Applied Energy 190 (2017) 222–231

Contents lists available at ScienceDirect

Applied Energy

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

Analysis of energy and control efficiencies of fuzzy logic and artificial neural network technologies in the heating energy supply system responding to the changes of user demands

Jonghoon Ahn [a], Soolyeon Cho [a], Dae Hun Chung [b,*]

[a] North Carolina State University, Raleigh, NC 27695, USA
[b] Korea Institute of Energy Research, Daejeon, South Korea

HIGHLIGHTS

- Advanced controllers are proposed to reduce control errors and energy consumption increases.
- The FIS and ANN models are utilized to compare conventional thermostat on/off controller.
- To provide appropriate thermal energy, the models control the amount of air and its temperature simultaneously.
- Control errors, heat gains, and output signals are compared to define models' effectiveness.
- The ANN model shows the best result for space heating responding to intermittent thermal changes.

ARTICLE INFO

Article history:
Received 17 August 2016
Received in revised form 28 December 2016
Accepted 28 December 2016

Keywords:
Energy efficiency
Control accuracy
User thermal demand changes
Fuzzy inference system
Artificial neural network

ABSTRACT

This paper presents hybrid control approaches for heating air supply in response to changes in demand by using the Fuzzy Inference System (FIS) and Artificial Neural Network (ANN) fitting models.

Since early 2000's, some advanced computing and statistical tools were introduced to replace conventional control models in improving control and energy efficiency. Among the tools, the FIS and ANN algorithms were used to define complex interactions between inputs and outputs, and were able to facilitate control models to predict or evaluate precise thermal performance.

This paper introduces the FIS and ANN control schemes for simultaneously controlling the amount of supply air and its temperature. Input and output data derived from the FIS results generate and validate the ANN model, and both models are compared to the typical thermostat on/off baseline control to evaluate conditions of supply air for a heating season. The differences between the set-point and actual room temperature and their sums indicate control efficiency, and the heat gains into a room and their sums define the energy consumption level. This paper concludes that the simultaneous control of mass and temperature maintains the desired room temperature in a highly efficient manner. Sensitive controls may have a disadvantage in terms of energy consumption, but the ANN controller can minimize energy consumption in comparison with simple thermostat on/off controller. The results also confirm the effectiveness of simultaneous control of mass and temperature using an ANN algorithm corresponding to intermittent or unpredicted changes in thermal demands.

1. Introduction

In order to maintain the desired temperature in thermal zones, there is much focus on improving Heating, Ventilating, and Air-Conditioning (HVAC) systems. To address these issues, the Proportional-Integral-Derivative (PID) algorithm has been used to improve control technologies to meet various conditions in the HVAC models. However, most technologies used in developing the PID algorithm focus on controls for optimizing fuel usage and fan motor speed. These models are useful for large-scaled HVAC system, plants, and buildings, but they have many disadvantages when applied to small, sensitive thermal models requiring immediate response. Recent computing and statistical technologies have been rapidly developed; such technologies propose effective approaches and solutions to make controllers more sensitive and able to immediately respond to various thermal demands.

* Corresponding author.
E-mail addresses: cdh@kier.re.kr, cdh950502@gmail.com (D.H. Chung).

http://dx.doi.org/10.1016/j.apenergy.2016.12.155
0306-2619/

Nomenclature

A	area (m^2)
Changes (%)	percentage of changes in comparison with thermostat on/off controller
Cv	specific heat capacity at constant volume (J/kg·K)
Cp	specific heat capacity at constant pressure (J/kg·K)
D	depth of envelope components (m)
E	error as difference between set-point and measured room temperature (°C)
ΔE	derivative of error
h	convection heat transfer coefficient (W/m^2·K)
h_{in}	specific enthalpy into room (J/kg)
h_{out}	specific enthalpy out from room (J/kg)
Heating	heat gain for heating (MJ/h)
IAE	Integral (Sum) of Absolute Error between set-point and measured room temperature (no unit)
k	transmission coefficient (W/m·K)
$\dot{m}_{ht}$	mass flow-rate from heater (kg/h)
$\dot{m}_{in}$	mass flow-rate into room (kg/h)
$\dot{m}_{out}$	mass flow-rate out from room (kg/h)
$m_{roomair}$	mass of room air (kg)
N/A	not applicable
Q_{loss}	convection and transmission heat loss (J)
Q_{gain}	convection and transmission heat gain (J)
R	thermal resistance (m·K/W)
R^2	fraction of variance
t	time
T_{ht}	air temperature entered into room (°C)
T_{out}	outdoor temperature
T_{room}	room temperature (°C)
T_{set}	set-point temperature (°C)
u	internal energy (J)
W	work (J)

1.1. Development of control models

Several studies developed models for effective control of coal and oil based plants, and some specific structures in boiler turbine or distribution controls [1–6]. Also, boiler control models or retrofitting focused on reductions of gas emission or water pollutants responding to changes in thermal loads and environmental impacts [7–11]. With the help of computing applications, other studies also improved some models to optimize output signals through the more refined control methods and PID tuning algorithms dealt with sensitive parameters and thresholds [12–17]. Statistical and mathematical predictive control approaches in building heating system mainly dealt with demand-response by simulation and Model Predictive Control (MPC) [18–20]. Muniak analyzed profiles of valve opening in the fluid heating system [21]. In large-scaled buildings and district level, heating control models were developed in terms of reduction of gas emission, improvement of energy conservation, and optimized design of distribution network [22–27].

These control models were developed from the advanced control systems such as Fuzzy Inference System (FIS). At the early stage, thermal control models were developed through the comparative analysis between conventional control model and the FIS model [28]. Signal control efficiency of FIS model was compared to the PID and conventional rule, and also it developed through the Genetic Algorithm (GA) and HVAC case studies [29–31]. Lianzhong and Zaheeruddin compared energy consumption from the various models combining PID and FIS model for boiler control [32]. Some researchers developed boiler control model by using both PID and FIS models, and provided conceptual structures for defining interactions between FIS and PID algorithms [33–35].

As energy related databases were accumulated, advanced statistics algorithms focused on dealing with large databases with the help of computing technology. Artificial Neural Network (ANN) was applied to evaluate energy performance of buildings which equipped various energy conservation measures [36]. Device control models such as damper control or fan speed with combining PID and FIS model were developed through the ANN model [37,38]. Fuzzy and ANN algorithms were utilized to define the effectiveness during energy transforming, distributing, and networking [39]. By using Artificial Neuro-Fuzzy Inference System (ANFIS), prediction of plant or system performance was performed more accurately [40,41]. Koulani, Hviid, and Terkildsen tested control of fan and damper combined models were tested to meet various demands of three different zones with weather data [42].

Adding to the technical applications, Dounis et al. applied environment comfort system to design fuzzy sets by using the concept of Predictive Mean Vote (PMV) [43]. Some energy efficient controls in office buildings were tested by using occupancy, lighting, equipment, and fenestration [44,45]. Also, occupants' quality such as adaptive responses and perception was analyzed as one of the major factors to optimized thermal environment [46]. Other researchers also developed FIS for human sensation and thermal comfort regulation by using window, ventilation, and relative humidity models [47,48]. And, Dounis and Caraiscos tested their own GA in FIS for improving both of energy efficiency and human comfort level [49]. Hussain et al. developed FIS by testing their own objective function in GA and concluded improvement of human comfort and energy efficiency by comparing two simulation results [50]. Modified fuzzy rule was used to develop on/off control model in residential buildings [51].

1.2. Problem statement

In terms of control methods and applications, several algorithms and tools have been developed. Conventional PID control schemes were typically utilized in practice to meet the thermal demands in buildings. However, this method is useful in that it measures fuel usage in boiler operations or electricity usage for fan motor. These strategies have some disadvantages to produce immediate response for thermal demands with respect to human comfort. Also, the thermostat on/off controllers typically used in practice lack the capability to respond to immediate changes in thermal demands that are directly related to human comfort and energy efficiency. Damper control models define only the estimated time to meet the requirement and explain the mass problem to infuse into thermal zones without considering temperature control. These conventional approaches are not appropriate to sensitive and immediate control corresponding to recent Internet of Things (IoT) or ubiquitous technologies.

This paper proposes a comparative analysis of supply heating air controllers dealing with amount of mass and air temperature by using machine learning tools such as FIS and ANN. The main purpose of the comparison is to define effectiveness of FIS and ANN models that control supply air mass and temperature in the both cases of fixed T_{set} and changed T_{set} as user's demand.