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Development of Coordination Control for Multiple Rooftop Units

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Abstract

Rooftop Units (RTUs) have been widely applied in providing space heating and cooling for commercial buildings. In total, they serve over 60% of the commercial building floor space in the U.S. Even through the current control approaches of a RTU can maintain the zone temperature corresponding to a set point temperature, it performs inefficiently due to several factors such as limited sensing capability, non- coordinated local control, inherent oversizing effects and so on. In addition to unnecessary power consumptions, the current control and operation technology on RTUs also lead to the space humidity problem, equipment efficiency degradation, and premature failure. To solve aforementioned problems and enhance the overall system performance, this paper presents the development of a coordination control technique for improving the system operations of multiple RTUs used in light commercial buildings with an open space. In the control algorithm, simplified building models were developed to potentially estimate the instantaneous building load. Utilizing this model-based technique, sequence control strategy is designed to automatically select suitable mode operations of a RTU including economizing, heating, cooling and ventilation mode while synchronizing with the supply fan control and damper operations. Using a developed building simulation platform implemented on Matlab software, the developed coordination control is applied in reducing energy penalty caused by an inherent oversizing problem on multiple RTUs. With the findings, the control algorithm can be further used as a soft-repair for temporally fixing faulty operations and improper commissioning of multiple RTUs such as excessive or insufficient air flow, outdoor air leakage, stuck dampers and simultaneous heating and cooling (RTU fighting).

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Keywords: Coordination Control; HVAC; Instantaneous Load; RTU; Fault Detection and Diagnosis;

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1. Introduction

As one of typical heating, ventilation and air-conditioning (HVAC) equipment, rooftop units (RTUs) have been intensively used in commercial buildings; they consumed around 60% of total energy to provide both cooling and heating systems for light commercial buildings with an open space in the U.S [1]. Specifically, multiple RTUs are commonly designed to maintain thermal comfort in multi- zone layout for low-rise cubicle offices or big-box retail stores. As a result, proper sizing and operations of RTUs lead to significant energy savings [2]. Although the current individual control methods of RTUs, such as a multi-speed fan control, demand-controlled ventilation and multi-stage compressor control, works fine in maintaining the thermal comfort of a conditioned space, they waste much energy due to RTU fighting, non-coordinated local control, and inherent oversizing effects [3]. These uncoordinated control approaches also decease the life cycle of equipment, affects the indoor humidity and can cause unsuitable interaction between RTUs and the refrigeration system in supermarkets. Fundamentally, the present retrofitting solutions are still individual control without embedded optimizing and solving function the inter-zone interactions between zones.

2. Model development

The simplified model of the coordination control was developed based on steady-state heat balance equations composing of: a balance temperature, cooling and heating set-point, outdoor air temperature and envelop load coefficient of an enclosed structure. The developed model was tested and validated through a building simulation platform [4]. The model was derived based on the assumptions which are: 1) a few windows are installed in retail stores. As a result, radiation term is neglected for the simplified instantaneous load model; 2) the model uses the two load points to construct a linearized curve including: the first point is at balance temperature (T_b) that mechanical cooling is not require d or it is no load condition. The second point is based on peak heating or cooling condition when outdoor temperature is maximum; 3) the cooling load is performing at RTU design capacity in terms of cooling set-point ($T_{sp,c}$), whereas the heating load performs design capacity at heating set-point ($T_{sp,h}$); 4) generated load, composes of internal loads from occupancy, lighting and plug equipment; and 5) Although the building structure may heat up and cool down during a day, the difference in energy between the start and end is small relative to the total energy. As a result, the change rate of energy storage is neglected. With the assumptions, the instantaneous heating load and cooling are defined as follows:

$$\dot{Q}_h = k_{env}(T_b - T_{amb}) \quad (1)$$

$$\dot{Q}_c = k_{env}(T_{amb} - T_b - (T_{sp,c} - T_{sp,h})) \quad (2)$$

, where k_{env} is the building envelop load coefficient, and T_{amb} is the ambient temperature.

3. Coordination control algorithm for optimizing energy consumptions of oversized RTUs

The characteristics of oversizing issue are observed from runtime fraction (RTF) and RTU operations [2]. The average RTF of some RTUs is much smaller than 1.00 at the design temperature conditions; it means oversizing issue being very severe. As a result, the on-time period of the RTUs in this case should be adjusted longer while satisfying thermal comfort of the zones. For the routine operations in terms of interactions among adjacent RTUs, the operations of RTUs are not synchronized; each one is controlled by the thermostat. With the interactions in terms of good sides, the thermal comfort of a zone could be satisfied even if the RTU associated with that zone operates occasionally. As a consequence, it is not essential to operate each RTU simultaneously so as to satisfy building comfort. The coordination control algorithm can be designed as tabulated in Table 1. ***In step 1***, since each RTU is over designed, a satisfied minimum airflow rate is required to be computed by Eq. 3 by selecting the maximum value from $\dot{V}_c$, $\dot{V}_h$ or $\dot{V}_v$ in the whole open space of a light commercial building such as a retail store as shown in Fig. 1; the simplified instantaneous models in Eq. 1 and 2 are used to compute total actual load ,and then are converted into $\dot{V}_c$ and $\dot{V}_h$ in Eq. 5 and 6. Meanwhile, $\dot{V}_v$ can be determined from Eq. 4. ***In step 2***, applying Eq. 7

and 8, the ideal minimum number of operating fans (N_i) is determined automatically. To reduce and optimize fan power consumption ***in step 3***, $\beta_{oa,required}$ is calculated by Eq. 9. N_i with the calculated $\beta_{oa,required}$ of operating fans are enabling in a sequential order in order to mainly satisfy thermal comfort and indoor air quality in each zone corresponding to the agreement between cooling set point and measured zone temperature (Eq. 10). ***In step 4***, the decision-making procedure will be performed in a period which is determined by the occupied hours; 30 minutes could be the default of run-time operation to stop each fan, and 5 minutes could be the default operating time to start a descending order of N_i. ***Finally***, to automatically select a mode operation according to Eq. 11, all compressor(s) or heater(s) are started if the fan status is on and a mode operation equals to cooling or heating, respectively. In Table 1, $\dot{V}_{ij}$ is RTU flow rate at row i and column j; R_p is the outdoor airflow rate required per person; P_z is the zone population; R_a is the outdoor airflow rate required per unit; R_h is the supply airflow rate required per unit ton of heating load; and R_c is the supply airflow rate required per unit ton of cooling load.

Table. 1 Equations and parameters used for the coordination control algorithm

Parameters	Equations or conditions		Units
$\dot{V}_t$ (total airflow rate)	$\dot{V}_t = MAX(\dot{V}_v,\ \dot{V}_c\ \ \dot{V}_h)$	(3)	CFM
$\dot{V}_v$ (minimum outdoor airflow rate) [5]	$\dot{V}_v = R_p P_z + R_a A_z$	(4)	CFM
$\dot{V}_c$ (minimum airflow rate for cooling)	$\dot{V}_c = R_c \dot{Q}_c$	(5)	CFM
$\dot{V}_h$ (minimum airflow rate for heating)	$\dot{V}_h = R_h \dot{Q}_h$	(6)	CFM
N_i (ideal minimum number of operating fans)	$N_i \approx \dot{V}_t / \bar{\dot{V}}_{RTU}$	(7)	dimensionless
$\bar{\dot{V}}_{RTU}$ (average RTU flow rate)	$\bar{\dot{V}}_{RTU} = \frac{1}{l \times m}\sum_{i}^{l}\sum_{j}^{m}\dot{V}_{ij}$	(8)	CFM
$\beta_{oa,required}$ (required outdoor air ratio)	$\beta_{oa,required} = \dot{V}_v / \dot{V}_t$	(9)	dimensionless
ΔT_{ij} (zone air temperature offsets)	$\Delta T_{ij} = T_z - T_{sp,c}$, cooling, $\Delta T_{ij} = T_{sp,h} - T_z$, heating	(10)	°F or °C
Mode operation	mode= $\begin{cases} \text{cooling} & if\ \ \dot{V}_t = \dot{V}_c \\ \text{heating} & if\ \ \dot{V}_t = \dot{V}_h \\ \text{econimizing} & if\ \ \dot{V}_t = \dot{V}_v \end{cases}$	(11)	dimensionless

4. Algorithm implementation results

The results of the proposed algorithm are compared with a benchmark control via a simulation platform, which uses conventional on-off control with one-stage fan and compressor operation with 24 hours in a store operation in terms of part load ratio (PLR). The outdoor damper of each RTU is set at $\beta = 0.2$, whereas the β_i of the coordination control can be computed and implemented as depicted in Fig. 2. The appropriately increased opening will extend RTU operation periods of each compressor or heater cycle to reduce oversizing effect while maintaining thermal comfort. By comparing the PLR of the proposed control (Fig. 3) with the PLR of the benchmark control (Fig. 4), the improvement of PLR via the algorithm leads to reducing energy savings between 15 and 30%.

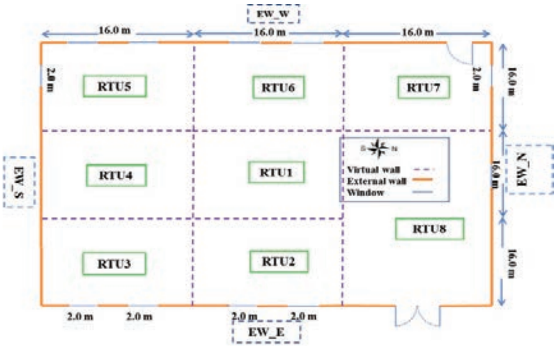

Fig. 1 A typical retail store layout

Coordination control (β of each RTU)			
N = 1	N = 2	N = 3	N = 4
β1 = 1	β1 = 0.9	β1 = 0.4	β1 = 0.3
β2 = 1	β2 = 0.8	β2 = 0.5	β2 = 0.3
β3 = 1	β3 = 0.8	β3 = 0.5	β3 = 0.3
β4 = 1	β4 = 0.9	β4 = 0.4	β4 = 0.3
β5 = 1	β5 = 0.8	β5 = 0.5	β5 = 0.3
β6 = 1	β6 = 0.9	β6 = 0.5	β6 = 0.3
β7 = 1	β7 = 0.8	β7 = 0.5	β7 = 0.3
β8 = 1	β8 = 0.9	β8 = 0.4	β8 = 0.3

Fig. 2 Outdoor air ratio of each outdoor damper

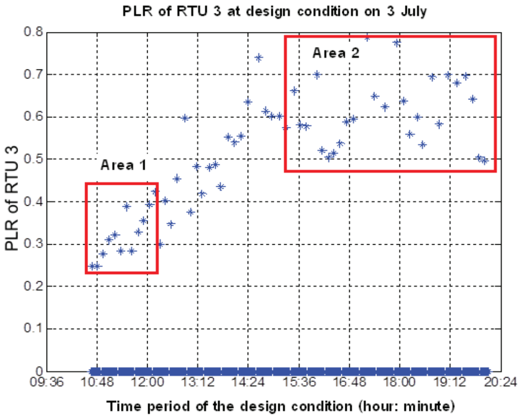

Fig. 3 PLR of a conventional control

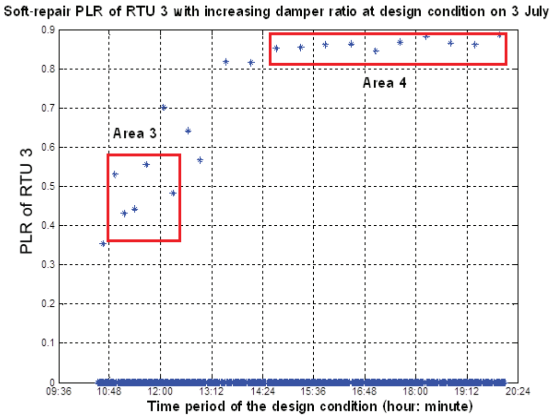

Fig. 4 PLR of the coordination control

5. Conclusion

This paper proposes the novel coordination control algorithm for improving the energy consumptions of oversized RTUs and for decreasing oversizing effect resulting in reductions of energy penalty. The proposed methodology can be further applied in fault detection and diagnosis applications for temporarily minimizing the degradation fault impact caused by faulty operations or improper commissioning and severe faults such as fail compressor, fail heater and some control-related faults while maintaining overall system performance in thermal comfort range until the faults are physically repaired.

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