

Wind Engineering Joint Usage/Research Center FY2016 Research Result Report

Research Field: Researches on indoor airflow, thermal environment and energy issues
Research Year: FY2016
Research Number: 162004
Research Theme:
Fast prediction of indoor pollutant dispersion based on the development of low-dimensional reduced-order ventilation models
Representative Researcher: Shi-Jie Cao; Weirong Zhang; Yelin Deng; Yu Zhou Xiang-Ri Kong;
Budget [FY2016]:230,000 Yen

- *There is no limitation of the number of pages of this report.
- *Figures can be included to the report and they can also be colored.
- *Submitted reports will be uploaded to the JURC Homepage.

1. Research Aim

Aim1: To investigate the thermal performance for a new type of ground heat exchanger (GHE) with higher thermal conductivity materials of steel by using methods of full-scale experiments (pipes buried underground with a depth of 100 m) and computational fluid dynamics (CFD).

Aim2: To investigate relationships between PM2.5, NO2 concentrations and relative humidity (RH) as well as their human health impacts for Subway systems in Suzhou.

Aim3: Aim at the construction of low-dimensional linear reduced-order ventilation models such that transient pollutant concentration can be accurately predicted.

2. Research Method

Method 1: Thermal performance of ground heat exchanger (GHE) for The GSHP system

The general methodology of this study is depicted in Figure 1. Firstly, a new type of GHE U-tube with steel material was designed. Next, the two types of U-tubes was buried with the same depth and backfilled with same materials (original soil). Then the thermal performance of two types of U-tubes was compared using experiment measurement based on temperature differences between inlet and outlet of U-tubes as well as the heat transfer per unit borehole depth. Finally, the feasibility of our new scheme was carried out.

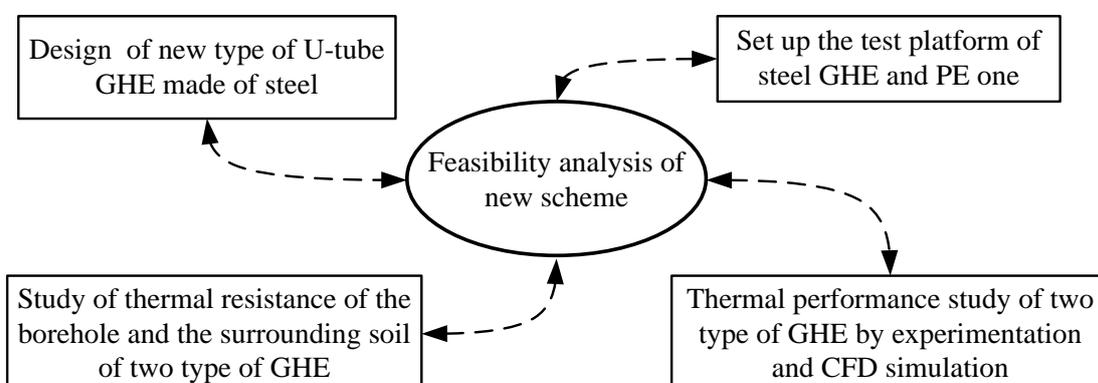


Figure 1. The GSHP system experimental test procedure

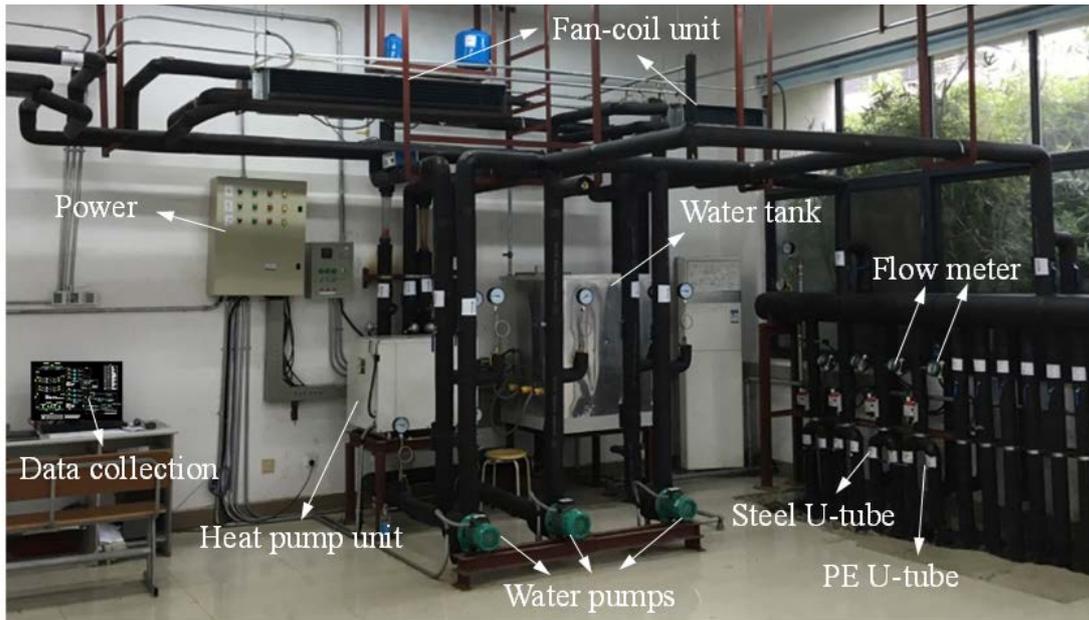


Figure 2. Laboratory test system of ground source heat pump

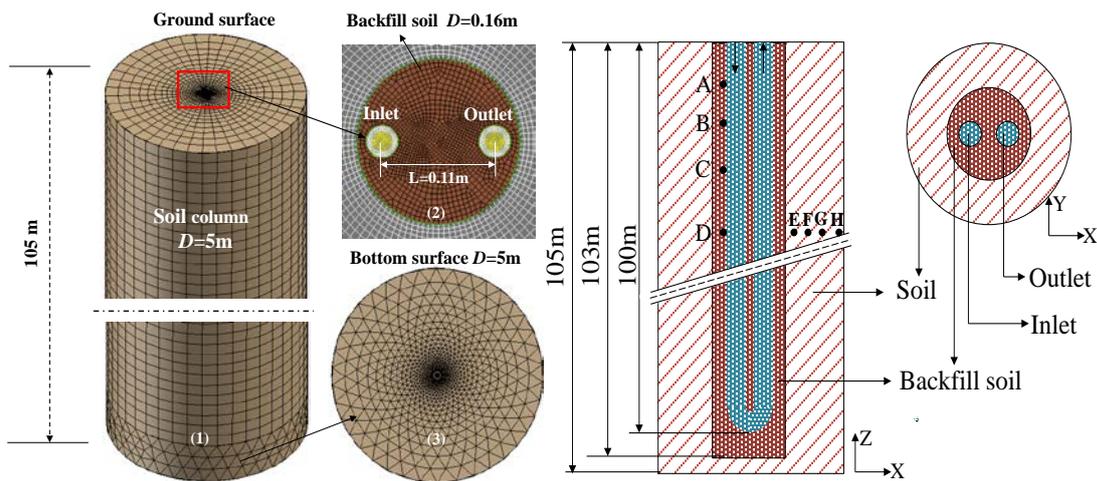


Figure 3. Computational geometry of model and mesh ;Schematic diagram of ground heat exchanger according to the cross-section (X, Y) and (X, Z)

Method 2: Study on PM2.5 and NO2 concentrations and their human health impacts for Subway Metro system of Suzhou

This work aims to provide the quantitative information on the overall human health damage (HHD) incurred by the air pollutions from the Suzhou Subway system (Fig.4). It is carried out in two steps: 1) The first step monitors the concentrations of the main air pollutants (NO2 and PM2.5) in the two lines of the subway system. Measuring spots include both the subway carriage and platform to provide a complete coverage on exposure; 2) The second step applies the USEtox framework to assess the human health damage of indoor air pollution. The quantitative human health impacts can then be served as a quantitative indicator to evaluate the effectiveness of pollution control measures.

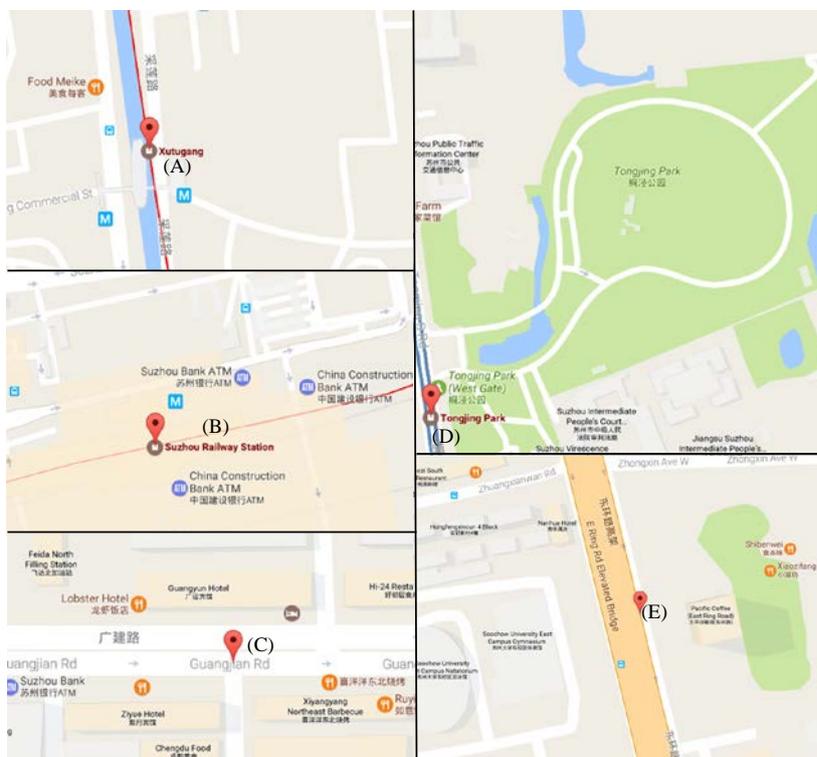
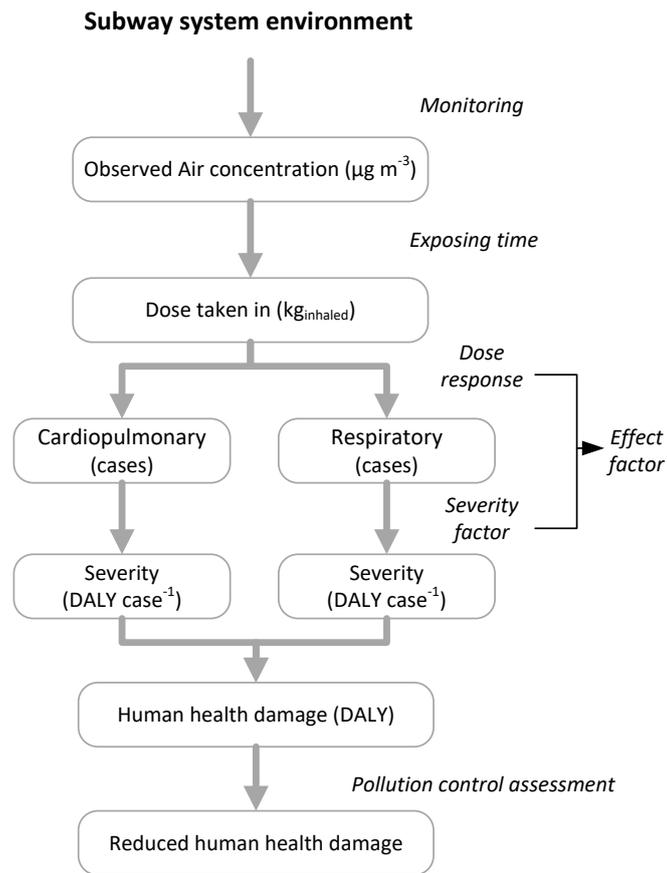


Fig. 5 Greening condition surrounding five stations (A: Xutu Gang; B: Suzhou Railway; C: Guangji Nan road; D: Tongjing Park; E: Donghuan Lu.)

Method 3: Fast prediction of indoor pollutant dispersion based on the development of low-dimensional reduced-order ventilation models

The low-dimensional “reduced-order” model is initiated for fast prediction of pollutant dispersion under steady state indoor airflow. The intention of using reduced-order ventilation models is to predict pollutant concentration based on several dominant Eigen modes, which saves lots of computation effort, further facilitating the design and control of indoor ventilation systems for practical application. A reduced-order ventilation model is the solution for this decay problem, derived from a large coupled system of Ordinary Differential Equations (ODEs) for concentration that can be cast in terms of a matrix exponential, that is accurately represented with only a few dominant Eigen modes. The spatial discretization of pollutant transport equation, e.g., using a finite-volume approach, leads to a large coupled system of Ordinary Differential Equations (ODEs) that can be cast in the form of $\partial c/\partial t + A \cdot c = 0, c(0) = c_0$, here $c \in \mathbb{R}^n$ is a long vector containing the discrete concentrations at every cell in the solution domain (with n cells). Further, $A \in \mathbb{R}^{n \times n}$ is a matrix that represents the discretization of the operator $-(\nabla \cdot u - \nabla \cdot D \nabla)$, including the spatial boundary conditions. Both methods of CFD simulation and experiment measurement were employed.



Fig. 6 Schematic description of experimental chamber and control system for moving body

3. Research Result

Result 1: Investigation of PM_{2.5} and NO₂ concentrations and their human health impacts for Subway Metro system of Suzhou in China

The mean PM_{2.5} concentrations at underground platforms are significantly higher than those at ground level. The human health impact is calculated to be 6300 annual DALYs due to particles exposure to the subway (or 375 deaths, nearly 1% of the total annual mortality in Suzhou). The reduction in human health impact from RH control illustrated, i.e., with 20% (1.2%~38%) human damage being reduced with a 10% increase of RH level. Considering the rapid expansion of the Suzhou subway system (or China), human health hazard from subway system could be significant in the future. It is important to take solutions for particles' reduction at subway.

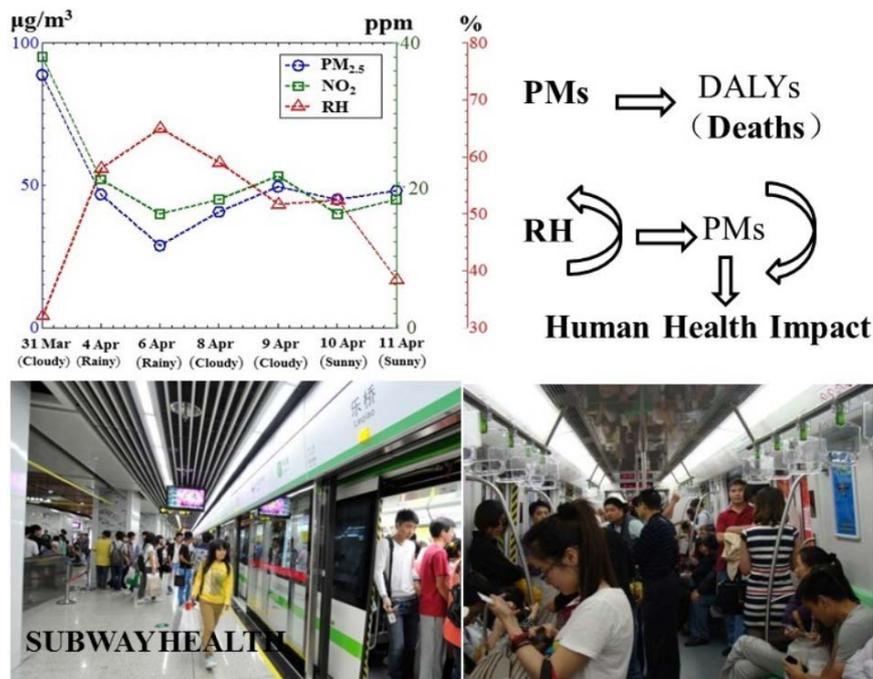


Fig 7. PM_{2.5} and NO₂ concentrations and their human health impacts for Subway Metro system of Suzhou in China

Result 2: Investigation on thermal performance of steel heat exchanger for ground source heat pump systems using full-scale experiments and numerical simulations

We investigated the thermal performance for a new type of ground heat exchanger (GHE) with higher thermal conductivity materials of steel by using methods of full-scale experiments (pipes buried underground with a depth of 100 m) and computational fluid dynamics (CFD). Thermal performance was based on the temperature differences between inlet and outlet of U-tubes and the heat transfer per unit borehole depth (Q_L). We analyzed the entire thermal resistance of the borehole and the surrounding soil as well as the soil temperature distribution around the heat exchanger U-tubes. We found the further apart from the U-tubes, the smaller the soil temperature. Due to smaller heat resistance magnitude, the GHE performance of steel pipe was always better compared to conventional PE types, with Q_L increased up to 36%. It was also found Q_L was increasing with the increase of inlet velocities. The designed distance of GHE borehole was recommended to be at least 1.4 m for steel pipe systems and 1.2 m for PE one when the system is operated for 8 hours. Finally, cost analysis were discussed for both systems. This study will further facilitate for the future application of steel Ground Source Heat Pump systems.

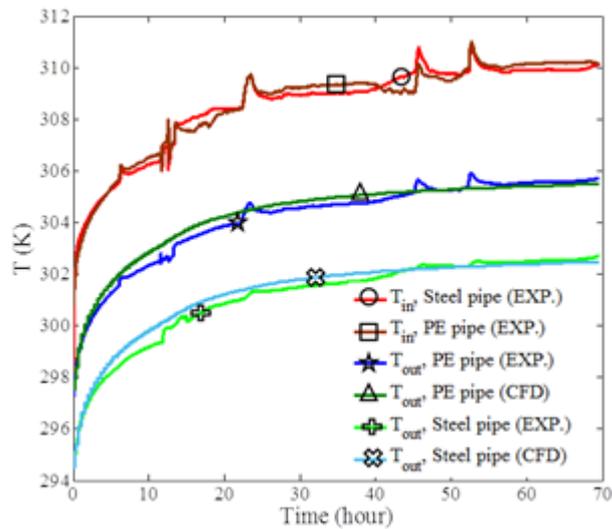


Fig. 8 The evolution of inlet and outlet temperature of PE and steel U-tube (with the length of 100m) based on experiment measurements and CFD simulation with the inlet flow velocity of 0.6m/s.

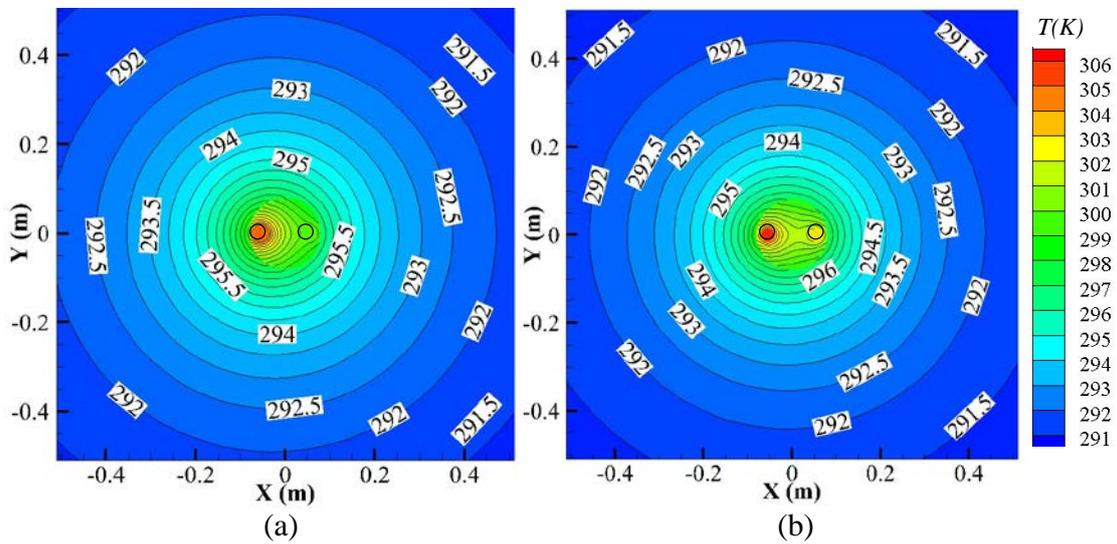


Fig. 9 The temperature field (at the depths of 50m underground) in the radial direction of the GHE (a, steel pipe; b, PE pipe) at inlet velocity of 0.6m/s in summer [black circle ● left: inlet; right: outlet]

Result 3: Fast prediction of indoor pollutant dispersion based on the development of low-dimensional reduced-order ventilation models

This work is still on going. We have first finished the experimental setup. Velocity distribution using CFD methods have been verified by experiments, show below.

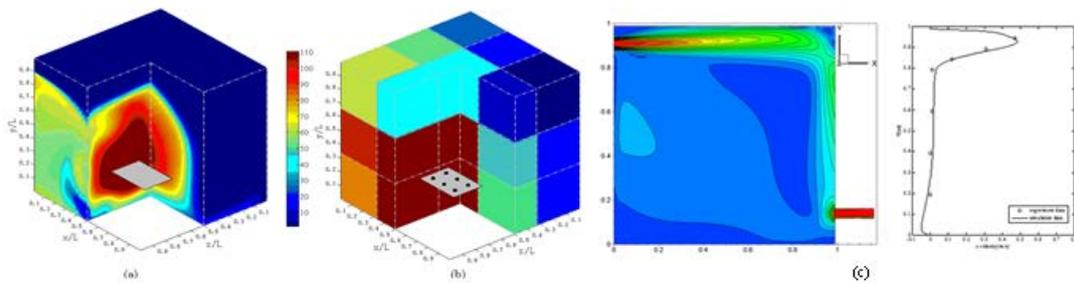


Fig. 10 Experiments validation for velocity profile

4. Published Paper etc.

[Underline the representative researcher and collaborate researchers]

[Published papers]

1. Cao, S.-J.(Cao Shi-Jie), Kong, X.-R., L. Li , Zhang W.(Zhang Weirong), Ye Z., Deng Y.* (2017), Investigation of PM2.5 and NO2 concentrations and their human health impacts for Subway Metro system of Suzhou in China , *Environmental Science: Processes and Impacts* (Accepted, DOI: 10.1039/C6EM00655H) (if,2.401)
2. Cao, S.-J. (Cao Shi-Jie) , Kong, X.-R., Deng Y., Zhang W. (Zhang Weirong), Yang L., Ye Z. (2017), Investigation on the thermal performance of steel heat exchanger for ground source heat pump systems using full-scale experiments and numerical simulations , *Applied Thermal Engineering*, 115, pp.(91-98). (if,3.043)

[Presentations at academic societies]

1. the 10th International Symposium on Heating, Ventilation and Air Conditioning – ISHVAC 2017 in Jinan, China from October 19th to 22nd, 2017
2. International Exchange Meeting on Wind engineering from indoor environment to urban area, Tokyo Polytechnic University, March 9th, 2017

[Published books]

[Other]

Intellectual property rights, Homepage etc.

5. Research Group

1. Representative Researcher

1. Weirong Zhang, Faculty of Engineering, Tokyo Polytechnic University, Associate professor
2. Yelin Deng, Civil and Environmental Engineering, Soochow University, Associate professor
3. Yu-Zhou, Civil and Environmental Engineering, Soochow University, Master Student
4. Xiang-Ri Kong, Civil and Environmental Engineering, Soochow University, Master Student