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Neural network based prediction method for preventing condensation in chilled ceiling systems

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ABSTRACT

Condensation is prone to occur at the startup moment in chilled ceiling systems, due to the infiltration and accumulation of moisture during system-off. To prevent condensation, an effective method is to operate the dedicated outdoor air system (DOAS) to dehumidify indoor air before operating chilled ceiling system. The pre-dehumidification time is critical. However, there is little experience in determining the pre-dehumidification time in both research and practice. In this study, neural network (NN) is used to predict condensation risk and the optimal pre-dehumidification time in chilled ceiling systems. Two NN models are developed to predict the temperature on the surface of chilled ceiling and indoor air dew-point temperature at the startup moment so as to evaluate the risk of condensation. The third NN model is developed to predict the optimal pre-humidification time for condensation prevention. Both training data and validation data are obtained from simulation tests in TRNSYS. The results show that 30 min pre-dehumidification is sufficient for the simulated building in Hong Kong. The influence of infiltration rate on the pre-dehumidification time is also investigated. This study also shows that NN-based method can be used for predictive control for condensation prevention in chilled ceiling systems.

1. Introduction

Chilled ceiling combining with dedicated outdoor air system, an alternative air conditioning manner, has been successfully utilized in north-west Europe for about 20 years in public buildings, such as hospitals, office buildings, libraries, and schools [1]. There are increasing interests in this kind of integrated system in North America [2,3] and Asian countries [4,5] in recent years. Dedicated outdoor air system integrated with chilled ceiling (DOAS-CC) systems can realize independent temperature and humidity controls. It can also improve indoor thermal comfort and decrease energy use for air conditioning compared with conventional air-conditioning systems [3]. However, the risk of condensation on the surface of chilled ceiling panels hinders its popularity, particularly in hot and humid regions [6].

Condensation occurs when the surface temperature of the chilled ceiling is lower than the indoor air dew point temperature (DPT). It most likely occurs in two situations. In situation 1, condensation occurs due to the increase of indoor air DPT caused by undesired opening windows or significant increase in occupant number (off-design conditions) during operation period [6,7]. In this situation, two approaches are commonly adopted to prevent condensation: regulate the supply chilled water temperature in chilled ceiling while keeping the supply water flow rate constant, or cut off the chilled water supply as soon as the monitored indoor DPT reaches the dangerous level [7,8]. The former approach is popular for single-zone applications, while the latter one is suitable for multi-zone applications. Both approaches sacrifice indoor thermal comfort to prevent condensation. In situation 2, condensation occurs at the startup moment of chilled ceiling systems, usually in the morning, because the indoor air moisture level is higher after one night's accumulation while the temperature of the chilled water entering ceiling panels is low. An effective solution is to operate DOAS before operating chilled ceiling systems [9]. The dry air from DOAS can remove part of the moisture in the space and decrease the space dew point temperature; therefore the condensation risk can be reduced.

Most of the studies reported in open literature [6–8] focus on preventing condensation in situation 1, while little attention has been paid to situation 2. The start time of DOAS before operating chilled ceiling systems, so-called the pre-dehumidification time, is critical, which influences both energy consumption and the effect of condensation prevention. The longer the pre-dehumidification time is, the better the effect of condensation prevention is. However, more energy is consumed in handling and delivering the outdoor air. In Zhang and Niu's [9] simulation study, they tested that 1 h in advance dehumidification/ventilation in summer could completely eliminate the condensation problem. However, due to changing weather conditions and diverse building materials, types and services systems, the required pre-dehumidification time in

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different chilled ceiling system is different. The key factors in determining the pre-dehumidification time are, firstly, the indoor air dew point temperature ($DPT_{a,in}$) before air conditioning system starts, and secondly the dynamic response of the temperature of the ceiling panels (T_{panel}) after the chilled ceiling system starts. To predict these two temperatures, predication models of building thermal behaviors during air conditioning system off and dynamic characteristics of chilled ceilings are needed. Physical modeling of building thermal behaviors (i.e. building heat and moisture gains, indoor air temperature and humidity, etc.) and the complicated convection and radiation heat transfer between the chilled ceiling and indoor space [10,11] are quite difficult. Therefore, the physical model-based analysis of condensation prevention in chilled ceiling systems is out of the scope of the present work.

Neural network is widely accepted to overcome the limitations of physical modeling of complicated systems and processes. It has been applied by a number of researchers for modeling and prediction in the field of building energy systems. Swider et al. [12] successfully used generalized radial basis function neural networks to model the performance of two vapor-compression chillers. The agreement between prediction results and measured data was found to be within ±5%. Ruano et al. [13] discussed the use of neural networks for inside air temperature prediction in a school building, which could be further used for predictive control of air-conditioning systems. Ben-Nakhi and Mahmoud [14,15] adopted general regression neural networks to predict the building cooling load and optimize thermal energy storage in buildings. In the research, the training and validation data for neural networks were generated by the building simulation software ESP-r. Yang and Kim [16] and Yang et al. [17] developed optimized artificial neural network models to predict the time of room air temperature descending for heating systems in buildings and to determine the optimal stop time for building heating systems to save energy. The results showed that the artificial neural network approach was effective and could provide high accuracy and reliability. In the above-mentioned research, air conditioning equipment and processes as well as building thermal behaviors were modeled, which are typically dynamic, multidimensional and nonlinear. It is not easy to build up physical models to describe the quantitative relations that exist among the variables. However, NN is quite eligible for modeling these processes and systems, because the NN has strong nonlinear mapping ability and requires less expertise and knowledge about the processes or systems concerned. In addition, in practical applications, building automation systems are widely used in modern buildings which are beneficial for the use of neural network because of huge numbers of data readily available for training and validating NN.

One of the major objectives of this study is to investigate the optimal or shortest pre-dehumidification time for typical chilled ceiling systems in typical office buildings. The second objective is to develop a NN-based prediction method for preventing condensation in chilled ceiling systems. A typical DOAS-CC system serving a multi-zone office building is studied. NN models are developed for examining the condensation risk on the ceiling panels and the optimal pre-dehumidification time to eliminate condensation at the startup moment of the chilled ceiling system. The NN based prediction method is evaluated and verified by simulation tests on TRNSYS platform [18].

2. Description of building and the DOAS-CC system

The prototype of the investigated building is a commercial building located in South China. A multi-zone space occupying half of a typical floor is served by a DOAS-CC system. The usable floor area is about 302 m^2. It is divided into five zones. Four of them, i.e. Zones 1–3 and Zone 5, are perimeter zones and Zone 4 is an interior zone, as shown in Fig. 1.

The heat transmission coefficient *U*-value for the opaque part of the façade is 1.506 W/(m^2 K). Single glazing windows having a *U*-value of 2.83 W/(m^2 K) is used. Blinds are installed for shading. The floor to ceiling height of the conditioned space is 2.7 m and the area ratio of window to wall is 40% for external walls. In each zone, about 70% of the ceiling is covered by chilled ceiling panels. The design occupant numbers of the five zones are 5, 2, 1, 13, and 56 persons, respectively. The CO_2, moisture and sensible heat generation rates per person are assumed to be 5×10^{-6} m^3/s, 2.2×10^{-5} kg/s and 65 W, respectively. The design amount of outdoor air required is 10l/(h person). Internal loads are taken as 10 W/m^2 for lighting and 20 W/m^2 for equipments.

The air-conditioning system operates from 9:00 to 18:00, and the design conditions in the office are 25 °C of dry bulb temperature and 60% of relative humidity (RH). In simulation tests, a moisture disturbance of 1.02 kg/h is introduced into Zone 5 in the operation period.

Fig. 2 shows the schematic of the DOAS-CC system and its control system serving the multi-zone space. In the integrated system, the DOAS subsystem is responsible for satisfying ventilation demand and removing the moisture load of the conditioned space. The fresh air flow rate from the DOAS can be either fixed or determined by demand controlled ventilation method [19]. A liquid desiccant dehumidifier is used to dehumidify the humid outdoor air to the state that its humidity ratio meets the set-point ($W_{sup,sp}$), which can be optimized from measurements of RH in all zones or is set manually. The detailed configuration of the liquid desiccant dehumidification system and its control method are presented in the previous paper [20]. The dry cooling coil after the dehumidifier is used to cool down the supply air to the set-point, i.e. 19 °C. The supply fan and the exhaust fan run at variable speeds. The supply fan speed is modulated to maintain the supply air static pressure, and the exhaust fan is controlled to maintain a difference between the supply and exhaust air flow rates. In order to improve energy efficiency, a total heat recovery ventilator is employed to recover energy from the exhaust air [21,22].

The chilled ceiling subsystem is responsible for removing the remainder sensible load of each zone, and independently controlling the indoor air temperature. In order to prevent from condensation on the surface of chilled ceiling panels, the temperature of the chilled water supplied to the panels is 17 °C, which is higher than the indoor air dew point temperature at the design condition.

3. NN models for condensation prevention in chilled ceiling systems

In the above introduction part, the reasons for choosing NN models have been given. This part explains the inputs, outputs and the structure of NN models developed in this study. The outputs are obviously the surface temperature of ceiling panels and the dew point temperature of indoor air which are used to identify whether condensation will occur or not, as well as the optimal pre-dehumidification time if condensation is likely to occur.

Condensation is prone to occur at the startup moment of chilled ceiling systems mainly due to the infiltrated moisture through building envelops at night when air conditioning system is off. The infiltration rate certainly influences the condensation risk. However, the infiltration rate can be assumed to be fixed for a given building, therefore it is excluded from the inputs of the NN models. Other important parameters affecting condensation occurrence are weather conditions, indoor occupant numbers, and operation of the equipments. For most commercial buildings, people and