
Ye Lin

Wind tunnel experiment on the influence of approaching wind direction on flow field under wall surface heating and low wind velocity conditions

Ye Lin[1], Toshiaki Ichinose[1], Yukio Yamao[1], Hideaki Mouri[2],
[1] *National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Japan, linye0625@gmail.com*
2 Meteorological Research Institute, Tsukuba, Japan

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1. Introduction

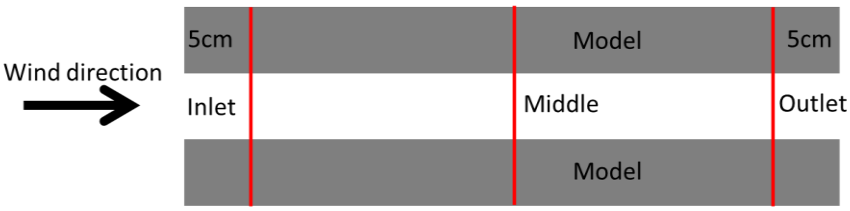
The urban heat island effects arise from the abundance of artificial surfaces, including buildings and ground covers. The temperature, heat storage, and heat flux from these surfaces to the atmosphere have a detrimental influence on the ambient environment. Solar radiation heats the wall and surface of canopy, generates a strong buoyancy flow. The impact of this buoyancy is more obvious at the condition of lower wind velocity.

Wind flow field is strongly influenced by building configurations, building surface and canyon aspect ratio H/W in urban area, so we tend to use scale models in wind tunnel to systematically investigate the influence of building orientation and surface heating on flow field.

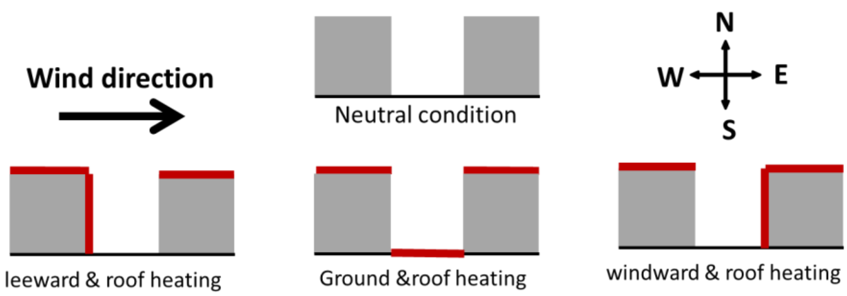
2. The abstract

Canopy structure is one of the most important factors that has significant influence on flow pattern in canopy, including aspect ratio, building shape, building orientation, etc.. Since wind flow field is strongly influenced by building configurations and building surface heating in urban area, we investigated systematically the effect of a long street canyon on wind field under five different approaching wind direction (included angles between wind flow and model's long side are 0° as parallel flow, 22.5°, 45°, 67.5°, and 90° as perpendicular flow), wall surface heating conditions (ground, leeward and windward wall heating), and different section of canyon (inlet, middle and outlet). 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.

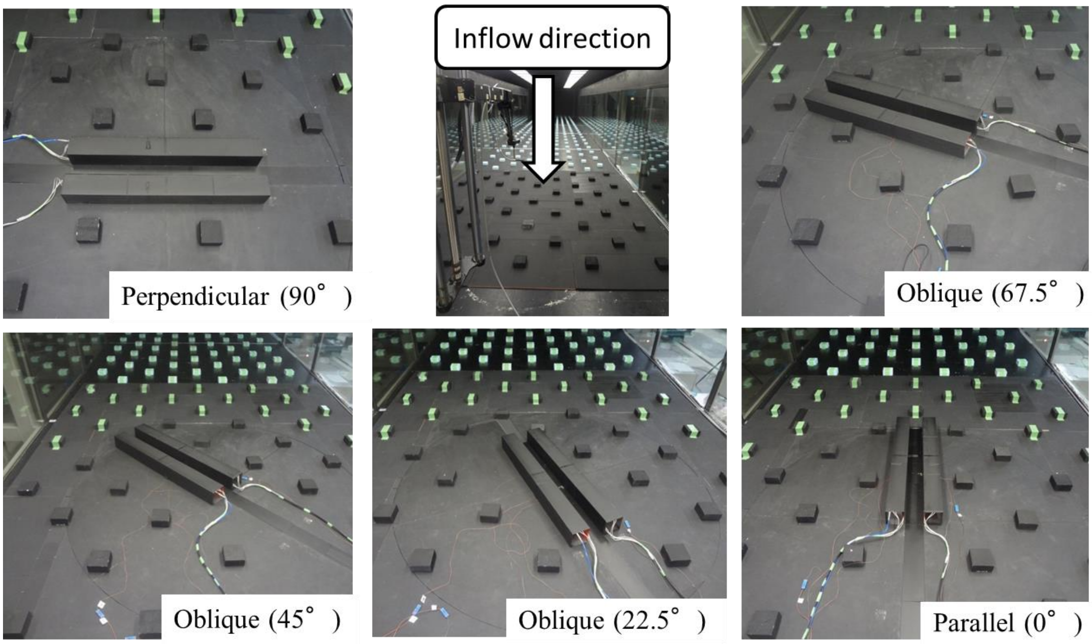
3. Layout of the experiments



(a) Different sections of canopy

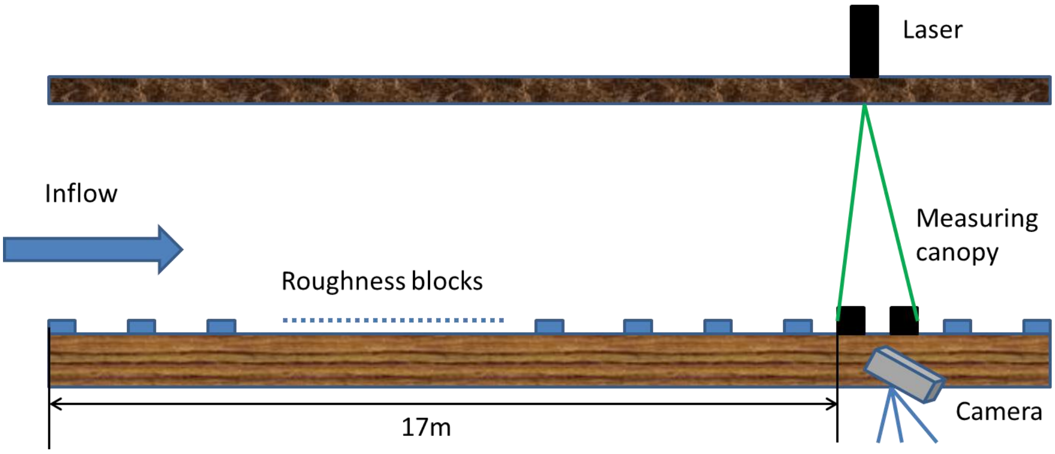


(b) Different surface heating cases

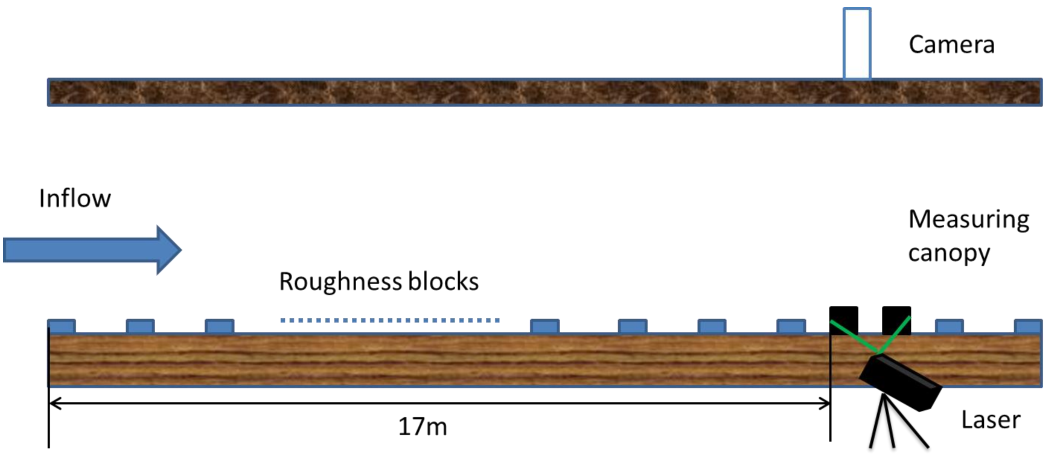


(c) Different orientations

Fig. 1 Model configuration



(a) Vertical



(b) Horizontal

Fig. 2 The layout of PIV

4. Discussion and conclusion

The effects of different aspect ratio were discussed. When H/W=2, two vortexes form, and it is very difficult for air to exchange between inside and outside of the canopy. The emitted heat and pollutants easily accumulate inside. In façade wall heating condition, around half of the model height has the biggest heat load in all aspect ratio cases, which means the half height of the canopy area needs more attention to be taken care of and would have impressive benefit. In ground heating condition, the heat intends to accumulate more in the leeward corner when H/W is 1 and 0.67, more in windward corner when H/W is 2, because of the change of the vortex's position. Vegetation line zone along the canyon is always an effective approach to mitigate both thermal and pollutant load. When velocity is 0.5 m/s, after applying heating, no vortex formed in the canopy, buoyancy flow is the main driving force on the airflow. When velocity is 1.5 m/s, the surface heating has little influence on the vortex only in H/W=0.67 case. When H/W is small enough, thermal effect and buoyancy flow would not be the issue.

Table 1 Comparison of different heating conditions in different aspect ratio canyon.

<table>
<tr><th></th><th>Ground heating</th><th>Leeward heating</th><th>Windward heating</th></tr>
<tr><td>H/W=1</td><td>Heat accumulates in leeward corner. Highest temperature distribution appears. Vortex was strengthened when v was 1.5m/s</td><td rowspan="3">The highest temperature distribution appeared at half of the model height level. Best thermal environment when H/W<1.</td><td rowspan="3">The highest temperature distribution appeared at half of the model height level.</td></tr>
<tr><td>H/W=2</td><td>Difficult for air exchange. Heat accumulates in windward corner. Lowest temperature distribution appears.</td></tr>
<tr><td>H/W=0.67</td><td>Heat accumulates in leeward corner. Highest temperature distribution appears.</td></tr>
</table>

Furthermore, the flow pattern in three cross sections along the canyon with different approaching wind directions, which means different canopy orientations, was discussed.

In neutral condition, for perpendicular flow, a stable vortex forms in the center of the canopy no matter where the cross section is. The air exchange is the worst. For oblique flow 67.5° and 45°, at inlet and middle section, a central vortex still appears, while at the outlet section, the vortex moves to the leeward wall, and is weakened, especially for oblique flow 67.5°. For oblique flow 22.5°, at inlet section, two count rotating vortexes form, and the lower one is small and in the windward corner. In middle section, only the big main vortex remains, and in the outlet section, no vortex can be observed. For parallel flow, from inlet to outlet, the flow moves forward helically, because of the wall's friction.

Table 2 Comparison of different orientation in neutral condition.

	Inlet	Middle	Outlet
Perpendicular	A stable central vortex	A stable central vortex	A stable central vortex
Oblique 67.5°& 45°	A central vortex	A central vortex	One weakened vortex near leeward wall
Oblique 22.5°	Two counter rotating vortexes, the lower one is small and in the windward corner	A large main vortex	No vortex
Parallel	From inlet to outlet, the flow moves forward helically, because of the wall's friction, multiple vortexes are observed.		

The effects of surface heating on different approaching wind conditions were also compared. Generally, at the inlet section, surface heating nearly has no influence on the flow pattern. Due to the accumulation of heat, the air temperature in middle section is generally higher than other section, except in parallel flow condition. Ground heating has more driving force than façade wall heating in most of the cases. So in urban design, the ground surface temperature decrease should be paid more attention. More appropriate cool materials, vegetation, water surface should be applied on the ground.

In perpendicular flow condition, the flow inside of the canopy was mainly influenced by buoyancy flow. Oblique flow 67.5° is similar to perpendicular flow in neutral condition. But after applying heat, the flow pattern became different from perpendicular flow. In most of the oblique conditions, the results of 1.5m/s inflow did not show much difference. When the include angle is smaller than 45°, the flow pattern mainly depends on the building configuration. The surface friction has more significant impact than buoyancy. Only when inflow velocity was 0.5 m/s, the influence on the flow field could be observed in ground heating condition. But in oblique flow 45° condition, ground heating influence every velocity case, and doesn't change with velocity increase. With included angles between wind flow and canopy decreasing, more wind went inside the canopy and took away most of the heat, which means the air temperature in the canopy decreases. Although in parallel condition, the thermal environment inside of the canopy is better than any other wind conditions, the effect of roof heating is more intense. Parallel or near parallel orientation combined with cool roof application is recommended. The closer to parallel flow, the more heat is taken away by the penetrating wind flow, the less influence of thermally induced flow occurs on flow field. And this penetrating flow is going forward helically.

Table 3 Comparison of different orientation in wall heating condition.

<table>
<tr><td></td><td>Angle</td><td></td></tr>
<tr><td rowspan="5">Air temperature decreases,
More heat taken away by channeling wind flow, less influence of thermally induced flow</td><td>Perpendicular</td><td>Mainly influenced by buoyancy flow</td></tr>
<tr><td>Oblique 67.5°</td><td>Similar to perpendicular flow in neutral condition, maintains a vortex in all heating conditions</td></tr>
<tr><td>Oblique 45°</td><td>Influenced by ground heating in all velocity cases</td></tr>
<tr><td>Oblique 22.5°</td><td>Influenced by ground heating only in 0.5m/s</td></tr>
<tr><td>Parallel</td><td>Received more heat in outlet section. More intense roof heating</td></tr>
</table>

Acknowledgment

I would like to thank Akihiro Hori, Toshimasa Yagi and Shigeru Onogi for assisting with the wind tunnel experiments.