Numerical Simulation of the Effects of Water Surface in Building Environment

LI Guangyao¹ (corresponding author), PAN Yuqing¹, YANG Li²,³
¹College of Electronic and Information Engineering, Tongji University, Shanghai 201804, China
²Architecture Department, College of Architecture & Urban Planning, Tongji University
³Key Laboratory of Ecology and Energy Saving Study of Dense Habitat (Tongji University), Ministry of Education, Shanghai, P. R. China
lgy423@126.com

Abstract. Water body could affect the thermal environment and airflow field in the building districts, because of its special thermal characteristics, evaporation and flat surface. The thermal influence of water body in Tongji University Jiading Campus front area was evaluated. First, a suitable evaporation model was selected and then was applied to calculate the boundary conditions of the water surface in the Fluent software. Next, the computational fluid dynamics (CFD) simulations were conducted on the models both with and without water, following the CFD practices guidelines. Finally, the outputs of the two simulations were compared with each other. Results showed that the effect of evaporative cooling from water surface strongly depends on the wind direction and temperature decrease was about 2~5℃. The relative humidity within the enclosing area was affected by both the building arrangement and surrounding water. An increase of about 0.1~0.2m/s of wind speed induced by the water evaporation was observed in the open space.

1. Introduction
In the building designs, energy consumption could reach a reduction up to 90% by utilizing the natural resources such as solar radiation and ventilation, which improve the thermal environment and wind field and thus reduce summer air-conditioning energy use [1]. Although the thermal environment is correlated to a number of factors [2], it depends strongly on the nature of the surface and its conditions [8].

Previous studies proposed that water body have a significant influence to the thermal state and wind field in open spaces; its evaporation procedure interacts with the air flow above; the change of vapor mass in the air modifies the humidity; the water surfaces are generally lower than the ground and have flat exteriors thus can accelerate the air flow. In the past few decades, researches were done to investigate the influence of water body on thermal environment. They were generally in meso-scale and macro-scale, using the satellite imaging and field experiments to reveal the role of water in affecting the neighbor microclimate [3-6].

Due to the varying scenarios and meteorological conditions, the field observations could not give the universal conclusion. In contrast, the CFD (Computational Fluid Dynamics) simulation method plays an important role in the research because of its convenience of modelling simplified or idealized...
cases. Some researchers compared the simulation outputs coming from the cases with and without a water body to analyze the microclimate. In these literatures, the water surfaces were set to be a wall boundary with a temperature obtained by applying the radiative and thermal model, and a saturated specific humidity which is a function of surface temperature [7, 8]. Song estimated the amount of vapor through a computational method of the heat and moisture exchange between water surface and atmosphere [9]. Arguably, the thermal characteristics, surface temperature of water and humidity over water are important to the evaporation procedure. However, the interaction between vapor and the airflow could be concealed with the water being set to wall type in the CFD software. On the other hand, the evaporation capacity is depending on the solar radiation, wind speed, surface temperature and air humidity. These were not taken into account to determine the vapor mass over water body.

In this paper, the open space including building groups and a river in the front district of the Tongji University, Jiading Campus, was chosen to perform CFD simulations. The river was set to be airflow inlet, corresponding to a selected evaporation model. The results were analyzed to express the physical phenomena that occur in open spaces.

2. Evaporation model
Since Dalton reported the positive correlation between evaporation and vapor pressure deficit (VPD) in 1802, a lot of theories and models for evaporation were proposed. The Dalton equation takes into account wind velocity and VPD. The Penman equation determines the evaporation by many variables including VPD, solar radiation, surface temperature and air humidity, coupling aerodynamics and energy balance. In China, parameters in the Penman equation and the Dalton equation are adjusted to agree with the local weather condition [10-13].

The factors mentioned previously are generally relative to each other. Tong highlighted wind speed, saturated VPD and net radiation as the three most important factors, and proposed a multivariate regression model which had a good agreement with the experimental data [14]. In this study, this model will be used to calculate the evaporation of water body:

\[
E = 0.76(e_a - e_d)^{0.733}(0.708u_2 - 0.469) + 0.0166R_n - 0.57
\]  
(1)

where E is the evaporation (mm d\(^{-1}\)); \((e_a - e_d)\) is the saturated VPD (hPa) given by equation (2); \(u_2\) is the wind velocity (m s\(^{-1}\)); \(R_n\) is the equivalent evaporation of net radiation given by equation (3);

\[
(e_a - e_d) = e_a(1 - RH)
\]  
(2)

\[
R_n = \frac{R}{L}
\]  
(3)

In equation (2) and equation (3), RH is the relative humidity (%); R is the net radiation (MJ m\(^{-2}\)); L is the vaporization heat of water.

The airflow comes from the evaporation is calculated by:

\[
u = \frac{E \cdot 10^{-3} \cdot \rho_0}{43200 \cdot \rho \cdot q}
\]  
(4)

where q is the specific humidity in the air (%); \(\rho_0\) is the density of water (kg m\(^{-3}\)); \(\rho\) is the density of saturated air (kg m\(^{-3}\)).

3. Numerical simulation
To illustrate the effects of water surface to surrounding microclimate, simulations have been carried out for a hottest day of summer, August the 1st, 2016, for the front district in Tongji University Jiading campus, Shanghai, which was an open space with a river around. Figure 1 shows the satellite imaging of the real scenario. There were four buildings and two giant gates, forming a semi-enclosing
arrangement facing South-West. The prevalent wind direction was South-East, perpendicular to the building arrangement orientation. An east wind pattern was therefore used and the building arrangement was adjusted for the convenience of calculations. Two cases were modeled: the front district in the campus without any water body, and the actual case with a river.

Figure 1. Aerial view of the target area.

Figure 2. Computational grids for the case.

3.1 Dimensions and grid of the domain
The CFD simulation approach is widely applied in the analysis for wind environment around buildings. Due to the challenges in modeling complex scenarios accurately, empirical settings are commonly used. Some guidelines for CFD settings are given by organizations like European Cooperation in Science and Technology (COST), The Association of German Engineers (VDI) and Architectural Institute of Japan (AIJ), etc. Zhuang had given an overview to the present researches and studies about CFD simulation techniques for outdoor wind environment [15].

According to these guidelines, the dimensions of the calculation domain were set to be 5H×5H×5H×5H in our cases. The blockage ratio was equal to 1.29%. The final mesh grid of the domain was an unstructured grid including 227,8281 elements. Figure 2 displays the grid of the building surface and water surface. The mesh gradually becomes coarser with increasing distance from the water surface.

3.2 Simulation model
Outdoor wind flow is commonly considered as incompressible and low-speed turbulence. The k-ε standard model of turbulence and some corrected models like RNG k-ε model and Realizable k-ε model are most used. In this paper, the Realizable k-ε model was selected for more accuracy.

3.3 Boundary conditions
3.3.1 Inlet boundary of the prevalent wind. The meteorological conditions on August 2nd, 2016, the hottest day in summer, were shown in Table 1. The wind speed profile resembles a power-law expression:

\[
U(Z) = U_s \left( \frac{Z}{Z_s} \right)^\alpha
\]

(5)

where \(U_s\) is the average wind speed at the reference height \(Z_s\); \(\alpha\) is the surface roughness. The reference height is usually set to be 10m from the ground. The roughness value and reference height were set according to the GB 50009-2012 “Load Code for the Design of Building Structures” [16].
3.3.2. Outlet boundary. The outlet boundary condition was set to free outflow. The airflow on the outlet surface is considered to be fully developed and resumed to the initial state which was not blocked by the buildings. The bottom and both sides faces were defined as free slip boundaries [15].

3.3.3. Inlet boundary of the water body. The surface temperature of water body was not included in the regular filed observation. It should be noted that the river in this case is connected with Yangtze River, thus has good mobility and heat storage capacity. Hence, the surface temperature of the river could be estimated according to the Yangtze River which is in similar latitudes. Sun reported that the water in Yangtze River has a lower monthly average temperature of 3~5℃ than the air in summer [17]. Yang observed that the surface temperature of water in QianDao Lake which was near to Shanghai was about 30℃ in summer [18]. Thus, the water temperature in this case was set to 31℃ reasonably. The velocity of inlet flow was set to 0.014m/s, calculated from the multivariate regression model described in Section 2. Some thermal characteristics of air and water were shown in Table 2.

| Wind velocity | Air temperature | Relative humidity | Prevailing wind | Average net radiation |
|---------------|-----------------|------------------|-----------------|----------------------|
| 2.3m s⁻¹      | 36 °C           | 75%              | southeast       | 11.53 MJ m⁻²         |

| Saturated vapor pressure | Density of saturated air | Vaporization heat | Density |
|--------------------------|--------------------------|-------------------|--------|
| 59.4hPa                  | 1.116 kg m⁻³            | 2441.7418 KJ kg⁻¹| 10³ kg m⁻³ |

4. Simulation results

4.1 Air temperature
Comparisons of air temperature at the height of 1.5m in CFD simulations with and without the river are shown in Figure 3. The figure shows that the air temperature was 33~35℃ inside the semi-enclosing area, and 30~32℃ in the leeward of the river. Notable reduction of the air temperature was observed.

The locations of three measurement lines were also illustrated in Figure 3, where the lines are: Line1, parallel to the wind direction; Line2 and Line3, perpendicular to the wind direction. The presence of the river was arguably reducing the air temperature around it. Line 2 located on the windward side of the river was less affected by the water and had an air temperature decrease of 0~3℃. In contrast, Line3 located on the leeward side of the river had an air temperature reduction of 2~5℃. The reason could be the fact that the vapor coming from the river had a lower temperature, modifying the thermal environment after having been spread over a period of time and reached a steady state. This trend can be also found in the Line1 measurement line. The temperature reduction gradually becomes larger along the wind direction from 0~1℃ to 1~5℃. The cold airflow was extended downwind.

It can therefore be concluded that the evaporation cooling effect of the water body is strongly depending on the wind conditions. When the wind direction has changed, the affected area can become larger or smaller. We should also note that the Reynolds average Navier Stokes Equations method is to calculate the airflow field in steady state. The airflow speed could fluctuate in actual situation thus changing the local temperature.
Figure 3. Comparisons of air temperature at the height of 1.5m in CFD simulations with and without the river.

4.2 Air humidity

Figure 4 displays the contour of relative humidity distribution at a height of 1.5m above the ground. In the case without river, the moisture from inlet was obstructed by the buildings, therefore increasing the vapor mass in the air. On the leeward side of the buildings, air humidity was also high (Figure 4 a). In the actual case with river, the distribution was in agreement with the previous one, but the humidity values were higher (Figure 4 b).

Areas with humidity over 100% were observed behind the buildings (Figure 4). The reason could be that the FLUENT software does not have a proper calculation model for the condensation of vapor. When the humidity exceeded 100%, moisture in the air would remain a liquid state, therefore affected the accuracy of simulation [19].

Figure 5 shows the longitudinal distribution of the relative humidity inside the semi-enclosing area. The lateral diffusion of vapor and the blocking buildings have formed an enclosing area. In the districts close to the water and the buildings, relative humidity was enhanced. It could be concluded that the air humidity was influenced by the combined effect of water body and building arrangement.
Figure 4. Simulated relative humidity at the height of 1.5m in CFD simulations (a) without the river (b) with the river.

Figure 5. Profiles of relative humidity distribution.

4.3 Airflow velocity

To investigate the velocity distribution in the cases, three measurement lines were chosen inside the semi-enclosing area (Figure 6). On the line4 which is the closest to the building entities, airflow speeds are in a good agreement between the two cases. On the line6 locating on the edge of the semi-enclosing area, airflow speeds were only lightly different between the two cases. These mean that the water body had less influence to the airflow velocity, compared to the building arrangement. Moreover, the turbulence on the edge was unsteady therefore caused the velocity difference fluctuating on Line6.

When considering the line5 measurement line located on the open space, the effect of evaporation to the wind speed was enhanced contributing to less influence from buildings. Specifically, on both ends of line5 close to the buildings, the velocity differences were still small. However, on the middle part of the line5, the velocity in the case with river increased by 0.1~0.2m/s than that in the case without river. Table 3 displays the velocity values on average in the three test lines. Therefore, the evaporation of water body could accelerate the wind velocity in open space.

Blocken employed the cross validation between CFD simulation and wind tunnel experiments for parallel building layout. The study pointed out that the velocity is generally predicted within an accuracy of 10% in the low-speed regions. In the high-speed area however, the predicted wind speed is generally significantly underestimated, at some location by a factor 5 or more [20]. Due to the underestimation of the wind speed, the velocity increase caused by the evaporation may be larger.
Figure 6. Comparisons of air velocity at the height of 1.5m in CFD simulations with and without the river.

| Average velocity (m/s) | Line4 | Line5 | Line6 |
|------------------------|-------|-------|-------|
| With river             | 0.33  | 0.68  | 0.63  |
| Without river          | 0.35  | 0.56  | 0.60  |
| Velocity increment     | -0.02 | 0.12  | 0.03  |

4.4 Wind vectors

Figure 7 shows the wind vectors at the height of 1.5m above the ground in the two cases. Some vortex zones were found inside the semi-enclosing area and in the leeward side of the buildings. Speed was low in these zones: 0~0.8m/s and 0~0.5/s respectively (Figure 7 a). Airflow was hard to exchange with the outside environment and caused the discomfort for the pedestrians. However, the vortex zone became smaller in the case with river (Figure 7). The reason could be that the evaporation from the large area waterbody modified the velocity field and thus improved the low-speed vortex zone. To be compared, the vortex zone inside the semi-enclosing area was not improved because of the long distance from the water.
5. Conclusion
The effect from water surface in Tongji University Jiading Campus front area was evaluated by choosing a suitable evaporation model and conducted CFD simulations. The results of the simulations were compared to find out the correlation.

Thermal environment was generally affected by the evaporation procedure of the water surface. The temperature reduction could reach 2~5℃ on the leeward side of the water. The air humidity was influenced by the combined effect of water surface and building layout.

As for the wind environment, the effect of evaporation was weak in the area close to the building blocks. However in the open space, the evaporation caused an increment of 0.1~0.2 m/s to the velocity field. Moreover, evaporation of large area water body could improve the vortex zone around, which then improved the comfort for the pedestrians.

Acknowledgement
This research is supported by the National Natural Science Foundation of China (project approval number: 51378365, 61771346).

References
[1] Yang Li. Green Building Design: Building Energy Efficiency[M]. Tongji University Press, 2016:176-177.
[2] Oke T R. The energetic basis of the urban heat island[J]. Quarterly Journal of the Royal Meteorological Society, 1982, 108(455):1-24.
[3] Li Shuyan, Xuan Chunyi, Li Wei,etc. Analysis of Microclimate Effects of Water Body in a City[J]. Chinese Journal of Atmospheric Sciences, 2008, 32(3):552-560.
[4] Liu Yonghong, Xuan Chunyi, Quan Weijun. Thermal environment effect of land surface water bodies in Beijing based on satellite data[J].Journal of Lake Sciences, 2013, 25(1):73-81.
[5] Ji Peng, Zhu Chunyang, Wang Hongyi,etc. Impact of rivers with different widths to thermal environment in urban space[J]. Wetland Science, 2013, 11(2):240-245.
[6] Xu Jingcheng, Zhu Xiaoyan, Li Guangmeng. Influence of Water Front Area Surrounding Small Scale Landscape Water Bodies in Cities on Human Comfort [J]. China Water & Wastewater, 2007, 23(10):101-104.
[7] Mirela Robitu, Marjorie Musy, Christian Inard, Dominique Groleau, Modeling the influence of vegetation and water pond on urban microclimate[J], Solar Energy, 2006, 80(4): 435-447.
[8] Tominaga Y, Sato Y, Sadohara S. CFD simulations of the effect of evaporative cooling from
water bodies in a micro-scale urban environment: Validation and application studies[J]. Sustainable Cities & Society, 2015, 19:259-270.

[9] Song Xiaocheng, Liu Jing, Ye Zuda, etc. Preliminary CFD Study on the Effects of Urban Water Body on Urban Thermal and Moisture Climate[J]. Building Science, 2011, 27(8):90-94.

[10] Chen Huiquan, Mao Shimin. Validation of common evaporation coefficient in China[J]. Advances in Water Science, 1995, 6(2):116-120.

[11] Hong Jialian, Fu Guobin. A New Calculation Method of Water Surface Evaporation[J]. Geographical Research, 1993, (2):51-59.

[12] Pu Peimin. Research on the Equations of Water Evaporation and Heat Transfer[J]. Journal of Lake Science, 1991, 5(1):1-10.

[13] Min Jian. Research on Water Evaporation Model[J]. Advances in Science and Technology of Water Resources, 2003, (01):41-44+70.

[14] Tong Xin, Liu Tingxi, Yang Dawen, etc. Simulation and Study on Water Surface Evaporation and Factors in the Semi-arid Sandy Meadow Area[J]. Arid Land Geography, 2015, 38(1):10-17.

[15] Zhuang Zhi, Yu Yuanbo, Yehai, etc. Review on CFD Simulation Technology of Wind Environment around Buildings[J]. Building Science, 2014, 30(2):108-114.

[16] Ministry of Housing and Urban-Rural Development of the People’s Republic of China. GB 50009-2012 Load Code for the Design of Building Structures [S]. Beijing: China Architecture& Building Press, 2012.

[17] Sun Daming, Tian Huifeng, Zhang Huan, etc. Monitoring of Water Temperature and Changing Relationship Between the Water Temperature and Air Temperature in the Upper Yangtze River, 2010, 38(12):74-77.

[18] Bai Yang, Zhang Yunlin, Zhou Yongqiang, etc. Vertical Distribution of Water Temperature in QianDao Lake and the Influence factors [J]. Oceanologia et Limnologia Sinica, 2016, 47(5):906-914.

[19] Li Yixing. Investigation on Some Key Problems of Saturator of HAT Cycle[D]. Shanghai JiaoTong University, 2007.

[20] Blocken. B, Carmeliet. J. Pedestrian wind conditions at outdoor platforms in a high-rise apartment building: generic sub-configuration validation, wind comfort assessment and uncertainty issues[J]. Wind & Structures An International Journal, 2008, 11(11):51-70.