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Optimal Control Strategy of Central Air-conditioning Systems of Buildings at Morning Start Period for Enhanced Energy Efficiency and Peak Demand Limiting

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Abstract: Air-conditioning systems in commercial buildings are usually switched on before office hour to precool buildings to create an acceptable working environment at the beginning of the office hour in cooling seasons. However, due to high cooling demand during morning start period particularly in hot seasons, often much higher than the capacity of cooling supply, the feedback control strategies in air-conditioning systems often fail to control this cooling process properly. The imbalanced cooling distribution and large difference of cooling-down speeds among different spaces result in the need of significantly extended precooling duration as well as over-speeding of water pumps and fans that lead to serious energy waste and high peak demand. An optimal control strategy is therefore developed to determine the number and schedule of operating chillers and particularly to achieve an optimal cooling distribution among individual spaces. Case studies are conducted and results show that the proposed control strategy could shorten the precooling time about half an hour because of similar cooling-down speeds among individual zones. The energy consumption of the air-conditioning system during morning start period is also reduced over 50%. In addition, the peak demand is reduced significantly contributed by the improved controls of secondary pumps and fans.

Keywords: air-conditioning, precooling control, building energy efficiency, indoor environment control, peak load limiting.

1. Introduction

1.1 Research background

The energy consumption of buildings has increased rapidly in recent years due to the increased population, the increased demand on indoor environment control, the global climate changes, etc. Approximately 40% of global energy is consumed by buildings [1-3]. In the United States, buildings accounted for 74% of electricity use in 2010 [4] and even more in Hong Kong (i.e., 91% of total electricity [5]). In addition to the challenge from buildings due to their large energy consumptions, peak load is another serious issue, which leads to huge investment in the power grid development and reduce grid energy efficiency. It is estimated that the capacity to meet demand during the top 100 hours in a year accounts for nearly 20% of electricity costs [6], since generation and transmission capacity of power grids are provided to meet the peak demand that occurs infrequently [7]. Facing to these two issues (i.e., large energy consumption and high peak demand), the monthly electricity bills of buildings paid for utility companies are always based on two parts, such as in Hong Kong. In Hong Kong, one is the charge for the monthly electrical peak demand, which refers to the maximum energy consumed in a demand interval (e.g. 30 min) for an entire month. The other is the cost for the overall energy consumption in the month. Although different price structures exist, the monthly peak demand cost of a commercial building always constitutes a great part of the electricity bill [8].

As buildings have great potentials in energy saving and peak demand reduction, many researches have been conducted aiming at minimizing energy consumption and/or operating cost of buildings. The efforts could be grouped into three main categories according to their targets: energy efficiency and conservation, peak load management and demand response. Energy efficiency and conservation focus on the energy saving of buildings [9-12] while the last two categories address the peak demand reduction using different mechanisms [13-18]. Heating, ventilation and air-conditioning (HVAC) system accounts for about 50% of building energy use on average and it could therefore play an important role to realize energy saving and peak demand management [18-21]. This can be achieved due to the elastic nature of buildings and building manager system (BMS), particularly for commercial premises.

Currently, many control strategies are developed and applied for the air-conditioning systems. In general, almost commonly-used automatic control strategies today for centralized air-conditioning systems are demand-based feedback control. The basic control principle of typical demand-based feedback control of an air-conditioning system is illustrated in Fig.1. The regulators, typically PID (proportion-integration-differentiation) controllers, modulate the cooling intakes from their suppliers to maintain the states of the spaces served by the terminal units (or the states of AHU (air handling unit) outlets) at their set-points. The distribution of the cooling based on the demand-based feedback control loops can be managed properly in normal conditions when the total demand to each device is not more than the available cooling and all users can get what they need from their suppliers. This demand-based feedback control with PID regulators based on feedback information is capable to ensure the accuracy, adaptiveness and simplicity of cooling distribution in buildings and it is hard for a simple predictive control to achieve the same control performance due to the complexity and ever change of conditions and disturbances. This is why this control method is widely adopted in buildings.

Fig.1 Basic principle of demand-based feedback control

1.2 Motivation and challenges

In fact, air-conditioning systems in commercial buildings are usually switched on before office hour in the morning to precool the indoor spaces. This can not only create an acceptable indoor environment at the beginning of office hour, but also avoid high peak demand if occupants turn on all the cooling devices at the beginning of office hour to force indoor temperature resume to its set-point immediately. Although this scheduled operating strategy is very easy to be implemented and widely adopted by air-conditioning systems, serious problems often exist in practice today.

First of all, serious energy waste caused by extended precooling time and failure of conventional control strategies. As the indoor air temperature is much higher than its corresponding set-point when air-conditioning starts in the morning, the cooling supply side cannot satisfy the very high cooling demand required by air-side (i.e., indoor spaces) and each air-conditioned spaces would compete for the limited cooling supply. Hence, all water valves and air dampers would be fully open, resulting in the failure of demand-based feedback control strategies. Due to pipe resistances and pressure losses, imbalanced cooling distribution would happen inherently and remote spaces get much lower cooling. Both the difference of space cooling load profiles and imbalanced cooling distribution would result in different cooling-down speeds among different indoor spaces. Consequently, time durations for indoor precooling of different spaces will be quite different and required precooling time has to be extended in order to allow all the spaces of a building reaching their indoor environment control set-points.

Moreover, high peak power demand would be potentially appeared during morning start period resulting from the excessive speeding of chilled water pumps and air delivery fans [22]. Although the number of operating chillers is usually limited during morning start period, the pumps and fans would fully operate, resulting in very high peak demand. The excessive speeding of pumps and fans are not helpful for cooling but would lead to some unexpected problems. For example, the excessive chilled water flow delivered by secondary pumps would cause serious deficit flow.

The aforementioned problems occurred during morning start period have not been addressed in academic literature and engineering practice. In this study, an optimal control strategy is therefore developed for morning start period to optimize the distribution of limited cooling supply among individual zones/rooms as well as the number and schedule of operating chillers. Examples of typical on-site data from a super-high-rise commercial building are collected and used in this paper to illustrate the problems during morning start period. Case studies are conducted to test and validate the proposed control strategy.

2. Problems illustration using on-site data

2.1 System description in a high-rise commercial building

In this session, on-site data collected from the BMS of a super-high-rise commercial building in Hong Kong is used to illustrate the problems during morning start period. The building has over one hundred storeys. A central chiller plant with six identical centrifugal chillers is responsible to provide cooling to the building spaces. Each chiller interlocks with one corresponding constant primary chilled water pumps and one constant condenser cooling water pump. All pumps in the secondary chiller water distribution system are equipped with variable frequency drives. Two AHUs involving variable air volume (VAV) boxes serve each office floor. The chillers and AHUs are switched on before office hour. The main parameters of the central air-conditioning system in the building are presented in Table 1.

Table 1 Main parameters of central air-conditioning system in the building

The central air-conditioning system in the building is a primary constant-secondary variable chilled water system. Fig.2 presents the schematic of such central system and the basic control principle is presented as follows: the water valve opening of each AHU is modulated to maintain supply air temperature at the pre-defined set-point. The speed control of secondary chilled water pumps will be adjusted to ensure the measured pressure drop of main supply side (or the remote critical loop) at its set-point. The chiller sequence/capacity will be properly controlled to meet the required building cooling load. Similarly, at the air side, the damper of each VAV box is controlled to keep indoor air temperature at its set-point. The supply fan is based on the pressure control to maintain the static pressure set-point in order to deliver sufficient air flow for each room. Such demand-based feedback control strategy, commonly-used today, is based on the assumption that the cooling supply by chillers is set to be enough to fully satisfy the requirements of the terminal units (e.g., AHUs). However, the limited cooling supply during morning start period, which is always exacerbated by the limit of operating chiller number, would lead to the extension of precooling time, extra energy waste and high peak demand. In the condition of limited cooling supply during morning start period, almost all the conventional feedback control strategies, which are based on a premise of sufficient cooling supply, would result in these inherent problems regardless of the type of central systems. In this study, precooling time refers to the time duration for precooling the indoor space back to its set-point of office hour in the morning.

Fig.2 Schematic of considered central air-conditioning system

2.2 Problems during morning start period

During morning start period, the cooling-down speeds of different indoor spaces are obviously different. Six rooms, which are used as offices, are selected at the fifteenth floor in the high-rise commercial building. Their cooling supply are served by an AHU. The ceiling height of each room is about 3.5m and the orientation of windows of each room faces north. Fig.3 presents the temperature deviations (TD) between the measured indoor air temperatures ($T_{measured}$) and their corresponding set-points (T_{set}) of six selected rooms. During the start period in the morning, it is obvious that the cooling-down speeds of different rooms are significantly different. In addition to the different room cooling load profiles, the failure of feedback control strategy would also be the cause of this phenomenon. In Fig.3, the indoor air temperature of Room 2 reached its set-point much more quickly than the others. In contrast, the indoor temperature of Room 1 reached its set-point nearly two hours later than Room 2. In such a case, the duration for precooling these rooms should be extended to meet the requirement of the worst one (i.e., Room 1) although the other five rooms had already finished the cooling-down process very earlier. As for Room 2, about two hours precooling time was unnecessary and just used to wait for the others back to their corresponding indoor air temperature set-points. Therefore, the different cooling-down speeds of indoor spaces would extend the precooling time and cause large amounts of energy waste as well as unfair thermal comfort among individual spaces during morning start period.

Fig.3 Measured cooling-down profiles of rooms during morning start period

Moreover, during morning start period, the cooling supply is often insufficient and therefore cooling devices at the demand side (e.g., AHUs and VAV boxes) will compete for the limited cooling supply. The water valves and air dampers at the demand side will be fully open in order to force the control variables (i.e., temperature) resume to their set-points as soon as possible. Fig.4 shows measured air damper openings of six VAV terminals served by an AHU. The openings of all VAV dampers were fully open during the start phase. They were eventually closed down to some extent can assume their abilities to control the indoor air temperatures at their set-points but at different times. Due to fully open valves/dampers, cooling distributions delivered by chilled water flow/air flow were not controlled properly. The remote rooms with larger hydronic resistances and at disadvantaged positions could only receive much less cooling than that received by the zones near to the cooling supply as well as the average cooling. Compared with the indoor air temperature profiles (i.e., Fig.3) at the same period, it can be observed that the sequences of rooms whose indoor air temperatures reached the set-points and the ending of damper saturation were similar. For instance, Room 1 was the very last one for both.

Fig.4 Measured air damper openings of VAV terminals during morning start period

Furthermore, the fully open valves of AHUs lead to secondary chilled water pumps over-speeding in order to maintain the differential pressure set-point according to the control logic. Similarly, air delivery fans also operate at full speeds to maintain the controlled static pressures at their set-points. Fig.5 shows the speed profiles of the AHU fans at the same floor in the building. The speeds of the fans reached the full speed right after being switched on. Similar phenomenon and problems also occurred on secondary pumps. The over-speeding pumps and fans will make the power demand of air-conditioning system increase significantly resulting in very high peak power demand at starting period. Such over-speeding of pumps and fans are not helpful for the indoor air temperature. Therefore, the operation of secondary pumps and air delivery fans during morning start period should be controlled properly to avoid energy waste and very high peak demand.

Fig.5 Measured speed profiles of AHU fans during morning start period

3. Proposed optimal control strategy for morning start period

3.1 Schematic of control strategy and chiller sequencing optimizer

The basic control logic of an air-conditioning system during morning start period is shown in Fig.6. This strategy optimizes the cooling distribution among individual zones during morning start period as well as determining the sequencing control of chiller (i.e. number and on-off schedule of chillers). According to the inputs, i.e., measured outdoor air temperature, relative humidity, average indoor air temperature of the building and the day in a week, the scheme of chiller sequencing optimizer determines the number and schedule of operating chillers for precooling the building. The cooling distribution optimizer optimizes the cooling distribution among different zones in order to achieve a uniform cooling-down speed of indoor spaces. The total chilled water flow to be distributed by the cooling distribution optimizer is equal to that in the primary loop to prevent excessive and unnecessary water flow circulated in the secondary loop. The secondary pumps are still modulated based on the pressure control. Same control logic of cooling distribution optimizer is used for the air side. The total air flow to be distributed by VAV terminals served by an AHU during morning start period is limited at its design flow rate and the air delivery fans are controlled to maintain the differential pressures at their set-points. The proposed control strategy is not back to the conventional control strategy until the indoor temperatures of all zones recover to their corresponding set-points.

In this study, the sequencing control of chillers during morning start period is determined by chiller sequencing optimizer using a performance map based on measured outdoor air temperature, relative humidity, average indoor air temperature of the building and the day in a week (i.e., weekday or weekend) [23]. The performance map for morning start chiller sequencing control is designed offline by analyzing the historical cooling load profiles of morning start period at different conditions.

Fig.6 Schematic of proposed control strategy for morning start period

3.2 Cooling distribution optimizer

A reasonable and proper cooling distribution can effectively shorten the precooling time and reduce the energy consumption by achieving a uniform cooling-down speeds among different indoor zones/rooms during morning start period. At the same time, the high peak demand resulted from ineffectiveness of conventional control strategies during morning start period can be prevented by the cooling distribution optimizer. To achieve these objectives, supply-based feedback control strategy is employed instead of conventional (demand-based) feedback controls.

Fig.7 illustrates the basic principle of the supply-based control strategy used for cooling distribution optimizer. This control strategy uses the actual measurements as the feedback information to ensure the accuracy, adaptiveness and simplicity of control in practical applications. The major difference compared with the conventional feedback control strategy is that all the feedbacks are from the end-users (i.e., space temperatures) rather than from their immediate outlets (e.g., outlet air temperatures of AHUs). At chilled water side, the cooling distribution optimizer (i.e., global cooling distributor) manages the distribution of the total available chilled water supply (i.e., water flow in the primary loop) among individual zones. The required measurements as the feedback information are the average temperatures (i.e., return air temperatures) and chilled water flows of zones as well as the total water flow in the primary loop. Similar to the air side, the cooling distribution optimizer (i.e., local cooling distributor) manages the cooling distribution among the spaces served by an AHU. The required measurements are the indoor air temperatures and air flows of all spaces in a zone as well as the total available air flow for the zone.

Fig.7 Basic control principle of supply-based feedback control strategy [24]

The analytical method of cooling distribution optimizer is adopted from an economic concept, utility function, to realize an expected cooling distribution under limited cooling supply, which also is used for building demand response control responding to smart grids [25-26]. The numerical procedure for cooling distribution at the water side is illustrated here as an example and the procedure is the same for cooling distribution at the air side, except the parameters and variables used at the water side are replaced by the corresponding ones.

Eq.(1) shows the calculation of utility value of a zone. Where, T_{band} is the deviation between T_i^k (measured indoor air temperature) and $T_{set,i}$ (original indoor set-point), which should be large enough to fully cover the whole possible indoor temperature range of zones in practical situations. Its value is set to be 10°C. U_i^k is the utility value, which is originally an economic concept adopted in this application.

$$U_i^k = 1 - \frac{\left|T_i^k - T_{set,i}\right|}{T_{band}} \qquad U_i^k \in [0,1] \tag{1}$$

The online calculation process for determining the chilled water flow set-points of individual zones is shown in Eqs.(2-4).

$$M_{U=1,i}^{k} = M_{w,i}^{k} - \sqrt{\frac{1-U_i^k}{a_i}} \tag{2}$$

$$M_{U=1,i}^{k} = \lambda M_{U=1,i}^{k-1} + (1-\lambda) M_{U=1,i}^{k} \tag{3}$$

$$M_{sp,i}^{k} = M_{U=1,i}^{k} + \sqrt{\frac{1-\overline{U}_{sp}^k}{a_i}} \tag{4}$$

where, $M_{U=1,i}^{k}$ is the required chilled water flow of i^{th} zone to maintain the original utility value, that is, when the indoor air temperature is at its set-point of office hour. $M_{w,i}^{k}$ is the measured chilled water flow of i^{th} zone at *kth* time step. λ is the forgetting factor selected to be 0.95 in this study. $\overline{U}_{sp}^k$ is the target utility value of all zones at *kth* time step, which is the expected utility value of all zones if utility values of all zones are controlled to be the same. The value is determined based on the available cooling capacity (i.e., total chilled water flow in the primary loop). $M_{sp,i}^{k}$ is the chilled water flow set-point for i^{th} zone at *kth* time step.

$$a_i = \frac{\Delta T_i}{T_{band} \times \Delta M_i^2} \tag{5}$$

$$\Delta T_i = (T_{out,i} - T_{set,i}) + 5 \tag{6}$$

Parameter a_i represents the thermodynamic characteristics of i^{th} zone and the values are calculated by Eqs.(5-6) [24]. Where, ΔT_i is the indoor air temperature rise (stabilized) of i^{th} zone from its set-point, which can be obtained when the air-conditioning system is shut down at a selected working point in the morning. The value is assumed to be 5°C higher than the design outdoor air temperature ($T_{out,i}$), as calculated by Eq.(6). ΔM_i is the chilled water flow rate of i^{th} zone at the selected working point when the air-conditioning is shut down in the morning. This value can be obtained based on the chilled water flow of i^{th} zone in the reference day considering the current outdoor temperature, relative humidity, the average temperature of the building and the type of the day.

4. Test platform

A virtual simulation platform is constructed using dynamic models developed in TRNSYS [27] to test and validate the effectiveness of proposed control strategy for morning start period. The detailed physical models, building envelop and major components (e.g. chillers, pumps, fans, hydraulic network, air ducts, AHUs) of a central air-conditioning system, are included in this dynamic simulation platform. The models used in the test platform are calibrated using real data [28-29]. The tests using conventional and proposed control strategies are simulated under a same day in order to have a clear comparison and hence to present the improvements clearly using the proposed control strategy during morning start period.

Table 2 Main parameters of simulated central air-conditioning system

The central chiller plant simulated is a typical primary constant-secondary variable chilled water system and the schematic of such system is shown in Fig.2. This type of system is typical and most popularly adopted in real projects and hence is selected for the test and validation. But the proposed control strategy would be useful for other types of central systems (not only limited on this specific system). This is because the proposed control strategy is based on the measured temperature and total available cooling supply to achieve its control function and not based on the specific information of considered systems.

The simulated central air-conditioning system is modified based on the air-conditioning system of a super-high-rise building in Hong Kong and the main parameters are presented in Table 2. It consists of four identical chillers, each with rated capacity of 4080 kW. Each chiller is associated with a primary chilled water pump of constant speed (172.5 L/s). Two variable speed chilled water pumps are employed in the secondary loop. The cooling source for the building comes from the chilled water circulating in the AHUs which cools down the supply air temperature to a pre-defined set-point. After the heat exchanger in the AHU, the returned chilled water is distributed evenly to the operating chillers to be chilled again. The building is simulated by a multi-zone model (Type 56) in TRNSYS. Six typical air-conditioned zones with different cooling load profiles in this building cooled by six AHUs are selected. For the air side, one zone served by one AHU is simulated, which contains a supply and a return fan with rated capacity 34 kW and 32 kW respectively. The zone consists of eight rooms with different cooling load profiles and air duct resistances are considered. The design supply air static pressure is 650 Pa and the fresh air flow set-point for a zone is set to be constant according to the ASHRAE Standard 62.1-2013.

A typical summer day in Hong Kong is selected. The outdoor weather condition of the test day is obtained by TMY (typical meteorological year) data and the outdoor air temperature and relative humidity are shown in Fig.8. The office hour of the building is from 08:00am to 20:00pm. The indoor air temperature set-point during office hour is set as 24°C. The simulation is run 24 hours (i.e., a whole summer day) and time step of simulation is 1second.

Fig.8 Outdoor dry-bulb temperature and relative humidity in the test day

5. Results and discussion

Based on measured outdoor air temperature (i.e., 28^{o}C), relative humidity (i.e., 76%), the average indoor air temperature of the building (i.e., 29.1^{o}C) and the day in a week (i.e., weekday), chiller sequencing optimizer determined two chillers to be switched on for precooling the building before office hour. In addition, the total water flow to be distributed was equal to that in the primary loop and the total air flow of each zone to be distributed was set as its design value in order to avoid the over-speeding of secondary water pumps and AHU fans.

5.1 Precooling time and control performance

The precooling time refers to the time duration for cooling down the indoor air temperature of all air-conditioned zones/rooms in a building back to the set-points or certain thresholds. Fig.9 shows the indoor air temperature profiles of the six selected zones using conventional control and proposed control strategies. In Fig.9(a), the cooling-down speeds of indoor air temperatures among the six zones were significantly different after switching on the air-conditioning system. The indoor air temperatures of Zone 5 and Zone 6 reached their set-points about one hour earlier than Zone 1. It meant that the precooling time needed to be extended to satisfy the thermal environment control requirement of the zone with slowest cooling-down speed (i.e., Zone 1). At the same condition, it could be observed that, using the proposed control strategy, the temperature profiles of the six zones were almost the same during morning start period, as shown in Fig.9(b). The precooling time duration using the proposed control strategy was shortened significantly, i.e. about half an hour (i.e., time duration ①), as shown in Fig.9.

Fig.9 Temperature profiles of six selected zones during morning start period using conventional strategy (a) and proposed strategy (b)

In order to achieve similar cooling-down speeds among different indoor zones/rooms, even cooling distribution (i.e. proportional to cooling loads) should be realized. Fig.10 shows the valve openings of AHUs using conventional and proposed control strategies. In Fig.10(a), the control valves were fully open to compete for the cooling supply to force their corresponding control variables (i.e., temperature) back to the set-points. Thus, the controllability of each control valve was failure and the imbalanced cooling distribution occurred during morning start period. Using the proposed control strategy, the openings of control valves were under control to achieve expected cooling distribution among different zones, as shown in Fig.10(b). Fig.11 presents the actual chilled water flow rates distributed to individual zones using conventional and proposed control strategies. In Fig.11(a), the distribution of chilled water flow was not properly controlled after switching on the air-conditioning system. The zone far from the cooling source, i.e., Zone 1, obtained the least chilled water flow, which was much less than that for the nearest one, i.e., Zone 6. Such uneven cooling distribution led to the cooling-down speeds of individual zones very different and the precooling duration had to be extended significantly. Using the proposed control strategy, proper and even chilled water distribution among individual zones was realized when the air-conditioning system started. In addition, the total chilled water flow was obviously decreased compared with that using the conventional control strategy. Thus, the excessive chilled water circulating in the secondary loop was avoided, achieving reduced energy consumption of secondary pumps. Similar to the air side, proper and even air flow distribution was achieved and the total air flow allocated was also reduced, as shown in Fig.12.

Fig.10 Valve openings of AHUs during morning start period using conventional strategy (a) and proposed strategy (b)

Fig.11 Chilled water flow rates of zones during morning start period using conventional strategy (a) and proposed strategy (b)

Fig.12 Air flow rates of rooms in a zone during morning start period using conventional strategy (a) and proposed strategy (b)

5.2 Energy saving and peak demand reduction

Fig.13 presents the energy consumptions of different components of the air-conditioning system using conventional and proposed control strategies. The system overall energy saving was mainly the results of two facts: shortened precooling time and reduced pump and fan speeds. The precooling time was shortened about half an hour due to the uniform cooling-down speed of different zones/rooms. At the end of precooling (i.e., 8:00am), the total energy consumption was reduced about 50% using the proposed control strategy. The details of energy consumption on the components concerned using conventional and proposed control strategies are listed in Table 3. The energy savings of secondary pumps and air delivery fans were significant, both more than 50%, as the results of two improvements: the reduced precooling duration and the improved control to avoid the over-speeding during morning start period. The energy savings of chillers and primary pumps were the result of reduced precooling duration and their saving percentages were nearly proportional to the reduction in precooling duration. The overall daily energy saving, achieved by the proposed control strategy, approximately accounted for 4.43% of the whole energy consumed in the test day (note: the total electricity consumption of the building in the test day was 75,937 kWh). According to the Hong Kong electricity tariff [30], the daily electricity cost saving of 2065 HKD was achieved for the building only concerned as the results of improved system control during morning start period.

Fig.13 Energy consumptions of air-conditioning components during morning start period using conventional strategy (a) and proposed strategy (b)

Table 3 Precooling duration and energy consumptions using conventional and proposed control strategies in morning start period (by 8:00am)

In Fig.14(a), the power demand of secondary pumps jumped to the maximum and the deficit flow was serious during morning start period. Using the proposed control strategy, the total chilled water flow distributed for the secondary loop was controlled to be equal to that in the primary loop. This effectively prevented the phenomenon of deficit flow and significantly reduced the power demand of secondary pumps (i.e., about 75%), as shown in Fig.14(b). Fig.15 presents the power demands of chillers, air delivery fans and overall air-conditioning system during morning start period using conventional and proposed control strategies. For air delivery fans, the total air flow delivered in a zone was set as a constant value (i.e., design flow) for a local distribution to avoid fans working at full speeds. Hence, the peak power demand of air delivery fans was significantly reduced (i.e. 36.4%). For chillers, the two profiles of power demand during morning start period using different control strategies were similar except the operating duration because two operating chillers both work at full load. The peak power demand of the air-conditioning system including the chillers, (primary and secondary) pumps and fans in the morning was reduced from 7300kW to 5400kW using the proposed control strategy. This not only avoids the possibly extra payments for end-users, but also benefits the power grids to relieve the stress if quite high power demands of many buildings occur at the same time in the morning.

Fig.14 Water flow in by-pass line and power demand of secondary pumps using conventional strategy (a) and proposed strategy (b)

Fig.15 Power demands of chillers, fans and air-conditioning system using conventional strategy (a) and proposed strategy (b)

6. Conclusions

In this study, on-site data collected in a super-high-rise commercial building is used to illustrate the operation problems occurred in air-conditioning systems during morning start period. The precooling time is extended significantly caused by obviously different cooling-down speeds of different indoor spaces. In addition, the secondary pumps and air delivery fans are over-speeding during this period caused by the failure of conventional feedback control strategies. These problems significantly increase the energy consumption and also induce quite high peak demand during precooling period in the morning.

An optimal control strategy is developed for morning start period. The proposed control strategy can effectively achieve an optimal cooling distribution, which ensures a similar cooling-down speed of indoor temperature among different zones during morning start period, and hence a possibly shortest precooling time. The control strategy determines the number and schedule of chillers to be operated for precooling. Then an optimized cooling distribution among individual zones/rooms is achieved by proposed optimal control strategy in order to shorten the precooling time and reduce the peak power demand. Test results show that the proposed control strategy can reduce the precooling time about half an hour, i.e., 35%. In addition, the over-speeding of secondary pumps and air delivery fans are avoided. During morning start period, about 50% of energy consumption for precooling is saved and peak power demand is decreased nearly 27%, while about 4.5% saving of the air-conditioning system overall energy consumption is achieved by the improved control during morning start period.

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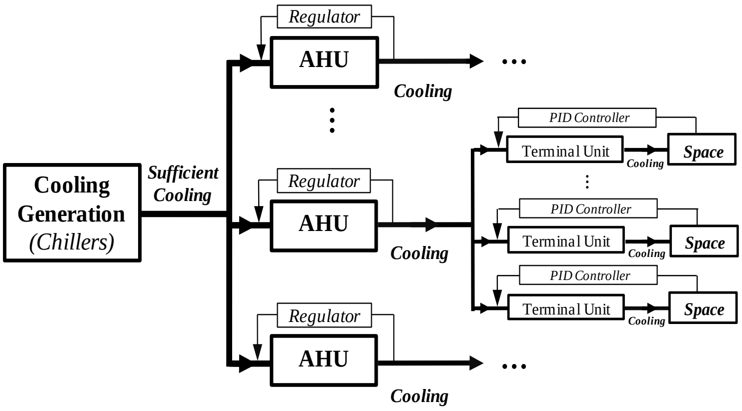

Fig.1 Basic principle of demand-based feedback control

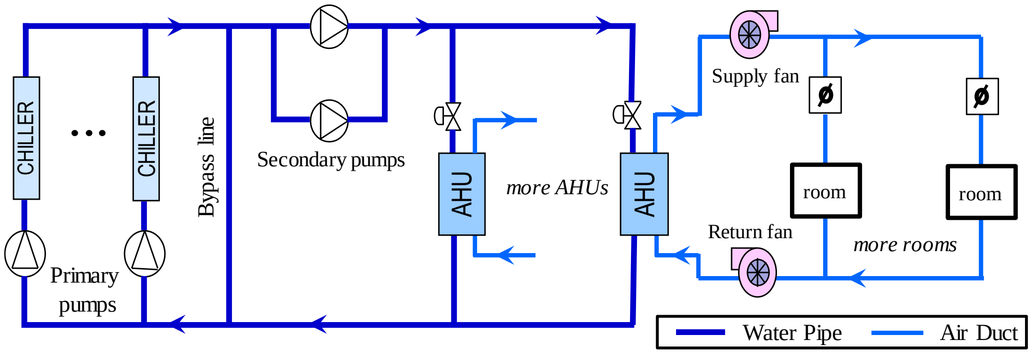

Fig.2 Schematic of considered central air-conditioning system

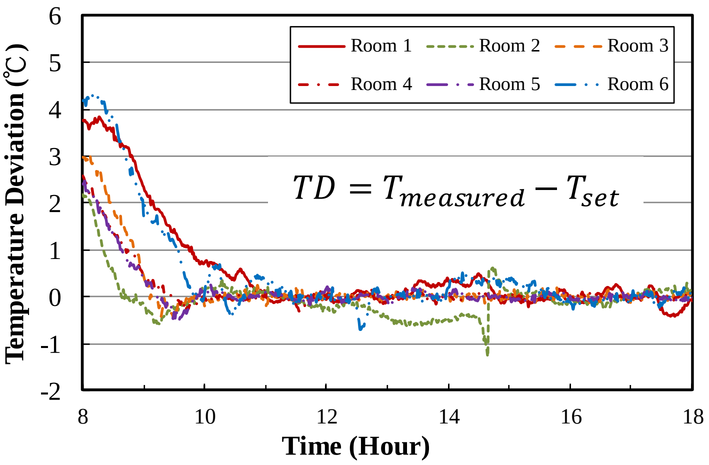

Fig.3 Measured cooling-down profiles of rooms during morning start period

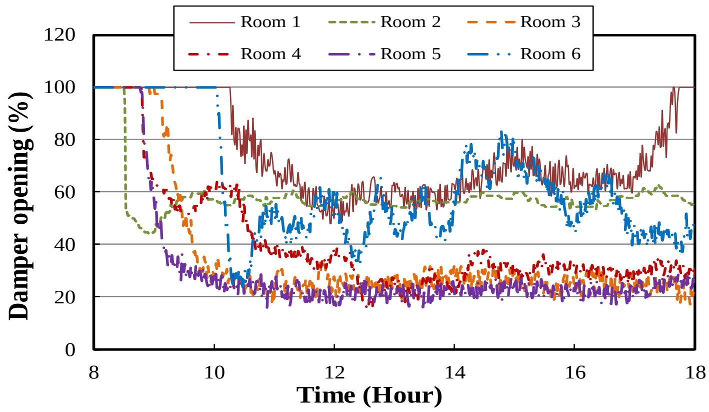

Fig.4 Measured air damper openings of VAV terminals during morning start period

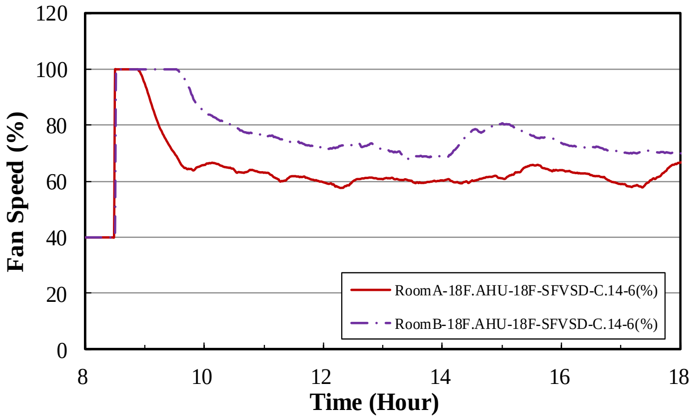

Fig.5 Measured speed profiles of AHU fans during morning start period

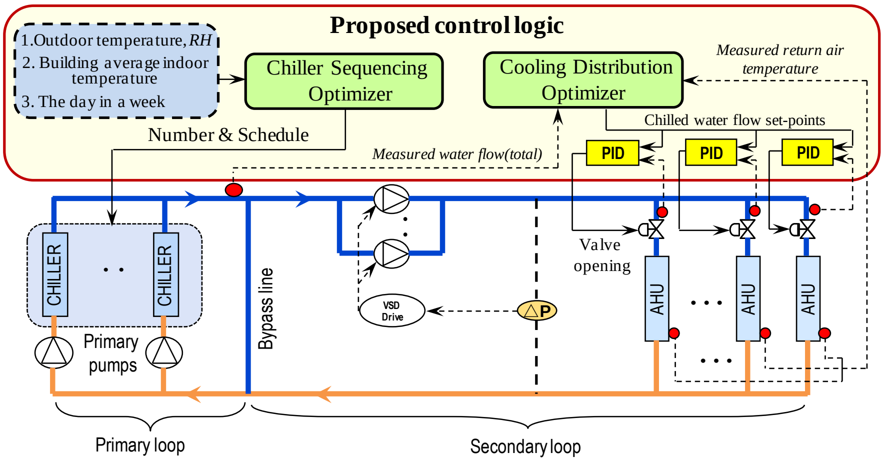

Fig.6 Schematic of proposed control strategy for morning start period

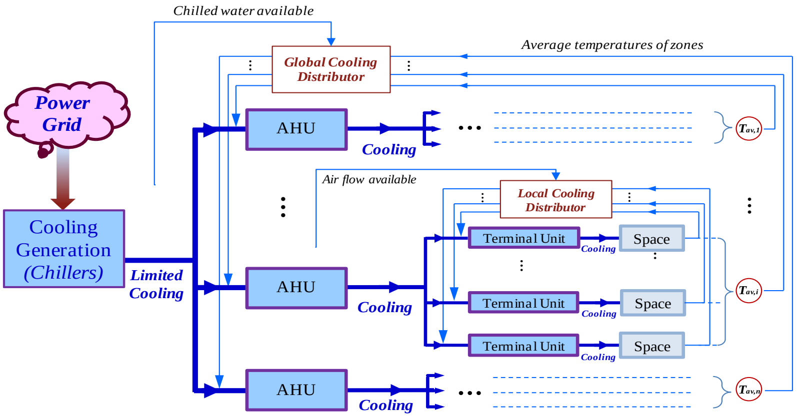

Fig.7 Basic control principle of supply-based feedback control strategy

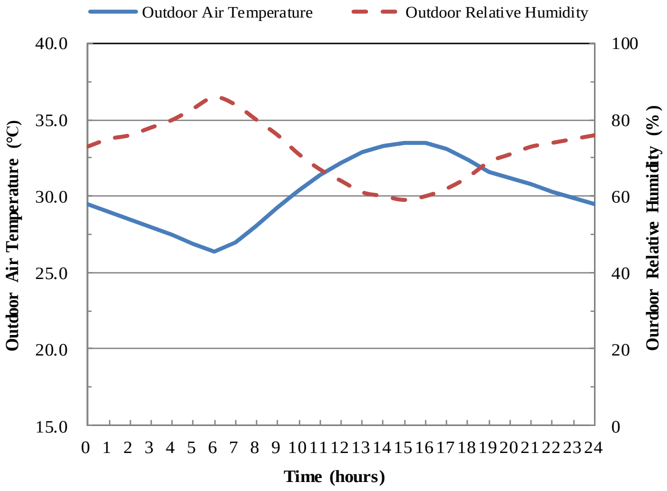

Fig.8 Outdoor dry-bulb temperature and relative humidity in the test day

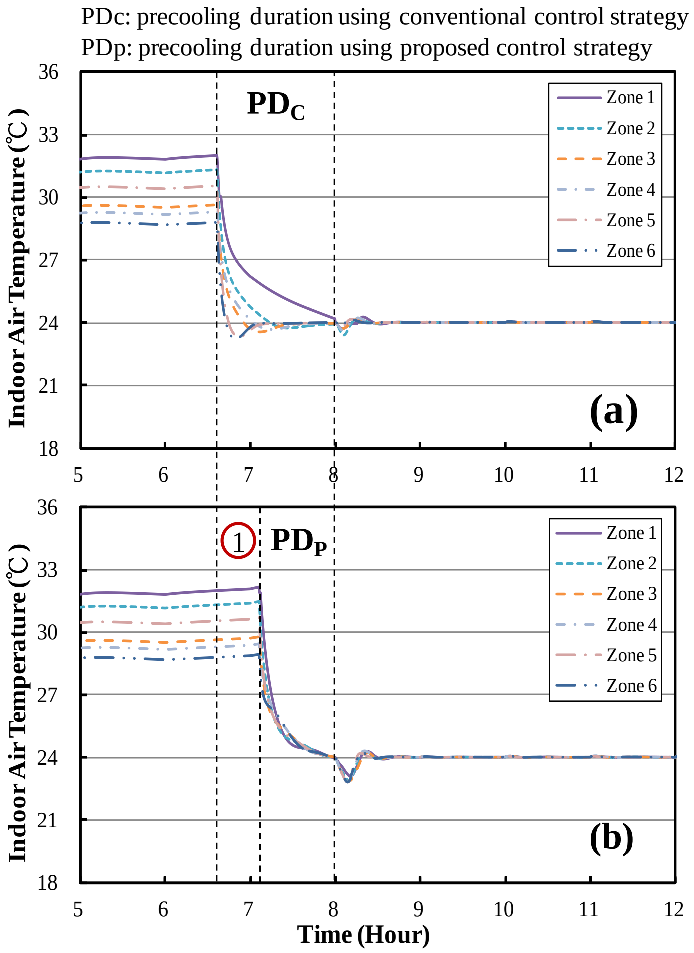
PDc: precooling duration using conventional control strategy
PDp: precooling duration using proposed control strategy

Fig.9 Temperature profiles of six selected zones during morning start period using conventional strategy (a) and proposed strategy (b)

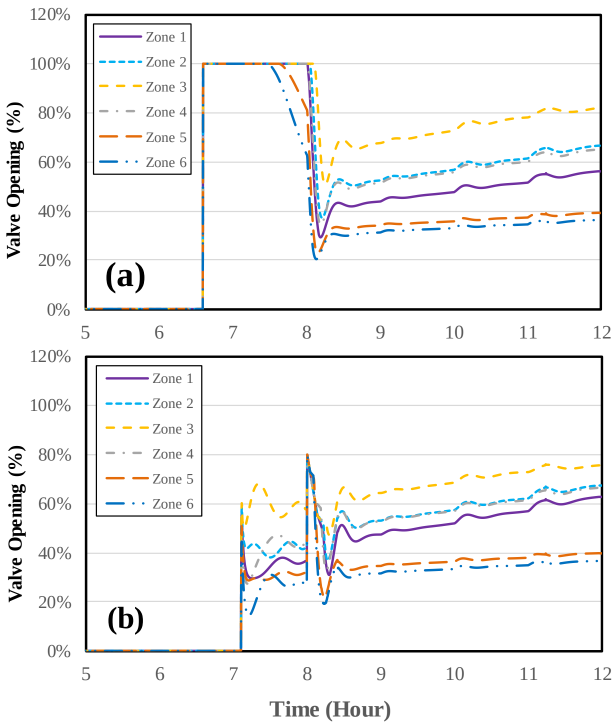

Fig.10 Valve openings of AHUs during morning start period using conventional strategy (a) and proposed strategy (b)

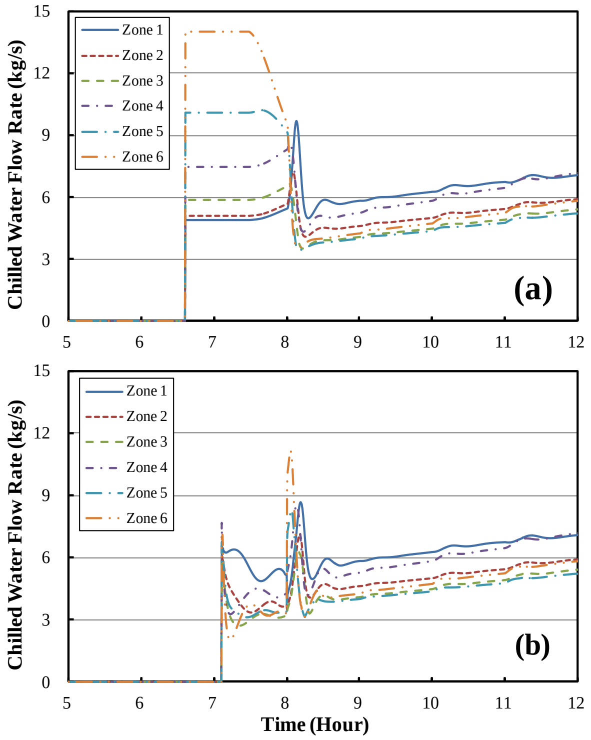

Fig.11 Chilled water flow rates of zones during morning start period using conventional strategy (a) and proposed strategy (b)

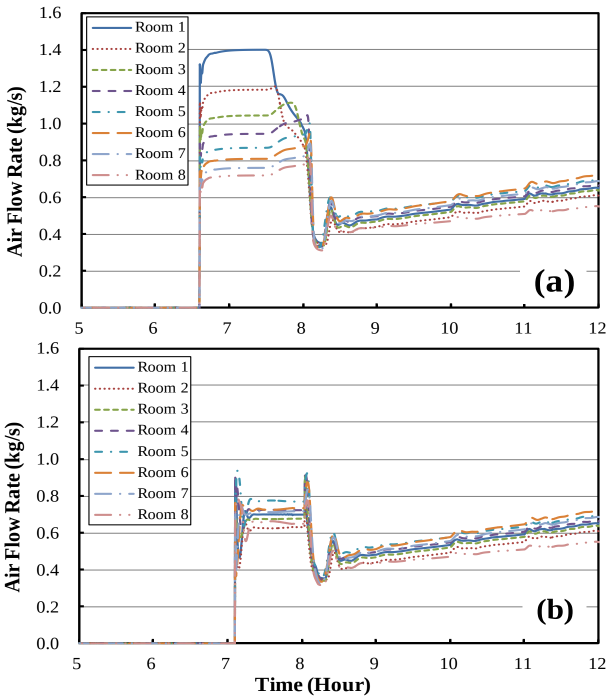

Fig.12 Air flow rates of rooms in a zone during morning start period using conventional strategy (a) and proposed strategy (b)

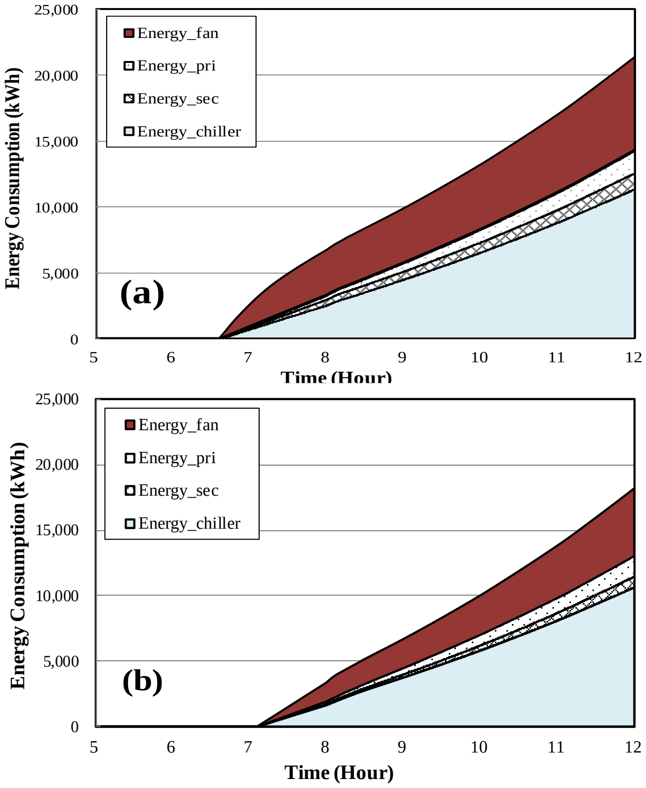

Fig.13 Energy consumptions of air-conditioning components during morning start period using conventional strategy (a) and proposed strategy (b)

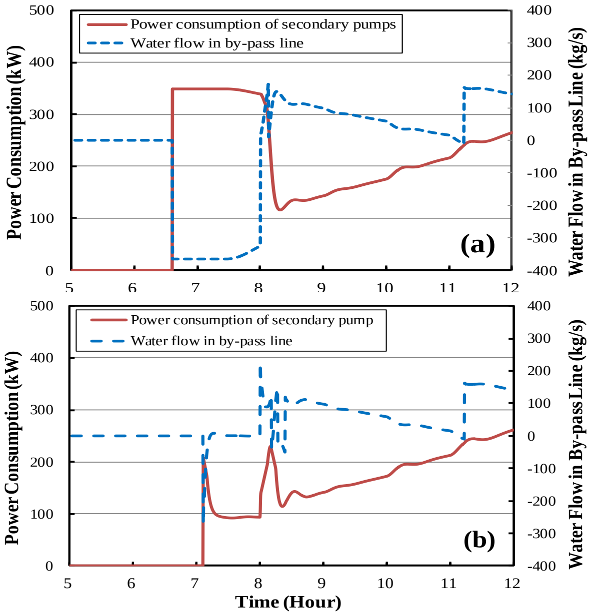

Fig.14 Water flow in by-pass line and power demand of secondary pumps using conventional strategy (a) and proposed strategy (b)

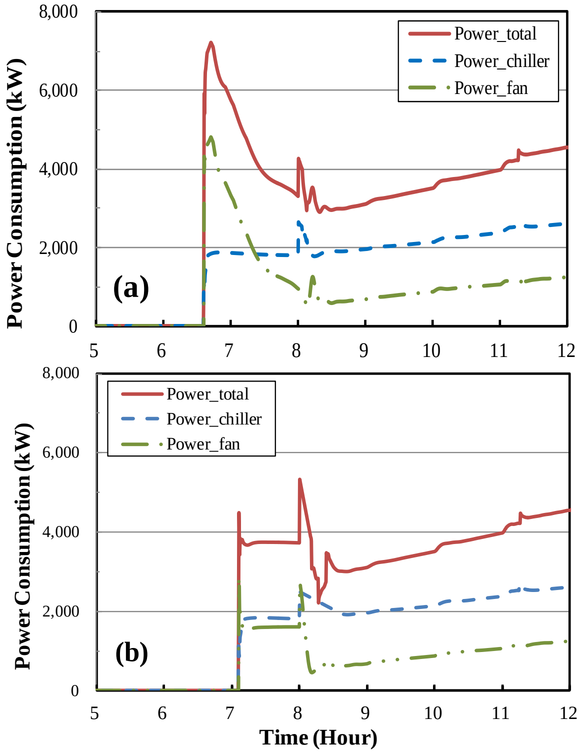

Fig.15 Power demands of chillers, fans and air-conditioning system using conventional strategy (a) and proposed strategy (b)

Table 1 Main parameters of central air-conditioning system in the building

Chiller	Cooling capacity (kW)	Rated power (kW)	Rated flow (evaporator) (L/S)	Rated flow (condenser) (L/S)	Number
	7230	1346	345	410	6

Pump	Head (m)	Rated power (kW)	Rated flow (L/S)	Description
Primary pump	31.6	126	345	Constant speed
Secondary pump	41.4	163	345	Variable speed
Condenser pump	41.6	202	410	Constant speed

Fan	Number	Total rated power (kW)
AHU fan	152	4600

Table 2 Main parameters of simulated central air-conditioning system

Chiller	Cooling capacity (kW)	Rated flow (evaporator) (L/S)	Rated flow (condenser) (L/S)	Rated power (kW)	Number
	4080	172.5	205	960	4

Pump	Rated flow (L/S)	Rated power (kW)	Head (m)	Efficiency (%)	Number
Primary pump	172.5	110	45.1	72.5%	4
Secondary pump	345	163	41.4	85.7%	2

AHU Fan	Impeller diameter (m)	Rated power (kW)	Efficiency (%)	Number
Supply fan	1.26	34	81%	One per AHU
Return fan	1.18	32	81%	One per AHU

[*] *The line filled with grey background indicates the pumps are constant speed pump*

Table 3 Precooling duration and energy consumptions using conventional and proposed control strategies in morning start period (by 8:00am)

	Precooling duration (*min*)	Overall (*kWh*)	Chillers (*kWh*)	Primary pumps (*kWh*)	Secondary pumps (*kWh*)	Fans (*kWh*)
Conventional	84	6749	2548	309	488	3404
Proposed	55	3385	1623	199	112	1451
Reduction	29	3364	925	110	379	1953
Reduction (%)	34.5%	49.8%	36.3%	35.6%	74.8%	57.4%
Cost saving (*HKD*)	--	2065	567	68	232	1198