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Technical Note

Summary This paper presents a transient simulation method for simulating an air-conditioning (AC) system in a commercial building. Using the simulation program, a typical air–water cooling system in a commercial building was simulated with real data from Hong Kong. The impacts of several different control strategies (start/stop, continuous, start/stop with night ventilation, economiser) on energy saving were computed and the energy consumptions were compared. The effects on energy saving of the control mode before the occupied period and the chilled water outlet temperature from the chillers were also simulated. The computational results show that the control strategy has a significant effect on the energy consumption of an air-conditioning system and that there is an optimal range of chilled water outlet temperature within which the system energy consumption is a minimum.

Air-conditioning control strategies: Computer simulation for a commercial building in Hong Kong

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List of symbols

T_{amb}	Ambient temperature (°C)
T_m	Room temperature (°C)
T_{chil}	Chilled water temperature outlet from chillers (°C)
P_{chil}	Energy consumption of chillers (kJ)
P_{ahu}	Energy consumption of AHU (kJ)
P_{pump}	Energy consumption of circulation pumps (kJ)
P_{tower}	Energy consumption of cooling towers (kJ)
P_{total}	Energy consumption of the system (kJ)
Q_{load}	Cooling load of the building (kW)

1 Introduction

Computer-based control systems have been widely used for controlling air-conditioning systems in commercial buildings. Computer-based control technology can increase control accuracy and can implement various sophisticated control strategies so that building energy consumption can be reduced$^{(1-3)}$. The problem is not how to implement a control strategy, but which control strategy should be used to control air-conditioning systems in commercial buildings. The aim of this paper is to study the impact of different control strategies on energy saving by simulating a typical air-conditioning system, and to provide general guidance for designing effective control strategies for air-conditioning in commercial buildings.

2 Computer approach to an air-conditioning system

A building simulation program must be adequate to model the dynamic effects of the building, and especially to simulate different control strategies for the purpose of energy consumption studies. Integrated air-conditioning system models are usually complicated and lack flexibility. In this study, an integrated air-conditioning system model is modified by a modular approach method$^{(4)}$ so as to reduce computing time.

2.1 Description of component models

Each component of the air-conditioning system is modelled individually: the chiller, the air-handling unit, the building thermal model, the control model, the cooling tower and the outdoor environment (weather data) model etc. Referred to the integrated air-conditioning model, these component models are called submodels. Each submodel is described by a set of differential and algebraic equations$^{(4-6)}$ written in FORTRAN. In a simulation process, the outputs of one submodel become the inputs of other submodels. The information transferred from one to another corresponds to the practical operational process of the air-conditioning system.

2.2 Information transfer between submodels

Because each submodel is described individually, there is no linking between different submodels. However, in the simulation of the air-conditioning system many submodels are used simultaneously. The interconnection of the subsystems requires the exchange of appropriate information between them. For this paper the mapping relational method was used. This means that every submodel has two 'windows', one defining the input and the other the output, as represented in Figure 1.

An input-defining window contains input information, whereas an output-defining window contains output information, each called an information set. By defining relations between information sets, the information transfer between submodels can be defined, correspondent to the input and output variables of the actual system components.

Figure 2 shows a mapping relation between two information sets involving the submodels X and Y. In a practical air-conditioning system X and Y can be referred to two

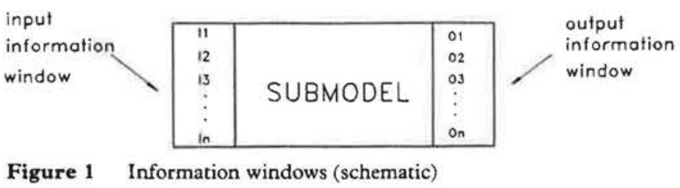

Figure 1 Information windows (schematic)

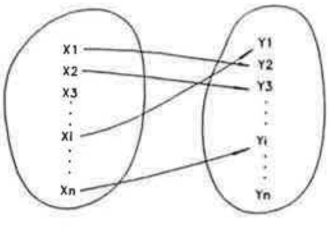

Figure 2 Mapping relation between information sets

submodels such as the chiller and the air-handling unit. The input of submodel Y is the output of submodel X.

It is easy to translate these mapping relations into FORTRAN programming with the ASSIGN statement. For example, to translate the mapping relation in Figure 2, we write:

$$
\begin{aligned}
Y(1) &= X(i)\\
Y(2) &= X(1)\\
Y(3) &= X(2)\\
&\cdots\\
Y(i) &= X(n)
\end{aligned}
$$

By defining different groups of these mapping relations, different air-conditioning systems can be simulated with the same set of submodels.

3 Description of building and air-conditioning system

The method was used to simulate the air-conditioning system of a typical commercial building located in Hong Kong. It is 20 floors high (each floor 3 m high) and 20 m wide. Each floor has an area of 1400 m^2 and is divided into five air-conditioning zones. The building is treated as being of the heavy thermal capacity type[7]. Air conditioning zones for a typical floor of this building are shown in Figure 3. The design building cooling load is 4200 kW. An air–water air-conditioning system is installed. Primary air is supplied from the central plant and secondary water is supplied to the terminal in each room. The secondary water system is a fan-coil system. The air-conditioning system consists of three variable-speed centrifugal chillers (each 2100 kW), three cooling towers (each cooling tower has a constant-speed water pump of 200 $\mathrm{m}^3\,\mathrm{h}^{-1}$ capacity and a built-in on/off controller serving one chiller), constant-speed chilled water pumps and variable-air-volume air-handling units (each AHU serves one floor and each AHU system has one air supply fan rated at 13 $\mathrm{m}^3\,\mathrm{s}^{-1}$ maximum volume flow rate and one air recirculation fan rated at 11.5 $\mathrm{m}^3\,\mathrm{s}^{-1}$ maximum volume flow rate), and a computerised control system. The water distribution layout is shown schematically in Figure 4. Air is supplied directly through air-handling units to each air conditioning zone. The fan speed of the AHUs is controllable.

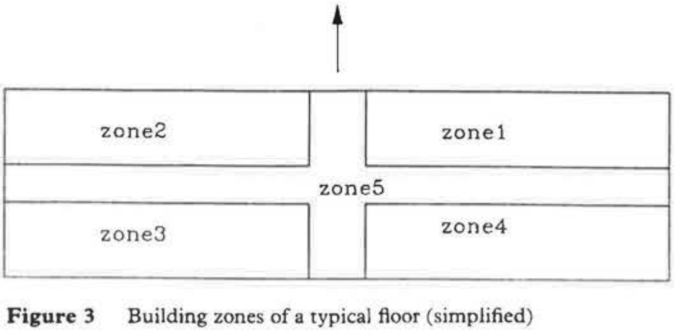

Figure 3 Building zones of a typical floor (simplified)

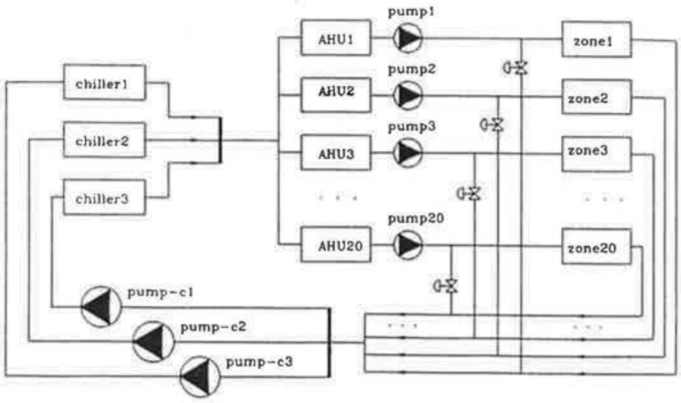

Figure 4 Chilled water distribution for air-conditioning system (schematic)

4 Control of air-conditioning system

The air-conditioning system includes computerised control of the operation of chillers, cooling towers, chilled water pumps and air-handling units in accordance with the defined strategies. The three chillers in the system operate in the sequence No. 1, No. 2, No. 3. Sensors in the chilled water supply loop signal the computer to actuate the chillers when the chilled water supply temperature is higher than the preset temperature (8°C). Refrigeration capacity is controlled in accordance with the cooling load condition by changing the centrifugal compressor velocity of the chiller. The primary chilled water pump runs at constant speed and is switched on when the corresponding chiller is on. The supply air volume flow rate of each AHU is controlled in VAV mode. The computer senses the temperature of the air-conditioning zones and then determines the fresh air and returning air volume flow rates by a PI control algorithm.

5 Simulation and results

Having developed the mapping relation method and the submodels, the building thermal characteristics and energy consumption could be simulated after defining the building and air-condition system. In the simulation process, the parameters of each component of the building and the air conditioning were initialised according to their characteristics. A main program managed all these component submodels. Each submodel was called once in one simulation time step. The time step is 0.1 h. The simulation calculation was performed on an 80486 microcomputer. It took about 50 min to simulate the system over a cooling season of 3539 h (from 1 May to 1 October). The impacts of different control strategies on energy saving and the control characteristics were simulated. Figure 5 shows the temperature profiles of a typical room with different control strategies for a set-point room temperature of 23.5°C. In the calculation, the room temperature is controlled in PI mode.

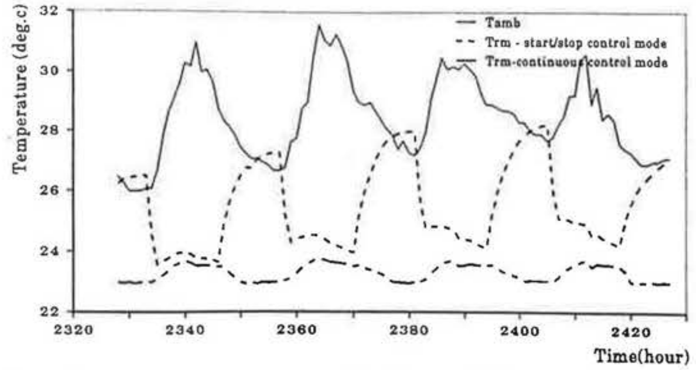

Figure 5 Room temperature profiles for two different control strategies

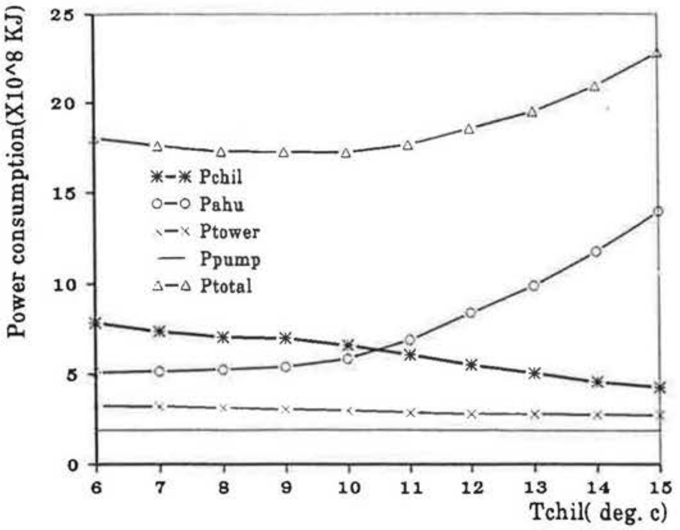

Figure 7 Power consumption versus chilled water outlet temperature for start/stop control strategy

5.1 Room temperature set point

Figure 6 shows the effect of room temperature set point on energy consumption. The total energy consumption of the air-conditioning system decreases slightly with increasing room temperature set point. When the room temperature set point is 24.5°C, the total energy consumption is 5.5% less than when room temperature set point is 23°C. This is because the cooling load decreases when the room temperature set point increases. But a higher room temperature set point may produce complaints from building users.

5.2 Effect of chilled water outlet temperature

The impact of chilled water temperature out from chillers on energy consumption is shown in Figures 7 and 8. In the calculation, the room temperature set point is 23.5°C. Figures 7 and 8 show that with increasing chilled water outlet temperature, chiller energy consumption and cooling tower power consumption decrease. In this respect increasing the chilled water outlet temperature can save energy. But when the chilled water outlet temperature increases, the total fan power consumption of the AHU increases dramatically. This increased energy consumption can far exceed the chiller and cooling tower energy savings. The two figures also show that there is an optimal range of chilled water outlet temperature. When the chilled water outlet temperature decreases from 8°C to 6°C, the total energy consumption of the air-conditioning system increases slightly, while the total energy consumption increases rapidly when the chilled water outlet temperature increases to 11°C. When it is 15°C, the total energy consumption of the air-conditioning system in the start/stop and continuous control modes is 24.4% and 33.7% higher than the minimum energy consumption point respectively.

Figures 7 and 8 also show that the minimum energy consumption point differs between control modes, possibly by several degrees.

5.3 Comparison of different control strategies

Figure 9 shows the impact of four different control strategies on energy consumption. Only the cooling season (from 1 May to 1 October) was simulated.

The four control strategies are: continuous, in which the air-conditioning system operates day and night; start/stop, in which the system operates only during the day for a seven-day week cycle (0600–1800); start/stop with night ventilation control, in which the system supplies cooling during the day and ventilates with full fresh air during the night; economiser (enthalpy) control, in

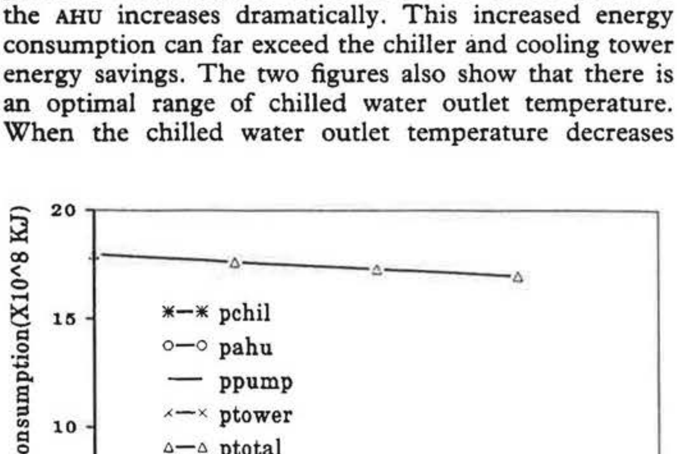

Figure 6 Power consumption versus room temperature set point for start/stop control strategy

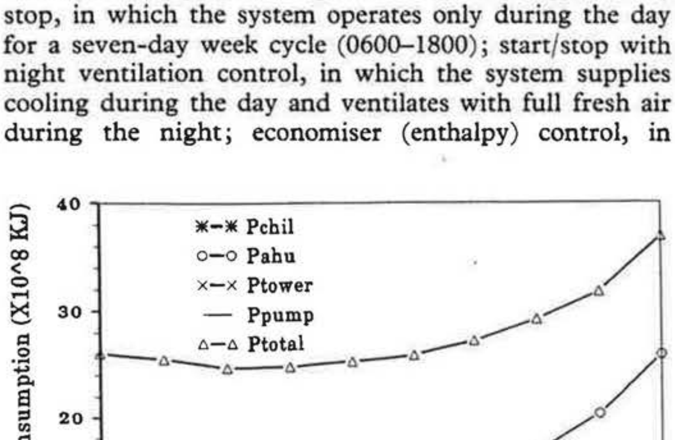

Figure 8 Power consumption versus chilled water outlet temperature for continuous control strategy

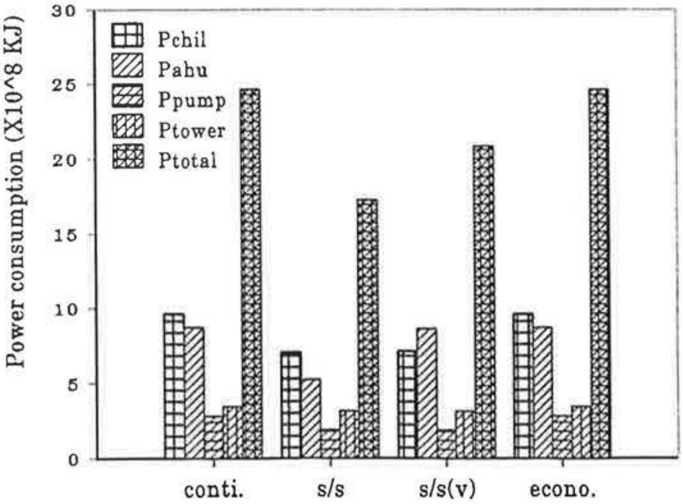

Figure 9 Power consumption for alternative control strategies

which, when the outdoor air enthalpy is lower than the room air enthalpy, outdoor air is used for ventilation, otherwise the air-conditioning system supplies cooling. The start/stop control strategy emerges as the most effective energy saving strategy. Compared with the continuous control strategy, the start/stop control strategy shows a 29.76% energy saving. Figure 9 also indicates that start/stop with night ventilation control cannot save energy as compared with the start/stop control strategy. This is because the outdoor air temperature and humidity ratio never drop low enough to remove the heat generated by the building during the Hong Kong night over the simulation period. Night ventilation increases fan power consumption. In Figure 9 it is clear that the economizer control strategy cannot save energy. In fact, when the enthalpy control set point is 50 kJ kg^{-1} dry air (24°C, relative humidity 50%) the outdoor air enthalpy was never lower than this value in the data file (the 1988 weather data file for Hong Kong) used for simulation. Figure 10 presents the cooling load profiles of the continuous and start/stop control strategies.

6 Conclusions

A transient method for simulating air-conditioning systems in commercial buildings has been introduced. Several different control strategies were simulated and their energy consumption compared. The control characteristics of air-conditioning systems were presented. The simulation study draws the following conclusions. (Although the results have been obtained for a particular building and air-conditioning, the model can be used for initial estimates for similar systems in similar climatic conditions.)

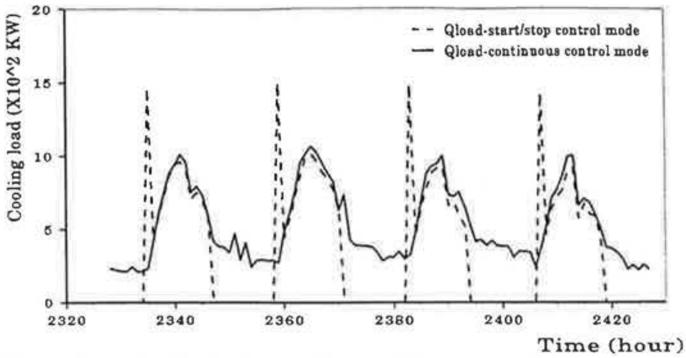

Figure 10 Cooling load curve for two different control strategies

(*a*) The room temperature set point has an effect on the total energy consumption of the air-conditioning system, but occupant comfort should be considered the higher priority in setting room temperature.

(*b*) the chilled water outlet temperature has a significant effect on the energy consumption of the air-conditioning. There is an optimal range of chilled water temperature within which the air-condition system consumes minimum energy. The range may shift through several degrees with different control strategies.

(*c*) Control strategies have great impact on the energy consumption of air-conditioning systems in commercial buildings. The start/stop control strategy is the most effective in saving energy; other strategies considered were continuous, start/stop with night ventilation and economiser. The start/stop control strategy shows a 29.76% energy saving as compared with the continuous control strategy. The start/stop with night ventilation control and economiser control strategies have no effect on the total energy consumption of air-conditioning systems in commercial buildings during the cooling season in Hong Kong.

Acknowledgements

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References

1 Van Thun G and Witte M J Applying building simulation tools to optimize system sizing and operation strategies *ASHRAE Trans.* **97**(1) 697–708 (1991)

2 Cascia M A Optimizing chiller plant energy saving using adaptive DDC algorithms *ASHRAE Trans.* **94**(2) 1937–1947 (1988)

3 Hackner R J, Mitchell J W and Backman W A System dynamic and energy use *ASHRAE J.* 29–37 (June 1985)

4 Ward H S, Fu H L *et al.* A general simulation process for solar energy systems *Proc. First International Conf. Energy Conversion and Energy Source Engineering* pp 527–530 (1990)

5 Park C, Bushby S T and Kelly G E Simulation of a large office building system using the HVACSIM$^+$ program *ASHRAE Trans.* **95**(1) 642–651 (1989)

6 Ho Wai fuk and Fu Hui li Simulation study of impact of control strategies on energy saving in air-conditioning system of commercial building *Proc. CLIMA 2000 Conf., London* (1993) (to be presented)

7 *ASHRAE Handbook 1985: Fundamentals* (Atlanta, GA: American Society of Heating, Refrigerating and Air-conditioning Engineers) (1985)