An energy-saving control strategy for VRF and VAV combined air conditioning system in heating mode

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ABSTRACT

Although variable refrigerant flow (VRF) systems have become attractive due to good energy performances in part load conditions, the shortcoming of no outdoor air intake has not been solved thoroughly. A VRF and VAV combined air conditioning system is proposed to solve this problem. VAV part of the combined system consists of an outdoor air processing (OAP) unit and VAV boxes. Generally the VRF unit operates to maintain indoor temperature and the OAP unit operates to process the outdoor air. A control strategy for the combined system aiming at reducing energy consumption is presented in this paper. When both VRF unit and OAP unit are operating, a load allocation optimization module is executed to find the best load allocation between them to minimize the energy consumption of the combined system. When the allocated load of the OAP unit is very small, the proposed control strategy stops the OAP unit, leaving only the VRF unit to operate to improve the overall energy efficiency of the combined system. When load requirements are met, the OAP unit is restarted and the load allocation optimization module is executed again. The proposed control strategy is evaluated based on the developed simulation platform. Results show that the proposed control strategy can effectively decrease the energy consumption of the combined system.

1. INTRODUCTION

The variable refrigerant flow (VRF) system has earned wide popularity due to high energy efficiency under part load conditions (Zhou *et al*., 2007; Liu *et al*., 2010; Aynur *et al*., 2009). However, the shortcoming that the VRF system has no outdoor air (OA) intake has not been solved thoroughly. On the other hand, many studies have demonstrated that ventilation has great impacts on health outcomes, absence rates and productivity (Seppanen *et al*., 1999; Wargocki *et al*., 2002). Ventilation is also an energy use contributor for processing and delivering the air especially in highly occupied spaces. When one considers these factors together -the importance of ventilation on occupants, the sufficiency of ventilation in VRF systems, and the energy consumption of ventilation, it is very clear that there is urgent need to develop and promote better energy efficient systems for providing ventilation while simultaneously taking advantages of the VRF systems.

In our previous studies (Zhu *et al*., 2014a; Zhu *et al*., 2014b), a VRF and VAV combined air conditioning system aiming at taking advantages of both parts was proposed and simulated. VAV part of the combined system mainly consists of an outdoor air processing (OAP) unit and VAV boxes. Previous studies found that the combined system could maintain all the air conditioning zones at their specific set-points no matter their set-points are the same or different, and no matter the number of operating indoor units changes or not. It can effectively solve the ventilation sufficiency problem of the VRF systems. In addition, the combined system was found having potential to decrease energy consumption without compromising thermal comfort and indoor air quality by intelligent (optimal) control from the system point of view.

This paper mainly presents a control strategy for the combined system in heating conditions aiming at decreasing the energy consumption. Remainder of this paper is organized as follows. Section 2 introduces the combined system and the testing facility. Section 3 discusses the proposed control strategy in details. Cases studies and evaluation of the proposed control strategy are carried out in Section 4. And Section 5 concludes this study.

2. DESCRIPTION AND SIMULATION OF THE COMBINED SYSTEM

Fig. 1 shows the schematic of the combined system. The VRF part consists of an outdoor unit and several indoor units. The VRF unit maintains the zone temperature at the set-point by varying refrigerant flow rate with the help of variable speed compressor and electronic expansion valves (EEVs). In each branch supply duct, there is a VAV box to modulate the OA flow in response to the zones' demand. Five types of control loops, the so-called *VRF* (*DX*) *capacity control*, *zone temperature control*, *VAV box control*, *supply fan control* and *EEV opening control*, as shown in Fig. 1 as well, are designed for the combined system for getting good thermal comfort and indoor air quality, and for reliable operation of the compressors. Demand-controlled ventilation (DCV) strategy is adopted to regulate the adequate amount of outdoor airflow.

Fig. 2 shows the typical floor pan of a conceptual office building for accommodating the combined system. The building has six floors in total above ground. Each floor of the building is divided into six conditioned thermal zones, corresponding to four outdoor exposures (east, west, south and north), an interior zone (including a ring-shaped corridor) and a center core. A summary of the key parameters of the building is listed in Table 1 of (Zhu *et al*., 2014a) . The air conditioned zones are numbered from zone 1 to zone 25 for conveniently identifying their locations.

The test facility (i.e. the simulation platform) is developed based on TRNSYS (Klein, 2009). The combined system is modeled and simulated by integrating the individual component or sub-system models into a complete system (Zhu *et al*., 2014a; Zhu *et al*., 2013). Models of other typical components, such as VAV box, supply fan, sensor, controller and actuator, can be found in authors' previous works (Jin *et al*., 2005; Wang and Jin, 2000).

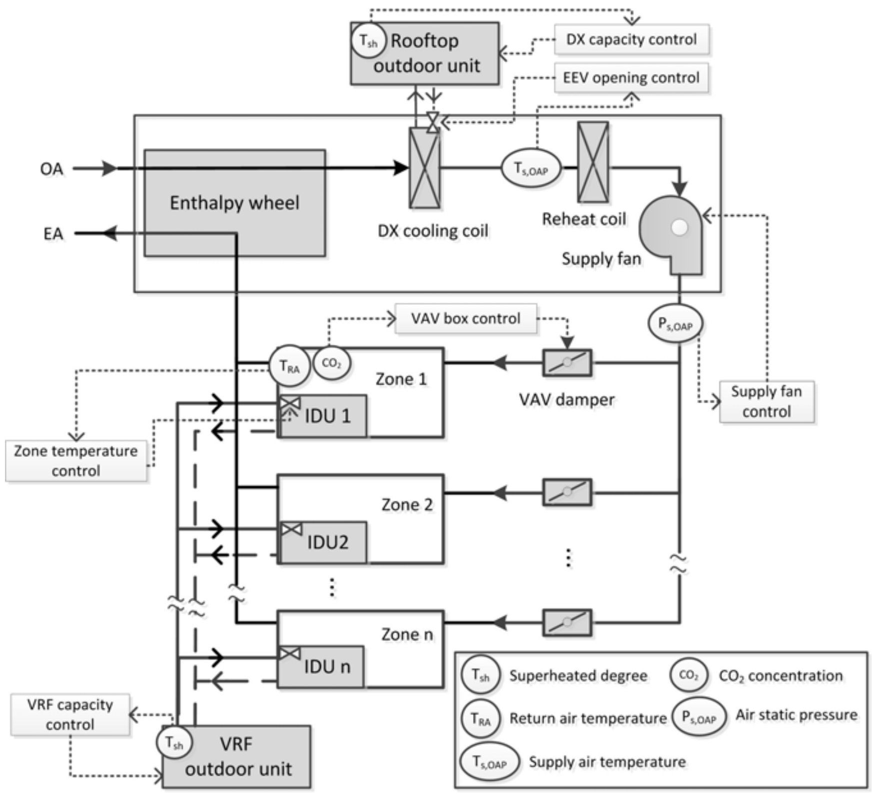

Figure 1: Schematic and control designing of the combined system

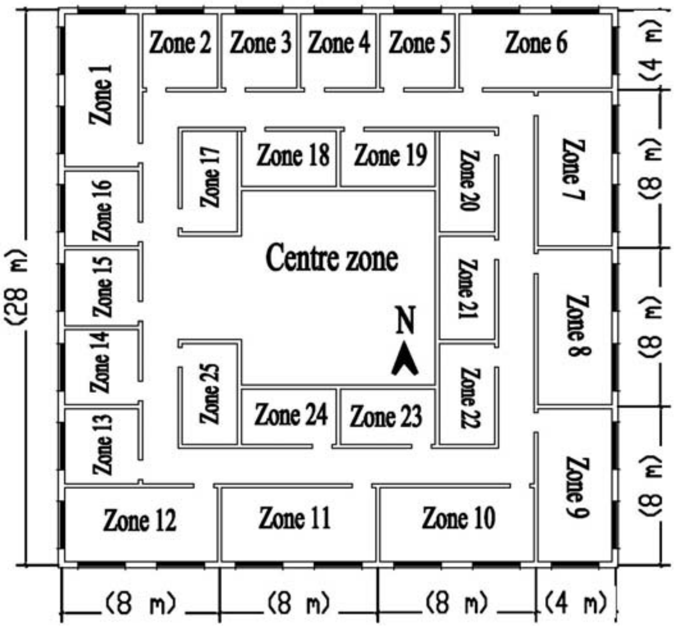

Figure 2: Typical floor plan of the conceptual building

3. THE PROPOSED CONTROL STRATEGY

3.1 Logic of the proposed control strategy

The objective of the proposed control strategy is to minimize the total energy consumption of the combined system (a sum of those of the VRF unit, the OAP unit and the fans) without compromising to thermal comfort and indoor air quality. It is found that variation of the OA supply temperature will lead to a reciprocal relationship of cooling/heating capacity as well as energy consumption between the VRF unit and the OAP unit (Zhu *et al*., 2014b). In the proposed control strategy (Fig. 3), when both the VRF unit and the OAP unit are operating, the load allocation optimization module (Fig. 4) will be executed to find the best load allocation to minimize the energy consumption of the entire combined system (Zhu *et al*., 2014c). The best load allocation is realized by optimizing the control variable, i.e., the OA supply temperature set-point. On the other hand, if the allocated load of the OAP unit is quite small, or the OAP unit operates at very low energy efficiency, the proposed control strategy will stop the OAP unit, leaving only the VRF unit to operate to improve the energy efficiency of the combined system. The VRF unit which is basically designed for maintaining the indoor air temperature should not be stopped. When requirements are met, the OAP unit is restarted and the load allocation optimization module is executed again.

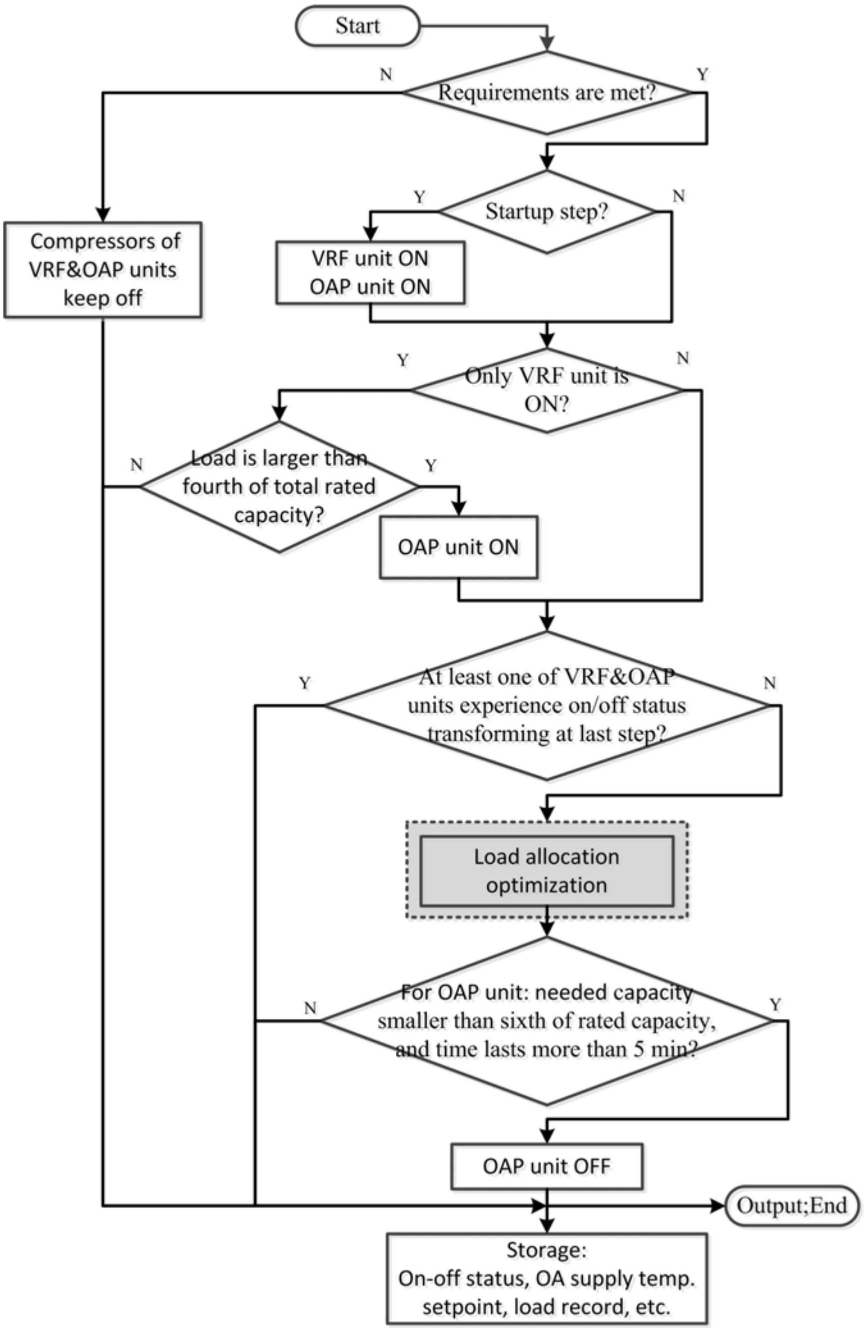

Figure 3: Logic of the proposed control strategy

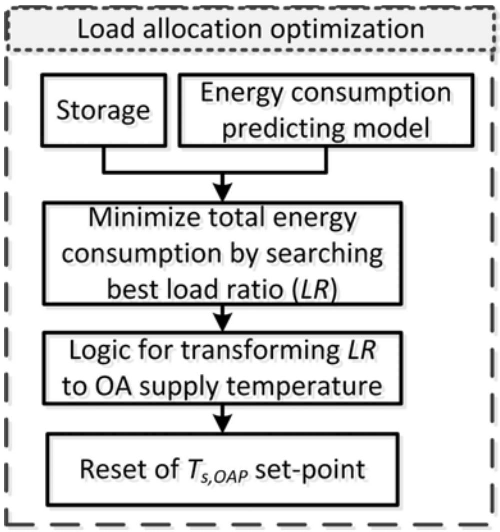

Figure 4: Logic of the load allocation optimization module

3.2 Modeling of the load allocation optimization

3.2.1 Energy consumption predicting model. The VRF unit includes an outdoor unit and several indoor units as shown in Fig.1. Each indoor unit consists of a DX coil and a supply fan. The OAP unit can also be simply treated as combination of a DX coil and a supply fan. Without loss of generality, all the DX coils are assumed to be of the same type and have similar characteristics. Similar to the modeling methodology illustrated in literatures (Zhou *et al*., 2008), the overall energy consumption of a VRF unit is estimated by the following equations.

$$W = W_{comp} + W_{fan} \tag{1}$$

$$W_{comp} = Q(RTF)(EIR) \tag{2}$$

$$Q = \sum_{i=1}^{n} Q_i \tag{3}$$

$$W_{fan} = \sum_{i=1}^{n} W_{fan,i} \tag{4}$$

$$RTF = \frac{PLR}{PLF} \tag{5}$$

$$EIR = \frac{1}{COP_{rated}}(EIR_T)(EIR_f) \tag{6}$$

Where, W_{comp} and W_{fan} denote energy consumption of the compressor and the supply fan respectively, Q and Q_i denote actual cooling capacity of total and single DX coil at operation condition respectively, *RTF* denotes run-time fraction and *EIR* for energy input ratio, *PLR* denotes part load ratio, a ratio of the practical cooling load divided by the rated design load (Zhang *et al*., 2006), *PLF* expresses degradation of efficiency for on-off switching of the compressor (Henderson *et al*., 1999) , COP_{rated} denotes rated COP of the VRF unit, EIR_T denotes temperature modifier of *EIR*, and EIR_f denotes air flow rate modifier of *EIR*(treated constant in this paper).

$$EIR_T = a\left(\frac{T_c}{T_{c,ref}}\right)^b \left(\frac{T_e}{T_{e,ref}}\right)^c \left(\frac{T_{db,OA}}{T_{db,ref}}\right)^d \left(\frac{T_{db,avg}}{T_{db,ref}}\right)^e \left(\frac{n}{n_{ref}}\right)^f \tag{7}$$

$$T_{db,avg} = \sum_{i=1}^{n} T_{db,i} Q_i / Q \tag{8}$$

Where, *a* to *f* are model parameters to be identified using the operation data collected in present time-step and recursive least square estimation technique (Ma and Wang, 2011; Nassif *et al*., 2008). T_c denotes condensing temperature of VRF unit, T_e denotes evaporating temperature of VRF unit, $T_{db,OA}$ denotes dry bulb temperature of OA, $T_{db,avg}$ denotes weighted average dry bulb temperature of the air entering the heating coils, *n* denotes the compressor speed. The subscript *ref* denotes referenced value of the corresponding variable.
3.2.2 Load allocation optimization. The objective function is the total energy consumption (W_{total}) of the combined system, which is a sum of that of the VRF unit and the OAP unit (calculated using Eqs. (1)~(8)). Assuming the OAP unit takes *LR* of the total load (noted as Q_{load}) of the combined system, theoretical cooling/heating capacity of the OAP unit is $Q_{load}\cdot LR$, and that of the VRF unit is $Q_{load}\cdot(1-LR)$ as a result. The value of Q_{load} should be determined at first. In this study, it is assumed that the load conditions are not significantly changed between current and last time step. Q_{load} can be estimated using operation conditions of the VRF unit and the OAP unit in last time step by recursive least square estimation technique.

According to Eq.(1), the total energy consumption is then given by

$$W_{total} = Q_{load}(1-LR)(EIR_{VRF})\frac{Q_{load}(1-LR)}{Q_{rated,VRF}} + W_{fan,VRF} + Q_{load}LR(EIR_{OAP})\frac{Q_{load}LR}{Q_{rated,OAP}} + W_{fan,OAP} \tag{9}$$

$$W_{total} = (k_1 + k_2)LR^2 - 2k_2 LR + k_3 \tag{10}$$

Where

$$k_1 = \frac{Q_{load}^2}{EIR_{OAP}Q_{rated,OAP}} \tag{11}$$

$$k_2 = \frac{Q_{load}^2}{EIR_{VRF}Q_{rated,VRF}} \tag{12}$$

$$k_3 = k_2 + W_{fan,VRF} + W_{fan,OAP} \tag{13}$$

3.2.3 Logic of determining OA supply temperature set-point. For the combined system in heating mode, the higher the *LR* is, the more loads the OAP unit takes and the higher OA supply temperature should be. Therefore, the *LR* can be transformed and used for the OA supply temperature control by rules depicted as follows.

$$T_{OA,set} = \frac{Q_{load}LR}{Q_{OAP,meas}}T_{OA,meas} \tag{14}$$

Where subscript *meas* indicates current measurement.

4. EVALUATION OF THE PROPOSED CONTROL STRATEGY

4.1 Conditions setting

Six zones, zone 7 to 12, of the typical floor as shown in Fig. 2 are selected for accommodating a combined system. Heat gains of light and equipment are set the same for each zone, but heat gains of occupants vary in different zones, which are simulated by multiplying the base occupant density by an occupant factor of each office. The set-points of the six zones are 22℃.The corridor adjacent to these zones is assumed to have an independent air conditioner, which has a thermostat set to 22° C. Rated capacity of the VRF unit is 25.6 kW, and that of the OAP unit is 11.8 kW. One day in January, which is the coldest month in Shanghai, is selected for the evaluation of the proposed control strategy. Fig. 5 shows the ambient temperature and relative humidity variation of the test day. The temperature rises as high as 16℃ in the late afternoon. The combined system operates from 8:00 to 20:00. The proposed control strategy starts from 8:30 to eliminate the impacts of system dynamics during the startup period.

Besides the proposed control strategy, a benchmark strategy which has a fixed OA supply temperature set-point of 22℃ is also evaluated for comparison purpose.

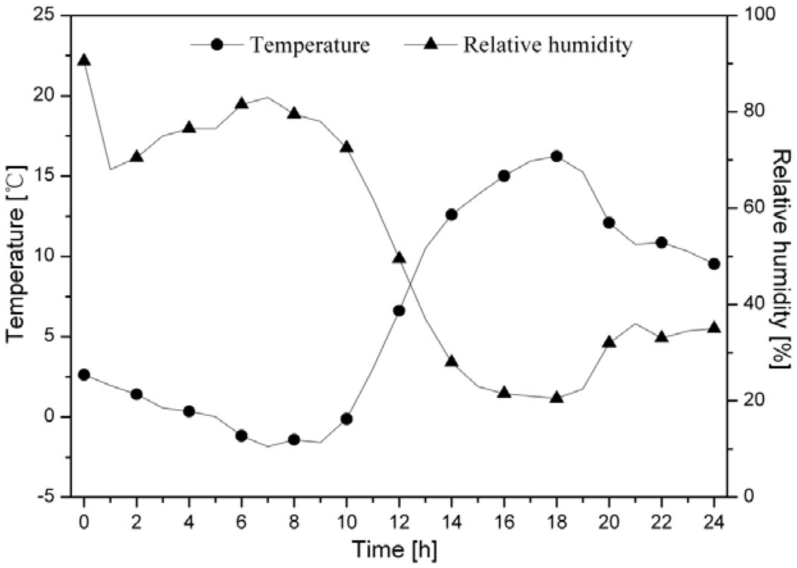

Figure 5: Temperature and relative humidity of the test day

4.2 Results and discussion

Fig. 6 shows a comparison of the zone temperature variation under the two control strategies. It can be seen from this figure that the zone temperature can be maintained at the set-point very well with both control strategies.

Fig. 7 shows the total load and the load allocation of the OAP unit under the proposed control strategy. The total load varies with the load conditions, and it gradually decreases from the morning to the early afternoon. The OAP allocated load also decreases during this time, and it meets the stopping requirement at about 13:15. The OAP unit is stopped at this time as a result. After the total load is high enough that the restarting requirement is met at about 18:45, the OAP unit is restarted, and the load allocation optimizing is executed again after this time.

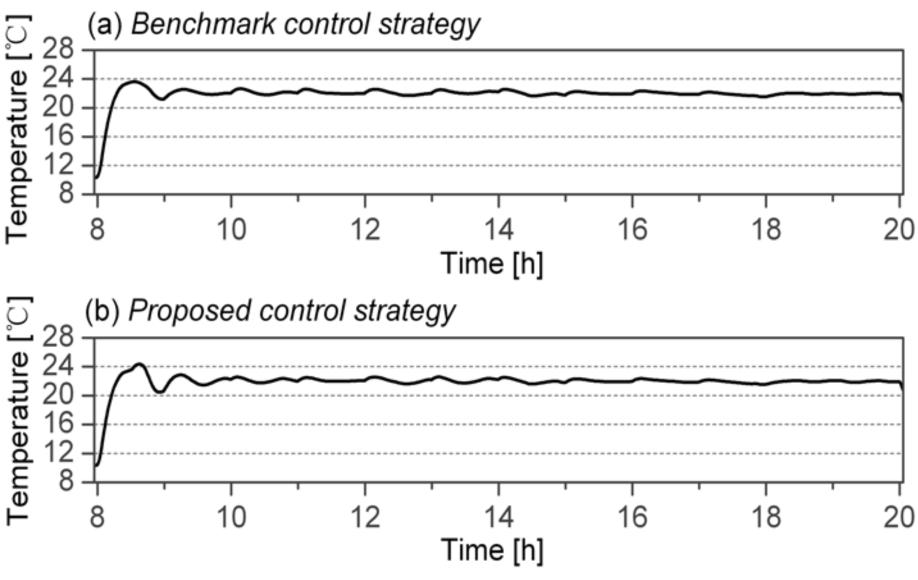

Figure 6: Zone temperature variation under two control strategies (Zone 7)

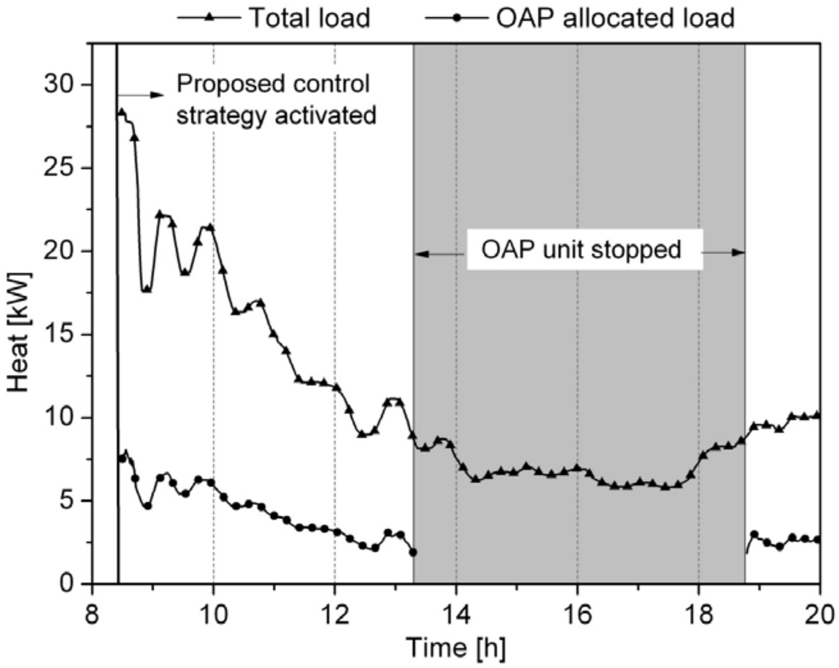

Figure 7: Load allocation results under the proposed control strategy

Table 1 lists the heating capacity and energy consumption of the combined system under the two control strategies. As seen in the table, the total heating capacity of the combined system, which is a sum of the VRF unit and the OAP unit, is almost the same under the two control strategies. However, the energy consumption of the combined system is different greatly. When the proposed control strategy is executed, about 5.17 % of energy can be saved, which indicates the superiority of the proposed control strategy over the fixed set-point control strategy.

Table 1: Heating capacity and energy consumption of the combined system

Item	Control strategy	
	Benchmark	***Proposed***
Heating capacity (10^3 kJ)		
VRF	354.82	371.96
OAP	135.26	117.92
Total	490.08	489.88
Energy consumption (kWh)		
VRF	27.60	27.68
OAP	11.68	9.51
Supply fan	1.15	1.15
Total	40.43	38.34
Energy saving (%)	-	5.17

The ratio of the allocated load to the rated capacity of the OAP unit determines when the OAP unit is stopped. It also affects the energy performance of the combined system. Table 2 lists the energy consumption of the combined system under different ratios.

Table 2: Energy consumption of the combined system under different ratios of allocated load to rated capacity of the OAP unit

Control strategy	***Benchmark***	***Proposed***			
		***ratio*=1/10**	***ratio*=1/8**	***ratio*=1/6**	***ratio*=1/5**
Energy consumption (kWh)	40.43	38.42	38.35	38.34	38.25
Energy Saving (%)	-	4.97	5.14	5.17	5.39

It can be seen from Table 2 that the changing ratio of the allocated load to the rated capacity of the OAP unit results in different energy performance of the combined system. The energy saving of the combined system under the proposed control strategy increases as the ratio does in the test day. However, too large ratio will lead to frequent on-off switching of the OAP unit when the restarting load is not very high. In other words, the ratio should not be too large for the reliable operation of the OAP unit despite of the much larger energy saving percentage.

5. CONCLUSIONS

An energy-saving control strategy is proposed and evaluated for the VRF and VAV combined air conditioning system in heating conditions. The proposed control strategy combines load allocation optimization and on-off switching logic to make a coordinating control of the VRF unit and the OAP unit. When both the VRF unit and the OAP unit are operating, the load allocation optimization module will be executed. When the load is quite small, the OAP unit will be stopped for efficient operation of the combined system. Once requirements are met, the OAP unit is restarted and the load allocation optimization module is executed again. Results showed that the proposed control strategy is feasible and superior to conventional fixed set-point control strategy. It could efficiently decrease the energy consumption of the combined system in heating conditions. The method can be easily extended to cooing conditions as well.

NOMENCLATURE

VRF	Variable refrigerant flow	
VAV	Variable air volume	
OAP	Outdoor air processing	
DX	Direct expansion	
OA	Outdoor air	
EEV	Electronic expansion valve	
PLR	Part load ratio	$(W \cdot W^{-1})$
RTF	Run time fraction	
PLF	Part load factor	
EIR	Energy input ratio	$(W \cdot W^{-1})$
LR	Load ratio	$(W \cdot W^{-1})$
T	Temperature	(°C)
n	Compressor speed	(rpm)
W	Input power	(W)

$a \sim f$	coefficients
$k_1 \sim k_3$	coefficients

Subscript

com	compressor*s*
fan	supply fan
sys	combined system
i	*i*th air conditioned zone
s	supply air
c	condensing
e	evaporating
db	dry bulb
wb	wet bulb
meas	measurement
set	set-point
ref	reference value
rated	rated value

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