Study on Energy Performance of Passive Zone and Non-passive Zone in Office Buildings

Panyu Zhu\textsuperscript{1}, Da Yan\textsuperscript{1,3}, Hongsan Sun\textsuperscript{1}, Yu Huang\textsuperscript{2} and Yuan Jin\textsuperscript{1}

\textsuperscript{1} School of Architecture, Tsinghua University, Beijing 100084, China
\textsuperscript{2} School of Civil Engineering, Guangzhou University, Guangdong 510006, China
\textsuperscript{3} Corresponding author email: yanda@tsinghua.edu.cn

Abstract. Building form has great influence on energy performance. However, the indoor volume was usually considered as a whole and the difference between perimeter (passive zone) and core (non-passive zone) were rarely discussed. Actually, the energy performance of perimeter space is very unlike the core because of the accessibility to building envelope. The distribution of passive zones has direct influence on building form as well as energy use. In this paper, energy performance of passive and non-passive zones were studied by numerical simulations in three Chinese cities. Results indicate that passive zones normally require more thermal energy than non-passive zone in severe cold climate zone (Urumqi), while south-orientated passive zone could achieve less thermal demand in cold climate zone (Beijing and Lhasa). Among different orientations, the highest and lowest annual energy demand occurs in north- and south-orientated zone, respectively. High potential of energy saving on the west orientation is also noticed. When natural ventilation or window shading are considered, energy demand in west-orientated passive zone could be even lower than non-passive zone in Beijing and Lhasa. Understanding the energy performance of passive and non-passive zone could help to guide building design with the aim of energy saving in the future.

1. Introduction

At the early stage of design, one important task is seeking for the most proper building form. In 1960s, to answer the question “Which building form make the best use of land”, Leslie Martin and other researchers has examined six simplified urban arrays based on archetypal building forms. That research focused more on land-use efficiency rather than energy demand. Forty years later, Ratti et al. restarted the discussion and did analysis on building form archetypes with the consideration of environmental impacts [1, 2]. Since energy saving in building sector has become a hot topic, the energy impact of building form also attracted more attention. Ligang Liu, Borong Lin and Bo Peng examined eight cases of typical high-rise office building plane in six categories [3]. According to their simulation, the difference of energy consumption among these cases was reported to be up to 17%. Li Liu et al. focused on high-rise office towers in Tianjin and reported similar results [4]. In their research, the energy saving rate caused by different geometric factors could vary by up to 18.9%. Tian et al. employed both global sensitivity analysis and statistical machine learning method to examine the relationships between building form and energy performance [5]. Non-linear relationship between building form and energy use was reported by that research. Since building form could significantly affect energy use [6, 7], architecture design should be studied beyond the consideration of pure aesthetic.

Shape coefficient was the most popular index for architects to link building form and its energy performance. It was defined as the ratio of building envelope area to building volume. It was
introduced to Chinese building design standard since the first version in 1986 (JGJ 26-1986). However, the shape coefficient could only suggest for a compact form (low shape coefficient) or an open form (high shape coefficient). Its applicability was questioned by many researchers. Lan et al. pointed out that the relationship between the shape coefficient and energy efficiency had certain prerequisites by deduction of thermal calculations [8]. According to that research, the ratio of building envelope area to building floor area is more suitable as an index in energy saving standard. Granadeiro et al. reported that the shape factor failed to correlate with energy demand with the presence of solar gains [9]. Depecker et al. argued that the shape coefficient should not be applied in case of mild and sunny climate [10]. Albatici and Passerini introduced a new index, which is called south exposure coefficient (south wall area/volume) to overcome the disadvantage of the shape coefficient [11].

All above-mentioned indicators treated indoor space as a whole zone without the consideration of perimeter area and core area. Actually, the energy performance of perimeter space is very unlike core space [12, 13]. On-site measurement has shown that in the same open office the core zone could be up to 4℃ warmer than perimeter zone [13]. Since these two parts of indoor area have different accessibility to building envelope, their energy performance should be examined separately. The indoor space whose depth was limited to twice the ceiling height was mentioned as “passive zone” (figure 2) by Ratti and some other researchers [1, 2]. Beyond this distance, indoor space (non-passive zone) is hardly be influenced by natural environment. This paper focused on the different energy performances of non-passive zone and passive zones. Based on this understanding, it is possible to propose more reasonable indicator to describe the relationship between building form and its energy performance in future research.

2. Methodology

According to the definition of passive zone, a unit with the volume of 6m×6m×3m was used to represent a typical zone in this research. As shown in figure 3, each passive zone contained one external wall (window included), three internal walls, one ceiling and one floor. In order to reduce the time cost of simulation, a composite model that was made up of 27 units was built as the basic model (figure 3). It could be considered as simplified prototype of a cubic-shape office building. In this composite model, all of these units were considered as office rooms with 3~4 persons each. Four units on the second floor were selected to represent passive zone with certain orientation. The unit in the core represented non-passive zone. No flow circulation between adjacent units were considered in this model.
Figure 1. Structure of this research.

Figure 2. Energy balance in a passive zone.

Figure 3. Passive zone unit, the basic model, and four representative passive zones.
Energy performance of these representative passive zones and non-passive zone were examined by using simulation tool DeST (Designer’s Simulation Toolkit), which was developed by Tsinghua University and widely used in China [14, 15]. Detailed information of the basic model and simulation settings was listed in table 1. Urumqi, Beijing and Lhasa were selected to represent three typical combinations of temperature and solar radiation (table 2). Thermal condition of building envelope and window-to-wall ratio followed Design Standard (table 3). Mechanical and natural ventilation were considered as two scenarios with the air change rate 1 ach and 10 ach, respectively. In natural ventilation scenario, when outdoor temperature was lower than 26 °C during working period in summer, windows were set to be open and cooling system was turned off. Shade coefficient of 0.3 is considered as shading equipment. When solar radiation on the façade is higher than 280W/m² (240 kcal/ m²h), blinds on that facade were turned on to avoid excessive solar gain. As control group, passive zones with no shading system were also simulated.

**Table 1.** Detailed information of the basic model and simulation settings.

| Settings                              | Values                      |
|---------------------------------------|-----------------------------|
| Type of Room                          | office                      |
| Occupant Density [m²/person]          | 10                          |
| HVAC Operating time                   | 08:00 – 17:00               |
| Heating Period                        | 15th Nov - 15th Mar         |
| Heating Setpoint [°C]                 | 18                          |
| Cooling Period                        | 1st Jun - 31th Aug          |
| Cooling Setpoint [°C]                 | 26                          |
| Lighting [W/m²]                       | 9                           |
| Electrical Equipment [W/m²]           | 15                          |
| Heating System                        | District Heating            |
| Heating System Efficiency             | 70%                         |
| Cooling System                        | Split Air Conditioner       |
| Cooling System Efficiency (COP)       | 3                           |
| PE-factor of Fuel Source (Gas)       | 1.1                         |
| PE-factor of Fuel Source (Electricity)| 2.7                         |

**Table 2.** Climate condition of Urumqi, Beijing and Lhasa.

| City       | Climate Zone                  | Outdoor Temperature | Solar Radiation |
|------------|--------------------------------|---------------------|-----------------|
|            | Average Temperature (January) | Average Temperature (July) | Global Radiation [MJ/(m²a)] | Annual Sunshine Hours [h/a] |
| Urumqi     | Severe Cold Zone               | ≤ -10               | ≤ 25            | II                      | 5400-6700 | 3000–3200 |
| Beijing    | Cold Climate Zone              | -10–0               | 18–28           | III                     | 4200-5400 | 2200–3000 |
| Lhasa      | Cold Climate Zone              | -10–0               | 18–28           | I                       | > 6700   | 3200–3300 |
Table 3. Thermal condition of building envelope according to GB50189-2015 (GB50189-2005).

| WWR       | Severe Cold Zone (Urumqi) | Cold Zone (Beijing + Lhasa) |
|-----------|--------------------------|-----------------------------|
|           | 30% | 50% | 70% | 30% | 50% | 70% |
| U-roof [W/(m²K)] | 0.28 (0.35) | 0.40 (0.45) |
| U-wall [W/(m²K)]  | 0.38 (0.45) | 0.45 (0.50) |
| U-window [W/(m²K)] | 2.4 (2.5)  | 1.7 (1.8)  |
| SHGC      | -  | 0.5 (0.5) | 0.5 (0.5) |

3. Results and discussions

The simulation result about thermal demand was shown as figure 4 and figure 5. In Urumqi, the heating demand of non-passive zone was always lower than that of passive zone. In Beijing and Lhasa, south-orientated passive zone required less heating supply than non-passive zone. This was mainly caused by different climate conditions. In Urumqi, because of the huge temperature difference between indoor and outdoor environment in winter, the heat loss through building envelope was a lot. In Lhasa, thanks to the rich solar energy, the heat loss could be covered by the benefit from solar gain. Besides of south-orientated passive zone, even the west-orientated passive zone was more energy-efficient than the non-passive zone in heating season in Lhasa.

![Figure 4. Heating demand in non-passive and passive zones.](image)

![Figure 5. Cooling demand in non-passive and passive zones.](image)

Regarding to cooling demand, non-passive zone had the lowest cooling demand in all cases, because in non-passive zone there was neither heat transfer through building envelope nor excessive solar gain.
Among different orientations, the west-orientated passive zone required the most cooling energy, while the north-orientated passive zone had the least demand.

By comparing heating and cooling demand separately, it could be concluded that non-passive zones require less thermal demand in cooling season, while passive zones may have advantage in heating season. In order to have a comprehensive consideration of energy performance in the whole year, it is necessary to convert energy demand into primary energy (including heating and cooling) by using system efficiency and primary energy factor of fuels. The result was shown as figure 6.

![Figure 6. Primary energy demand of passive zone and non-passive zone.](image)

According to the simulation result (figure 6), non-passive zone has lower energy demand than passive zones in Urumqi, while south- and west-orientated passive zone require less thermal energy in Lhasa, where solar energy was abundant. The update of design standard reduce energy demand of passive zones in Urumqi but show a negative impact in Beijing and Lhasa. It is caused by the combined effect of heat transfer coefficient (U-value) of building envelope and the solar heat gain coefficient (SHGC) of external window. Both U-value and SHGC were lower in the new version. The reduced U-value led to less heat loss but the reduced SHGC would cause less solar gain, which increased the heating load. In Beijing and Lhasa, the advantage of better envelope was compensated by the reduced solar gain. In Lhasa, where solar energy was abundant, this effect was more significant.

![Figure 7. Impact of WWR on primary energy demand.](image)

The impact of Window-to-Wall Ratio (WWR) was also studied. Because of the combined effect of heat loss and solar gain through building envelope, high WWR seems to be more suitable in Beijing and Lhasa, while low WWR be fit for Urumqi. However, this impact was not significant in this research. It was because that, according to Design Standard, SHGC of window decreased while WWR increased in cold climate zones, where Beijing and Lhasa locate in. This rule could get rid of overheating in summer, but also limit the passive solar gain in winter.
It was also noticed that the cooling demand of passive zone was significantly reduced by using shading system (figure 8). Although cooling demand of non-passive zone was still slightly lower than that of passive zone, the difference between passive-/ non-passive and among different orientations was much smaller. The narrowed gap between non-passive zone and passive zones was also found when natural ventilation is applied (figure 9).

Figure 8. Comparison of cooling demand between different shading concepts.

Figure 9. Comparison of cooling demand between different ventilation concepts.

4. Conclusion
This research discussed energy performance of passive and non-passive zones in three Chinese cities by numerical simulations. Compared to passive zones, non-passive zone requires less thermal energy in severe cold climate like in Urumqi. However, in cities whose climate is not severe cold (Beijing and Lhasa), south-orientated passive zone is better. Among different orientations, north-orientated passive zone has the highest thermal demand while south-orientated passive zone has the lowest. The west-orientated passive zone was highlighted by its high potential of saving energy. Natural ventilation and window shading have shown very positive impact on the energy performance of passive zones. When natural ventilation or window shading was considered, energy demand in west-orientated passive zone could be even lower than non-passive zone in cold climate zone (Beijing and Lhasa). It was also noticed that, adapting updated version of Design Standard did not reduce energy demand significantly. Understanding the energy performance of passive and non-passive zone could help to guide building design with the aim of energy saving in the future.

5. References
[1] Ratti C, Raydan D and Steemers K 2003 Building form and environmental performance archetypes analysis and an arid climate J. Energy and Buildings 35 49-59.
[2] Ratti C, Baker N and Steemers K 2005 Energy consumption and urban texture J. Energy and Buildings 37 762-776.
[3] Liu L, Lin B and Peng B 2015 Correlation analysis of building plane and energy consumption of high-rise office building in cold zone of China J. Build Simul 8 487-498.
[4] Liu L, Wu D, Li X, Hou S, Liu C and Jones P 2017 Effect of geometric factors on the energy performance of high-rise office towers in Tianjin, China J. Build Simul 10 1-17.

[5] Tian W, Yang S, Zuo J, Li ZY and Liu YL 2016 Relationship between built form and energy performance of office buildings in a severe cold Chinese region J. Build Simul 10 11-24.

[6] Weng Z, Ramallo-González AP and Coley DA 2015 The practical optimisation of complex architectural forms J. Build Simul 8 307-322.

[7] Wang W, Rivard H and Zmeureanu R 2006 Floor shape optimization for green building design J. Advanced Engineering Informatics 20 363-378.

[8] Lan B and Huang L 2013 Query on Relationship Between Shape Coefficient of Building and Energy Efficiency J. Building Energy Efficiency 41 65-70.

[9] Granadeiro V, Correia JR, Leal VM and Duarte JP 2013 Envelope-related energy demand: a design indicator of energy performance for residential buildings in early design stages J. Energy and Buildings 61 215-223.

[10] Depecker P, Menezo C, Virgone J and Lepers S 2001 Design of buildings shape and energetic consumption J. Building and Environment 36 627-635.

[11] Albatici R and Passerini F 2011 Bioclimatic design of buildings considering heating requirements in Italian climatic conditions. A simplified approach J. Building and Environment 46 1624-1631.

[12] Shen H and Tzempelikos A 2013 Sensitivity analysis on daylighting and energy performance of perimeter offices with automated shading J. Building and Environment 59 303-314.

[13] Xue Z and Jiang Y 2003 System zoning in the VAV system design J. HV&AC 33 87-90.

[14] Yan D, Xia J, Tang W, Song F, Zhang X and Jiang Y 2008 DeST—An integrated building simulation toolkit Part I: Fundamentals J. Build Simul 1 95-110.

[15] Zhang X, Xia J, Jiang Z, Huang J, Qin R, Zhang Y, Liu Y and Jiang Y 2008 DeST—An integrated building simulation toolkit Part II: Applications J. Build Simul 1 193-209.

Acknowledgments
Project Prediction method of building energy consumption in urban scale based on DEM (Digital Elevation Model) and occupant behavior research was supported by the National Natural Science Foundation of China (Grant No. 51708324).