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Development of an ambient air temperature prediction model

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ABSTRACT

The time series prediction of the ambient air temperature of a surrounding is necessary for the development of optimal energy-saving operations in heating, ventilation and air conditioning (HVAC) systems in buildings. A new model and methodology of predicting the time-series ambient air temperature is proposed in this paper. This model is based on the physical relationship between air temperature, direct solar radiation, clouds and ground heat radiation, and heat convection. A specific location in Singapore is adopted as a case study example in this work. The proposed prediction model is verified against a set of measurement data obtained from a weather station situated at Nanyang Technology University, Singapore. At sub-hourly intervals, the predicted ambient temperature is closely aligned with the obtained data at most times. At thirty-minute and hourly intervals, the prediction error is under 1 K and 3 K, respectively. The absolute mean error is less than 1 K when the prediction time horizon is less than two hours.

1. Introduction

The ability to accurately predict the ambient air temperature is critical towards the development of globally-optimized control settings for heating, ventilation and air conditioning (HVAC) systems in buildings. Although existing HVAC systems include automatic control provisions and/or synthetic building management systems for such purposes [1], they typically comprise basic features covering only full load occasions and not necessarily the part load situations [2–4]. Moreover, information of the thermal conditions is often not accounted in its control strategies. Many times, the operating capacities are overtly subscribed, which led to the HVAC system operating far from optimal conditions. It is necessary to take into consideration the thermal parameters of the surrounding in the control strategies so that effective energy management of the HVAC systems can be attained.

The heat transfer processes between buildings' indoors and their ambient environments are the major causes of thermal load changes in HVAC systems. The HVAC system for an entire building is normally a big system where the instantaneous adjustments of the control settings (such as chiller flow rate and temperature, cooling water flow rate and temperature etc.) do not produce instantaneous change in the room temperature. There is a large time delay effect due to the large thermal inertia of the building and the HVAC. If we take the current measured temperature in the optimization calculations and implement the obtained control settings, the change of the room temperatures takes place 10 min or 15 min later. In this case, the temperatures fluctuate in a large range. The building either gets too hot or too cold. However, if we implement the control settings in advance, which need to predict the ambient temperature to calculate the thermal load of rooms or building, the temperature fluctuations can be reduced. Large temperature fluctuations should be avoided in the HVAC management system. An ability to accurately predict the ambient temperature in advance will allow the energy management controllers of HVAC systems to adaptively pre-plan and adjust the control settings optimally. This reduces indoor temperature fluctuations which results in improved thermal comfort and more importantly, increases the overall energy saving of the system. The time interval for the optimization implementation of the HVAC is basically decided by the thermal response time of the system, which is typically between 10 min for a smaller system and 30 min for a larger system.

Several models on the prediction of short-term ambient air temperature are reported in [5–10]. In [5], extending from earlier works by Bhumralkar [11] and Blackadar [12], Deardorff presented an improved analytical model for predicting ground surface temperature that is based on heat-flow interaction between soil and ground surface air. Obviously, the ground ambient air temperature is mainly affected by the solar radiation. Other factors influencing the air temperature change include landscape, air thermal mass, sky cloudy conditions and wind speed etc. [6]. In particular, most of these factors exhibit random and intermittent characteristics. It

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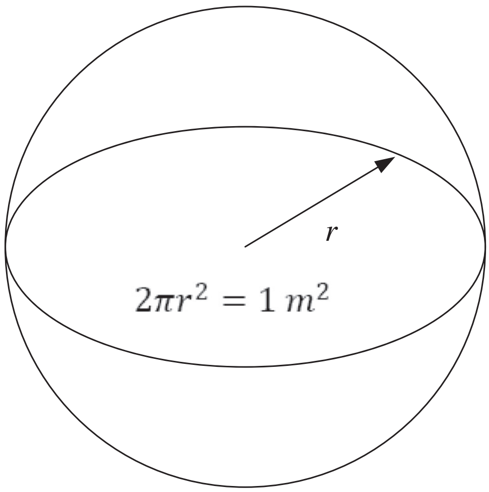

Fig. 1. A spheric control volume in the atmosphere.

is difficult to accurately predict the ambient air temperature over short terms using parameterized analytical models. The artificial neural network (ANN) is a robust computational technique primarily used for pattern recognition, classification and prediction [13]. It has been intensively studied in applications concerning air temperature forecast [7–10,14,15]. For time-series temperature prediction for a specific location, the ANN model has to be trained for the defined weather patterns based on the prior weather observations including the air temperature, humidity, wind speed and solar radiation [9].

In this paper, an ambient air temperature prediction model applicable to the optimization of the building energy management of the HVAC system is proposed. The model predicts the time-series air temperature sub-hourly using information on prior and forecasted solar radiation. The proposed prediction model is adaptable to all weather patterns and is computationally inexhaustive, making it easily incorporable into a real-time operating energy management system. The verification of the model is performed for a specific location in Singapore using the simulation platform MATLAB.

2. Model mathematics

The changes of ambient temperature are mainly determined by the heat sources from the solar and environmental bodies (i.e. land, buildings, clouds etc.). For a specific location, the heat input to the air within a defined space is contributed by the direct solar radiation, the environmental bodies heat radiation, and heat convection. The amount of heat radiation from the environmental bodies is dependant on the temperature of the body surface, which is mainly affected by the solar radiation. The environmental bodies can be perceived as a form of thermal storages. They delay the solar radiation effect on air temperature due to their thermal inertia. Therefore, the change of the air temperature can only be ascribed to the variation of solar radiation. The prediction model is simply the dependent mathematical relationship between the ambient air temperature and solar radiation. If we regard the atmosphere within the defined specific area as the modeling object, the heat transfer between the atmosphere and the solar and environmental bodies in the ways of heat radiation and convection are the boundary conditions. However, for simplifying the model calculation, we can define the modeling object as a spheric control volume in the earth atmosphere as shown in Fig. 1. The temperature change within the spheric control volume represents the atmospheric temperature variation at the corresponding location. It should be noted that the control volume is just a representation of the atmosphere. The area in the middle section of the spheric control volume equals to 1 m^2. The heat balance for the control volume can be written as follows:

$$\frac{4}{3}\pi\rho c_p r^3 \frac{dT}{dt} = \dot{q} \tag{1}$$

where T represents air temperature, $\dot{q}$ represents the heat flow rate, and r represents the radius of the sphere. Here, the air density ρ and specific heat capacity c_p are respectively given by

$$\rho = \rho_d(1-\varphi) + \rho_v\varphi \tag{2}$$

and

$$c_p = c_{pd}(1-\varphi) + c_{pv}\varphi, \tag{3}$$

where ρ_d, ρ_v, c_{pd}, and c_{pv} represent the dry air density, vapor density, specific heat capacity of dry air and specific heat capacity of vapor, respectively. The air specific absolute humidity φ is calculated by

$$\varphi = \frac{0.622 x p_s}{p - p_s x}, \tag{4}$$

where x represents relative humidity of air.

The atmospheric pressure p in Eq. (4) is assumed to be 1 bar. The calculation of air saturation pressure p_s can be referred to [16] and is given as:

$$\ln(p_s) = 54.842763 - \frac{6763.22}{T} - 4.21\ln(T) + 0.000367T + \tanh[0.0415(T - 218.8)]\left[53.878 - \frac{1331.22}{T} - 9.44523\ln(T) + 0.014025T\right] \tag{5}$$

Integrating Eq. (1) over time and putting T as the object of the function gives

$$T = \int C_{th}(t)\dot{q}(t)dt \tag{6}$$

where $C_{th} = 3/4\pi\rho c_p r^3$. The boundary of spheric control volume shown in Fig. 1 is completely open to the atmosphere. The air density and specific heat capacity can be assumed to be the same as the atmosphere, which are functions of time due to the variation of air humidity with time (see Eq. (2) and Eq. (3)). The spheric control volume is defined as the representive for calculating the temperature of atmosphere. If we consider the ambient atmosphere as the control volume, the quantity of heat flow $\dot{q}$ for the defined control volume shown in Fig. 1 can refer to the heat exchange calculation of ambient atmosphere. The heat sources of atmosphere include the solar radiation, the heat radiation from the environmental bodies (e.g. land, clouds) and the heat convection with the environmental bodies. Obviously, the intensity of heat radiation and heat convection from/with the environmental bodies depends on the temperature, which is closely related with the solar radiation. Due to the thermal inertia of the land, cloud and building etc., there is a time delay in the effect of solar radiation on the atmosphere. The heat radiation and heat convection between the atmosphere and environmental bodies can be simply considerred as heating effect given by the past solar radiation. Thus, the heat flow $\dot{q}$ can be modeled as the function of solar radiation as follows:

$$\int_{-\infty}^{t} \dot{q}(t)dt \approx \int_{-\infty}^{t} \chi f_{decay}(t)\dot{q}_{rad}(t)dt \tag{7}$$

The parameter χ is defined as the heating factor of air. It is related to the local landscape and atmospheric conditions (e.g. humidity and cloud condition). The time interval of executing the optimization of HVAC control settings is usually less than one hour, typically at 10–15 min. Within such short prediction time intervals, the variations of air density, specific heat capacity and heating factor are negligible as compared to the change of solar radiation.