Analysis of Direct Outdoor Air Cooling Efficency for Combined Variable Air Volume Air-conditioning System in Stores in Cold Climates of China

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ANALYSIS OF DIRECT OUTDOOR AIR COOLING EFFICIENCY FOR COMBINED VARIABLE AIR VOLUME AIR-CONDITIONING SYSTEM IN STORES IN COLD CLIMATES OF CHINA

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ABSTRACT

Direct outdoor air cooling contributes a lot not only to the improvement of the indoor air quality but also to the energy saving. Its full use will reduce the water chiller's running time especially in some stores where cooling load keeps much higher and longer than that in other buildings. A novel air-conditioning system named Combined Variable Air Volume system (CVAV), combining a normal AHU with a separate outdoor air supply system, was proposed firstly by the authors. The most attractive feature of the system is its full utilization of cooling capacity and freshness of outdoor air in the transition period of the year round. On the basis of the obtain of the dynamic cooling loads of the typical shopping malls in different four cities located in cold climates in China with the aid of DOE-2, the possibility of increasing the amount of outdoor air volume of CVAV system in the transition period instead of operating the water chillers was confirmed. Moreover, a new concept, Direct Outdoor Air Cooling Efficiency (DOACE), was defined as the ratio of cooling capacity of outdoor air to the water chiller, indicating the degree of outdoor air's utilization. And the DOACE of the CVAV was calculated and compared with that of conventional all-air constant volume air-conditioning systems, the results showed that CVAV bear much more energy saving potential with the 10%~19% higher DOACE and it is a kind of energy efficient systems and can improve the indoor air quality as well.

INTRODUCTION

The concerns over global warming and the need for reduction of high emissions of greenhouse gases demand the utilization of passive strategies for indoor climate modification in promoting comfortable indoor environments. As one way of passive cooling strategies, the direct utilization of outdoor air to cool the air indoors has been drawn high and increasing attention since the old time. The fresh outdoor air plays a vital role in creating a comfortable and healthy indoor air environment. Many researches have made it clear that the prevalence of SBS is partly attributed to the limited amount of outdoor air introduced. Moreover, the utilization of the outdoor air can also cut down the water chiller's running time and thus achieves a good energy consumption reduction.

The best way to make full use of outdoor air is natural ventilation. Natural ventilation, as a kind of sustainable strategies for cooling, has its profound root and has been always welcome by the architects. However, it is affected by many parameters including regional climate conditions (outdoor air temperature and moisture, wind speed and direction, etc), building site (outdoor air quality, outdoor noise, outdoor environment and urban structure, etc) and the building itself (indoor pollutant sources, indoor heat sources and stored heat, indoor air quality requirements, position and size of the ventilation openings, building type, orientation, height and structure, indoor temperature, etc)(Yang et al). Accordingly, it is not a stable cooling approach. On the other side, the usually used air-conditioning system is more than often a recycled system for the energy reduction sake. It has a minimum outdoor air ratio (10% according to Chinese code) and the maximum does not exceed the total air flow volume. But we consider that during the transition period when the outdoor air itself has the capacity of cooling, if more outdoor air (more than 100%) is delivered into the occupied space, it will delay the start of the water chiller unit or share the cooling load with it, and thus reduce the energy as well.

In this paper, we focused on the biggest possibility of direct utilization of outdoor air in transition time. Therefore, a novel air-conditioning system named Combined Variable Air Volume system (CVAV), combining a normal AHU with a separate outdoor air supply system, was proposed firstly by the authors. Based on the analysis of the active cooling load in the typical shopping malls located in four different cold climatic cities of China, i.e., Harbin in the farthest north, Beijing in the northeast, Urumqi in the northwest, and Xi'an in the north middle, the application of CVAV system was studied and the possibility of increasing the amount of outdoor air volume of CVAV system in the transition period instead of operating the water chillers was highly confirmed. In the end, a new concept -- Direct Outdoor Air Cooling Efficiency (DOACE) defined as the ratio of cooling capacity of outdoor air to the water chiller was introduced and compared between CVAV and CAV systems.

COMBINED VARIABLE AIR VOLUME SYSTEM

The so-called CVAV system is consisted of two sub-systems: one is a conventional all-air system, namely System 1 (S_1), placed in the air-conditioner room, mainly to treat the return air; the other one is a system for the direct outdoor air delivery, namely System 2 (S_2), placed on the ceiling of the air-conditioned room, not to perform the heat or humid air treatments, in Figure 1. Because the maximum running air volume of the air conditioning system is greater than the summer design one, the air volume of the system based on the summer design volume can be increased as well as be decreased alternatively. So, the outdoor air cooling can be used during transition seasons, and further reduction of the runtime of the chiller units is secured.

This novel air-conditioning system has more advantages over its limited flaws such as more noise and inconvenience in servicing. The most attractive feature is its full utilization of cooling capacity and freshness of outdoor air in the transition period of the year round. Besides, 1) when the outdoor air fans are located in the ceiling, it will save a considerable occupied space; 2) the outdoor air delivery system is independently installed, operated and modified which makes the outdoor air fans easier to work under the highest efficiency point; 3) the large amount of fresh air can create and maintain comfortable and healthy indoor air environment.

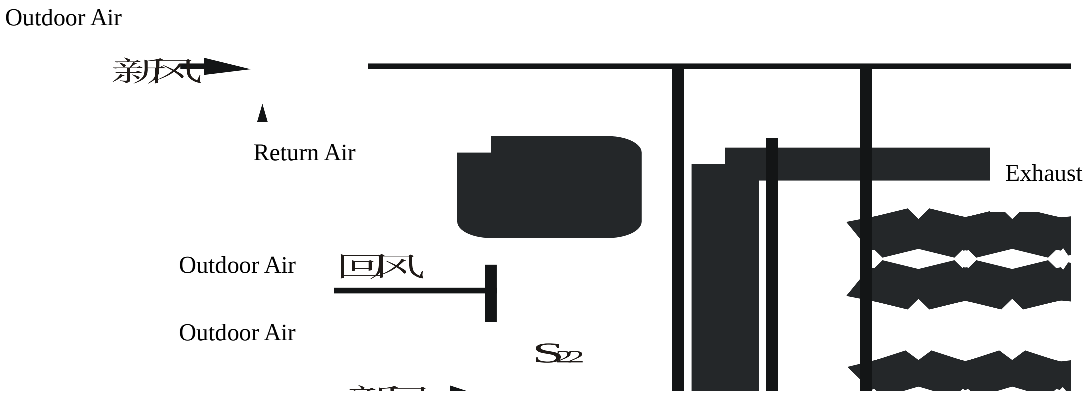


Figure 1. Sketch of CVAV system

In this paper, we narrow our interest in the cooling strategies only. And we classify the operation periods of the air-conditioning system in all year as follows:

Heating period: the time when the artificial heating is available;

Cooling period: the time left except for heating period;

High enthalpy period: the time when the outdoor wet-bulb temperature is higher than that indoors;

Transition period: the time left except for high enthalpy period during the cooling days

CHARACTERISTICS OF COOLING LOAD OF STORES

The potential for direct outdoor air cooling varies with the outdoor climate, regions, as well as the cooling load characteristic of the buildings. It is easy to understand that it does the biggest benefit when the cooling load is notable and the transition period keeps long. When the building bears high cooling load and lasts long, it indicates that it is in demand of more cooling. Meanwhile, when the outdoor air has more capacity of cooling, this will make a good match. The big stores like shopping malls are kind of buildings with high cooling load all year round, because they take on high occupancy density. Therefore, we put our emphases on the big stores located in four different cities, i.e., Harbin in the farthest north of China, Beijing in the northeast, Urumqi in the northwest, and Xi’an in the north middle. All of them lie in cold regions, of which Harbin and Urumqi belong to severe cold regions, see Figure 2.

Based on the formerly developed model of dynamic cooling load for typical stores in China (Li and Zhao), the dynamic cooling load in four cities are calculated with the aid of DOE-2 and summarized in Figure 3. As depicted in Figure 3, the total cooling loads behave positive in most of year in all four cities, even if in such a severe cold region as Harbin. This indicates that the indoor cooling load takes a considerable part in the total one which corresponds to one of the greatest features of the Chinese stores. Moreover, it shows that the cooling load of the outdoor air is negative from March to October in Harbin and Urumqi, and from March to November in Xi’an and Beijing while the indoor cooling load keeps positive always. This claims that during this long period, the outdoor air always maintains the capacity of cooling, to cool the indoor air down. However, it can not totally replace the artificial cooling scheme, because the total cooling load is also above zero.

In practical HVAC design scheme for stores, the designers get used to divide the whole building

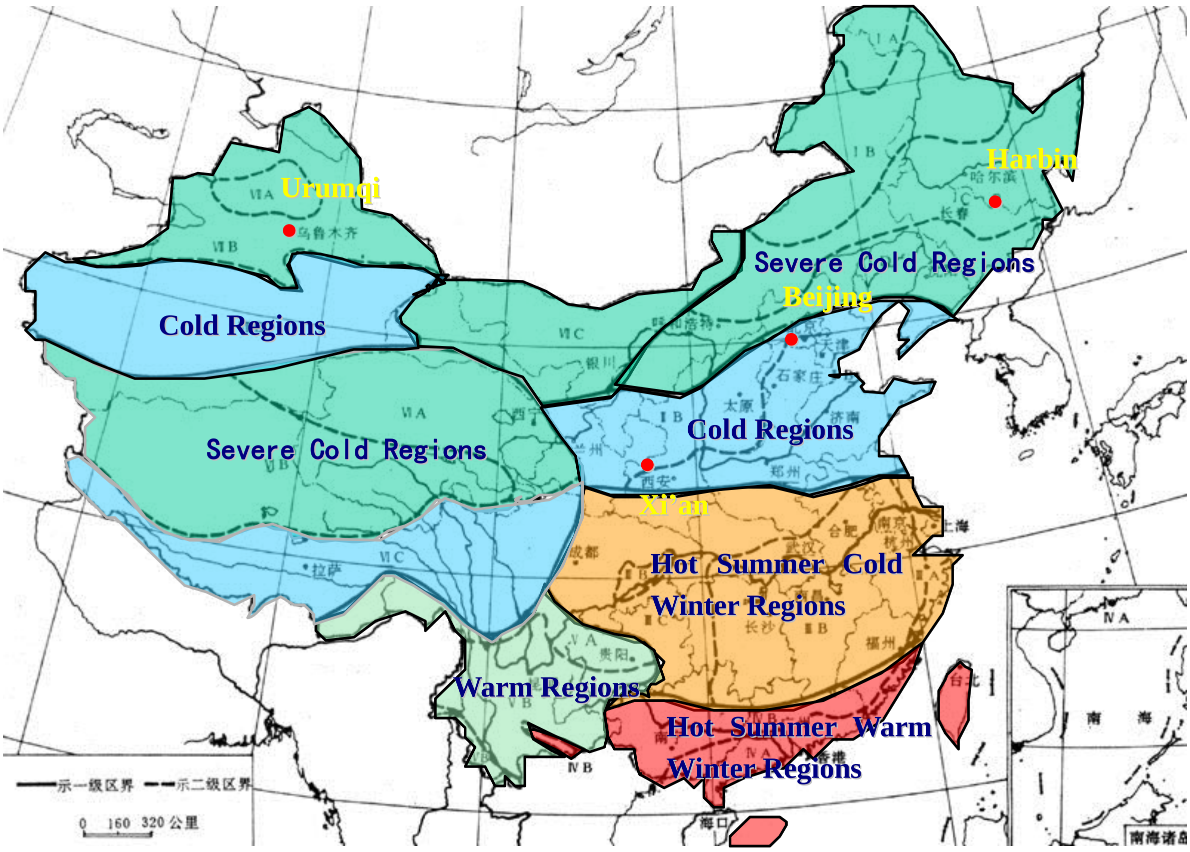
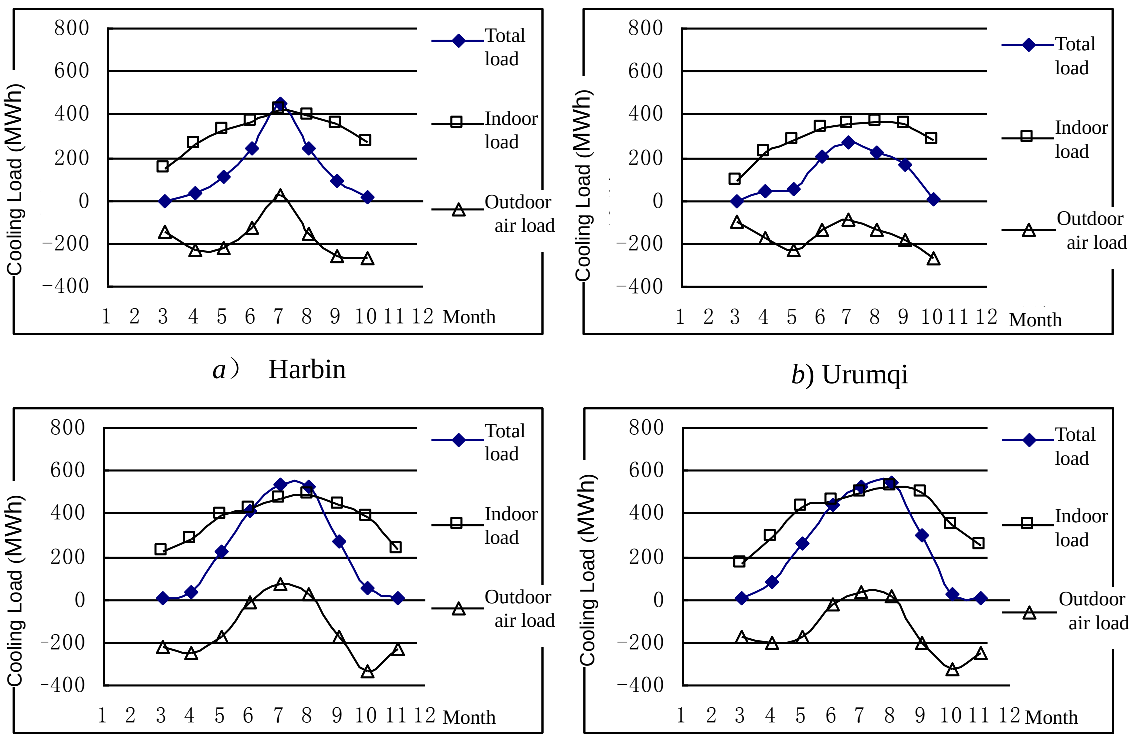


Figure 2. A sketch of map of China where the climate regions are classified and four cities are indicated



a) Harbin

b) Urumqi

c) Xi'an

d) Beijing

Figure 3. Curve of dynamic cooling load in stores in different four cities

into several zones according to the number of its floors to cut down its size, usually one floor one zone. Here we assume the store as a hexahedron for simplification. According to Equation (1) (Li and Zhao), which expresses the relationship between shape coefficient and the area of building, we obtain that the store with the total area of 15 000m^2 should be a four-storey building with 3 750m^2 floor area each.

$$SCOB = 0.131227 - 0.324103(A - 0.1766009) + 0.996475(A - 0.1766009)^2 - 1.442516(A - 0.1766009)^3 \quad (1)$$

Where

SCOB——Shape Coefficient of the Buildings;

A——Ratio of the area of the building; *A* = Area of the building / 10 000.

Here the second floor is selected as our focus and the business time for stores is regarded from 9:00 am to 19:00 pm both in Harbin and Urumqi and from 9:00 am to 21:00 pm in other cities owing to the inhabitants' different living customs. Therefore, the operating hours for Constant Air Volume system (CAV) in all year, the yearly cooling hours, the transition period, the operating hours for water chillers, and the ratio of cooling hours to the operating hours are obtained and specified in Table 1. The results show that the stores always keep long cooling period in all year and the time increases as the longitude decreases. Specially, even if in Harbin as a severe cold place, the ratio of the cooling period stays more than 63%. Accordingly, it shows the greatest energy saving potential in cooling period for stores and how long the transition period lasts will indicate the possibility and degree of direct outdoor air cooling strategy.

Table1. The operating time of CAV for stores:

Location	Total Air Flow Rate (M^3/h)	Minimum Outdoor Air Flow (M^3/h)	Operating time in all year	Operating time in cooling period (h)	Cooling period/ All year	Operating hours in transition period (h)	Transition period/ All year	Transition period/ Cooling period	Operating time for water chillers (h)
Harbin	9 9892	22 500	4 015	2 549	0.635	2 264	0.564	0.888	1 499
Urumqi	103 732	22 500	4 015	2 606	0.649	2 341	0.583	0.898	1 390
Beijing	104 842	22 500	4 745	3 791	0.799	2 769	0.584	0.730	2 221
Xi'an	106 709	22 500	4 745	4 227	0.891	3 203	0.675	0.758	2 225

DIRECT OUTDOOR AIR COOLING EFFICIENCY

Direct outdoor air cooling benefits a lot to the energy saving as well as the improvement of the indoor air quality. However, how to evaluate the potential of the outdoor air utilization? To solve this problem, a new concept named Direct Outdoor Air Cooling Efficiency (DOACE) is introduced and defined as the ratio of cooling capacity of outdoor air to that of the water chillers operate alone, indicating the degree of outdoor air's utilization. The concept of DOACE can be expressed as follows:

$$DOACE = \frac{LQ_o}{LQ_1} \times 100\% \quad (2)$$

Where

LQ_o —the cooling capacity provided by outdoor air in transition period（kWh）;

LQ_1 —the cooling capacity provided by water chillers when no outdoor air is introduced（kWh）;

Also, Equation (2) can be rewritten as:

$$E = \frac{LQ_1 - LQ_2}{LQ_1} \times 100\% = (1 - \frac{LQ_2}{LQ_1}) \times 100\% \tag{3}$$

Where

LQ_2 —the cooling capacity shared by water chillers during the transition period（kWh）.

Another item named outdoor air ratio is also defined here as the ratio of the outdoor air flow volume to the total amount of air delivered by the air-conditioning system. Figure 4 shows the comparison of outdoor air ratio between CAV and CVAV in four cities. Theoretically, during the transition period, the outdoor air ratio can be extensively increased to meet the cooling load demands. But the outdoor air flow rate will increase to infinity which is not applicable in practical application as depicted in Figure 4. It is also easy to find that the curves represent similar in all four cities and the inflexion point falls in the range of 150% to 300% which indicates that the DOACE will rise as the outdoor air ratio lies in that range in transition time. Moreover, considering the thermal comfort indoors, the outdoor ratio can be increased to 200% but not disturb the thermal comfort. We hence obtain the optimum outdoor ratio 200% for CVAV system. The results of DOACE for both CAV and CVAV systems are expressed in Table 2. This displays that the DOACE for CVAV system could be 10% to 19% higher than CAV system during the transition time, which also promises counterpart energy saving potential.

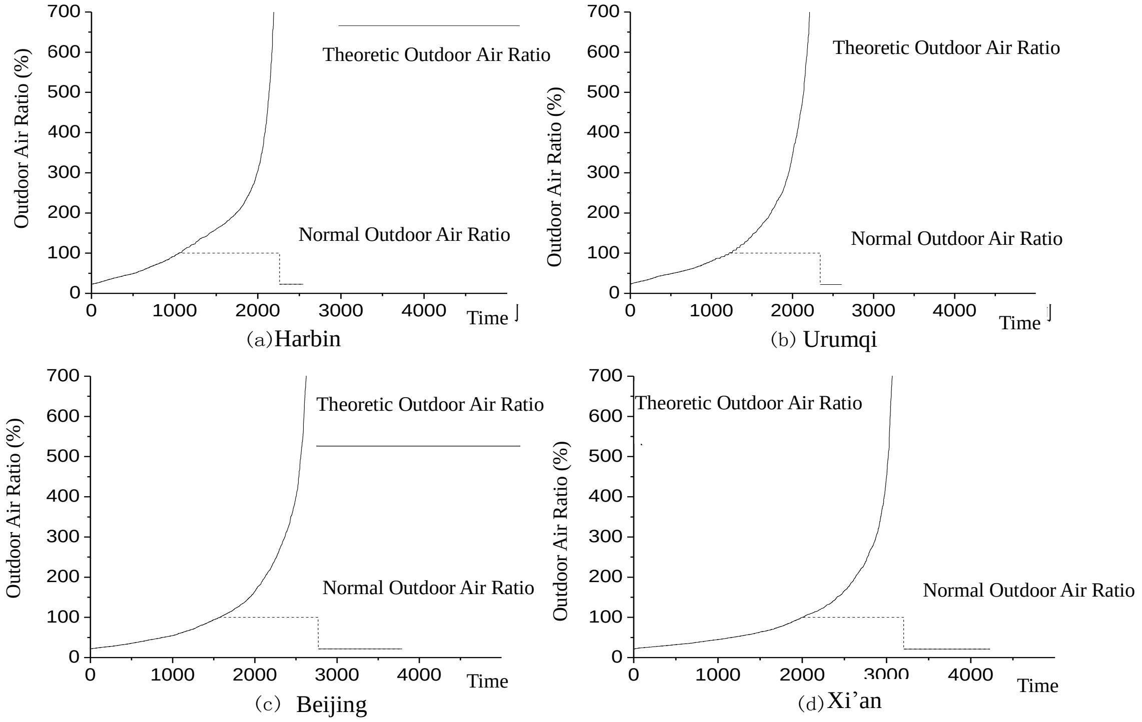


Figure 4. Normal and theoretical outdoor air ratio of constant all-air system in cooling period

Table 2. DOACE for CAV and CVAV in transition period:

Location	Cooling load in transition period (MWh)	Cooling capacity of the outdoor air for CAV (MWh)	DOACE for CAV (%)	Cooling capacity of the outdoor air for CVAV (MWh)	DOACE for CVAV (%)
Harbin	776.802	557.477	71.77	699.530	90.05
Urumqi	727.575	532.118	73.14	632.111	86.88
Beijing	880.567	649.479	73.76	764.579	86.83
Xi'an	1013.29	783.099	77.28	907.517	89.56

CONCLUSIONS

Maintaining high indoor cooling load is one of typical characteristics of large stores in China. As the results shown in this paper, there are more than 8 months in all year that indoor cooling load behaves positive while the outdoor air cooling load is negative, i.e., the outdoor air is capable of providing the cooling demand indoors. Therefore, if more outdoor air is delivered indoors during this period, the operating time of the water chillers can be remarkably cut down. Compared the simulation results between the CVAV and CAV systems, the DOACE can get up to 70% for CAV but to more than 86% for CVAV system because it bears 200% outdoor ratio rather than the maximum 100% ratio for conventional CAV systems. All of these indicate that direct outdoor air cooling holds huge potential for both energy saving and improvement of IAQ in large stores in China as well as the newly developed air-conditioning system—CVAV has splendid prospect.

ACKNOWLEDGEMENT

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LITERATURE

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