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CLIMATIC COOLING POTENTIAL EVALUATION AND VENTILATION STRATEGY OPTIMIZATION FOR BUILDING ENERGY SAVING IN CHINA

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ABSTRACT

Reasonable mechanical ventilation strategy and system design can effectively save building energy usage for space cooling in summer. In this paper, the climatic cooling potential of major cities in China is evaluated based on the CCP index values, and a guide map for accessing night cooling potential is provided. Furthermore, for ventilation strategy optimization in city buildings, the ideal air change rate (ACH) is obtained by using inverse problem approach. The preliminary results indicate that the ideal ventilation strategy is favorable for free cooling energy exploitation in the night, to save cooling energy consumption in summer. It also shows that both CCP value and energy saving ratio of ventilation optimization decreases from north to south in China. This study is significant in guiding and optimizing building ventilation systems in engineering applications.

Keywords: building energy efficiency, night ventilation, inverse problem, space cooling

1. INTRODUCTION

Energy consumption increased by 5.6% annually in China [1]. While near 1/3 of the total energy usage comes from buildings, including space heating, cooling and ventilation systems [2]. Mechanical ventilation, integrated with free cooling and air-conditioning in summer and transient seasons can effectively save the energy consumption of air conditioning systems [3].

By making most use of natural cooling sources, climatic ventilation proves to be a good measure to reduce the energy consumption of air conditioning in buildings [3, 4]. To determine the ventilation strategy of free cooling and heating, Artmann [5] designated a new index, climatic cooling potential (CCP), according to the indoor and outdoor air temperature difference. Based upon that, he figured out the applicability of night ventilation for energy saving, for typical European countries of different climatic conditions respectively. Then he further investigated the impact factors of night ventilation and conducted sensitivity of main climatic conditions [6]. Lin [7] integrated phase change materials into building envelopes, and combined them with night ventilation to store the cooling capacity in the night.

In this paper, the climatic cooling potential of major cities in China is evaluated based on the CCP values, and a guide map for accessing night cooling potential is provided. Furthermore, for ventilation optimization in city buildings, the ideal air change rate (ACH) is determined through inverse problem method.

2. METHOD

2.1 Climatic cooling potential of cities in China

To assess the cooling potential of night ventilation under known climatic parameters, Artmann [8] defined a novel concept, climatic cooling potential (CCP), to represent the cooling potential of specific regions. According to its definition, the CCP value for a certain ventilation system can be obtained by [8, 13]

$$CCP = \frac{\sum_{n=1}^{N}\sum_{h=1}^{24} m_{n,h}(T_{i,n,h} - T_{a,n,h})}{N}, m = \begin{cases} 1, T_i - T_a \geq \Delta T_{cri} \\ 0, T_i - T_a < \Delta T_{cri} \end{cases} \quad (1)$$

where ΔT_{cri} is the critical value of indoor and outdoor air temperature difference, which determine to active the night ventilation system. For the studied case, it is assumed that night ventilation starts at 7 p.m. and ends at 7 a.m. of the next day. As the climatic cooling potential various dramatically between different climatic conditions, it is very important to derive the optimized combined ventilation strategies to make full use of the calculated cooling potential, also the maximum energy saving potential should be analyzed based on the optimized strategies, which is similar to the function of Carnot cycle.

2.2 Ideal air exchange rate

To maintain a comfortable thermal environment, the indoor operative temperature ($T_{i,o}$) is used to comprehensively evaluate the effects of indoor air temperature and radiations. If $T_{i,o}$ exceeds the upper temperature value of thermal comfort zone (i.e., 26 °C), the air conditioner works to fulfil the cooling demand. When the amount of daily cooling loads (Q_c) and the coefficient of performance (COP) of air conditioner are known, the energy consumption (EC) of space cooling can be expressed by EC=Q_c/COP.

To simplify calculation, the air change rate (ACH) of the room is assumed to be a constant value in each hour throughout the simulated day. It is assumed that the mechanical ventilation is provided by an ideal fan, whose air volume speed is variable, and its power (P) has a cubic correlation with its rotate speed (n_{fan}):

$$\frac{P_{fan}}{P_r} = (\frac{n_{fan}}{n_r})^3 = (\frac{ACH}{ACH_r})^3 \tag{2}$$

where subscript r denotes the value under rated condition. Thus, the daily energy consumption of the ventilation fan can be obtained by the accumulation of fan power in each hour for a given air volume speed n_{fan} (r/min). Therefore, the daily total energy consumption derives from the electricity usage of both air conditioner (AC) and ventilation fan: $EC=EC_{AC}+EC_{fan}$. For one thing, stored cooling capacity of night ventilation rises with growing ACH, leading to the reduction of EC_{AC}. For another, EC_{fan} increases with increasing ACH.

To obtain the ideal ACH value of the lowest total energy consumption for night ventilation, inverse problem approach is utilized here [14]. Therefore, the mathematical model of this optimization problem is built as follows [3, 8].

Unknown: air exchange rate (ACH).

Optimization objective:

$$\min EC_{AC} + EC_{fan} = \int_{day} \frac{Q_C(\tau)}{COP} d\tau + \int_{day} EC_{fan}(\tau) d\tau \tag{3}$$

Constraint conditions: indoor thermal comfort and fresh air supply requirement (ACH>0.5) [3]. To address such a non-linear optimization, sequence quadratic programming (SQP) algorithm is applied, which solves a quadratic model of the objective function to a linearization of the constraints [3, 8]. The next part provides a case study to show the results of night ventilation optimization.

2.3 Illustrative example

Fig 1 shows a simplified heat transfer model in a room with ventilation. This model had been validated and applied to building simulations [3].

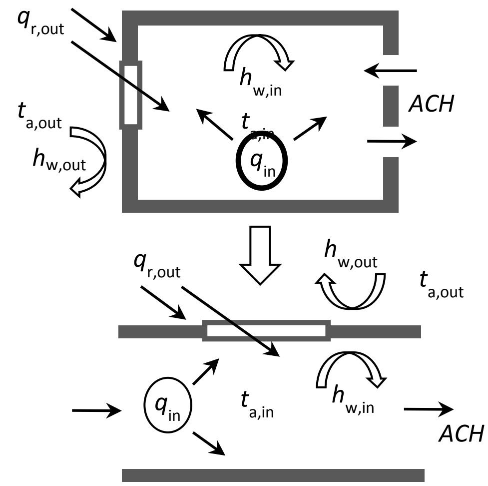

Fig 1 Heat transfer processes in two-plate room model

Table 1 Simulated room information

Iterm	Value
Size	6.0 m × 4.0 m ×3.5 m
Window wall ratio	0.3
Internal wall	0.2 m concrete hollow block (ρc_p =1500 kJ/m^{3o}C, k=1 W/m ^{o}C)
External wall	0.25 m reinforced concrete (ρc_p =2300 kJ/m^{3o}C, k=1.74 W/m ^{o}C) + 0.07m polystyrene board (ρc_p = 48 kJ/m^{3o}C, k=0.046 W/m ^{o}C)
Window	k=3.1 W/m$^{2\ o}$C, Shading coefficient=0.44

For the illustrative example, a south-faced room of an office building in Beijing is studied in this case. Table 1 gives the key information of the studied room. Besides, the average indoor heat source is assumed to be 10.8 W/m^2 and the air conditioner will open for space cooling if indoor temperature exceeds 26 °C.

3. RESULTS AND DISCUSSION

The CCP values of major cities include various climatic conditions in China were calculated out, respectively (Fig 2). It can be inferred from Fig 2 that the CCP value decreases from northwest to southeast, which reveals higher cooling potential in northwestern regions. That may be caused by the higher daily temperature difference in northwestern places.

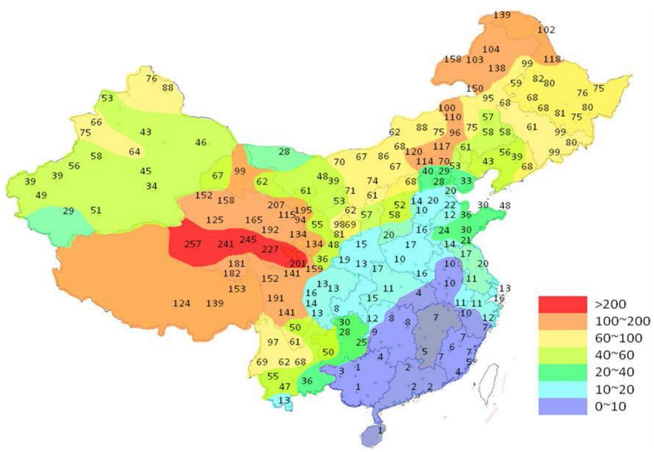

Fig 2 CCP values of major cities in China

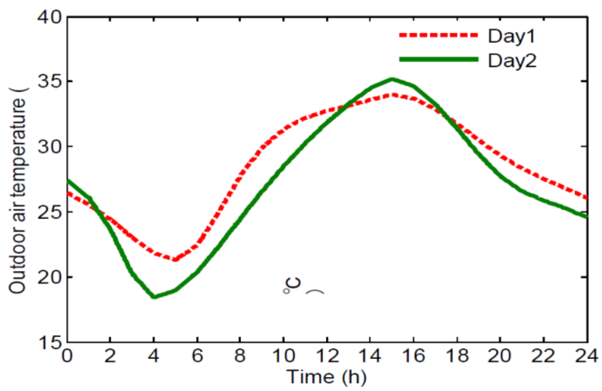

Fig 3 Ambient temperature in summer in Beijing

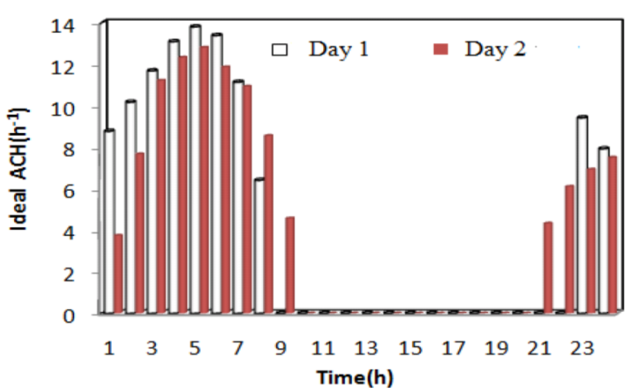

Fig 4 Ideal hourly ACH values of the stuided office room

Two days are picked out to represent different kind of climatic conditions of Beijing in summer (Fig 3). The optimal ventilation strategies of simulated room can be derived using the formal proposed inverse problem method (Fig 4). It is clear that the optimized ACH value is larger than that of the conventional natural ventilation system (0.5 h^{-1}), especially in the night, when ACH can reach as high as 14^{-1}, aimed to store free cooling capacity by the building envelope to reduce the cooling energy usage for the next day.

Fitting analysis is applied to the optimized results. A strong correlation between the ideal ACH value and difference between wall surface (T_s) and outdoor temperature (T_o) is found (Fig 5). It is clear that the ideal ACH value always rises with the growth of temperature difference between indoor and outdoor air. Under such optimized ventilation strategy, the total daily energy consumption can be obtained. As Fig 6 shows, the cooling energy consumption can be reduced by about 78 % after ventilation strategy optimization.

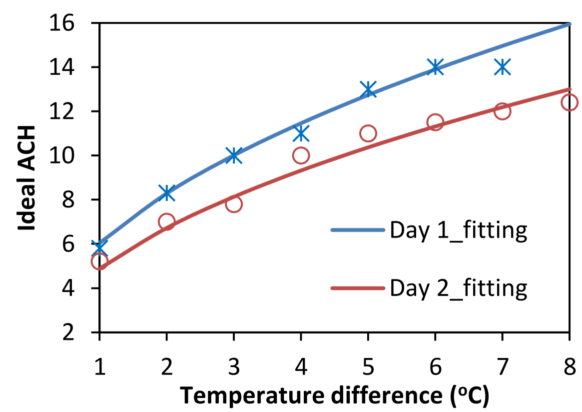

Fig 5 Fitting results of ACH on simulated days

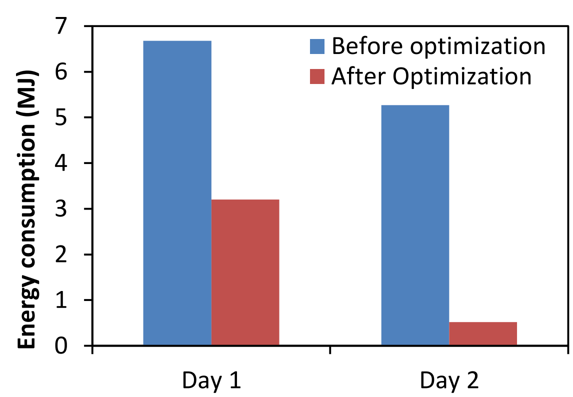

Fig 6 Cooling energy consumption in one summer day

After optimization of night ventilation ACH, the overall total energy consumption decreases by 52.0% and 90.2% compared to traditional ventilation system (ACH=0.5 h^{-1}) for Day 1 and Day 2 respectively. In addition, the peak cooling demand decreases by 45.89% after optimization, and the working time of air conditioner has been put off to nearly 10 hours.

According to the previous analysis, the energy saving ratio of ventilation optimization highly depends on the local climate condition (Fig 2). So as Fig 7 shows, 5 typical cities in different climate zones are chosen to compare the cooling energy saving ratio in summer of ventilation strategy optimization.

Fig 8 clearly shows that the energy saving ratio of the studied cities decreases from north to south in China. Among these cities, Harbin is of the highest energy saving potential (97 %) of ventilation strategy optimization in summer, whereas Guangzhou shows the lowest energy saving ratio (28 %). Moreover, the variation trend is similar to the CCP value distribution (Figure 2), in terms of that bigger CCP value seems to be consistent with higher cooling energy saving ratio.

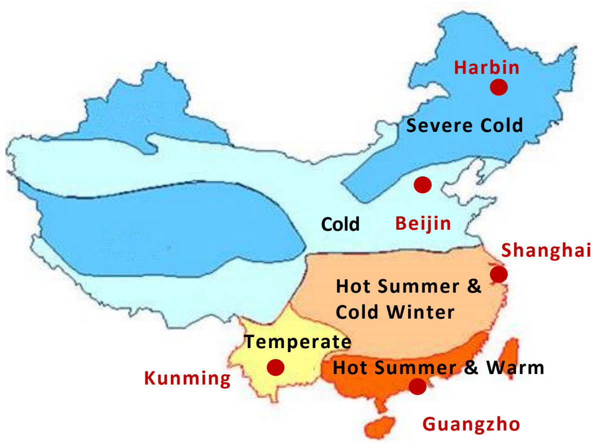

Fig 7 Cooling energy consumption in one summer day

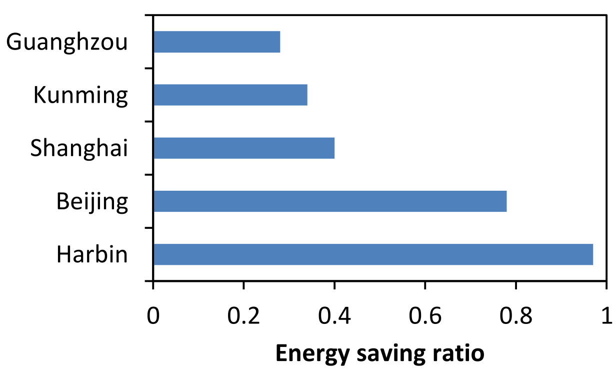

Fig 8 Cooling energy consumption in one summer day

4. CONCLUSIONS

Climate ventilation is of high energy saving potential in summer through the exploitation of free night cooling capacity. In this paper, the climatic cooling potential of major cities in China is evaluated based on the CCP index values, and a guide map for accessing night cooling potential is provided. Furthermore, for ventilation strategy optimization in city buildings, the ideal air change rate (ACH) is obtained by using inverse problem approach.

The preliminary results of the case study indicate that the optimal ACH is larger than the conventional natural ventilation system, in terms of that it can reach about 14 h^{-1} in the night. The case study also illustrates that under such ventilation strategy, the overall daily cooling energy consumption can be saved by 78% in summer. It also indicates that both CCP value and energy saving ratio of ventilation strategy optimization decreases from north to south in China. This study is significant in guiding and optimizing building ventilation systems in engineering applications.

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