

Thermal Dynamic Modeling and Simulation of a Heating System for a Multi-Zone Office Building Equipped with Demand Controlled Ventilation Using MATLAB/Simulink

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Abstract— Energy consumption of the office buildings demonstrates potential energy savings. One of the major parts of the energy consumption in these building is related to the heating, ventilation and air conditioning systems which keep thermal conditions in a comfort zone and indoor air quality in an acceptable range. Nowadays, building management systems are developed to reduce the energy consumption of these systems besides supplying occupants with comfort conditions. Furthermore, these complex systems can be faced by different operation faults. To diagnose and detect these faults, getting the knowledge about the system behavior through modeling is substantial. This paper introduces a scalable multi-zone office building model that was established in Matlab/Simulink using Simscape toolbox. The model contains the thermal dynamics of the building elements and the heating control system which is equipped with demand-controlled ventilation. The results show that the model can correctly describe and predict the dynamics of the system. The proposed approach is intended to be used for HVAC systems in building automation with a specific focus on faults diagnosis and detection.

Keywords— *Simulation; modeling; Simulink; thermal dynamic; natural ventilation; carbon dioxide; demand control*

I. INTRODUCTION

The building sector in the European Union (EU) consumes 40% of the total energy in the union [1, 2]. The energy consumption in the office building sector is almost 18% of the global energy consumption [3]. Energy consumption of the buildings is very dependent on the occupancy pattern, the outdoor environment, the structure specifications, and the materials. These statements demonstrate the importance of energy saving in the office building sector. One of the major parts of the energy consumption in these building relates to the heating, ventilation and air conditioning (HVAC) systems which keep thermal conditions in a comfort zone and indoor air quality in an acceptable range. Recent research trends emerged based on advanced control strategies in building energy management systems (BEMS) which indicate that there could be a potential energy saving up to 30% of total energy consumed in a building

[4]. To optimize a complex building automation model, it is important to get the knowledge about the system behavior by analyzing the system model, because the model specifies what a system does. C. Lapusan et al. developed a multi-room building thermodynamic model based on 3R-2C network (3 resistors and 2 capacitors) using Simscape library from Matlab/Simulink [5]. A. Thavlov et al. presented a model for prediction of indoor air temperature and power consumption from electrical space heating in an office building, using stochastic differential equations [6]. This model was developed by SYSLAB. A. Thavlov showed that due to the high amount of natural ventilation in FlexHouse especially the nonlinear properties of wind, conditions should be integrated into the model, due to their influence on the indoor temperature.

This paper presents a different configuration for dynamic scalable thermal model of the heating system for a multi-zone office building which was carried out in Matlab/Simulink using Simscape toolbox. The Simscape schematic components of Simulink demonstrate physical phenomena or elements. The signal lines between these components are considered as physical connections of the real system which transmit power. Each Simscape domain uses a distinct color and line style for the connection lines and block icons. The developed models by these blocks implement a physical network approach which allows the designer to analyze the system as a physical structure and not only by mathematical equations [7].

Carbon dioxide (CO₂) proliferation in office spaces due to human respiration could cause some negative characteristics for occupants comfort e.g. feeling unwell, lack of concentration, and deterioration in efficiency. Natural ventilation is an effective method to improve indoor air quality (IAQ) and to dilute indoor CO₂ concentration in offices. Therefore, this studied model includes the single-sided natural ventilation, a type of ventilation that the air change is limited to the zone close to the opening. Demand-controlled ventilation (DCV) is a control strategy that modifies the amount of fresh air coming from outside environment delivered to a room by adjusting the position of damper actuator based on the CO₂ sensor measurement. Most

codes and standards specify some constant for required air change volume per person or per area for different places which can lead to over ventilation and increased energy consumption [8], while DCV profits the potential energy saving in heating systems by preventing excess outside low-temperature air from coming into the building spaces. Studies demonstrate that 15% to 25% of the HVAC system's energy can be saved by setting the ventilation rates based on the maximum occupancy fresh air requirement [9]. According to this concept, the investigated model that shows the thermal behavior of the system, was equipped with a DCV system as a subsystem in the Simulink environment that was named damper subsystem. The control strategies in this study aim to keep the indoor temperature and the CO₂ concentrations of the office rooms around the set point (within the scalable thresholds), despite the variation of the different parameters e.g. occupants, outside temperature pattern, heating system output power, status or size of air damper, and wind speed.

II. MODEL DESCRIPTION

A. Modeling and Simulation of the Heating System

This paper presents a model which is simulated by Matlab/Simulink version R2017a, using Simscape toolbox. The model contains six office rooms and one corridor based on the real dimensions and thermal specification of the Institute of Embedded Systems located at the University of Siegen, Germany, during a typical winter day in February. Figure 1 shows the office building sketch which the complex model was established based on this sketch with thermal dependencies among different rooms or spaces and outside environment. The model dynamics consist of various equations and coefficients that can show the heat transfer effects of different zones of the building on each other. Figure 2 demonstrates the Simulink model for one room. The Simulink model of the room thermal subsystem that includes the heat transfer elements of the model can be observed in figure 3 which was based on the MathWorks Inc. House Heating System example. The occupancy in each room was simulated as an occupancy pattern which determines the number of persons. This occupancy pattern can be taken from visiting counting sensors [10]. This pattern was modeled in a matrix by Matlab code (occupants.mat) and can be seen in the middle subplot of figure 9. The model contains a constant power electrical heater which can be simply replaced by hydronic radiators (figure 4), two sensors to get the room temperature and the CO₂ concentration output signals, and one inward opening which was connected to an actuator in each office room. This controllable opening was considered as the air damper and the actuator can control the status of the damper (open/close). The amount of ventilation is affected by outdoor wind and Buoyancy phenomena, and indoor and outdoor temperature. There were some assumptions in the model e.g. the air in all the rooms and the corridor was assumed well mixed, so the air temperatures in different locations of one room are considered equal. Also, the density of the air was assumed to be constant and is not affected by temperature variation, the temperature distribution was uniform, and there was no heat transfer between the ground and the building spaces.

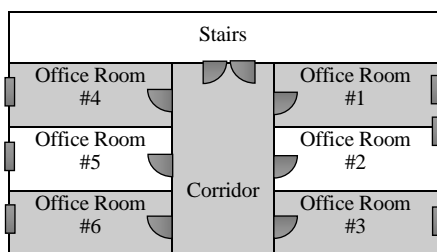


Fig. 1. Office building sketch

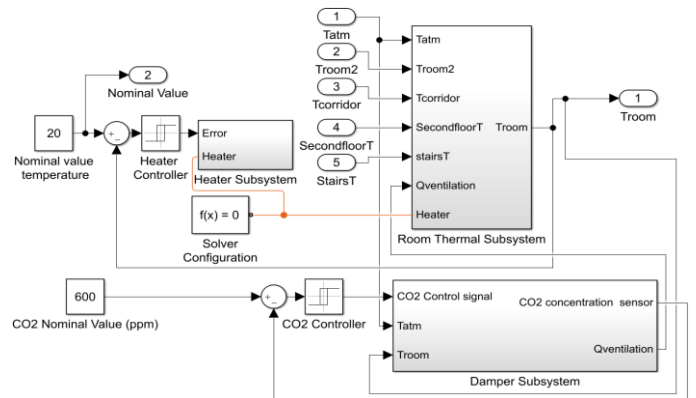


Fig. 2. Simulink model of an office room

B. Demand-Controlled Ventilation Modeling

The model of the CO₂ concentration sensor output signal was based on the calculation of CO₂ concentration is shown by the following equation and frequently can be found in different references [11]:

$$V \frac{dC(t)}{dt} = G(t) + Q(C_0(t) - C(t)) \quad (1)$$

where

- V = building or space volume in m³
- C = indoor CO₂ concentration in ppm
- C_0 = outdoor CO₂ concentration in ppm
- t = time in s
- G = indoor CO₂ generation rate in m³/s
- Q = building or space ventilation rate in m³/s.

Indoor CO₂ concentration rate is the summation of CO₂ generated by the occupants and the room CO₂ concentration. The CO₂ generation rate was considered 0.0052 L/s or 0.31 L/min based on ANSI/ASHRAE standard 62.1-2010 for an adult sedentary employee at the activity level of 1.2 met units [11, 12].

The pressure difference across the envelope causes the inward flow of outdoor air through openings into the building space. The pressure difference in this study was due to wind pressure or stack effect because of outdoor and indoor temperature difference. This model didn't include mechanical ventilation. Equation (2) was used in this study to calculate the building or space ventilation rate (Q) that was demonstrated by H. Awbi [13].

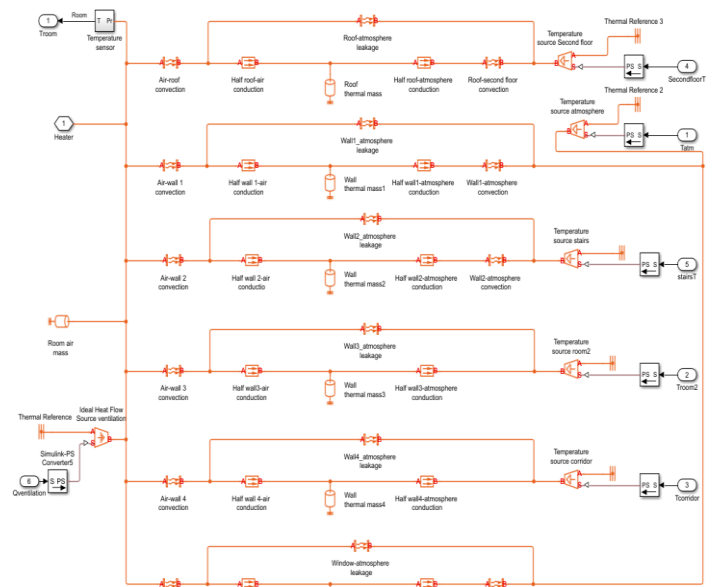


Fig. 3. Simulink model of the room thermal subsystem

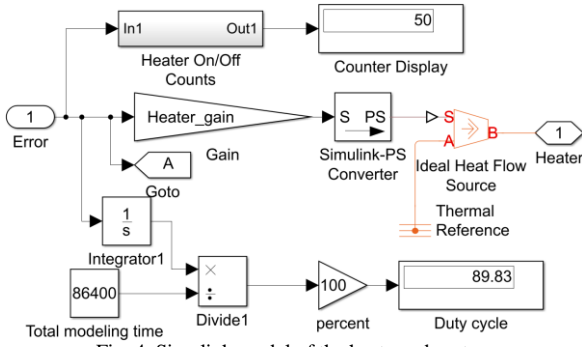


Fig. 4. Simulink model of the heater subsystem

$$Q = C_d A \sqrt{2 \Delta p / \rho} \quad (2)$$

where

C_d = discharge coefficient

A = damper area in m^2

Δp = pressure difference across the opening in Pa

ρ = fluid (air) density in kg/m^3

The discharge coefficient value of 0.6 for the sharp-edged rectangular opening is used [14].

The building ventilation rate in this paper was calculated by accumulation of flows through an opening, Buoyancy-driven flow and wind-driven flow. For Buoyancy-driven flow through a small opening, the pressure difference is calculated by the following equation:

$$\Delta p = \rho g H (\Delta T / T_i) \quad (3)$$

where

g = gravitational acceleration in m/s^2

A = damper area in m^2

Δp = pressure difference across the opening in pascal

T_i = inside temperature in Kelvin

ΔT = temperature difference across the opening in Kelvin

by substituting the equation (3) in the equation (2), the Buoyancy-driven flow is calculated by equation (4):

$$Q_{Buoyancy-driven} = C_d A \sqrt{g H (\Delta T / T_i)} \quad (4)$$

For wind-driven flow through a small opening, the pressure difference is calculated by the following equation [15]:

$$\Delta p = 0.5 \rho V_r C_p \quad (5)$$

where

V_r = reference wind speed in m/s

C_p = pressure coefficient at the opening.

The constant value of 13 km/h (3.6 m/s) was considered for the reference wind speed in this investigated model with consideration of the geographical specification of modeled office building. The Simulink model of damper subsystem and the air flow rate are demonstrated in figure 5 and 6, respectively.

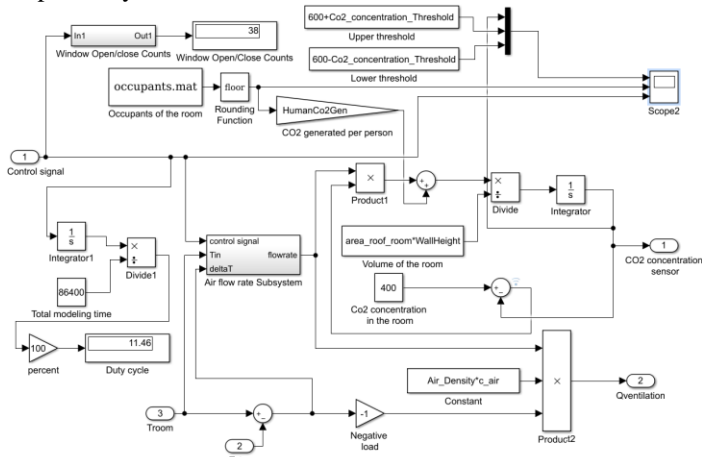


Fig. 5. Simulink model of the damper subsystem

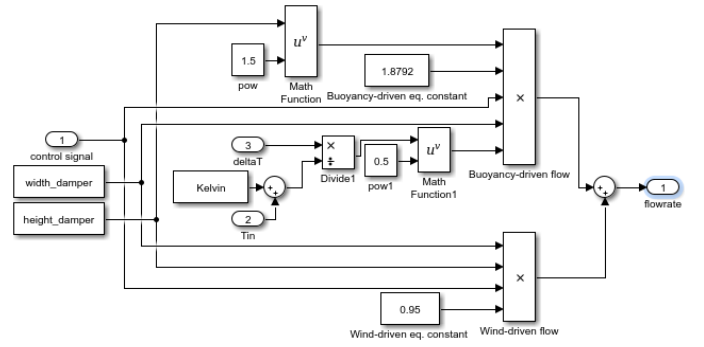


Fig. 6. Simulink model of air flow rate subsystem

Also, the model values of wind speed and wind angle for other cases can be updated in the model workspace. The dimensionless pressure coefficient C_p is an empirically derived parameter that accounts for the changes in wind-induced pressure caused by the influence of surrounding obstructions on the prevailing local wind characteristics. Its value changes according to the wind direction, the building surface orientation and the topography and roughness of the terrain in the direction of the wind. The constant value of 0.7 for pressure coefficient was considered in this investigation based on typical design data sets of experimental results that shows for a complete exposed wall at 0° angle between wind and facade [16]. By substituting the equation (5) in the equation (2), the wind-driven flow is calculated by equation (6):

$$Q_{wind-driven} = C_d A \sqrt{V_r C_p} \quad (6)$$

From the heat transfer, heat rate is defined [17] by equation (7):

$$\dot{q} = mc \frac{dT}{dt} \quad (7)$$

where

\dot{q} = heat loss in watts (W)

m = mass of air in kg

c = specific heat capacity in $kJ/kg K$

and the heat loss due to air change inside the building is calculated using the definition of heat rate by equation (8):

$$\dot{q} = \rho Q_{total} c \Delta T \quad (8)$$

where

ρ = Density of air in kg/m^3

Q_{total} = total of $Q_{Buoyancy-driven}$ and $Q_{wind-driven}$ in m^3/s .

III. VALIDATION

The simulated model needs to be evaluated to demonstrate the correctness of the system response. For this purpose, the two main sections of the heating behavior and damper response signal were investigated.

- Figure 7 shows that the steady state air temperature of the office rooms was matched to the outside environment temperature, When the adjacent stair and second floor temperature are the same as the outside temperature, the heating system and the demand controlled ventilation system are turned off, and the damper openings for all of the rooms are in closed position.
- The model was compared with another reference based on ANSI/ASHRAE standard 62-1989 to valid the modeled demand-controlled ventilation part. Figure 8 illustrates that the CO_2 concentration variation pattern based on the occupant changes was matched to the reference [18].

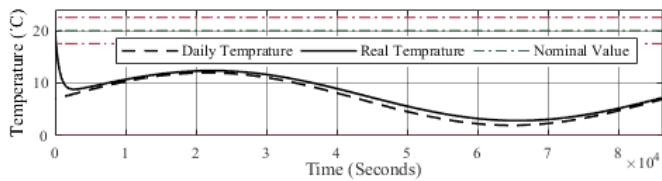


Fig. 7. Heating system validation

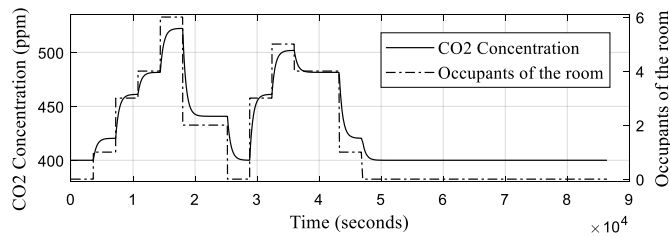


Fig. 8. Demand-controlled system validation

IV. RESULTS

The investigated model of this study shows that it can describe the system response considering input parameters which can be inserted in the model workspace. This model is a scalable model, which means that the user can configure the number of spaces on the same basis or there is the capability to change input variables, e.g. occupants or outside temperature pattern, heating system output power and settings, dimensions of spaces or their elements e.g. windows or damper size, desired amount and limits for indoor CO₂ concentration, air and building material specifications, and wind speed. This model is able to produce the output signals which are indoor temperature and CO₂ concentration variation, the duty cycle of the heater, and the frequency of on/off switching for heater and damper for each room. Also, the cost of the heating system for each zone can be calculated by putting a gain after the heater gain block in heater subsystem. Example values were considered by the author but this model is not limited to these values and can be changed for the other studies. The outdoor air temperature was modeled as a sinusoidal wave during a day or 86400 seconds (simulation stop time) where the initial temperature is 7°C (considered 6:00 a.m.) and it fluctuates between 2°C and 12°C. The value of temperature for the second floor and the adjacent stair space were considered 20°C and 13.5°C, respectively. The office room area and height were considered as 37.5 squared meter and 3 meter, respectively. Generally, outdoor environment CO₂ concentrations range between 300 ppm and 500 ppm, and indoor CO₂ concentrations in office buildings range often between 400 ppm and 900 ppm [19]. In this study, outdoor CO₂ concentration was considered to be the constant value of 400 ppm. The desired indoor CO₂ concentration was considered as the value of 600 ppm with upper and lower fluctuation thresholds that were controlled by the embedded CO₂ concentration controller. The model is able to monitor different parameters of the system by inserting a scope block, and example simulation results will come in the following text. Figure 9 and Figure 10 show that the studied model can keep the indoor temperature and the CO₂ concentrations of the office rooms around the set point (within the scalable thresholds) with consideration of a minimum heating system output power and a maximum damper opening size. Figure 9 includes three subplots that demonstrate indoor CO₂ concentration based on the occupancy in an office room and damper status. For better view, the figure was cropped for the first 52000 seconds of simulation. It can be observed that more occupants will produce more CO₂ emission as it can be perceived by steeper slopes for indoor CO₂ changes.

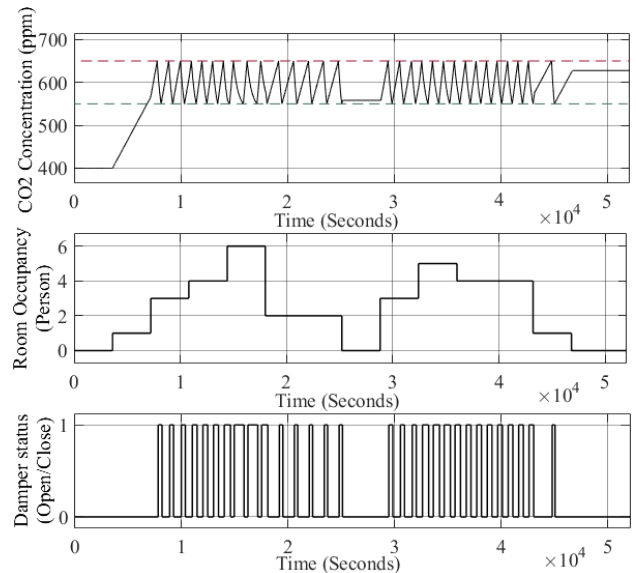


Fig. 9. Indoor CO₂ concentration based on the occupancy and damper status

Also, figure 9 shows that the open position time of the damper is more frequent in more populated times. As a result, the damper status could be remained closed in the rest and it prevents the coming of low-temperature excess air from outside the building (potential energy saving). The frequency of damper switching also depends on the size of the damper openings, meaning bigger damper size brings more air into the room, so it would be closed more quickly. These parameters can be changed in the Simulink model to find the optimized one depending on other model parameters e.g. wind speed or outside temperature pattern. The double y-axes figure 10 shows the room temperature variation of room number 1 based on outside temperature variation, heating system and damper status. Heater and damper are considered to have just two possible statuses, on: 1 or off: 0, and open: 1 or close: 0. It is evident that the room temperature variation was affected by the heat transfer among different rooms and the outside environment. When the inside temperature drops to the lower temperature thresholds, then the thermostat switches on the heating system and the inside temperature would be increased. Also, it can be observed that the environment temperature increase in middle of the day (around 18000 to 32000 seconds) can help the heating system to keep the room temperature within the desired thresholds. As a result, the heating system sometimes could be turned off in middle of the day. The other aspect is that the fresh air due to DCV system can be considered as the heating load for the heating system, which makes the temperature drop in the room.

CONCLUSION

This paper has presented the thermal dynamic modeling and simulation of a heating system for a multi-zone office building equipped with demand-controlled ventilation. The results showed that the behavior of the system can be predicted through the simulation. The investigated model empowers the user to monitor and control the real-time system performance, the duty cycle for the heating system, the frequency of heater on/off switching, damper open/close status to identify maintenance problems, fault detection, and diagnosis. The user can change various parameters and thresholds to monitor the system operation with desired values in the Matlab/Simulink model workspace and find the optimum set points. This model can be used to develop the HVAC systems in building management systems with the networks of sensors and actuators for the means of commissioning, fault detection, and diagnosis.

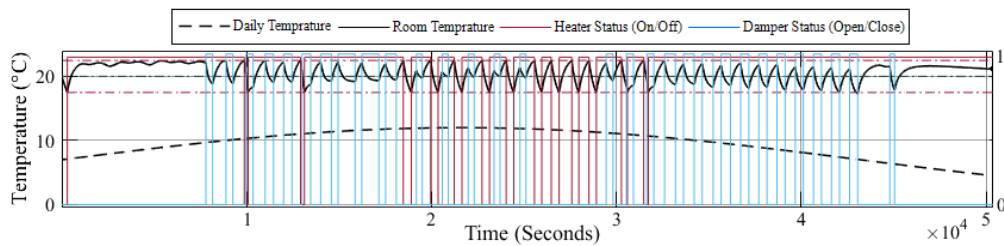


Fig. 10. The room temperature variation based on outside temperature variation, heating system and damper status

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