Analysis of the consumption and efficiency of different AC system types in residential buildings

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ABSTRACT

In residential buildings, the operation and management of AC systems are usually conducted by the inhabitants. Various Air Conditioning (AC) systems have been applied in residential buildings. AC systems would limit the adjustment by inhabitants and influence the AC usage in reverse. Therefore, different AC systems in residential buildings have different features of operations and managements, and few literatures focused on how the consumption and efficiency change among different AC systems. In this study, three different kinds of AC systems (Household central AC system, FCU and split AC system), together with two typical AC usage in residential buildings are compared to figure out the influence of AC systems on the consumption and AC efficiency. Different reactions of AC systems to user preferences in the three systems are analyzed, and their influence on the cooling load distribution, energy consumption and system efficiency are presented in this paper. Firstly, field measurements were conducted in two residential communities. The performance of the AC system, the energy consumption and the AC usage of residents were investigated. In this way, general understandings of user preferences for indoor temperatures, AC use time and so on can be presented. Then simulations were applied to analyze the influence of different reactions of AC systems to user preferences on the performance of systems. Taking the investigated AC usage as input, simulations was used to calculate the energy performance of three AC systems. Through this way, the key elements which lead to the different energy consumption and system efficiency between various AC systems are discussed. This paper preliminarily verified that, at the edge where the feature of the AC system cannot meet the cooling load feature of residents, the problems of high energy consumption or low energy efficiency would easily happen.

KEYWORDS

Residential buildings, AC usage, energy consumption

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INTRODUCTION

In residential buildings, the operation and management of AC systems are usually conducted by the inhabitants. Inhabitants modify the set temperature point, supply air volume or run time of AC equipment to adjust the internal thermal condition. Influenced by the stochastic characteristics of AC usage among different households, the cooling load and AC electricity consumption would have sharp discrepancies (Peng et al. 2012). The operation and management of AC systems by inhabitants would influence the cooling demand profile greatly, which will reflect on the energy efficiency and consumption of HAVC system.(Korolija et al. 2009; Hitchin R 2014)

Recently, more and more centralized AC systems, like variable air volume (VAV) system and fan coil units (FCU) system, have also appeared in residential buildings, and are approved and supported by certain policies (Zhang et al. 2009). In these residential buildings, the operation and management of AC systems are usually conducted by facility managers, and in most of these residential buildings, system components are designed based on the industry standards such as the ASHRAE (American Society of Heating, Refrigerating and Air- Conditioning Engineers) standards, where comfort criteria are represented through comfort indices, like PMV (Fanger 1970) and ISO 7730 (1994), which leads to that the adjustments of internal thermal condition by inhabitants are limited by system configurations. In the absence of real time and personalized comfort information from occupants, facility managers have to use predefined set points in centrally controlled HVAC systems (Farrokh et al. 2013). The lack of the reaction of an HVAC system to user preferences will influence the satisfaction of inhabitants with thermal environment and change the cooling load profile, which will also reflect on the energy efficiency and consumption of HAVC system. (Tolga et al. 2009; Adolph et al. 2014; Yan et al. 2008)

From the analysis above, different AC systems in residential buildings have different features of operations and managements, and few literatures focused on how these features influence the performance of AC systems. In this study, three different kinds of AC systems (VAV, FCU and split AC system) in residential buildings are compared to figure out the influence of different operation and management on the consumption and efficiency of AC systems in cooling season. Different reactions of AC system to user preferences in the three systems are analyzed, and their influence on the cooling load distribution, energy consumption and system efficiency are presented in this paper.

METHODOLOGY

1. Field measurements

Two residential communities were investigated. Key characteristics describing the area and shape of buildings are presented in Table 1.

Table 1. *Key characteristics of buildings in the two communities*

Characteristics	*community*	
	A	*B*

Number of floors of each building	5	18
Number of households	294	413
Net site area, m^2	28000	19000
Habitable floor area, m^2	41200	50000
Average window-wall ratio	0.5	0.29
Average external wall area, m^2/building	1971	38640
Thermal transmittance of building envelope U, W/(m² K)		
External wall	1.84	0.62
Windows	2.5	2.5
Attic floor	0.6	0.81

The fan coil units (FCU) are taken as AC terminals in both communities, and water source heat pumps are used as cooling source. Users are charged for the cooling consumption according to the operation situation of the FCU terminals. Namely, the payment of cooling consumption is related to the measured operation hours of fan coils under high, middle and, low fan speeds, which is recorded by the FCU on-off metering system in the AC system. When the AC terminal is closed, there would be no cooling fees.

Field measurements included indoor dry bulb temperature measurement, surveys on user preferences for AC system (set temperature point, temperature point when the AC terminal open, AC system run time) and measurements of the performance of AC system. Data of every ten minutes (flow rate of chilled water from each building, supply and return water temperature of each building, flow rate of chillers, supply and return water temperature of chillers, electricity power of chillers and pumps) were measured in the two residential communities over three-month period. Data about the cooling consumption of each household were collected from the FCU metering system on a monthly basis over the whole cooling season (June to September). The FCU metering system recorded the run time of AC terminals under different fan speeds and converted the run time data to the corresponding cooling consumption.

2. Simulations

The building energy modeling program DeST developed by Tsinghua University (Zhang et al. 2008) was used for the simulations. The simulations were used to calculate the load profile, energy consumption and system efficiency of different AC systems, to analyze the influence of different operations and managements.

In order to conduct a reasonable analysis about the realistic AC system operation situation, simulation model of community B was built for the better operation performance, and the model was calibrated based on field measurements, user AC use modes and measured indoor climate results.

The difference between simulated and measured energy consumption data of community B is within 10%, which means the simulation data of DeST is reliable.

Then the model of community B was simulated again after several boundary conditions were changed. Three kinds of AC system types, VAV, FCU and split AC system, were analyzed in this paper. The simulation cases are listed in Table 2. Finally, the load profiles, energy consumption and system efficiency of three AC system types were compared to make a comprehensive analysis of technical suitability about AC systems in residential buildings.

Table 2. *Simulation cases*

	Case 1	*Case 2*	*Case 3*	*Case 4*	*Case 5*	*Case 6*	*Case 7*
	AC system type						
	VAV			*FCU*			*Split AC system*
Set T	Predefined	User control		User control			User control
On-off Valve	x	x		with		without	x
Chilled Pump control	Constant speed	Constant speed	Variable speed	Variable speed		Variable speed	x
Refrigeration units	Centralized installed	Centralized installed	Centralized installed	Centralized installed	Distributed installed	Centralized installed	x

RESULT

1. Measured energy consumption and system efficiency

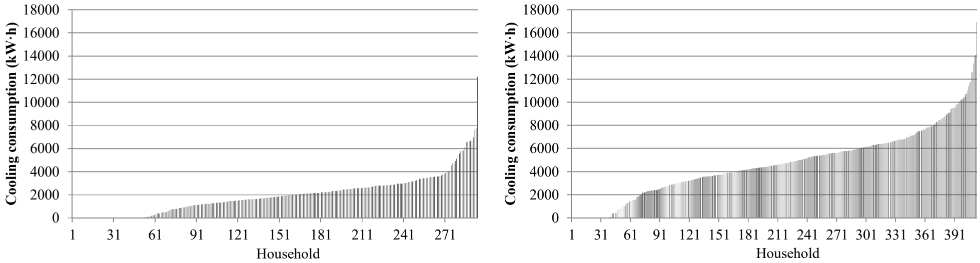
The AC system energy consumption includes heat pumps, chilled water pumps and cooling water pumps. The consumption and system performance data were shown in Table 3.

Table 3. *Energy consumption of AC systems in the cooling season (July to September)*

	Electricity consumption（EC）(kWh/m²)			*Cooling consumption (kWh/m²)*	*EER*
	EC of chillers	*EC of water pumps*			
		Chilled water pumps	*Cooling water pumps*		
Community A	4.4	1.5	1.7	9.0	1.2
Community B	6.0	1.1	0.8	23.6	3.0

2. AC operation by inhabitants

Based on the AC terminals on-off data from the FCU metering system, the cooling consumption of each household in the two communities is presented in Figure 1. Large different can be detected in terms of the cooling consumption of each household in the two communities. Not only does the amount of cooling consumption have large discrepancies, but the distribution of cooling consumption among different households is quite different.



(a) Community A (b) Community B

Figure.1. *Cooling consumption of each household in the two communities during the cooling season (July to September)*

Through surveys about AC use modes and the indoor dry bulb temperature measurement in typical households, five kinds of typical AC operation by inhabitants were concluded in Table 4.

The five kinds of AC use modes have been detected in households of both community A and B, but the compositions of the five kinds of inhabitants are different, as Figure 2 shows. In community A, more inhabitants follow the AC use modes of 1, while in community B, the AC use modes of inhabitants tends to be 3-5.

Table 4. *Five kinds of AC use modes*

AC Use mode	***Description of AC use modes (T is short for temperature)***
1	Living room: Open T: 29℃, setting T: 28℃; Bedroom: Open T: 29℃, setting T: 27℃; Air conditioning would only be opened at night.
2	Living room: Open T: 30℃, setting T: 26℃, open time: at noon and at night; Bedroom: Open T: 29℃, setting T: 26℃, open time: at night.
3	Living room: Open T: 29℃, setting T: 27℃, open time: only related to indoor T; Bedroom: Setting T: 27℃, open time: all day long.
4	Living room: Setting T: 26℃; Bedroom: Setting T: 27℃; Air conditioning would be opened all day long.
5	Air-conditioning would be opened all day long, and the setting T is 24℃ in both living room and Bedroom

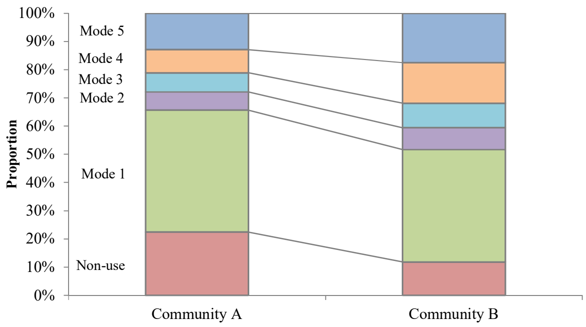


Figure.2. *proportion of each typical AC use mode in the two communities*

3. Simulation results

Influence of operation by inhabitants

Figure 3 compares the different electricity consumption and system efficiency caused by the composition of inhabitants. The Δ value is the percentage change, which equals the variation is divided by the original data. A reduction of 14% in the electricity consumption of the AC system can be seen in Figure 3. And the electricity consumption of chillers and pumps also declined 17% and 5% separately. An interesting finding is that as the reduction of electricity consumption, the efficiency of the system and each component also decrease, as Figure 3 shows.

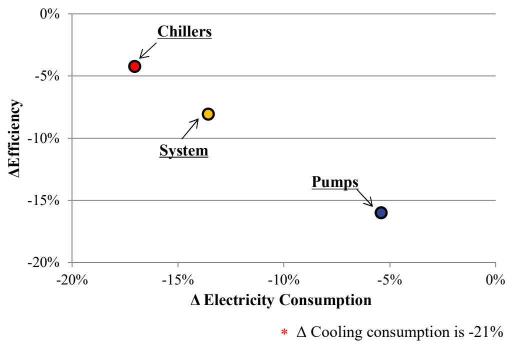


Figure 3. *The influence of operation by inhabitants*

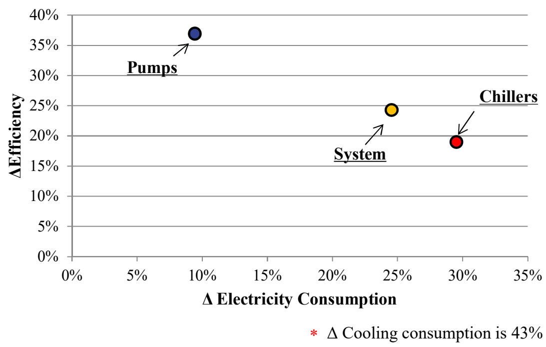


Figure 4. *Influence of the absence of operation by inhabitants*

Based on the model of community B, Case 1 and Case 2 in the Table 2 were simulated to detect the influence of the absence of inhabitants' control, and the results were compared in Figure 4. The percentage change of cooling consumption (Δ cooling consumption) is 43%. As the growth in cooling consumption, the electricity of pumps and chillers also rise by 9% and 30% separately, and it makes the increase of electricity consumption of the AC system to 25%. On the other hand, under the predefined set temperature, the cooling load profile becomes steadier, which benefits the operation of the AC system. With the high requirement of cooling load, the load ratio of chillers maintains at a high level, and the water pumps can deliver more cooling consumption with the same electricity consumption. As Figure 4 shows, the efficiency of pumps and chillers is improved by 37% and 19%, which leads to an increase of 24% in the system efficiency.

Influence of operation by managers

1) The control of pumps

Case 2 and Case 3 in Table 2 is simulated to compare the influence of the control of pumps. Figure 5 indicates the influence of the control of chilled water pumps to the operation of the AC system. The introduction of pump frequency regulations reduces the electricity consumption of chilled water pumps by 67%, and improves the efficiency of pumps by 2 times. In addition, the electricity consumption of the AC system decreases 12% with the increase of system efficiency by 14%.

2) The set-up of chillers

Case 3 and Case 4 in the Table 2 is compared to figure out the influence of the set-up of chillers. As figure 6 shows, with the distributed installed set-up of chillers, the electricity of chillers can be reduced by 5%, and the COP of chillers increase by 5%. However, for the increase of resistance in the cooling water side, the electricity of cooling water pumps becomes larger, and it covers the advantages of the chillers. On the whole, the distributed installation of chillers leads to more energy consumption of the AC system and worse system performance on the contrary.

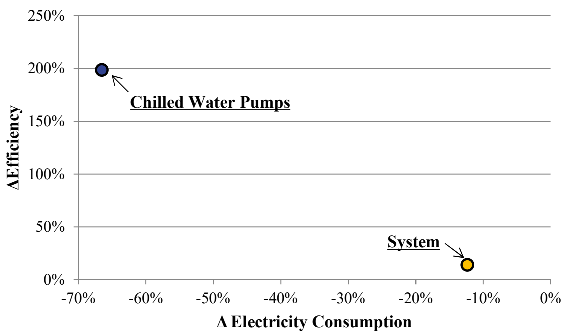


Figure 5. Influence of the control of pumps

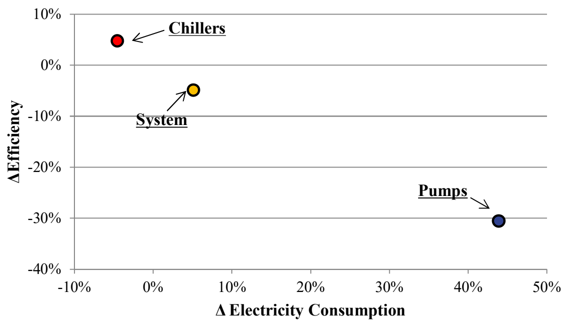


Figure 6. Influence of the set-up of chillers

3) The control of on-off valves in the water side

Case 5 and Case 6 in the Table 2 are compared to indicate the influence of the on-off valves in the water side in this section. Taking Case 5 as the basic case, the comparison results are presented in Figure 7. Without the on-off valves in the water side, the electricity consumption of chilled water pumps would increase 1times, and the efficiency would reduce 50%. Influenced by the chilled water pumps, the influence of the on-off valves in the waterside would lead to 7% more of the electricity consumption and 7% less of the system efficiency.

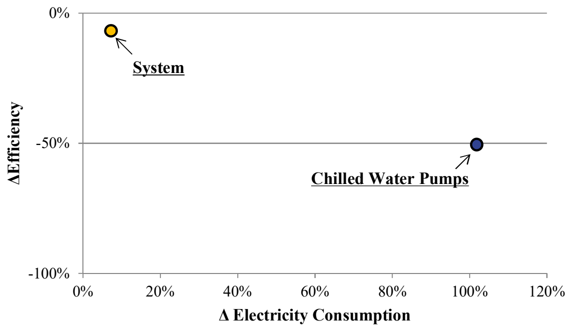


Figure 7. Influence of the on-off valves

CONCLUSION

Field measurement and simulations were conducted and analyzed in this paper. The following conclusions can be drawn from this study:

1. The operation and management have an important influence on the electricity consumption and system performance of AC system. In residential buildings, if the inhabitants have the right to adjust the AC terminals, the cooling load would express

the features of de-synchrony and low load ratio. Under different operation by inhabitants, the corresponding cooling load would make the suitable AC system different;

2. In residential buildings, influenced by the requirement of user terminals, the distribution energy consumption becomes the main composition of system consumption in centralized AC system;

3. Adjustability has an important influence on the system energy consumption. The design scheme should improve the system operation efficiency on the premise of realizing the systems' adjustability.

REFERENCES

Adolph M, Kopmann N, Lupulescu B, Muller D. Adaptive control strategies for single room heating. Energy and Buildings 2014, 68: 771–778

Fanger PO. Thermal comfort. Copenhagen: Danish Technical Press; 1970

Farrokh J, Franco M M, Burcin B. A thermal preference scale for personalized comfort profile identification via participatory sensing. Building and Environment 2013, 68: 140-149

Hitchin R. Heating and cooling load frequency distributions implied by monthly building energy use models. Building services engineering research & technology 2014, 35(1): 53-68

I. Korolija, Y. Zhang, L. Marjanovic-Halburd, V.I. Hanby, Selecting HVAC systems for typical UK office buildings, in: Proceedings of the 6th International Symposium on Heating, Ventilating and Air Conditioning, vol I–Iii, Southeast Univ. Press, Nanjing, China, 2009, pp. 388–396.

ISO 7730. Moderate thermal environments—determination of the PMV and PPD indices and specification of the conditions for thermal comfort. Geneva: ISO; 1994.

Peng C, Yan D, Wu R, Wang C, et al. Quantitative description and simulation of human behavior in residential buildings. Building Simulation 2012, 5: 85-94

Tolga N A, Yunho H, Reinhard R. Simulation comparison of VAV and VRF air conditioning systems in an existing building for the cooling season. Energy and Buildings 2009,41: 1143–1150

Yan D, Xia J, Tang W, Song F et al. 2008. DeST—An integrated building simulation toolkit, Part Ⅰ: Fundamentals. Building Simulation, 1: 95-110

Zhang WJ, Huai LL, Liu JL. Comparison analysis of energy consumption characteristics between decentralized and centralized AC systems in residential buildings by commissioning. Proceedings of the fifth international workshop on energy and environment of residential buildings and third international conference on built environment and public health, vol I and II 2009: 1768-1775

Zhang X, Xia J, Jiang Z, Huang J et al. 2008. DeST—An integrated building simulation toolkit, Part Ⅱ: Applications. Building Simulation, 1: 193-209