Study on Thermal Environment Evaluation in the Central Business District of Shanghai

Jian Wang1, Weijun Gao2, Li Haifeng3, Penglin Zhao4, Jianxing Ren5 and Toshio Ojima6

1Senior Engineer, The Architectural Design & Research Institute of Tongji University, P.R. China
2Associate Professor, Faculty of Environment Engineering, The University of Kitakyushu, Japan
3Research Associate, Department of Architecture, Waseda University, Japan
4Chief Engineer, Shenzhen Municipal Planning & Land Bureau, P.R. China
5Professor, Department of Power Engineering, Shanghai Institute of Electric Power, P.R. China
6Professor, Department of Architecture, School of Science and Engineering, Waseda University, Japan

Abstract
With the quick development of Shanghai, energy consumption has increased fast in recent years, which leads to the environmental problems. In this paper, we proposed a cluster model to the CBD of Shanghai and have an evaluation on this plan in order to give a way to reduce the energy consumption and the emission of CO2 for air conditioning. The basic concept of cluster model in urban planning is that buildings and natural conditions (green lands or rivers) should be co-existed. Based on natural conditions in current urban area, we set more land for green areas and rivers as possible. And the decrease of land area will be made up with the construction of high-rises. The results were found that the cluster model could give a good answer to mitigate the thermal environment and CO2 emission. And this will also be available for reference for other megalopolis in Asia.

Keywords: cluster model; high-rise; thermal environment evaluation; cooling load; Shanghai

1. Introduction
Many high-rise buildings have been constructed in Shanghai in recent 10 years, and the total number has reached nearly 3000 with floor area of 45 million m² by the end of 1998. At the same time, energy consumption had increased from 32.2 million ton Standard Coal Equivalent (SCE, one SCE=about 7000kcal/kg) in 1990 to 39.3 million ton SCE in 1999\(^1\). On the other hand, the large amount of energy consumption has caused serious environmental problems, especially in the Central Business District (CBD), which are densely populated and clustered by high-rises. The emission of CO2 had reached to about 3.4 tons per person in 1998, which was the highest all over China, and the total amounted to nearly 50 million tons. In addition, the “Heat Island” phenomenon has been more and more obvious in the CBD, where the air temperature is 2–3°C higher than that in the suburbs during the summer in recent years.

While today’s mega-cities in advanced industrial countries took more than 100 years to build, the mega-cities of Asia have experienced large increases in population in a very short period of time. For example, Shanghai had a population of six million in 1970(figure 1). In 1995, merely one generation later, this ballooned to 12 million, an increase of 100% (Shanghai 1997)\(^2\). Moreover, we see further rapid increases in the population of urban centers in Asia, surpassing the levels in major centers in the U.S. and Europe. This is the problem of excessive urbanization, and with it comes a host of problems, not least of which is environmental deterioration. The cause of such deterioration, however, is not due to explosive population growth alone. Our investigations have focused on how the lack of greenery in urban centers actually contributes to the environmental problem (Haifeng Li)\(^3\). Urban centers in the U.S. and Europe

Contact Author: Jian Wang, Senior Engineer, The Architectural Design & Research Institute, Tongji University Siping Load 1239, Shanghai, P.R. China Tel: +86-21-63130327 Fax: +86-21-65985121 e-mail: wjandqqk@online.sh.cn
(Received May 7, 2002; accepted August 19, 2002)

Fig.1. The Yearly Change of Population in World Big Cities
now enjoy a better air quality while Asian urban residents suffer from high doses of pollutants from combustion of heavy oil and coal fuels. It is interesting to note that urban centers in the U.S. and Europe also have much more greenery and better transportation systems compared to Asian cities. In this article, we propose a cluster model to study the energy consumption and emission of CO\textsubscript{2} in the CBD of Shanghai with an area of 10km\textsuperscript{2}. Thus to try to find out a way to reduce energy consumption and the emission of CO\textsubscript{2} for Shanghai, and this will also be available for reference for other Asian megalopolis in future.

2. Cluster Model

The basic concept of cluster model (figure 2) in urban planning is that buildings and natural conditions (green lands or rivers) should be co-existed, and they can also be sub-divided into small blocks. Based on natural conditions in current urban area, we set more land for green areas and rivers as possible. And the

![Fig.2. Cluster Model](image)

![Fig.3. Merit from Clusterization](image)

![Fig.4. Urban Planning in the CBD of Shanghai (Area 10km\textsuperscript{2})](image)
decrease of land area will be made up with the construction of high-rises. In addition, the floor area of residential buildings will be increased, thus to improve people’s living situations.

The urban district is consisted with many small clusters, which contain green lands and rivers each. Here we assume crossing of traffic infrastructures, such as roads, railways, as the center of clusters. Each cluster is connected with others through these crossings. Thus they make up a network. So the urban district is composed of the network of buildings and natural conditions in our Cluster Model (Figure 2). The figure 3 gives us the merit by introducing the cluster model.

3. Cluster Model in the CBD

As is shown in figure 4, many high-rise buildings have been constructed in CDB. Referring to clusterization of Tokyo5), we divide the CBD of Shanghai in meshes with the size of 500m×500m(Table 1). Based on cluster model, buildings in CBD can be divided into 2 categories. One is for residence and the other is non-residence. Besides, one mesh is only for one purpose. We take one non-residence mesh as the central point and locate it at crossing point of existing traffic infrastructure. There are many other residence and non-residence building meshes surrounding this non-residence mesh. Natural conditions, such as green lands and rivers, are included in these meshes. At the same time, refuge places for disasters and rest places for emergency have also been considered.

Our Model is set based on following conditions:
1. Population: Maintain existing population of Shanghai
2. Green land and water areas: Reserve existing water area and green land. Take river as center to do planting, thus to join water area with green land. And the area of water and green land accounts for at least 50% of the total.
3. Residential facilities: Residential area will be 2 times of existing area. Try to construct independent dwelling houses as possible.
4. Non-residence facilities: Maintain the present floor area.
5. General conditions of building: When the building coverage ratio is below 50%, we assume the working areas are adjacent with the residential ones in different districts.

The land use in two cases was shown in figure 5.

4. Evaluation Method of Urban Thermal and Energy Environment

The evaluation process was shown in figure 6. Firstly, we have established databases of land use and artificial heat release. Based on those databases, a thermal environmental simulation has been carried out based on present condition and cluster model. And then, the decrease of energy consumption for cooling and absorption amount of CO2 by green land have been calculated and evaluated. Relative improvement measures have finally been discussed. Each item is calculated as follows:

| 3D image | Core High-rise Buildings | Penthouse1 | Penthouse2 | Collective Housing | Dwelling Houses |
|----------|--------------------------|------------|------------|--------------------|-----------------|
| Land use (ha) | Building 3.20(13%) | 10.38(41%) | 9.23(37%) | 3.38(14%) | 4099(20%) |
| Road 12.04(48%) | 11.16(45%) | 8.80(35%) | 9.00(36%) | 10.79(43%) |
| Green land 9.76(39%) | 3.46(14%) | 5.74(23%) | 12.62(50%) | 8.74(35%) |
| Water area - | - | 1.23(5%) | - | - |
| Floor area (ha) | Residence 250.00 | 62.28 | 55.38 | - | - |
| Non-residence - | 10.38 | 9.23 | 77.74 | 12.48 |
| Gross coverage ratio (%) | 13.80 | 41.52 | 36.92 | 310.96 | 19.96 |
| Gross capacity ratio (%) | 1000 | 290.64 | 258.44 | 13.52 | 49.92 |
4.1 Thermal Environment Evaluation

In order to evaluate the thermal environment by changing the urban land use, the three dimensions model by Ojima laboratory, Waseda University, has been used in this study. The conservation equation for momentum, mass, and energy can be generally described as below.

**Energy equation**

\[
\frac{dT}{dt} = D_j \frac{\partial}{\partial x_j} \frac{\partial T}{\partial x_j} + \frac{Q}{\rho C_p \rho}
\]

**Mass equation**

\[
\frac{\partial U_i}{\partial x_i} = 0
\]

**Momentum equation**

\[
\rho \frac{dU_i}{dt} = \frac{\partial P}{\partial x_i} + D_j \frac{\partial U_i}{\partial x_j} + \rho g_i
\]

Where, 
- \(T\): air temperature (°C)
- \(U_i(U,V,W)\): air velocities at x, y, z directions (m/s)
- \(D_i\) (Dx,Dy,Dz): diffusive coefficients at x, y, z direction (m²/s)
- \(Q\): internal heat source
- \(g_i\): air gravity (Kgf/m³)
- \(P\): air pressure (kg/m)
- \(C\): air specific heat (kJ/kg°C)

In this study, the following assumption has been used to simplify the above equation as below,
1) air flow is uniform with a constant air gravity and thermal capacity
2) turbulent eddy diffusive for energy and momentum are equivalent
3) the effects of thermal capacity of the buildings are neglected.
4) the air flow is divided into two arts. one is the general

![Fig.6. Evaluation Flow Chart](image)

![Fig.7. Results of Thermal Environmental Simulation](image)
current and the natural current defined as follows.

\[ U = (\overline{U} + u_i) \quad P = (\overline{P} + p) \]

5) The vorticities are defined as follows,

\[ \omega_i = \frac{\partial U_i}{\partial x_j} - \frac{\partial U_j}{\partial x_i} \]

6) The natural current flow \((a, b)\) is generally smaller than the general current flow \((A, B)\). Therefore, the following assumption can be assumed.

\[ AB = (\overline{A} + a)(\overline{B} + b) = \overline{A}B + a\overline{B} + \overline{A}b + ab \]

The calculated area has been selected in this study shown in figure 4. The urban has been assumed to be continuous. The boundary condition above the z direction has been assumed to the same climate condition, which is a general weather condition, recorded in the weather station.

In the ground surface, the heat balance can be written by the following equation

\[ Q_i = Q_{so} + Q_{d} + Q_{vp} + Q_{cd} \]

where

- \(Q_{so}\) = solar radiation absorbed by the ground surface (kJ/m²h)
- \(Q_{d}\) = convection heat flow (kJ/m²h)
- \(Q_{vp}\) = evaporation heat flow (kJ/m²h)
- \(Q_{cd}\) = long-wave radiation heat flow (kJ/m²h)
- \(Q_{cd}\) = heat conduction into the earth (kJ/m²h)

Although the air temperature and wind distribution should be gained through solving the above equation together with the energy and momentum equation, the separate step has been applied that the surface temperature distribution firstly is determined by assuming the air temperature is known and then the air temperature and wind distribution can be calculated using the surface distribution.

4.2 Energy Calculation

Because there is no energy consumption unit for buildings in Shanghai, we use the index of Tokyo for reference and make relative amendments with climate.

\[ E_{shanghai} = E_{tokyo} \frac{ECD_{shanghai}}{ECD_{tokyo}} \]

Where, \(E_{shanghai}\) = energy consumption unit of Shanghai
\(E_{tokyo}\) = energy consumption unit of Tokyo in summer
\(ECD_{shanghai}\) = Extented Cooling Degree Day in Shanghai and Tokyo, respectively

4.3 Absorption of CO₂ Emission

Plant absorbs CO₂ through photosynthesis function as well as discharge CO₂ by breathing. Therefore, net CO₂ absorption by plant can be determined by difference between photosynthesis and breathing.

\[ C = 3.9 \times \frac{G}{10000} \]

Here,
\(C\) = Absorption quantity of CO₂ emission (ton/year)
\(G\) = Green Land Area (m²)

5.Results

5.1 Thermal Environmental Evaluations

The thermal environment of urban area has predicted by using the model presented in 4.1. Figure 7 showed the air temperature distribution between the present situation and cluster model. The present situation gave a maximum air temperature about 35.5 °C while the cluster model gave it about 32.4 °C. About 3.1 °C decrease in air temperature has been observed although the capacity and artificial heat release have not been increased. The average air temperature of cluster model is 3 °C lower than that of existing conditions. From this we can see, green land area has great impact on city’s air temperature. In addition, thermal diffusion can greatly mitigate high
temperature of ground surface and have the effect of restraining temperature rise of ground surface.

5.2 Energy Consumption Evaluation

Figure 8 gave a comparison of summer cooling load between present situation and cluster model by using corrected summer cooling energy unit. Summer peak cooling energy in present condition is about 109(kcal/m².h). In cluster model it will be about 70 (kcal/m².h). About 39(kcal/m².h) will be cut down. The decrease is mainly due to thermal environment improvement and the decrease of envelope area by high-rise buildings.

5.3 Absorption Quantity of CO₂ Emission by Green Land

Because the green area is increased from 3% in present situation to 43% in cluster model, the absorption of CO₂ in cluster model significantly increase. As Figure 9 shows, absorption quantity of CO₂ emission can be about 14 times of the current value.

6. Conclusion

With the quick development of Shanghai, energy consumption has increased fast in recent years, which leads to the environmental problems. In this paper, we proposed a cluster model to the CBD of Shanghai and have an evaluation on this plan in order to give a way to reduce the energy consumption and the emission of CO₂. The basic concept of cluster model in urban planning is that buildings and natural conditions (green lands or rivers) should be co-existed. The results were found that the cluster model could give a good answer to mitigate the thermal environment and CO₂ emission. And this will also be available for reference for other megalopolis in Asia.

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