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# Development and validation of online models with parameter estimation for a building zone with VAV system

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**Abstract**

The energy consumption by building heating, ventilating, and air conditioning (HVAC) systems has evoked increasing attention to promote energy efficient control and operation of HVAC systems. Application of advanced control and operation strategies requires robust online system models. In this study, online models with parameter estimation for a building zone with a variable air volume system, which is one of the most common HVAC systems, are developed and validated using experimental data. Building zone temperature and zone entering air flow are modeled based on physical rules and only the measurements that are commonly available in a commercial building are used. Various validation experiments were performed using a real-building test facility to examine the prediction accuracies for system outputs. Using the online system models with parameter estimation, the prediction errors for all validation experiments are less than 0.28 °C for temperature outputs, and less than 84.9 $m^3$/h for air flow outputs. The online models can be further used for local and supervisory control, as well as fault detection applications.


*Keywords:* Parameter estimation; HVAC system; Recursive least square method; Variable air volume system; Online modeling

## 1. Introduction

Heating, ventilating, and air conditioning (HVAC) systems in industrial and commercial buildings consumes 14% of the United States primary energy [1], and about 32% of the electricity generated in the United States is consumed to heat, cool, ventilate, and light commercial buildings [2]. Current research demonstrates that advancements in building control and operation systems are needed to decrease the building HVAC energy usage while maintaining or even improving the occupant comfort [3]. Application of advanced control and operation strategies often requires an online system model that describes adequately system behavior. But the complex nonlinear nature of building thermal process, unknown and time varying thermal loads and other parameters, and limited available measurements in real buildings make modeling of building HVAC systems a challenging task. Existing models for building HVAC systems vary from very complicated computational fluid dynamics model to simplified linear models. An online model for building HVAC system application should have the following features: (1) use only the measurements that are commonly available in a commercial building; (2) be able to update its parameters to represent the current building and HVAC system status; and (3) exhibit the ability to predict the system behavior in the near future time.

Wen and Smith [4] suggest that models using system identification and parameter estimation techniques can satisfy the above requirements for HVAC systems. A more detailed literature review [4] indicates that these techniques, especially the recursive least square (RLS) method, have been applied to HVAC systems. However, most of the applications (1) assume that the thermal loads are known or are measured variables; (2) employ statistical models that require a set of system identification processes; and (3) lack experimental validation. Wen and Smith [4] developed and validated a building zone temperature ($T_z$) model that does not require information about the solar and internal thermal loads. However, in the model, the temperature of the discharge air from a variable air volume (VAV) unit ($T_{da}$) is needed, which is not a commonly available

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**Nomenclature**

AVG average absolute value
$c$ specific heat (J/kg °C)
$C$ flow capacity (W/°C)
$C_{dp}$ damper signal
$C_{vlv}$ reheat valve signal
hA convective conductance (W/°C)
NTU number of heat transfer units
$q$ heat transfer (W)
$Q$ volumetric flow (m$^3$/h)
STD standard deviation
$t$ time (h)
$\Delta t$ time interval (h)
$T$ temperature (°C)
UA overall conductance (W/°C)
$V$ volume (m$^3$)
$y$ output variable vector

*Greek letters*
$\alpha$ damper authority
$\beta$ lumped parameter
$\varepsilon$ prediction error or heating coil effectiveness
$\eta$ fin efficiency
$\theta$ parameter vector
$\lambda$ unknown parameter
$\rho$ density (kg/m$^3$)
$\phi$ regression variables

*Subscripts*
a air
da discharge air
dp damper
e exterior environment
ea entering air
ew entering water
i interior environment
min minimum
r ratio
RH reheat
s solar
sa supply air
w water
z building zone
zs building zone set point

*Superscripts*
∧ estimated variable
. . . predicted variable

*Acronyms*
AHU air handling unit
HVAC heating, ventilation, and air-conditioning
RLS recursive least square
VAV variable air volume

measurement. Furthermore, the entering air flow ($Q_a$), was not modeled in Ref. [4]. In a VAV unit, $Q_a$ is modulated by the unit damper position ($C_{dp}$), which is calculated by a controller based on zone temperature. Therefore, to use the model described in Ref. [4] to predict zone temperature, the relation between $C_{dp}$ and $Q_a$ needs to be modeled. Without removing $T_{da}$ from the model and using a good prediction for $Q_a$, the proposed method in Ref. [4] is unlikely to be widely applied in commercial buildings. As an enhancement to the previous study [4], the objectives of this research are to (1) modify the previous model proposed in Ref. [4] to accommodate only commonly available measurements; (2) develop a model that describes the relation between $Q_a$ and $C_d$; (3) apply parameter estimation that utilizes the RLS method with variable forgetting factor to estimate the unknown model parameters; and (4) validate the models with experimental data.

## 2. Building zone and VAV unit model description

The relations for the RLS method with a variable forgetting factor are introduced in Ref. [4] and are not repeated here. In this section, new models for the building zone temperature and VAV air flow are described.

### 2.1. Building zone with VAV unit modeling

A typical building zone with a VAV unit is illustrated in Fig. 1. A thermostat installed on an interior wall measures $T_z$. The zone has exterior and interior walls that separate the zone from the exterior and interior environments. The exterior and interior environments have temperatures of $T_e$ and $T_i$. The solar load of $q_s$ includes the beam and diffuse components of the solar energy. The interior load of $q_z$ accounts for thermal loads generated by zone occupants and equipment, such as lights and computers. All variables are assumed to be time varying. The zone is equipped with a VAV unit with damper and a hydronic reheat coil. Air conditioned by the air handling unit (AHU) is supplied to the VAV unit at an entering air temperature of $T_{ea}$. By adjusting the position of the VAV damper, a desired value of $Q_a$ is achieved. The reheat provides an adjustable heat of $q_{RH}$ to the air. The air enters the room at $T_{da}$ and $Q_a$. The zone has a local controller that uses a proportional and integral loop to control the damper and reheat valve to maintain the zone temperature at a given zone set point ($T_{zs}$). Although the building zone and VAV unit are the same as those described in Ref. [4], a new zone

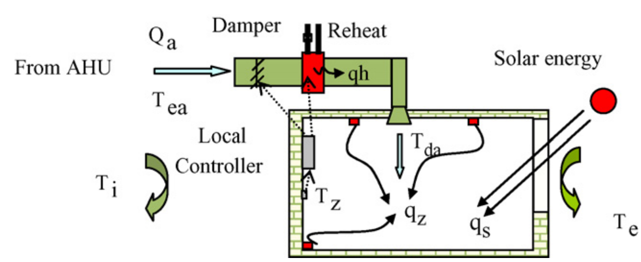


Fig. 1. A building zone.