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Development and implementation of a virtual outside air wet-bulb temperature sensor for improving water-cooled chiller plant energy efficiency

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ABSTRACT

Over the past decades, virtual meters or sensors have been rapidly developed and widely adopted within a number of different fields especially in the building section, and have enabled many intelligent features that would otherwise not be possible and economical. Ambient wet-bulb temperature is normally measured either by a psychrometer, or a combination of dry-bulb temperature sensor and relative humidity sensor. These physical sensors are notoriously costly and problematic considering their accuracy and reliability. Furthermore, ambient wet-bulb temperature is critical in a water-cooled chiller plant to enhance its holistic energy efficiency through specific control strategies, such as cooling tower temperature relief, condenser water supply temperature reset, and so on. This paper introduces a virtual ambient wet-bulb sensor through a black-box method using one low-cost dry-bulb temperature sensor and local weather data, either typical meteorological year (TMY) or real-time weather data. A control algorithm for the cooling tower fan operation was also developed to calibrate this virtual wet-bulb sensor, thus to minimize its measuring deviation. Two case studies in Beijing, China and Texas, USA were adopted to demonstrate the feasibility of this strategy under different climate scenarios. It shows that the virtual sensor combined with the control algorithm has high potential to improve the accuracy of the ambient wet-bulb temperature, and guarantee the chiller plant performance by the proposed control strategies.

1. Introduction

Over the past decades, virtual meters or sensors have been rapidly developed and widely adopted within a number of different fields, especially in the process controls and automobiles, and have enabled many intelligent features that would otherwise not be possible and economical. In the building section, virtual sensor technology also shows a promising application and provides a niche for replacing the conventional physical sensors to benefit from the unique advantages of the virtual sensors, such as low-cost, easy maintenance, high-accuracy guaranteed, etc. (Gawthrop, 2005; Gustafsson & Forssell, 2001; Kestell, Hansen, & Cazzolato, 2001; Jos de Assis & Maciel Filho, 2000).

In large commercial buildings, a water-cooled type central chiller plant is frequently adopted as a major cooling source, which includes chillers, cooling towers, a water distribution system and a condenser water distribution system. Energy performance of water-cooled chiller plant could be improved through resetting chilled water supply temperature (ChWST), resetting condenser water supply temperature (CWST), using variable flow under partial load scenarios and optimizing chiller staging control algorithm (ASHRAE Inc. 2005; Liu, Claridge, & Turner, 2002).

The measure of CWST reset is to decrease CWST, which is realized through an optimal cooling tower control. Ambient wet-bulb temperature (T_{wb}) is frequently adopted as an indicator for CWST setpoint reset schedule to maximize chiller energy efficiency; therefore, both the ambient wet-bulb temperature sensor accuracy and long-term stability are critical during the implementation period. Currently, wet-bulb temperature is measured either by a psychrometer or a combination of OA (outside air) dry-bulb temperature (T_{db}) and relative humidity (RH) sensor. These traditional methods use physical sensors, which are notoriously costly and problematic in terms of sensor accuracy and reliability.

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Fig. 1. General procedure for virtual sensor development.

This study developed a virtual sensor for measuring ambient wet-bulb temperature using ambient dry-bulb temperature combined with a specific control algorithm, a real-time dynamic calibration procedure to improve sensor accuracy. The developed control algorithm could also be adopted as a stand-alone strategy to decrease the deviation of a physical ambient wet-bulb temperature sensor adopted for CWST control of water-cooled chiller plant.

2. Sensor development

According to the modeling methods utilized during the process of virtual sensors development, it is generally classified into three categories, black-box data driven method, grey-box method and first principle model-driven (white-box) method. The black-box approach utilizes empirical correlations without any knowledge of the physical process. The grey-box method utilizes a combination of physical and empirical models in estimating the output of an unmeasured process. The first-principle (physical or white-box) virtual sensor is most commonly derived from fundamental physical laws and has parameters with some physical significance.

Fig. 1 illustrates general steps of developing the virtual sensor, which include data collection and analysis, model selection and data training, and sensor calibration and implementation. The details of each step are shown in Figs. 2 and 3 respectively.

The virtual sensor development process is briefly illustrated in Fig. 2 and each step is described as follows:

- The first step is to collect specific location information and acquire corresponding weather data, either local typical meteorological year (TMY) or real-time weather data. The weather data is normally in an hour-by-hour format.
- Pre-processing may include data pre-filtering, data outliers eliminating, or data format conversion. Depending on the availability of T_{wb} from acquired weather data, experienced equations for T_{wb} calculation on the basis of RH or T_{dp} (dewpoint temperature) may be required when only RH or T_{dp} is available.
- Based on T_{wb}, either calculated or directly-obtained, statistical and nonlinear regression analyses are implemented to get the relation between T_{wb} and T_{db} (dry-bulb temperature), which is the foundation of the virtual wet-bulb temperature sensor.

Fig. 3 explains sensor implementation for a water-cooled chiller plant system. A dynamic real-time calibration algorithm is integrated into the process to compensate for sensor errors. The main purpose of applying this algorithm is to compensate for the error from the measured T_{wb} value. In this process, inputs include field ambient T_{db} sensor reading, field CWST sensor reading, and cooling tower (CT) fan speed (VFD, variable frequency drive) signal value. The CWST setpoint is composed by ambient T_{wb}, deviation and approach. The deviation is defined as the error between readings from virtual T_{wb} sensor and true T_{wb} value, and the approach value is as same as the one at cooling tower design condition. To prevent excessive cooling tower fan power consumption, the CWST setpoint could be at least 2.5 °C (adjustable according to the design approach) higher than the ambient T_{wb} temperature. Additionally, CWST should not be lower than 18 °C for chillers made before 1999 and should not be lower than 13 °C for newer chillers based on the available manufactures information.

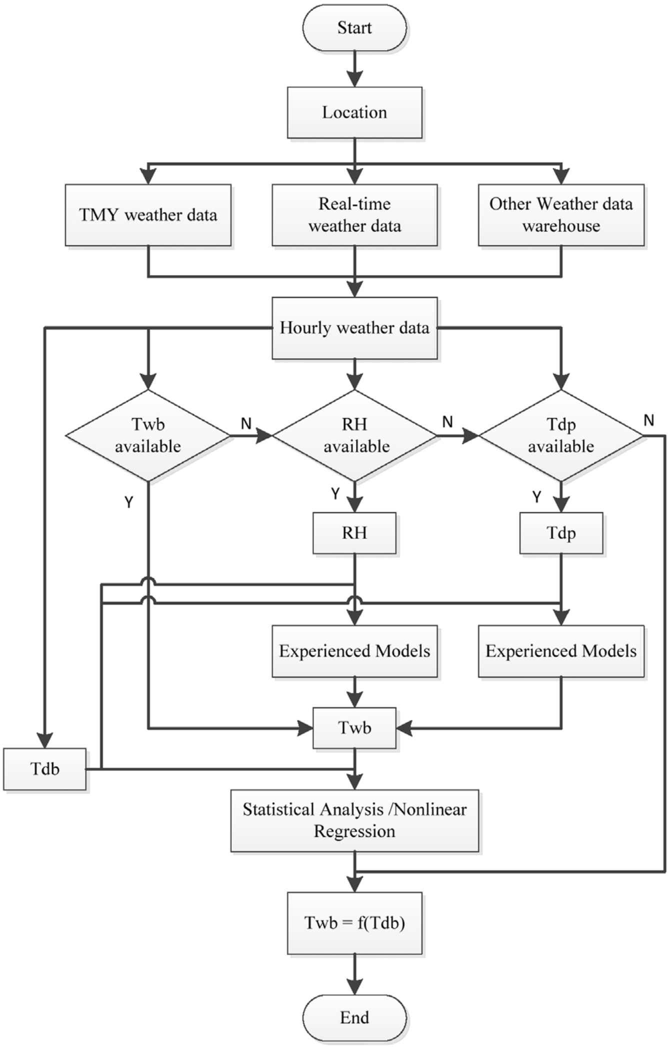

Fig. 2. Detailed procedures during sensor development phase.

Through the PID control loop with CWST and its setpoint as inputs, the control loop output, i.e., the cooling tower fan speed, is adjusted to keep CWST close to the setpoint. If the output is over or equal to 90% for a fixed time interval such as five minutes, the deviation value will increase by one degree for each additional fixed time interval. If the output is less than 90% but higher than 30%, the current deviation value is kept as default value, and decreased by one degree if the output is less than 30%. For a chiller plant with multiple cooling towers, the minimum fan speed among all enabled fans will be selected as input.

With this control algorithm, cooling tower temperature relief could also be realized, i.e., the maximum fan speed value can be restraint in order to follow actual thermal load requirement, thus avoiding over-running the cooling tower.

3. Case studies

3.1. Case study A

CABR Nearly Zero Energy Building (Fig. 4) is located in Beijing, China. It is a four-story building with the total space area of