) used fluid dynamic simulations to estimate that 4500 m^2 of cool pavement in a park in Athens would reduce the peak ambient temperature by 1.9°C and lower the surface temperature of the pavement by 12°C during a typical summer day. Similarly, Synnefa et al. (2011) found that replacing conventional asphalt on the road could lower the average air temperature by 5°C under low wind speed conditions.

4. Review on the scale model and wind tunnel experiments

To accurately reproduce real urban conditions, scale model requires geometrical, kinematical, and dynamical similarity to the realistic world. Geometrical similarity concerns the length dimension and requires all body dimensions in all three coordinates have the same linear-scale ratio. Kinematical similarity requires both length scale ratio and time scale ratio; therefore the velocity-scale ratio would be the same. Dynamical similarity exists based on the requirements of geometrical and kinematical similarity (White, 1998). Accuracy of the scale models depends on the ability to match the most relating dimensionless numbers, to minimum the number of unmatched dimensionless numbers, and to reduce the impacts of unmatched dimensionless numbers.

The scale model can be carried out in a wind tunnel, water tank or directly outside (Vardoulakis et al., 2003). The motivations for scale model studies include understanding the flow regime, scalar dispersion, transfer coefficients, radiation, and energy balances. Most of the previous experiments focus on the flow pattern and scalar dispersion characteristics in neutral condition (Kanda, 2005). The most advantage of outdoor scale model experiments is the reality of the meteorological conditions. Especially the models that are used to study radiation can be accurately scaled like urban areas without physical similarity requirements (Aida, 1982). Dallman et al. (2014) conducted a field experiment on the effect of buoyancy flow in a wide canyon. A dimensionless parameter B, called buoyancy parameter, was introduced. When B is larger than a threshold value (0.05), the thermally induced flow becomes important. But fewer outdoor experiments were conducted because of the difficulty of controlling the needed conditions, the high cost and the time consuming, even though the field experiments could provide qualitative data and valuable insight to better validate the simulation models and understand the flow, turbulence and dispersion pattern (Longley et al., 2004).

However, variables are easy to be controlled in wind tunnel. Scale model in wind tunnel can also provide quality data to validate CFD models. Especially the impact of buoyancy flow in CFD simulation only occurs in a very thin layer near the surface, which is hardly observed, while in wind tunnel and field experiment, strong buoyancy can be observed.

Early indoor scale model experiments were mainly concerned with the overall flow pattern in neutral condition and pollutant dispersion in street canyon. Later, the influence of wall heating on flow pattern attracted attention because of the increasing of UHI. Variables could be easily controlled. The main concerns include the investigation of flow regime (Allegrini et al., 2013; Marciotto and Fisch, 2013), pollutant dispersion (Kovar-Panskus et al., 2002), transfer coefficients (Barlow and Belcher, 2001), and radiation and energy balances (Spronken-Smith and Oke, 1999). Mass transfer coefficient and heat transfer coefficient has been measured and estimated by very few researchers. For turbulent transfer coefficients, empirical formulations are used due to the lack of accurate values. Because it's difficult to control the radiation and thermal conditions, and scale thermal admittance, few indoor experiments have been conducted to study the performance of radiation and energy balances. Spronken-Smith and Oke (1999) used scale model made of fir slab and successfully observed the Park Cool Island effect.

Many studies have been conducted to clarify the influence of surface heating induced by solar radiation on the flow pattern in the street canyon under low wind velocity condition in the wind tunnel. Kovar-Panskus et al. (2002) observed the influence of heated windward wall on the generation of a weak secondary flow near the ground with very low Froude numbers. Sato et al. (2010) also achieve the similar results about windward heating condition, and further found a large-scale updraft in the canyon in leeward heating condition. Gromke and Ruck (2012) conducted wind tunnel experiment to investigate the traffic pollutant dispersion in avenues of trees with different aspect ratio and wind direction. With crown porosity decreasing or tree-stand density increasing, the pollutant intends to accumulate at leeward wall rather than windward wall under perpendicular wind direction. For an oblique wind direction, which is 45°, the pollutant intends to accumulate at both side walls. Yassin and Ohba (2012) investigated the effect of canyon structure and wind direction on the vehicle emitted pollutant dispersion in wind tunnel, and concluded that the pollutant concentration is strongly influence by canyon geometry and wind direction, and increases with the aspect ratio decreasing and wind direction angle increasing.

All of these are important studies but have limitations to idealize the thermal conditions. Experiments under more realistic conditions are needed. The real conditions have more complexity (Mirzaei and Haghighat, 2010). It is very difficult to meet all the similarity requirements. Therefore, scale model must be complemented with numerical simulations and field investigations to overcome the mismatch of the related dimensionless numbers between scale models and the real world.

5. Conclusions

Based on the above reviews, the impact of materials on outdoor surface and ambient temperature which is related to UHI and the effect of aspect ratio in perpendicular flow condition have been well discussed. However, various configurations exist and the impacts on flow field need to be clarified. And this concern becomes our research goal: investigate the effects of building materials and street canyon configuration on outdoor thermal environment with different approaching wind directions.

A wind tunnel experiment using a scaled model made of real construction materials was conducted to explore the possibility of applying artificial light as solar radiation (Lin et al., 2014). Under the low inflow condition, the wind velocity was easily influenced by the shape of building and buoyancy flow. After heating the roof top, the velocity increased while turbulent intensity decreased. This might make pollutant transporting faster but inhibited pollutants from mixing. We also changed the roof surface properties by applying insulated coating (composed of micro-size hollow silica particles; Virtudazo et al., 2014), the velocity decreased while turbulent intensity increased. We assume this might indicate the influence of radiation on wind flow, and thus feasible to introduce radiation in wind tunnel. Using radiation appropriately in wind tunnel can help better representing the different solar angle and shading effects, and understanding the UHI phenomenon. However, there are still many difficulties to overcome, such as measuring the air temperature precisely. Also we should take consideration on the effect of the lamp body, and conduct a better simulation technique for solar radiation study. The detail is introduced in our poster presentation (ID: 488, Lin et al. of July 23).

For the purpose of applying these results to the actual designing the block scale of the city, the following wind tunnel experiment were conducted (Lin, 2015). We investigated systematically the effect of a long street canyon on wind field under five different approaching wind direction, wall surface heating conditions, and different section of canyon. Wind tunnel experiments were conducted using PIV (Particle image velocimetry), observing both vertically and horizontally. At inlet and middle section of neutral conditions, every direction of flow except parallel flow formed a vortex in the center of canopy. With the decrease of angle, at outlet section, the vortex became weaker until disappeared. For parallel, two parallel counter rotating vortexes were formed. There is a downward flow in the center of canopy, which induces the outside air going inside. In heating cases, a strong buoyancy flow generated and effected flow pattern and air exchange between inside and outside of the canyon. The detail is introduced in our oral presentation (ID: 487, Lin et al. of July 22).

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