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An inverse method for calculation of thermal inertia and heat gain in air conditioning and refrigeration systems

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HIGHLIGHTS

- An inverse method is proposed to calculate thermal inertia in HVAC-R systems.
- Real-time thermal loads are estimated using the proposed intelligent algorithm.
- Calculation algorithm is validated with on-site measurements.
- Freezer duty cycle data are extracted only based on temperature measurements.

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ABSTRACT

A new inverse method is proposed for estimation of thermal inertia and heat gain in air conditioning and refrigeration systems using on-site temperature measurements. The method is applied on a walk-in freezer room of a restaurant in Surrey, British Columbia, Canada during one week of its regular operation. The thermal inertia and instantaneous heat gain are calculated and the results are validated using actual information of the materials inside the freezer room. The proposed method can be implemented in intelligent control systems designed for new and existing HVAC-R systems to improve their overall energy efficiency and reduce their environmental impacts.

1. Introduction

Heating, Ventilation, Air Conditioning, and Refrigeration (HVAC-R) contribute to a tremendous portion of the global energy consumption in a wide array of residential, industrial, and commercial applications worldwide. HVAC-R consumes half of the energy use in buildings and 20% of the total national energy use in European and American countries [1]. Predictions indicate a further increase of 50% from the current figure during the next 15 years in the European Union countries [1]. Furthermore, Air Conditioning (AC) is the second most energy consuming unit in vehicles [2]. In an electric vehicle, AC power consumption can be as high as 12% of the total vehicle power during regular commuting [3]. As such, efficient design of new HVAC-R systems and devising intelligent control methods for existing systems can lead to significant reduction of total energy consumption and greenhouse gas emissions in large scales.

Proper design and intelligent operation of an HVAC-R system requires: (i) accurate prediction of thermal loads, and (ii) appropriate design and selection of the cooling unit. Accurate cooling load calculations are a prerequisite to proper sizing, selection, and control of any HVAC-R system. Modern air conditioning systems are equipped with feedback controllers that allow them to manipulate the operation of the HVAC unit in order to efficiently sustain thermal comfort. Although parameters such as room temperature, humidity, and occupancy level are used as control variables, it is advantageous to extend the first design step, *i.e.*, the load estimation to the operation stage of the unit. Real-time estimation and prediction of the upcoming thermal loads alongside raw measurements can be beneficial for energy-efficient control of HVAC systems, especially in Mobile Air Conditioning (MAC) applications that experience highly dynamic load variations.

In many applications, controllers based on on–off action or modulating control are successfully used that utilize the room temperature as the controlled variable [4]. Nevertheless, it is inherently impossible to predict upcoming thermal conditions by using conventional controllers that only rely on the current room status. It is shown that intelligent control of the HVAC operation based on

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prediction of the load can help maintain air quality while minimizing energy consumption [5,6]. By predicting thermal loads, controllers are enabled to not only provide thermal comfort in the current condition, but also adjust the system operation to cope with the upcoming conditions in an efficient manner. Thus, improvement of load calculation methods and the ability to estimate and predict the loads in real-time can improve the feedback information for the control of the HVAC system, which, in turn, result in significant reduction of total energy consumption and greenhouse gas emissions. Furthermore, in applications where the room contents may vary over time, an algorithm that can estimate the thermal inertia in an unsupervised manner can aid the HVAC-R system to adapt to the new conditions. Given the automatic adaptability of the HVAC-R system, it can be further controlled to perform at different capacities in order to reduce the overall energy consumption.

The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) established an extensive methodology for calculation of heating and cooling loads. The heat balance method [7,8] is an example of such methods. It is a straight-forward and rigorous method that involves calculating a surface-by-surface heat balance of the surrounding walls of a room through consideration of all conductive, convective, and radiative heat transfer mechanisms. The method has been extensively used in residential and non-residential applications [5,6]. Mobile Air Conditioning (MAC), especially in electric vehicles, is also a crucial application where potential HVAC energy savings are possible. Less energy consumption by mobile HVAC systems directly results in higher mileage and better overall efficiency on the road [9]. Zheng et al. [10] devised a simple method to calculate thermal loads in vehicles. In their approach the different load categories such as radiation and ambient loads were considered. A case study was performed and the results were validated by experiments. Although their methodology has shown good agreement with experimental results, much details of the vehicle cabin and service conditions is needed to perform the necessary modelling calculations. Arici et al. [11] developed a computer code for simulation of the dynamic operation of a climate control system in a typical vehicle. Khayyam et al. [12] collected a set of models to calculate the different categories of thermal loads encountered in a vehicle. After using appropriate models for calculation of each of the load categories, they implemented control algorithms to improve the overall efficiency of the mobile air conditioning system.

In many applications, thermal loads vary dynamically. Novel approaches are being studied in the literature for real-time estimation of thermal loads. Several methodologies are introduced in the literature for estimation of thermal loads in existing buildings. Kashiwagi and Tobi [13] proposed a neural network algorithm for prediction of thermal loads. Ben-Nakhi and Mahmoud [14] also used general regression neural networks and concluded that a properly-designed neural network is a powerful tool for optimizing thermal energy storage in buildings based only on external temperature records. They claimed that their set of algorithms could learn over time and improve the prediction ability. Li et al. [15] presented four modeling techniques for hourly prediction of cooling loads. The methods included back propagation neural network (BPNN), radial basis function neural network (RBFNN), general regression neural network (GRNN), and support vector machine (SVM). Other researchers have used fuzzy control algorithms to propose load prediction methods. Among many, Sousa et al. [16] developed a fuzzy controller to be incorporated as a predictor in a nonlinear model-based predictive controller. Wang and Xu [17,18] used a Genetic Algorithm (GA) for identification of parameters in a model for estimation of thermal performance. In their approach, a thermal network of lumped thermal masses and parameters was identified using operation data and GA estimators.

A disadvantage of most existing load calculation methods is that they require much information about the air-conditioned space to estimate the loads. For instance, the heat balance method requires knowledge of material properties, thickness of walls, geographical location, fenestration data, weather information, occupancy, appliances, and other detailed information. Such an approach rarely relies on feedback information from the existing air-conditioned space. That type of methodology is a "forward" approach which makes the redesign/retrofit of existing HVAC-R systems a laborious and time-consuming task.

Alongside forward approaches, ASHRAE also recognizes data-driven or "inverse" methods of load calculation [7]. The data-driven modelling methodology consists of gathering the performance data of an existing system and analyzing them. Relatively few parameters are required in an inverse approach compared to forward methodologies. In an inverse method, model parameters may be deduced from the room data. Thus, the inverse model can predict the "as-built" system performance more accurately [7]. Inverse methods concentrate on the study of existing HVAC-R systems and allow the thermal performance of the system to be inferred based on measured temperature data. This is particularly convenient for retrofitting existing systems. Major input data to an inverse algorithm are the room temperature under regular operation, as well as the performance/capacity of the HVAC-R system. Therefore, in an inverse method, the entire system, *i.e.*, the conditioned space plus the HVAC-R unit is merely seen as a black box that is investigated for a period of time.

In this study, a new inverse methodology is proposed for identification of the duty cycles in a typical refrigeration system. The lumped thermal inertia and heat gains are quantitatively calculated. The present approach is scalable and is irrespective to the shape of the conditioned room. Therefore, it can be applied to any HVAC-R application. The proposed analysis enables an accurate and real-time calculation of thermal loads. Therefore, it can be used for intelligent control of the corresponding HVAC-R unit. Many existing HVAC-R devices are equipped with constant-speed compressors and fans. Nevertheless, Qureshi and Tassou [19] reviewed the application of variable-speed capacity control in refrigeration systems. They argued that in order to compensate for half-load usage conditions, the option of variable-speed compressor consumed the least percentage of the full load power compared to other methods. Hence, implementation of the present algorithm combined with variable-speed compressors can further reduce the energy consumption and environmental impact of HVAC-R systems.

In the following sections, the acquisition of experimental data is first explained. Based on the collected data of the sample refrigeration system, the proposed model is discussed in a subsequent section. Results of the modelling approach are finally presented and the accuracy of the results is validated using experimental information of the freezer room.

2. Experimental study

A freezer room in a restaurant in Surrey, British Columbia, Canada was selected to collect data during its regular operation. Fig. 1 shows a picture of the inside of the walk-in freezer room as well as a 3D schematic of it. Dimensions of the room are shown in Fig. 1 as well.

Temperature sensors were installed in different locations inside the freezer room. Temperature data loggers (Track-It, Monarch Instruments) were used for logging the room temperature over a period of one week. The maximum error of the temperature data loggers is ±1 °C for the range of −20 °C to 85 °C. Fig. 2 shows the 7 locations where temperature data loggers were installed.