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Enhanced Building Thermal Model By using CO_2 Based Occupancy Data

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***Abstract*— Prevailing low energy buildings attracts lots of attention in the world. Many studies have contributed in introducing higher thermal efficiency towards rooms with low energy heating, ventilation, and air-conditioning (HVAC) systems. However, current HVAC systems do not consider CO_2 concentration change and thermal contribution towards human bodies in a room. This paper presents a novel method to predict thermal dynamics, including person count. Occupancy data are dynamically estimated by CO_2 concentration and thermal contribution from the human bodies. The model is formulated as a resistor-capacitor circuit (RC circuit) in the Modelica modeling language. All parameters in a simulation are identified using actual building data during the winter season in Japan. Results are validated using measured information of actual building environment, and the test results concluded an improvement of absolute percentage error by 0.16 % over the conventional model. From the test results, it was concluded that the moving average filter of 20 minutes was an appropriate mean time to represent the time delay value.**

Keywords—Building simulation; Thermal modeling; CO_2 concentration; Occupancy estimation; Modelica

I. INTRODUCTION

Energy transition is currently migrating from fossil fuel to renewable energy in the world. This tendency is occurring due to various reasons: to reduce greenhouse gas emissions, to lower the usage of fossil fuels, to utilize local resources. Many face various challenges from several perspectives, which include technical, economical, and political issues. However, according to a WWF report entitled "The Energy Report (2011)", we could fulfill the energy requirements from renewable energy sources by 2050 with taking account of all the technical, economical, and political issues [1]. To achieve the scenario, smart grid is one of the critical concepts for connecting distributed resources and managing these energy resources successfully. In a technical perspective, standardizations are being approved in some organizations. For instance, IEEE 2030 and 1547 define interoperability of distributed resources in its power grid [2]. IEEE 1888 describes basic XML based communication protocol between isolated Building Energy Management System (BEMS), which enables data energy management beyond different vendors [3]. All these standardizations contribute to support the growth of smart grid infrastructure.

In smart grids, buildings are considered as a significant part where a larger portion of energy is consumed during daytime hours. The building sector currently accounts about one-third of the total energy usage in our society, and most of the energy consumption is strongly related to HVAC systems and building construction [4]. In controlling the HVAC systems, most buildings apply just on/off or PID controllers for their HVAC control because of its simplicity. These simple control systems cannot observe the thermal model of the target building precisely. In order to minimize the energy consumption, advanced control technique considering occupancy information is mandatory. The purpose of this paper is to propose a simple building model considering occupancy information estimated from CO_2 concentration and to evaluate the model accuracy using actual building data obtained from Keio University, Yagami Campus.

This paper is structured as follows: Section 2 presents a strategy of occupancy estimation derives from CO_2 concentration. Then, Section 3 introduces building RC model including occupancy in a room. The experimental site used in the paper is described in Section 4. Finally, an accuracy assessment of the proposed model is discussed in Section 5.

II. OCCUPANCY ESTIMATION

In case of office and campus environments, a wide number of people in a room is dynamically influencing to a thermal environment. Therefore, when discussing thermal dynamics in a room, considering the occupancy is highly required. Although various methods of estimating the number of people in a room have been proposed, such as video-based systems, these estimation methods have problems, such as introduction cost or protection of privacy. Therefore, a CO_2 based estimation method is introduced as a solution to these problems [5].

A. Occupancy estimation in a room

In order to predict thermal dynamics of indoor environments, information regarding the number of people present in a room is required. Video surveillance systems using cameras and image analysis techniques are used for counting people in a space [6]. Even the video-based estimation provide comparatively accurate estimation results; it still has several problems in 1) cost, 2) privacy, and 3) misrecognition caused by shadow perspective. Another solution to count people is using an optical sensor at

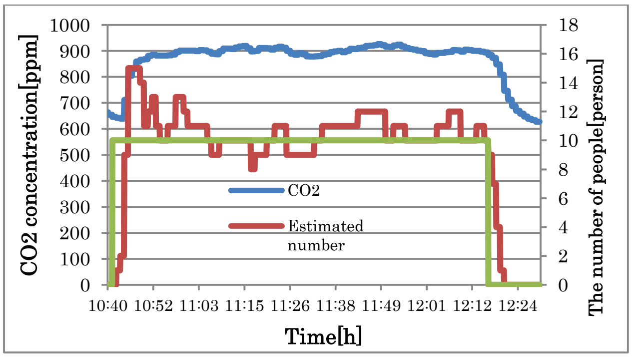

Fig. 1 Estimation of occupancy [6]

entrances. This estimation method can solve cost and privacy issues. However, it still contains a severe error of person count, especially in a long use.

In order to solve the above three issues, the following approach is employed in our laboratory [7]. CO_2 concentration inside a room can be effective information to count occupancy and human breathing is a principal CO_2 source in a closed room, such as classroom or office. To measure the number of people, the following equation was used. The equation was inherited from the Seidel's equation for seeking CO_2 concentration under constant air circulation situation [8].

$$n = \frac{Q}{k\left[1-exp\left\{-\frac{Q}{V}(i-s)\right\}\right]}\left[C_i - C_0 - (C_s - C_0)exp\left\{-\frac{Q}{V}(i-s)\right\}\right] \quad (1)$$

In this equation, C means the concentration of indoor pollutant CO_2, and variable s and i denotes a specific time, C_0 represents the indoor CO_2 concentration of initial state under no CO_2 source. An amount of ventilation and mass of a target room are Q and V respectively. CO_2 emission per person is denoted by k, and number of people in a room is denoted by n. Therefore, occupancy n can be estimated from CO_2 concentration.

The performance of the estimation method is validated in our laboratory's room by using low-cost CO_2 concentration sensor and by controlling frequency of the ventilation fan. The test result when the ventilation works is depicted in Fig. 1. In the study, a number of the people can be estimated with a few error rate from 20% to 30% of error rate. It is true that there is some considerable error in this method. However, it is worth for the use of controlling the indoor thermal environment by using the method of counting people present under preserving person's privacy and reducing the system cost.

B. Metabolic equivalent (MET)

The metabolic equivalent (MET) is a widely-used physiological concept that represent a simple procedure for expressing energy cost of physical activities as multiples of resting metabolic rate. One MET (1 kcal/kg/hour) is equated with the resting O_2 consumption of one person, a 70 kg, 40 years old man [9]. In this paper, the heating value from a human body who is seated is defined as 58.1 W, and the latent heat is ignored for simplicity.

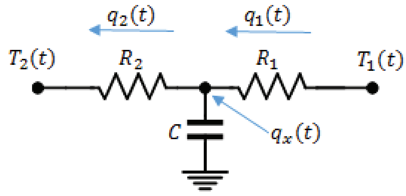

Fig. 2 Basic 2R1C model representing thermal flow

III. Building Modeling

Modeling of buildings requires insight into the thermal flow, fluid dynamics, and control engineering of HVAC. As an approach to this complex building model, a thermal model using RC network is outlined in this section. This model consists of following components:

- Rooms acting as thermal storages
- Walls and windows acting as isolators of the rooms
- Lights, solar irradiation, air conditioners and occupancy for each room as thermal energy sources
- An outdoor temperature component including climate change
- An airflow between rooms and outside.

The formal description is provided as follow.

A. RC modeling

The principal of thermal dynamics is illustrated in Fig 2. This RC model is composed of heat transmission in the resistance R_1 and R_2 respectively. $T(t)$ is the temperature at time t, C is the heat capacity, $q(t)$ is the thermal flow, and $q_x(t)$ is the thermal gain (e.g. lights, solar irradiation, air conditioner, and occupancy). Here, the whole energy transmission can be represented with the following differential equation:

$$C \cdot \frac{dT(t)}{dt} = \frac{T_1(t)-T(t)}{R_1} - \frac{T(t)-T_2(t)}{R_2} \quad (2)$$

The main building physical properties that are affecting to thermal transfer are a building envelope, an internal mass, and a thermal gain. The envelopes are external walls, roof, and windows. Because most materials store thermal energy inside them, external walls and roof are simplified as 2R1C models, respectively. Internal mass is the air mass inside rooms, which absorbs or releases heat to the air space such as a capacitance. Since the windows have negligible energy storage, they are described as simple one resistance R. Thermal gains are energy sources which directly increase the heat, such as solar irradiations through windows, human bodies, and air conditioners.

B. Modeling of rooms

A room is acting as a thermal storage isolated by a thermal resistor such as walls, ceiling, and windows from the ambient environment. The following equation describes the stored thermal energy in the room:

$$Q_{room} = C_{room} \cdot T_{in} \quad (3)$$

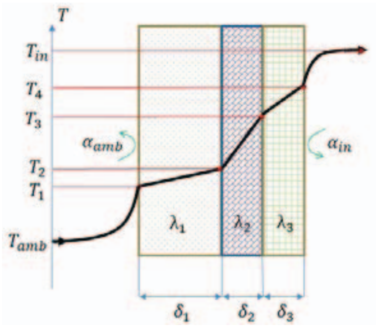

Fig. 3 Thermal transmission through a wall

$$C_{room} = \rho \cdot V \cdot cp \tag{4}$$

where T_{in} is the indoor temperature, ρ and cp are the density and thermal capacity of the air. V denotes the cubic content of the inside volume. The thermal capacity in RC modeling C_{room} is described by multiplying ρ, cp, and V.

Walls works as an isolator in-between internal and external environments. The image of thermal transition is shown by Fig.3 as one dimension heat transmission. An estimation of whole energy flow can be carried out by using the coefficient of overall heat transmission K. Then the heat transmission through walls is given by following 2R1C equation:

$$C_{wall}\frac{dT_w(t)}{dt} = K_1\big(T_{in}(t) - T_w(t)\big) - K_2\big(T_w(t) - T_{out}(t)\big) = \frac{T_{in}(t)-T_w(t)}{R_1} - \frac{T_w(t)-T_{out}(t)}{R_2} \tag{5}$$

In this equation, C_{wall} denotes the thermal capacity of the wall, K_1 and K_2 are coefficients of overall heat transmission, T_w and T_{out} are the temperatures of wall and outside, respectively. The thermal capacitance C_{wall} is computed as:

$$C_{wall} = \rho_{wall} \cdot V_{wall} \cdot cp_{wall} \tag{6}$$

where ρ_{wall}, V_{wall}, and cp_{wall} denote the density, mass and thermal capacity of the wall respectively. The coefficient of overall heat transmission K is described by:

$$\frac{1}{K} = \frac{1}{\alpha_i} + \sum_i \frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_o} = R_{wall} \tag{7}$$

where α_i, and α_o are combined heat transfer coefficient of inside and outside of the room, δi and λi are the thickness and heat conductivity of a layer i in the wall, respectively. The combined heat transfer coefficient shown by Fig. 3 considers the effect of heat convection and heat radiation toward a surface of the wall. For vertical external and internal walls, a fixed number 9 and 23 is commonly applied for approximation of these coefficients [10]. In order to simplify the wall model, we assume the wall has two layers and R_1 (or R_2) is considered as:

$$R_1 = R_2 = \frac{R_{wall}}{2} \tag{8}$$

Gaps of temperature from one point to another cause heat exchange with air infiltration. Under a constant ventilation rate, heat loss or gain can be represented by the following equation:

$$R_{inf} = \frac{1}{\rho \cdot cp \cdot q} \tag{9}$$

where R_{inf} is the thermal resistance of air infiltration, and q is the ventilation rate of the rooms.

C. Thermal gain

Main thermal sources in our building model are the human body, incoming radiation from windows, air conditioners, and lights in the rooms. A thermal model representing human body using occupancy information is described in Section 2. Here, following thermal gain are explained: solar irradiation, air conditioner, and light. The Meteorological Agency in Japan provides climate data including solar irradiation in every hour. However, it is worth noticing that the dataset provided by the Meteorological Agency have many missing values and predicting solar irradiation is preferably valid when simulating internal thermal gain of a sunbeam.

1) Solar Irradiation

The solar irradiation at the Earth's surface has three primary radiation: direct radiation, diffuse radiation and reflected radiation. Then, total heat gain from the solar irradiation can be calculated by adding all these radiation as:

$$J = J_d + J_s + J_r \tag{10}$$

where J is a global irradiance, and J_d, J_s and J_r denote direct radiation, diffuse radiation and reflected radiation, respectively.

Direct radiation J_d travels on the straight line from the sun down to the surface of the earth. These rays are blocked by clouds or objects. Hence, diffuse radiation J_s comes from many directions simultaneously (e.g. clouds and blue sky) because molecules and particles in the atmosphere scatters the sunlight. The direct radiation is around 85% of the global irradiance when the sky is clear and the sun is high in the sky. Although the amount of diffuse radiation can be changed depending on the clouds, its ratio is around 15 %. Both variables are calculated by solving Bouguer equation and Berlage equation [11] respectively. Reflected radiation J_r comes from ground or objects around the building and is relatively smaller than the other two types of radiations. It can be described by the following equation as:

$$J_{r\theta} = \left(1 - \frac{1+\cos\theta}{2}\right)\rho_G(J_{dh} + J_{sh}) \tag{11}$$

where J_{dh} and J_{sh} are direct and diffuse radiation towards horizontal surface, and ρ_G is a reflection coefficient of a surface called albedo. A variable $cos\theta$ is a geometric factor which is fixed to zero when the plane of incidence is vertical. Most dry-soil is in the albedo (ρ_G) range of 0.08 to 0.35 [12]. In addition, the difference between urban and rural albedos of some selected areas are given in [13]. In this paper, a fixed value of 0.1 is applied to ρG.

2) windows

Thermal gain through windows is one of a significant factor in the building model. Heat flow through windows composes of three ways: conduction, convection, and radiation. Because the windows have negligible energy storage, its thermal model is described as simple one resistance in this paper. Besides, windows are closed during the heating period and assumed there was no convective effect of heat by the movement of gasses or

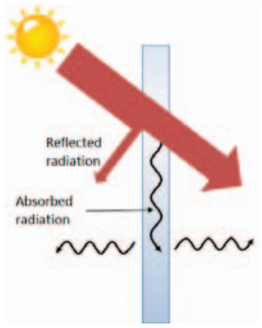

Fig. 4 Thermal flow through a window

liquids through windows. Hence, an effect of solar radiation through windows is discussed in this part.

Some of the global solar radiation (J) comes from sun or blue sky, and directly transmitted through the windows into the room. Moreover, the part of it is absorbed in the glazing or frame. The absorbed radiation is indirectly transferred to the room as long wave radiation. In addition, other is reflected by the glazing. The whole image of window model is illustrated in Fig. 4. In order to simplify the complex thermal flow, some standards (e.g. g value, SHGC, and SC) are applied for modeling actual heat gain. The actual heat gain inside the room is calculated by the following equation:

$$Q_{window} = g \cdot A \cdot J_v = G \cdot J_v \qquad (12)$$

where Q_{window} is a thermal gain from windows, g is expressed as a dimensionless parameter from 0 to 1, A is the total size of windows in each room, J_v is the global solar irradiation into a vertical plane, and G is a product of g and A. The detailed effect of g value and SHGC is studied by numerical and experimental analysis [14]. The thickness of the glass is assumed as 3 mm and 0.85 is applied for the g value.

3) Air conditioner and lights

The heating system in the experimental building maintains a certain temperature of a room by using gas-engine-driven heat pump (GHP). GHP improves overall energy efficiency by conducting the fuel conversion process that the exhaust heat can be productively reused [15].

Since some complex factors are required to be considered for estimating the thermal gain from GHP, the amount of thermal gain is simplified in this paper to a fixed thermal gain Q_{heat}. If the indoor temperature is over T_{set}, or the indoor equipment are turned off, the thermal gain from GHP immediately stops.

Another energy source is the lights on the ceiling in each room. Thermal gain from lighting can be split into convective and radiative components according to the ASRAE [16]. Both components eventually contribute to thermal gain inside the room. Henceforth, electric consumption of lights are approximated as an energy source in this study. A light is assembled with two parts: lighting part and stabilizing part. The total thermal gain of each light is fixed at 45 W.

D. *Sol-air temperature (SAT)*

Under conditions of solar radiative flux and infrared exchanges from the sky, a heat transfer from external walls into rooms needs to be considered as well. In order to enable the

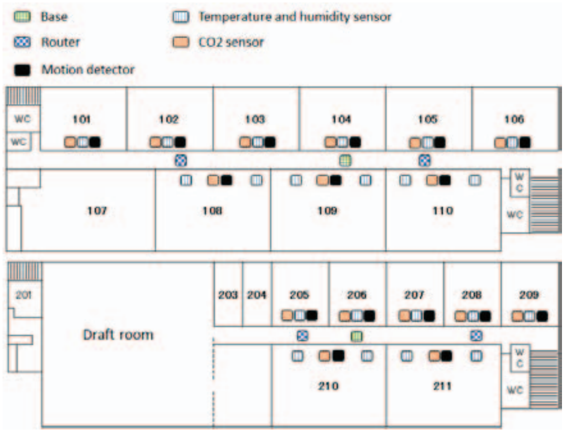

Fig. 5 Maps of the experimental environment of 12th building

concept, sol-air temperature (SAT) is introduced for calculating the amount of heat transferred per unit area [17]. It is given by the following formula:

$$T_{SAT} = T_o + \frac{1}{\alpha_o}(\alpha_s J - E) \qquad (14)$$

where T_{SAT} is the equivalent heat including atmospheric conditions, T_0 is the outdoor air temperature, α_o is the combined heat transfer coefficient including effects caused by radiation and convection, α_s is the surface solar absorptivity of external walls and E is the effective radiation, which is the difference between the longwave radiation emitted and received by the surface.

IV. Environment Configuration

The presented thermal modeling of section 3 is applied to the BEMS of 12th classroom building, Yagami Campus, Keio University in Yokohama. Environmental information (e.g. a dynamics of temperature, humidity, illuminance, and CO_2 concentration) and the state of heating system were monitored there in January 2015.

A. *Building description*

As Fig. 5 depicts, the building in this study consists of two floors. The building is divided in to 10 rooms and a corridor in both floors. All the rooms were used for lectures during daytime from 9:00 to 18:00. Here, six rooms in first floor (room 101 to 106) are focused. The volume is 229.3 m^3 (12.3 × 8.6 × 3.13 m), and ventilation rate is 79.5 m^3/h according to an investigation of gas tracer method using CO_2 [18]. Each space contains wooden desks, chairs, lights, and indoor equipment for air conditioning. The building is air-conditioned with GHP on the rooftop, and the indoor equipment works on a 27.3 degree Celsius energy source in rooms. The indoor equipment stops when the indoor temperature is over 23 degrees Celsius.

The primary material of the whole building is assumed as heavy weight concrete, and walls are composed of two layers of homogeneous materials. The thermal conductivity of concrete and glass are 1.4 W/m·K, and 1.0 W/m·K, the specific heat and specific gravity of concrete is 0.88 J/g·K and 230 kg/m^3 respectively. The ratio of window to wall in the building is approximately 20 %. There are 36 lights in each room. The soil temperature under 1 m of the building is constantly 11.5 degree

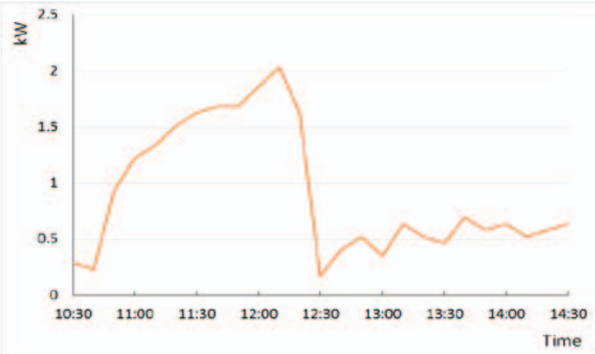

Fig. 6 Measured occupancy data in room 101

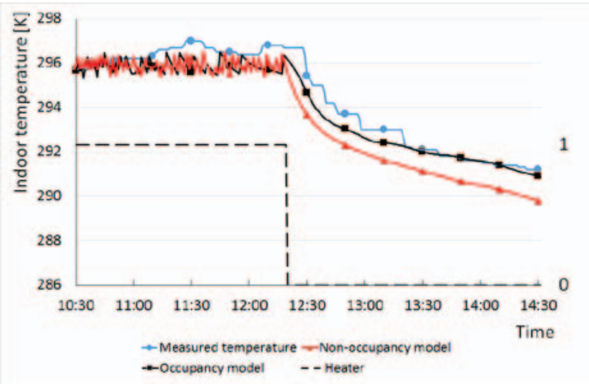

Fig. 7 Measured temperature and simulation result

Celsius throughout the day, which is an average number of Yokohama on January, and thermal conductance of soil is 0.6 W/m·K [19].

For simplifying the modeling process, following simplified assumptions were made. 1) The residential rooms are air-conditioned and heat exchange can be neglected. 2) The air inside rooms are exchanged only between that of corridor. 3) The door and windows in each room were closed and the amount of air infiltration is constant.

B. Sensor network and data collection

A wireless sensor network is constructed in the building, and a site survey is conducted in order to build the building simulation. For the experiment, generic SW-3230-1000 CO_2 sensor models were used. According to the floor map illustrated in Fig. 5, some environmental information were monitored in the building (e.g. indoor temperature, humidity, illuminance, motion detector, and CO_2 concentration, gas use of GHP, and electricity consumption of the building). All the sensor information were stored in a local server at our laboratory through terminal KNIVES. The KNVIES is an Internet based demand and supply control system by using distributed and cooperative power control algorithm which is deployed in an armadillo based embedded server. The detailed properties of KNIVES are described in [20]. The main server was deployed in a machine with an Intel Core i7 3.2GHz CPU, 95 GB RAM, 1TB hard disk, running CentOS 6.5 64-bit operating system.

According to Fig.5, all the sensor information regarding temperature, humidity, illuminance, motion detector, and CO_2 concentration level, are send to KNIVES through coordinators.

TABLE 1 THERMAL PROPERTIES OF SIMULATION

Description	Resistance	Capacitance	$G (= g \cdot A)$
External wall	2.73×10^{-2}	2.91×10^{5}	
Wall between corridor and indoor	8.35×10^{-3}	1.44×10^{6}	
Ground	1.88×10^{-2}	6.42×10^{6}	
Window	6.05×10^{-3}		2.27×10
Air Infiltration	8.45×10^{-3}		

Then, KNVIES transfers the information to a local server through the Internet. The sensor module is SII sensor and its sampling period is 60 seconds [7]. The average error range of temperature and CO_2 concentration module are 0.5 K and 10 % respectively. Flow sensor is placed on the rooftop, and the electric sensor was installed outside of the building.

V. Simulation and Assessment

The parameter values used in the simulation are summarized in Table 1, and occupancy dataset is illustrated in Fig. 6. Fig. 6 illustrates the calculated thermal gain from human body at room 101 which is measured using the occupancy estimation explained in section 2. The sky was clear all day, and the solar irradiation (J_v) through windows into the rooms can be calculated by using the equation (10). SAT is calculated by using both the equation (14) and the effective radiation data provided from the Meteorological Agency in Japan. In this paper, we used off-line data, in order to validate the correctness of proposed method using a simulation. However, the system can be applied in real-time environment without making any changes. The simulation results are compared with non-occupancy model because most thermal models are based on the RC network which ignores occupancy effect or just apply constant numbers replicating the number of people present in a room [21].

The simulation was constructed using the simulation software, Dymola [22]. Dymola allows the modeling of the multi-engineering domain, which means that models consist of components from various specific domains (e.g. electrical, mechanical, control, thermal, air-conditioning, etc.). The modeling language is Modelica [22], and Modelica Building library from Berkeley lab is used as open-source Modelica library [23].

Performance of the proposed thermal model with occupancy data collected from 10:30 to 14:30 are evaluated in Fig. 7. The measured temperature is the actual thermal dynamics in room 101. In this environment, the occupancy model and the non-occupancy model are simulated with and without the occupancy information respectively. The break line denotes working schedule of the air-conditioning equipment inside the room which shows working and stopping as 1 and 0 respectively. The indoor temperature maintained around 296 Kelvin degree, because the air-conditioning equipment was working till 12:20. After the GHP stopped, the indoor temperature slowly declined through thermal exchange between ambient environments. The occupancy model and the non-occupancy model agreed with the measured temperature with an average error of 0.5 and 1.0 Kelvin degree respectively. The occupancy model can provide

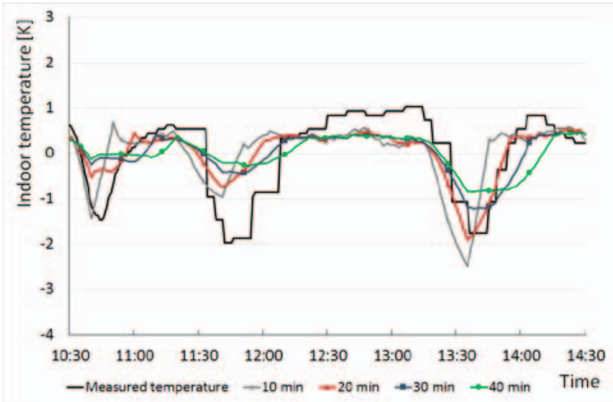

Fig. 8 Measured temperature and filtered result

thermal performance prediction of good accuracy than non-occupancy model.

Since an actual thermal dynamics have appropriate time delay, the simulation result contains high-frequency components. Therefore, a low-pass filter is applied for the simulation results in order to represent the actual environment. Fig. 8 illustrates the measured temperature at room 103, where the period of selected moving-average levels were 10, 20, 30, and 40 minutes. In the graph, average temperature values were sorted as zero in each data-set in order to focus on the effects of leveling. According to Fig. 8, mean average absolute error is minimized when the moving-average value is applied as 20 minutes. In other rooms, similar results were observed. Therefore, we can conclude that the moving average value of 20 minutes is better to improve the accuracy in case of the campus building from a stand point of minimizing the mean absolute value.

VI. Conclusion

In energy area, buildings are considered as a major portion because they consume a large amount of energy. Therefore, more effective control method of HVAC system is required for such higher energy consumption areas. In order to minimize the energy consumption, advanced control technique considering occupancy information is mandatory. This paper estimated the number of people present in a room using CO_2 based occupancy data, and has proposed a simple thermal model considering thermal gain from the human body. The proposed thermal model is evaluated using actual building data in Japan. Besides, building parameters at the simulation is estimated according to the actual environment. The results show that the thermal model with occupancy information can provide a prediction of thermal dynamics with twice the accuracy compared with the conventional model. Furthermore, the mean absolute percentage error is improved by 0.16 % by the proposed novel method. Moreover, a moving average filter is applied in representing the delay of thermal dynamics, and the appropriate meantime was about 20 minutes in the proposed campus building.

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