High-rise Building Integrated with Solar Chimney and Bioenergy

Biao Wang¹,* and Zhihao Wang²
¹,²Gold Mantis School of Architecture, Soochow University, China

*Corresponding author email: uangning@suda.edu.cn

Abstract. In dense mega cities, high-rise buildings huge energy consumption on mechanical ventilation and overheat produced by the air conditioners are among big challenges for the sustainable building development and green city construction. Solar chimney is proved to be an efficient method to promote natural ventilation for buildings. Different types of solar chimney are presented with a high-rise building layout example. Solar chimney geometry and environment basic data is suggested to be evaluated to optimize the Solar chimney's natural ventilation. In addition, aiming as well a clean and sustainable environment, bio-energy can be adopted in buildings by integrating with algae-fluid window and wall system. Different materials of radiation absorber can be studied and integrated with solar chimney. An outline of research on solar chimney integrated with bio-energy for high-rise building is given in this paper. In order to succeed, close multidisciplinary cooperation is necessary for the project which involves at least architecture, thermal physics, air dynamics, materials science and biology. Experiment conditions and potential risk should be discussed beforehand.

Keywords: High-rise building; Solar chimney; Bio-energy, CFD.

1. Introduction
The demand of electricity for air conditioning in dense cities in summer counts a big part for the building consumed energy and the heat generated by the air conditioners conversely makes the city heat island effect more severe. Solar chimney is found as an efficient way to heat and ventilate buildings in the hot and humid areas as well as cold climate countries. The main mechanism is like this: Air enters the chimney at its lower level; solar radiation is absorbed by the main body of the chimney with high thermal storage opaque materials on surfaces or on inner wall with glass surfaces; the absorbed solar radiation then increases the air inside the chimney, and then generates a natural ascending flow till the top of the chimney and finally it is evacuated outside (Suárez-López et al., 2015).
In Fig 1, we find that there are two typical solar chimney integration modes with building: one with opaque materials inside the chimney with glass outside surfaces and the other one with opaque material just placed outside the chimney surfaces. Normally, the second type is simpler for construction, but the first type has a better heat absorption and less energy loss, thus has a wider usage. There are currently many papers discussing solar chimney in order to reduce the building temperatures by applying natural ventilation. As solar chimney has been proved to be a reliable clean energy system and largely applied in built environment in response to global energy shortage (Shi et al. 2018). Among the researchers on solar chimney many adopted physical experiments to evaluate the ventilation effect. Cheng et al. (2018) introduced a solar chimney platform with a size of 1.5 m ×1.5 m ×0.9 m to evaluate natural ventilation and smoke exhaustion, and considered four influencing factors which include height of cavity inlet from the floor, cavity depth, solar radiation and fire size. Results show that the external radiation of solar chimney has obvious benefit on improving natural ventilation, however its benefit on smoke exhaustion is insignificant. Ahmed and Hussein (2018) made a hybrid solar chimney with PV panels (348 cm × 67 cm × 10 cm) and studied two types of solar chimney with different cover and absorber materials. The two types of solar chimney are similar as show in Fig.01, while the thermal storage material is changed by PV panels. It is found that the system with collector glass roof and PV panel absorber had higher thermal gain than the system with PV panel collector and plywood base absorber, but the latter’s daily average of electrical power was a little higher (6%). Zha et al. (2017) have studied a solar chimney with a dimension of 6.2m × 2.8m × 0.35m, and found that the air flow rate was 70.6 m³/h ~ 1887.6 m³/h during the test daytime of the transition seasons (from April to October), and solar chimney can save 14.5% of energy in Shanghai area. Some other researchers (Li and Liu 2014; Bashirnezhad et al. 2018; Fadaei et al. 2018) investigated the thermal behaviour of a solar chimney with different Phase Change Material, which is approved to be a promising research orientation of solar chimney application in future.

Currently, as the development of computation technology, CFD method is becoming an important tool to evaluate solar chimney for detailed design. Suárez-López et al. (2015) has built a three-dimensional CFD model validated with bibliographic experimental data. The study marks that the essential ways to enhance the solar chimney effectiveness include: 1. control fluid dynamic losses, 2. optimize the channel geometry with consideration of transversal distribution of the parameters, 3. reduce the energy losses by the glass and maintain the absorbed radiation. Ayadi et al. (2018) have adopted the code Ansys-Fluent platform to evaluate different impact of five turbulence models on the distribution of the air flow features. The work showed that the turbulence model types affect directly the numerical results. Zhang et al. (2021) used CFD simulation on the study of a one-storey wall solar chimney with different parameter of the wind channel. Neves and Silva (2018) have studied a solar chimney with both wind tunnel experiments and numerical simulations with EnergyPlus. It found out that the character of airflow at the outlets of solar chimney have close relationship with the thermal gradients and the outdoor wind environment. Ghanbari and Rezazadeh (2019) have studied a novel giant
chimney in order to improve the ventilation and to mitigate the urban air pollution problem. Authors found that a chimney in conditions with high altitude, low ambient temperature and unstable weather environment generally shows a better working performance.

Overall, most of the existing literature studied solar chimney on its geometry, layout and outdoor environment (such as temperature, wind velocity and direction), based on a small scale model (1-2 storey high) or a numerical model. However, examples of high-rise building with solar chimney are hardly found. As we know, high-rise buildings with huge facade areas normally have a big potential to produce renewable energies from solar radiation. There are many famous buildings that are well designed to utilise solar radiation to promote natural ventilation, for example, the Frankfurt Commerzbank Tower and the Pinnacle London Tower, which are separately analysed on the solar design aspects (Lotfabadi 2015a, 2015b). For many high-rise buildings in the metropolises, the vast facades can act as a great solar radiation gainer, which would be much potential to integrate solar chimney.

On the other side, the materials for radiation absorber for the solar chimney need to be selected. Most researchers use simple black-painting concrete wall (Al-Kayiem et al. 2018, Neves and Silva 2018), dark porous materials (Esmail et al. 2017) as heat-absorbing materials, while some others adopt PV panel (Ahmed and Hussein 2018). In fact, micro-algae integrated panel can be a good choice. Cervera and Pioz (2015) have introduced the micro-algae integrated panel for building envelop (window, wall and roof). Micro-algae photo-bioreactor has advantages such as energy storage, Co2 absorber, sugar, protein and oxygen producer, etc (Ai et al. 2008). Fig.02 shows an example of facade and roof design with micro-algae photo-bioreactor panels. In building integrated solar chimney design, vast of facade and roof area can be used for this algae photo-bioreactor panels as the envelop glass and solar radiation absorber.

![Figure 2. Algae photo-bioreactor integrated building facade and roof design (Cervera and Pioz 2015).](image)

2. Methodology

Inspired with the prototype of solar chimney power plant in Manzanares of Spain, a new type of building-integrated solar chimney is discussed in a previous paper (Wang et al. 2014), as shown in Fig. 3. Here an 11 story building is designed to integrate three types of solar chimney (SC): outside-wall SC, elevator shaft SC and atrium SC. The outside-wall SC here, which benefits from the neighbouring staircase as an additional radiation collector and chimney, can run much better than the separated wall SC. Also, to make the SC function more effectively, every atrium space for different floors is connected like a whole, so all the small atria can better benefit from the SC ventilation effect. For the two shaft SCs, the set of elevator shafts are the main chimney, with some other small facility shafts connected for greater flow, which acts as a smoke engine to improve the ventilation of the interior offices and the whole underground garage, but also to drive the set of turbines to generate electricity. In addition, apart from the big roof of the skirt-building, which connects to the SC shaft by hollow floor slabs, some solar vent-caps are applied as additional radiation collectors for the shaft SC and atrium SC. Furthermore, because the seasonal wind direction is southeast, the southeast side of the cap needs a wind-baffle system to reduce the counteraction to the upward airflow.
Figure 3. Example of high-rise building design integrate with solar chimney, R&D office building, Wuhan Solar-valley Software Park, China (Wang et al. 2014).

With consideration of other experiments results in the literature, wind flow in the buildings integrated SC may not strong enough to generate electricity, but efficient natural ventilation is generally obvious, especially for high-rise buildings as they offer higher air-pressure variance and bigger solar radiation receiver surface. With the objective of promoting natural ventilation for high-rise buildings, the research tries to study the integration of the three types of SC with parametric study. The proposed research ternary of the project can be drawn in Fig.4.

In the Fig.4, we can see that the research itinerary takes progress step by step as follows:
(1) Literature review, from literature review we learn from other experience methods and relevant research results.
(2) Primary Analysis of different SC. The three types of SC would be discussed separately on their geometry and layout optimisation as they varies from building to building. Each potential high-rise building would adopt 1-3 types of SC, define their forms and layout, with consideration of integrate with other functions such as atrium garden, vertical farm, green roof, etc. Different climate types, environment data and materials need to be analysed for all types of SC. Some of the influence aspects would become parameters and conditions for following evaluation.
(3) Parametric study plan is then defined by selecting the most influenced parameters. The plan should be logic and clear in operation.

(4) Possible experiments with small scale physical model would be undertaken. Most of the analysis would be done with the help of CFD simulation. The two methods would be compared in order to validate CFD simulation parameter and turbulence model.

(5) Optimised strategies of SC application then can be drawn from experiments and simulation. They would be varied in category with different type of high-rise buildings.

(6) Some real projects with high-rise buildings would be applied for new SC integration design with the drawn strategies.

Generally, the project adopts mainly 3 research approaches:

(1) Literature review. This enables definition of the research direction, and learning from relevant research results and research methods. Literature should be of high quality and better newly published. Similar documents should be compared of their research object, methods and research results.

(2) Experiments with physical SC model. In a small scale built a SC model, test the performance with some basic geometry and layout variances, as well as experiment with algae photo-bioreactor panel. Wind flow velocity, direction, temperature, solar radiation, humidity inside and outside the SC are measured and evaluated. The physical model is also the validation of CFD numerical simulation. A physical model example for solar chimney study is shown In Fig.5. Fig. 6 shows a scheme diagram of overall micro-algal cultivation system. And Fig. 7 shows a horizontal photo-bioreactor design for roof.

(3) CFD numerical simulation. This is the main method of this research. As the number of parameters to evaluate sorts of high-rise building SC is big, the experiments with physical model are far from enough to evaluate them. Thus CFD numerical simulation is adopted. When using it, first of all, its settings and turbulence model should be analysed and validated by the reference physical model experiments. CFD simulation has advantages such as: cost is relatively low; simulation time can be much saved due to high performance computer; initial conditions have little limit; measurement points

---

Figure 4. Project research itinerary.
can be set freely. However, its limits should also be considered such as: expert skill is necessary; easily misleading if inappropriate parameters are applied, thus validation and verification are usually needed. A CFD model for solar chimney study is shown in Fig.8.

Figure 5. Physical model example of solar chimney study (Ahmed and Hussein 2018).

Figure 6. Scheme diagram of overall micro-algal cultivation system (Yoo et al. 2003).

Figure 7. Horizontal photo-bioreactor for roof (Cervera and Pioz 2015).
3. Discussion
In this section we talk about the perspective and feasibility of this project.
Firstly, we could find the following originalities for implementing this project:
- Summarizing solar chimney types fitting for high-rise buildings in architecture design field.
- Parametric study of different high-rise building solar chimney by CFD simulation.
- Integration with roof garden and algae integrated window/wall system.
Secondly, we must search for multidisciplinary cooperation in this project, which concerns architecture, thermal physics, air dynamics, materials science and biology. For the whole stage architecture is concerned, for the earlier stage in the experiments and simulation thermal physics and air dynamics are concerned; while at later stage material analysis and biology are concerned.
Then for implementing this research, there are some necessary conditions of experiments:
- Basic office facility with high performance computer prepared to run CFD simulation;
- An outdoor site with full sun-access, minimal 0.6m*0.6m on plan and 5m in height. Empty flat roof or south or west facing walls are applicable for physical SC model installation;
- Apparatus such as illuminometer, anemometer, barometer, thermometer which can measure on probe points inside the solar chimney;
- Bio lab for biomass test and cultivation, apparatus to measure the biomass density and algal growth in the cultivated grey water.
With the conditions above we can implement the project. However, some of potential risks should be concerned beforehand, which include:
- Physical experiment installation and maintenance: site safety and permission of installation would be considered for physical solar chimney model. These potential problems would be tackled with the local institute.
- Experiment apparatus shortage and finance aid may not be enough. Possible solution: find a balance of the finance income and outcome, adjust the experiment measurement plan.
- Experiments within the Bio lab may not produce efficient materials for high-rise building solar chimney. Possible solution: accept the results but can analyze the reason and give suggestions for future research improvement on similar field.
- Instability of experiment condition due to some unexpected influence, which may lead to failure. Solution: repeat experiments and make comparison between some similar ones.

Figure 8. CFD model example of solar chimney study: (a) model profile, (b) wind velocity results (Suárez-López et al., 2015).
4. Conclusion
Solar chimney is proved to be an efficient method to promote natural ventilation for buildings. Though wind flow in the buildings integrated SC may not strong enough to generate electricity, but efficient natural ventilation is generally obvious, especially for high-rise buildings as they offer higher air-pressure variance and bigger solar radiation receiver surface. Three types of SC, namely outside-wall SC, elevator shaft SC and atrium SC, can be integrated with high-rise buildings. For better promoting and evaluating natural ventilation in high-rise buildings, parametric study with CFD simulation and physical experiments are proposed. On the other part, with the same aim to a clean and sustainable environment, bio-energy can be adopted in buildings by integrating with algae-fluid window and wall system. Different materials of radiation absorber can be studied and integrated with solar chimney. In order to succeed, close multidisciplinary cooperation is necessary for the project which involves at least architecture, thermal physics, air dynamics, materials science and biology. Experiment conditions and potential risk should be discussed beforehand.

Acknowledgments
Thanks to Prof. María Rosa Cervera Sarda from Universidad de Alcalá de Henares for her support on the resources on algae photo-bioreactor integration. This project is financially supported by the National Natural Science Foundation of China (51908002), Sino-Portuguese Culture Heritage Protection “One-belt-one-road” Joint Laboratory Project (2021YFE0200100), and the Academic Start-up Fund of Soochou University (GJ13800120).

References
[1] Ahmed O. K., Hussein A. S.. New design of solar chimney (case study). Case Studies in Thermal Engineering 11 (2018) 105–112.
[2] Ai W., Guo S., Qin L., Tang Y.. Development of a ground-based space micro-algae photo-bioreactor. Advances in Space Research 41(2008) 742-747.
[3] Al-Kayiem H.H., Sreejaya K.V., Chikere A.O.. Experimental and numerical analysis of the influence of inletconfiguration on the performance of a roof top solar chimney. Energy and Buildings 159 (2018) 89–98.
[4] Ayadi A., Nasraoui H., Bouabidi A., Driss Z., Bsisa M., Abid M. S.. Effect of the turbulence model on the simulation of the air flow in a solar chimney. International Journal of Thermal Sciences 130 (2018) 423–434.
[5] Bashirnezhad K., kavyanpoor M., Kebriyae S. A., Moosavi A.. The experimental appraisement of the effect of energy storage on the performance of solar chimney using phase change material. Solar Energy 169(2018) 411–423.
[6] Cervera R., Pioz J., Architectural Bio-Photo Reactors: Harvesting Microalgae on the Surface of Architecture, en Pacheco Torgal et al.(ed.), Biotechnologies and Biomimetics for Civil Engineering, New York, London: Springer. 2015.
[7] Cheng X. D., Shi L., Dai P., Zhang G.M., Yang H., Li J.. Study on optimizing design of solar chimney for natural ventilation and smoke exhaustion. Energy & Buildings 170 (2018) 145–156.
[8] Esmail M.A., Mokheimer, Mohammad Raghib Shakeel, Jihad Al-Sadah. A novel design of solar chimney for cooling load reduction and other applications in buildings. Energy and Buildings 153 (2017) 219–230.
[9] Fadaei N., Kasaeian A., Akbarzadeh A., Hashemabadi S. H.. Experimental investigation of solar chimney with phase change material (PCM). Renewable Energy 123 (2018) 26-35.
[10] Ghanbari M., Rezazadeh G.. Giant Chimney for Air Ventilation of Metropolises. Atmospheric Pollution Research 10(2019)462-473.
[11] Li Y, Liu S.. Numerical study on thermal behaviors of a solar chimney incorporated with PCM. Energy Build 80(2014) 406–14.
[12] Lotfabadi P.. Analyzing passive solar strategies in the case of high-rise building. Renewable and Sustainable Energy Reviews. 52(2015) 1340-1353.
[13] Neves L. O., Silva F. M.. Simulation and measurements of wind interference on a solar chimney performance. Journal of Wind Engineering & Industrial Aerodynamics 179 (2018) 135–145.
[14] Shi L., Zhang G.M., Yang W., Huang D.M., Cheng X.D., Setunge S., Determining the influencing factors on the performance of solar chimney in buildings, Renewable Sustainable Energy Rev. 88 (2018) 223–238.

[15] Suárez-Lópe M. J., Blanco-Marigorta A. M., Gutiérrez-Trashorras A. J., Jorge Pistono-Favero, Eduardo Blanco-Chungloo S., Limmeechokchai B., Application of passive cooling systems in the hot and humid climate: the case study of solar chimney and wetted roof in Thailand, Build. Environ. 42 (2007) 3341–3351

[16] Wang B., Adolphe L., Léa D. COT. New building typology for solar chimney electricity. In Cavallo R, Komossa S, Marzot N, Pont MB, Kuijper J (Eds), New urban configurations (293-298). IOS Press: Amsterdam. 2014.

[17] Yoo J.J., Choi S.P., Kim J.Y.H., Chang W.S., Sim S.J., Development of thin-film photobioreactor and its application to outdoor culture of microalgae. Bioprocess Biosyst Eng 36(2013) 729-736.

[18] Zha X.Y., Zhang J., Qin M.H., Experimental and Numerical Studies of Solar Chimney for Ventilation in Low Energy Buildings. 10th International Symposium on Heating, Ventilation and Air Conditioning, ISHVAC2017, 19-22 October 2017, Jinan, China Procedia Engineering 205 (2017) 1612–1619.

[19] Zhang H.H, Yao Tao, Kate Nguyen, Fengling Han, Jie Li, Long Shi. A wall solar chimney to ventilate multi-zone buildings. Sustainable Energy Technologies and Assessments 47(2021) 101381.