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Development of an accurate gray-box model of ubiquitous residential HVAC system for precise performance prediction during summer and winter seasons

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ABSTRACT

In this paper, gray-box models of a residential HVAC system commonly found in Canadian households are developed. The system comprises of four mjor subsystems called heat recovery ventilator (HRV), air handling unit (AHU), air source heat pump (ASHP) and zone. Models were developed by writing energy balance equations of each subsystem. Measured data from residential HVAC system of Archetype Sustainable House located in Vaughan, Canada was used for parameter estimation and validation of each subystem model. The house is outfitted with temperature, flow rate and power consumption measurement sensors for all subsystems. Two distinct sets of parameeters were found using winter and summer datasets. Parameter estimation was carried out using pattern search with Latin hypercube method and Active-Set algorithm. Developed models were evaluated against measured data using several performance comparison metrics and showed a very high value of goodness of fit in the range of 70% and 88% during both winter and summer seasons.

1. Introduction

Residential HVAC systems are particularly of interest to many researchers due to the sheer size of the install base of such systems. Inspite of their large installation numbers, residential HVAC systems are rarely studied and optimized by HVAC researchers. This is due to relatively simple system design; fewer number of subsystems; and simplicity of control systems/ actuators used in residential HVAC systems compared to a commercial or industrial HVAC system. Simple design makes residential HVAC systems cost effective but, it is less flexible and makes the optimization of these systems difficult since not many control variables are available. For example, a commercail HVAC system may use chillers and boilers with variable capacity heat pumps and smart supervisory controller that can optimize the operation of HVAC system based on several factors such as occupancy schedules, time-of-use electricity cost and weather. Commercial HVAC systems may also integrate active thermal energy storage to shift the load to off-peak hours in order to minimize the operating costs. In contrast, most ubiquitous residential HVAC systems have a fixed capacity compressor and heating furnace with simple on/off control system based on a single zone thermostat which is essentially the cheapest design but not the most energy efficient and results in higher operating costs and thermal discomfort of the occupants. Designers of residential HVAC systems do not have the flexibility to use variable capacity heat pumps, multi-zone air handling units, high efficiency heat pump systems (such as ground source heat pump), active thermal energy storage and smart supervisory controllers due to the initial equipment cost constraints. In order to further the research in residential HVAC system optimization and improved control design, accurate models are required so that researchers can test different scenarios in simulation. Accurate performance prediction is also very important in order to design advanced controllers such as model predictive control for HVAC systems. Advanced controllers can help reduce the energy consumption and operating cost of HVAC system by taking anticipatory actions instead of corrective actions taken by simpler on/off and PID controllers [1].

Three types of models can be developed for a system commonly known as white-box, black-box and gray-box models [2,3]. White-box models, also known as forward models or physics-based models, are developed by writing system equations based on physics and engineering principles. A comprehensive knowledge of system's operation is needed to develop white-box models. White-box model parameters are estimated from system's physical proper-

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ties (e.g. area, dimensions, density, etc.) or manufacturer's supplied data. Measurements of system input-output data are not needed to develop white-box models. Black-box models on the other hand require data. During the development of black-box models, measured data is used to find a linear or nonlinear function which approximates the behaviour of system. Compared to white-box models, black-box models are more precise; however, they have poor generalization capabilities since their performance degrades sharply when operating conditions deviate from training data. Third class of models, i.e., gray-box models, uses both system physics and measured data [4], therefore, the model development is more complicated. However, the advantages of gray-box models include better generelaization capabilities compared to black-box models and higher accuracy compared to white-box models. In gray-box modeling approach, mathematical structure is based on a physics-based model whose parameters are found using optimization-based techniques (such as simplex search, nonlinear least squares search and pattern search).

Researchers have used several simulation tools for performance analysis and controller development of HVAC systems including TRNSYS [5–7], Energy-Plus [8,9], and MATLAB® Simulink® [4,9–16]. TRNSYS and Energy-Plus provide a quick and easy ways to simulate HVAC systems since their interfaces have drag and drop components for simulating several common HVAC components (e.g. duct, pipe, pump, fan, heat exchanger, boiler, chiller). These programs mostly use white-box models whose parameters need to be specified by the user. Majority of models for simple systems such as temperature variation in ducts, cooling coil, heat exchanger and thermal zone dynamics, used in TRNSYS, EnergyPlus or Simulink are physics-based or white box models. On the other hand, more complicated systems such as boiler and chiller models are based on polynomial curve fitting and hence are black box models. Drawbacks of using TRNSYS and Energy-Plus are that these programs have limited support for advanced controller development and integration of energy conservation strategies (such as thermal energy storage [17,8,9,18], temperature reset [19], precooling during off-peak and set-point changes during peak hours [20,21], optimum start-stop times, ventilation control [22,19], and economizer cycle control [19,23,24]). It is also difficult to integrate customized black-box models and gray-box models into these simulation programs. Therefore, recent trend in HVAC research is to utilize generic programming/scripting interfaces such as MATLAB® Simulink® for their versatility and ease of integration with advanced controller designs and energy conservation strategies. More advanced models, e.g. hybrid models comprising of a mix of white-box, black-box and gray-box models, can be developed in MATLAB® Simulink®. Researcher have developed several toolboxes for MATLAB® Simulink® for HVAC systems such as international building physics toolbox (IBPT) [25], SIMBAD toolbox [26], conventional and renewable energy optimization toolbox (CARNOT) [27], heat, air and mosture modeling toolkit (HAM-tools) [28] and ASTECCA toolkit [11,29]. Similar to TRNSYS and Energy-Plus, these toolboxes use physics-based models whose parameters can be supplied by the user for a quick development of system simulation. Furthermore, since these toolboxes are developed in MATLAB® Simulink® therefore, it is easy to extend the capabilities of these interfaces by developing advanced controllers in MATLAB®. Models developed in this paper also use generic Simulink® math blocks for implementation and can be easily integrated into these toolboxes. Advantage of developing customized gray-box models of a specific HVAC system in Simulink® is that the parameters can also be estimated from measured data using Parameter Estimation Tool in Simulink®, resulting in high accuracy of these models. Some researchers have also developed co-simulators for TRNSYS and MATLAB® where scheduling and control tasks are performed in MATLAB® whereas system simulation is carried out in TRNSYS [30].

Fig. 1. Twin archetype sustainable houses A and B located at Kortright Centre for Conservation, Vaughan, Ontario Canada.

Rest of this paper is structured as follows. In Section 2, HVAC system is described and its operation is explained in detail. In Section 3, physics-based models of each subsystem are developed. System inputs, outputs and parameters to be estimated are identified. Measured modeling and validation data for both winter and summer seasons are presented in Section 4. The procedure for parameter estimation is explained in Section 5. The results of modeling are presented in Section 6, and the paper is concluded in Section 7.

2. System description

There are two identical semi-detached houses called Archetype Sustainable House A (ASHA) and B (ASHB) at Kortright Centre for Conservation, Vaughan, Ontario, Canada (Fig. 1). House A, which is the focus of this paper, is outfitted with a residential HVAC system commonly found in many Canadian households comprising of heat recovery ventilator (HRV), single-zone air handling unit (AHU) and air-source heat pump (ASHP). On the contrary, House B is outfitted with a futuristic HVAC equipment focused at energy conservation and high efficiency despite its high initial deployment cost. Modeling of House B was carried out previously in [4,31,32]. This paper focuses on the modeling of House A since the systems used in this house are more commonly used and any effort to improve the energy consumption efficiency and operating cost reduction of such systems would benefit more people at a greater scale.

Fig. 2 shows a block diagram of residential HVAC system installed at ASHA. The symbols are defined in Table 1. A brief description of ASHA HVAC system is provided below. For further information regarding ASHA and ASHB systems, the reader is referred to previous research papers [30,33,7,34,6,35–39].

Fresh air enters the house and exhaust air leaves the house through a ventilation system comprising of a HRV. HRV unit has two fans and a heat exchanger inside it. One fan supplies fresh air to the AHU and the other fan extracts exhaust stale air from the house. AHU circulates fresh air inside the house. In winter, fresh air is at a much lower temperature compared to the exhaust air which is at room temperature. Therefore, heat is transferred from exhaust air to fresh air which preheats it. During summer season, reverse happens since fresh air is warmer than the room temperature exhaust air, therefore, heat is transferred from the fresh air to the exhaust air thus precooling the fresh air. HRV helps to reduce energy consumption of the system and improves its efficiency.

Temperature control in the house is provided by a thermostat (consisting of a temperature sensor and a zone temperature con-