 https://doi.org/10.1051/e3sconf/202339603035

Data-driven Optimal Control of Single Duct VAV Terminal Unit

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Abstract. The purpose of this study is to propose a control method that optimizes the set point of the variable air volume (VAV) terminal unit using real-time prediction model of indoor thermal and air environment and energy consumption. Indoor thermal environment and air environment are predicted through indoor load and carbon dioxide (CO_2) concentration. A prediction model was developed through operation data of the VAV terminal unit by artificial neural network (ANN) algorithm. The developed prediction model was used for real-time set point control of the VAV terminal unit. The optimal control of VAV terminal unit can be expressed in 3 step. First, it predicts the current indoor load and CO2 concentration. Second, all supply temperatures and supply air flow rate that can be provided in the predicted condition are repeatedly simulated. Finally, the set point of the minimum energy consumption is applied to the control. The evaluation of the proposed control method was compared with the dual maximum control logic. Comparative evaluation was performed using TRNSYS. It was confirmed that the proposed control method reduced the reheat coil energy consumption by about 20% and the air supply fan energy consumption by about 17% compared to the existing control method.

1 Introduction

To control the variable air volume (VAV) system, it is essential to control the terminal units installed in each zone[1]. The terminal unit of a general VAV system sets and controls the minimum and maximum air flow rates based on the peak load [2]. Among them, the minimum air flow rate of the VAV terminal unit is closely related to indoor air quality and energy consumption. When the minimum air flow rate is set low, indoor air quality problems occur, and when the minimum air flow rate is set high, energy is wasted due to excessive air flow rate supply. A fixed minimum air flow rate wastes energy when there are no occupants, and when the occupants increase, problems with indoor air quality may occur [3]. These fixed setpoints do not reflect various situations of the building, and setpoints and control methods suitable for indoor conditions are required. In order to solve these problems, studies have been conducted to reset the setpoints to fit the indoor conditions using mathematical models [4]. Although a control method was presented by deriving control settings that satisfy heating load and indoor air quality through a mathematical model, it requires expertise to interpret the numerous information and data and systems required for model construction, making it difficult to apply to the field. There are limits. In the field of building equipment systems, big data and machine learning are being applied to improve building performance and save energy consumption [5]. Building equipment systems are controlled and operated through sensors and setpoints installed in various systems, and various techniques (statistical techniques, big data, machine learning, etc.) are used to predict system performance and optimize control technology [6].

Cho and Liu [7] confirmed the relationship between the supply temperature and the VAV terminal unit minimum air flow rate through mathematical models and simulations. In addition, the relationship between air flow rate and supply temperature that can minimize energy consumption was presented through proper supply temperature, stratification analysis, and energy analysis according to load, and verified through laboratory application. Liu [8] proposed a demand ventilation control method using an occupant sensor for the existing demand ventilation based control technology using a carbon dioxide(CO_2) concentration sensor in a VAV terminal unit system. Through this, system cost and energy cost were reduced. Kang et al. [9] presented the relationship between supply temperature, air flow rate, and energy according to various floor heights, and suggested a control method for air flow rate and supply temperature of terminal units considering indoor load, stratification, and indoor air quality. Kim et al. [10] reset the air flow rate and supply temperature considering the ventilation volume in multi-zone, and conducted performance evaluation through energy simulation.

Therefore, in this study, for optimal control of the VAV terminal unit, based on the data obtained during the operation of the building system, the indoor load and CO_2 concentration are predicted, and by using this, an

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optimal control technology for deriving minimum energy consumption is intended to be developed.

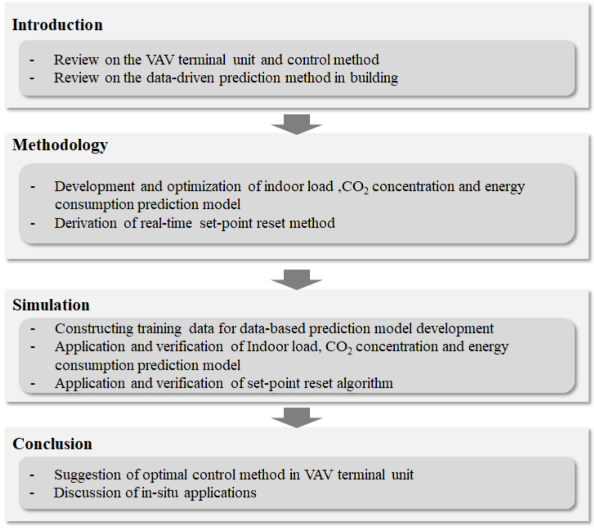

Figure 1. Research flow

2 Methodology

In general, the control setpoints of VAV terminal units are set to control indoor load and indoor air quality. In the case of the VAV terminal unit including the reheating coil, which is the target system of this study, the maximum and minimum air flow rates are generally selected and controlled as target setting values. However, the target setpoint is calculated based on the maximum load of the target space calculated at the time of design, and the air flow rate considering the indoor air quality is also selected based on the maximum number of people in the occupied space. These setpoints do not affect comfort, but they are far from the fluid thermal and air behavior characteristics of real buildings, so they are not appropriate in terms of energy.

In order to solve this problem, it is possible to predict the indoor load and CO_2 concentration, which are factors that can determine the indoor heat and air environment, based on a mathematical model, and based on this, setpoints can be applied variably according to the indoor situation. However, in the case of a mathematical model, there are many input factors required for prediction, and when input factors are omitted, the reliability of the prediction model decreases or a problem in which prediction is impossible occurs.

A data-based predictive model (Black-box model) is a method of finding and predicting the relationship between input data and result data using various theoretical techniques, and requires a large amount of data. Building facility systems collect and utilize various data using BAS for system operation and monitoring, and the data collected at this time can be used to apply data-based prediction to buildings and facility systems. The facility system operation data of the building is made up of time series. Physically, the dynamic behavior of the facility system is that the previous state (room status, external environmental conditions, etc.) affects the environment of the current room (or zone). The system must provide appropriate control for the situation.

Using the developed indoor load, CO_2 concentration, and energy consumption prediction model, VAV terminal unit setpoints (supply air flow rate, supply temperature) in the minimum energy consumption situation were derived. The setpoint derivation process is as follows.

First, the load and CO_2 concentration are predicted based on operational data (outside air temperature, supply fan speed, terminal damper opening rate, outside air damper opening rate, occupancy rate). Second, energy consumption is predicted based on load and CO_2 concentration prediction models and control setpoints (supply temperature, supply air flow rate). Thirdly, iterative simulations are performed while changing the control setpoints within a range according to the indoor conditions (load and CO_2 concentration). Fourth, the VAV terminal unit supply air flow rate and supply temperature setpoints of the minimum energy situation are derived. Finally, input the derived setpoint as the terminal unit control setpoint for the next timestep.

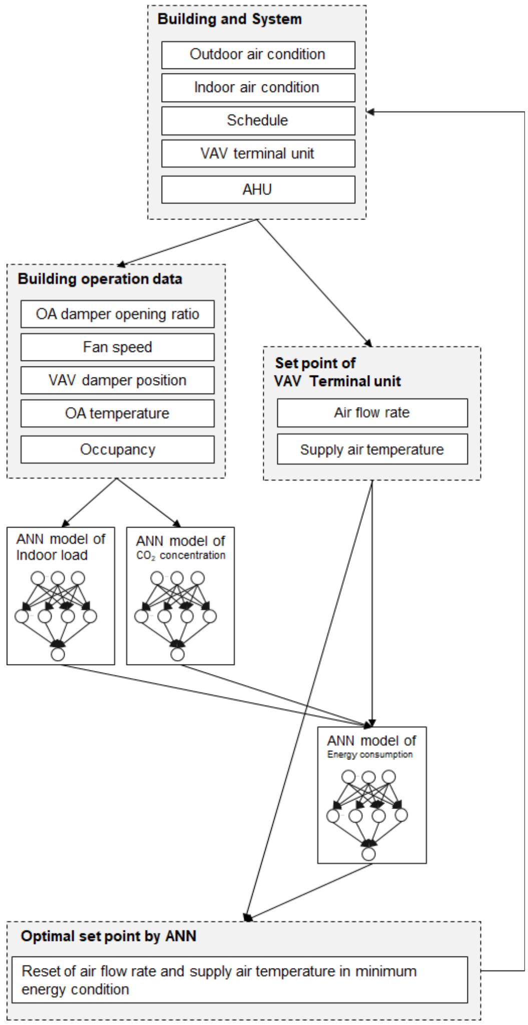

Figure 2. Schematic diagram of optimal control method

3 Simulation

The target building of a chosen building for the validation of the ANN based optimal control algorithm of the VAV terminal unit is a laboratory with an area of approximately 116.64 m^2 and equipped with a single duct VAV system and a VAV terminal unit with a reheat coil (Tab.1). The air conditioning system installed in the laboratory is operated 24 hours a day, and the operating conditions are set to maintain the set temperature of the room at 24℃.

Table 1. Overview of VAV systems

Category		Specification		
AHU	Fan	Air Flow (CMH)	Static Pressure (MMAQ)	Power (kW)
	Supply Fan	12,000	92	5.5
	Return Fan	9,600	35	3.7
	Coil	Capacity (kcal/h)	Flow (LPM)	Area (m^2)
	Cooling Coil	74,000	247	1.33
	Heating Coil	37,000	123	1.33
Terminal unit		Rated air flow rate (CMH)	Capacity of reheating coil (kcal)	
		1360	4000	

The external conditions for the simulation utilized data in TMY format. And the building material properties and internal heat gain (occupancy, light and equipment) for building modeling and simulation are shown in Tab.2.

Table 2. Input data for energy simulation

Category		Contents
K-value	Outdoor Wall	0.310 W/m^{2}K
	Indoor Wall	0.508 W/m^{2}K
	Floor	0.039 W/m^{2}K
	Roof	0.316 W/m^{2}K
Load Condition	Occupancy	Seated, Light work, typing 150W/person
	Light	13W/m^2
	Equipment	16W/m^2

In this study, repeated simulations were conducted while changing variables that could affect indoor conditions and energy through TRNSYS17, a dynamic simulation tool. The data collected through this was used as learning data used to develop a predictive model.

The operation data of the target building is composed of annual operation data at 1-hour intervals. Learning data was collected at 1-hour intervals through simulation, and data was collected while changing indoor heat (occupancy, equipment) conditions and VAV terminal unit setpoints (minimum air flow rate, supply temperature). Simulations were conducted while changing the density of occupants and devices (computers and monitors) that affect the indoor load. Among the setpoints of the VAV terminal unit, the minimum air flow rate (supply air flow rate) setpoint was reflected in the supply air flow rate calculation formula to control the air flow rate supplied to the room, and the supply temperature setpoint was used to control the temperature of the terminal unit reheat coil through the controller. It was modeled so that as for the simulation period, two months in winter, when the minimum air flow rate setpoint of the VAV terminal unit affects, was selected as the simulation period.

To develop an artificial neural network-based energy prediction model, determine the composition, use function, and learning method of the input layer, hidden layer, and output layer, and then optimize the model to derive the optimal number of hidden layers and neurons to improve the accuracy of the prediction model. steps were carried out. The number of hidden layers was varied from 1 to 4 and the number of neurons from 1 to 16, and optimization was performed. sigmoid was used as the transition function and Adam (Adaptive Moment Estimation) was used as the optimization algorithm.

4 Result and discussion

The accuracy of ANN based prediction model was validated and evaluated using CvRMSE and MBE[11]. As a result of the analysis of the indoor load prediction model, the MBE was -1.8%, CvRMSE was 3.4%, and R^2 was 0.97 confirming the excellent performance of the prediction model. As a result of the analysis of the CO_2 concentration prediction model, the MBE was -3.2% and the CvRMSE was 5.4%, R^2 was 0.99 confirming the excellent performance of the prediction model. As a result of the analysis of the energy consumption prediction model, MBE was 6.4% and CvRMSE was 8.5%, R^2 was 0.98 confirming the excellent performance of the prediction model. Figure 3 shows performance validation result of prediction model.

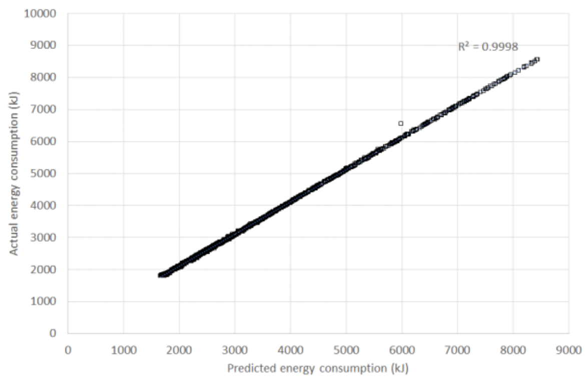

Figure 3. Comparison of prediction and actual energy consumption data

The control performance of the existing control algorithm with dual maximum control logic and the data-based optimal control algorithm developed in this study was compared. When the proposed algorithm was applied, it was confirmed that the supplied air flow rate decreased in the heating season full load situation compared to the existing algorithm, and it was confirmed that the air flow rate decreased up to about 150CMH.

In the case of the supply fan, about 308 MJ was consumed in the existing algorithm, and 257 MJ was consumed when the proposed algorithm was applied. By resetting the setpoint, the fixed minimum air flow rate is reset according to each load and indoor air quality condition, reducing the supplied air flow rate. It was also confirmed that about 17% of fan energy was saved (Fig. 4). In the case of reheating coil energy, 5,197 MJ was consumed in the existing algorithm, and 4,183 MJ was consumed when the proposed algorithm was applied. It was confirmed that the reheating coil energy was reduced by about 20% due to the reduction of the air flow rate set as the supply fan energy saving and the change of the supply temperature setpoint (Fig. 5).

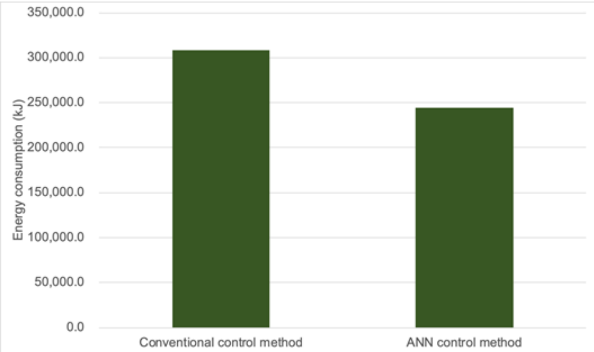

Figure 4. Comparison of supply fan energy

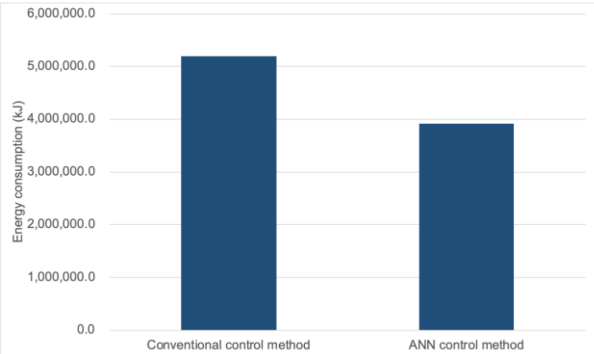

Figure 5. Comparison of reheating energy

5 Conclusion

In this study, a technology was developed to predict the building energy consumption by inputting the indoor load and CO_2 concentration prediction model, the minimum air flow rate, and the supply temperature setpoints, and derive and reset the setpoints that minimize energy consumption as well as indoor comfort. As a result of analyzing the accuracy of the energy consumption prediction model, MBE was 6.4% and CV (RMSE) was 8.5%, which was confirmed as a meaningful model. In addition, in order to evaluate the performance of the ANN-based control algorithm, a comparison was made with the existing control algorithm, Dual maximum control logic, and the mathematical model-based control algorithm developed through previous research. As a result of comparing the energy consumption with the conventional control algorithm using a fixed set point, it was confirmed that about 17% of fan energy and about 20% of reheat coil energy were saved.

Acknowledgements

This research was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2021R1A4A1031705). And This research was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (No. 2022R1C1C2010251).

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