Energy and Buildings 42 (2010) 412–421

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Adaptive HVAC zone modeling for sustainable buildings

Glenn Platt [a], Jiaming Li [b,*], Ronxin Li [b], Geoff Poulton [b], Geoff James [a], Josh Wall [a]

[a] CSIRO Energy Technology, Australia
[b] CSIRO ICT Centre, Australia

ARTICLE INFO

Article history:
Received 16 April 2009
Received in revised form 28 September 2009
Accepted 4 October 2009

Keywords:
Genetic algorithms
HVAC control
HVAC zone modeling
Kalman filtering

ABSTRACT

Control of energy flows within a building is critical to achieving optimal performance of heating, ventilation and air-conditioning (HVAC) systems. To design optimal HVAC control strategies, a dynamic model of the HVAC system – particularly the building zones that it services – is essential. As analysis of building energy consumption is facilitated by the accurate prediction of indoor environmental conditions, techniques that dynamically model HVAC zones are crucial, and as such, is an active area of research. This paper focuses on real-time HVAC zone model fitting and prediction techniques based on physical principles, as well as the use of genetic algorithms for optimization. The proposed approach is validated by comparing real-time HVAC zone model fitting and prediction against the corresponding experimental measurements. In addition, comparison with prediction results using an algorithm based on feedback-delayed Kalman filters has demonstrated the superiority of the proposed approach in terms of prediction accuracy.

1. Introduction

Heating, ventilation and air-conditioning (HVAC) systems play a dominant role in regulating the indoor climate, providing people with a comfortable and safe work environment. In most buildings the performance of the HVAC system can influence energy consumption as well as indoor air quality. The amount of energy used by HVAC systems is a significant concern that impacts on issues from national policy to personal desires of cost and comfort, and as such, HVAC modeling is a very active research topic [1,2].

A HVAC system comprises a variety of continuous and discrete control components interacting with the building via sensors and actuators. Control of the energy flows in the building and its environment is the key to achieving optimum performance from an HVAC system. Such control is secured through monitoring and altering the cooling/heating sources to maintain the desired thermal and air quality conditions in a space, while external and internal conditions change over time. The building with its technical equipment and its environment consists of several coupled processes which, in general, cannot be influenced independently. This complicates the design of high-quality control algorithms and requires model-based design methodologies for optimum performance. For the energy-efficient design of buildings and their associated control systems, it is necessary to obtain approximate dynamic mathematical models for system components. These models are used for a wide range of tasks including operating strategy planning, cost analysis and comfort evaluation. The dynamic model can be especially useful for control strategies that require knowledge of the dynamic characteristics of HVAC systems.

The system component that we will focus on in this paper is the zone. A HVAC zone is a group of adjacent offices and/or spaces serviced by a common air-handling unit (AHU) or air-terminal device. Since the external and internal environment of the zone always changes, any model of the zone has to emulate the dynamic thermal processes within the zone as well as the interaction with the environment. Modeling such a time-variant system is a challenging task.

Traditionally, zone models are mainly based on static or short-term modeling of the HVAC zone. Four approaches have been reported in recent literature. The first uses lumped capacitance in an analogue electric circuit to represent thermal elements of a building [1,3,4]. A second approach is a building thermal model based on energy-and-mass balance [5], where every component of the HVAC system is represented by energy-and-mass balance equations. The third approach is based on machine learning, in which artificial neural networks [6] or support vector machines [7] model non-linear processes, such as utility loads or an individual building's energy consumption.

A fourth approach is evident more recently, as researchers have started exploring the response of HVAC systems to dynamic

Abbreviations: AHU, air-handling unit; BMCS, building management & control system; OA, outside air; RA, return air; SA, supply air; CHWV, chilled water valve; HWV, hot water valve; SP, set-point; OAF, outside air fan; SAF, supply air fan; RAF, return air fan.

* Corresponding author. Tel.: +61 2 9372 4707; fax: +61 2 9372 4161.
E-mail address: jiaming.li@csiro.au (J. Li).

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doi:10.1016/j.enbuild.2009.10.009

Nomenclature

T_{wo}	outlet water temperature (°C)
T_{wi}	inlet water temperature (°C)
T_o	external (outside) temperature (°C)
T_z	zone temperature (°C)
T_{sp}	supply air temperature set-point (°C)
F_{sp}	supply air fan speed set-point (% of maximum speed)
T_{sa}	supply air temperature (°C)
F_{sa}	supply air fan speed (% of maximum speed)
f_a	supply air flow rate (m^3/s)
C_a	specific heat of air (kJ/(kg °C))
ρ_a	density of the air (kg/m^3)
V_z	volume of the zone (m^3)
U_w	thermal conductivity of the wall (W/mK)
A_w	heat transfer area of the wall, i.e. area of each wall (m^2)
G_w	wall thickness (m)
R_o	resistor of outside wall representing its function of transferring heat between outside and inside
I_o	current of outside air representing its heat flow
I_a	current of supply air representing its heat flow
R_a	resistor of supply air representing the air convection
I_z	current of zone air representing its heat flow
C_z	overall thermal capacity (kJ/C) of the zone

environments [8–12]. These models, however, tend to be rather cumbersome, and do not adequately adapt to the dynamics of the zone environment in real time. In addition, many existing models do not take into account long-term dynamic properties of the building, due to changes accumulated over a long time period.

We investigate a real-time model fitting and prediction algorithm using only few parameters, that is well suited to short-term predictions and also adapts to long-term dynamics. In Australia, the electricity market cycle is half-hourly [13], and our proposed algorithm is very suitable for applications on this time scale.

The algorithm is applied to a dynamic zone model of a HVAC system, intended to allow the implementation of control strategies to reduce energy consumption and improve the quality of the indoor environment. The paper has two major contributions. One is the formation of a mathematical model of the zone based on physical principles and circuit theory—the model we propose is the first one that combines energy/mass balance and basic circuit theory. The second contribution is the real-time model fitting and prediction algorithm for a time-variant zone, taking advantage of genetic algorithms (GA). The model and algorithm are then validated using measurements of a real HVAC system.

Throughout the paper the HVAC zone is represented as a six-faced box. The zone model is firstly deduced from an energy-and-mass balance and then represented using electric circuit theory. Electric circuit elements are used to represent functions of the building elements, e.g., a wall is modelled as a resistor to represent its function of transferring heat between outside and inside, and an entire zone is modelled as a capacitor to represent its heat storage function. This kind of zone model is very simple and generic, applicable to a zone with any internal structure and material. Following development of the zone model structure, a methodology of soft real-time zone model fitting and prediction is given, e.g., zone model fitting and prediction every 5 or 30 min. Since the zone model is fitted in soft real-time (every 5 min) it can easily cope with the changes of the zone's dynamics and give accurate internal temperature prediction.

Lastly, we present results using an alternative technique, the Kalman filter, to perform the model fitting. The Kalman filter [14] is an efficient recursive filter that predicts the state of a dynamic system from a series of incomplete and noisy measurements. The Kalman filter is traditionally viewed as a prediction-correction filtering algorithm and is a classic method used for dynamic systems. Recently, various parameter estimation techniques based on extended Kalman filters have been applied to thermal modeling and model refinement (e.g. [15,16]). A series of experimental results using a modified Kalman filter with delayed feedback is presented for comparison with our own technique. The results show that our model is capable of giving more accurate prediction for the indoor temperature of a dynamic zone compared to the Kalman filter technique.

This paper is organized as follows. Section 2 introduces the HVAC system. Section 3 presents a mathematical zone model based on physical principles. Section 4 introduces soft real-time zone model fitting and prediction based on genetic algorithms. Section 5 gives a series of experimental results to quantify the performance of model fitting and prediction. For comparison purposes, a feedback-delayed Kalman filtering method is presented in Section 6. Finally, a conclusion is drawn in Section 7.

2. HVAC system description

Many HVAC systems use a central plant to provide hot water (e.g., with temperature of 32 °C) for heating purposes or cold water (e.g., with temperature of 6 °C) for cooling purposes. Fig. 1 is a schematic diagram of a typical HVAC system with multiple zones for cooling purpose.

The water path is presented by black arrows, which shows that cold water with temperature T_{wo} flows from the central plant along the pipework and into the cooling coils. The chilled water valves (CHWV) are used to control the volume of water flowing through the coils. A cooling coil exchanges heat energy between air from the mixing box and water from the central plant, with the output water flowing back to the central plant with a slightly higher temperature T_{wi}.

The air path is represented by grey arrows. The outside air can be drawn in by an outside air fan (OAF) and outside air damper into the mixing box. A mix of outside air and return air then flows through the air filter and passes over the cooling coil. A supply air fan (SAF) then forces the air through an insulated supply duct into the zone area as supply air (SA) for the zone. The supply air gains part of its heat from the zone to replace the heat that is leaking through the walls, roof, etc. The supply air then passes through the

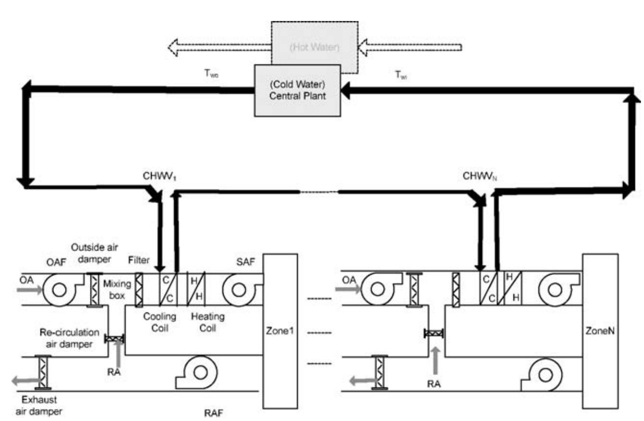

Fig. 1. Schematic diagram of a typical HVAC system for cooling purpose.