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Dynamic Thermal Model of a Lighting System and its Thermal Influence within a Low Energy Building

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Abstract

This paper focuses on the heat gain of a lighting system, one of the most-used appliances in buildings, and its thermal effect within a low energy building. In this study, a dynamic thermal model of a lighting system is first established based on the first principle of thermodynamics. Then, thermal parameters of this model are estimated by experiments and an optimization process. Afterward, the obtained model of the system is validated by comparing simulation results to experimental one. Finally it is integrated into a low energy building model in order to quantify its thermal influence within a low energy building. As a result, heat flux of the lighting system, indoor temperature and heating energy demands of the building are obtained and compared with the results obtained by the conventional model of a lighting system. This paper helps to understand thermal dynamics of a lighting system and to further apply lighting systems for energy management of low energy buildings.

Key Words : Low Energy Building, Heat gain, Lighting System, Thermal Model, Parameter Identification, Building Energy Simulation

1. Introduction

Because it improves the quality of human life, energy consumption has continuously increased and global concerns about climatic change and resource depletion have been highlighted over the past few decades. The primary energy is used in four main areas, including buildings, industry, transport, and others. The building sector accounts for 30-40% of the primary energy consumption in most countries. Buildings are not only the largest energy consumers but they also in turn emit huge amounts of CO2. Hence, energy efficiency in buildings must be improved in order to resolve the above-mentioned problems [1-2].

To achieve a low energy building, thermal insulation and thermal inertia levels become higher. This leads to a reduction of unwanted heat losses in winter and prevention of overheating in summer. Hence, internal heat gains obtained by solar

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irradiation, metabolism, lighting systems, and electrical appliances/equipment remain longer in low energy buildings than in conventional buildings, allowing them to play roles as effective heat sources in low energy buildings and to influence more thermal behavior of the buildings [3].

Since thermal behavior of a building is closely related to its heating and cooling energy demands according to the occupants′ thermal preferences, it is important to model it so as to calculate the energy demand of the building and attain a certain level of thermal comfort for the occupants. Therefore, the factors interacting with building thermal dynamics, which are geological and meteorological characteristics, building structure and materials, occupant activity, load profiles of lighting systems, and electrical appliances and equipment, have been modeled and applied to building energy simulation tools and HVAC control systems [4-8]. Among internal heat gains of buildings, the heat dissipations of electrical appliances and lighting systems were relatively small as compared to the heat gain of heating systems and to heat loss by structures. Therefore, these heat gains were statically modeled by power density or the usage profile of the sources. However, as they become more significant heat sources within low energy buildings, greater model detail is required.

In this context, this paper focuses on the thermal gain due to lighting systems within a low energy building. A dynamic thermal model of a lighting system is first established based on the first principle of thermodynamics and of which parameters are identified by the interior reflective Newton method. Afterward, the obtained model is validated by comparing simulation results to experimental one. Finally, it is integrated into a low energy building model in order to quantify its thermal influence within a low energy building. The influence of the dynamic model on the thermal behavior of the building is also compared with the influence of a static model.

2. Thermal Model of a Lighting System

2.1 Physical Model

A thermal model of a lighting system within a building zone is deduced from the first principle of thermodynamics:

$$\Delta U_{ls} = \delta Q_{ls} + \delta W_{ls} \tag{1}$$

$$\begin{aligned} C_{ls}\frac{dT_{ls}(t)}{dt} &= P_{ls}(t) - \Phi_{ls}(t) \\ &= P_{ls}(t) - \frac{1}{R_{ls}}(T_{ls}(t) - T_i(t)) \end{aligned} \tag{2}$$

$$\Delta U_i = \delta Q_i + \delta W_i \tag{3}$$

$$\begin{aligned} C_i\frac{dT_i(t)}{dt} &= \Phi_{ls}(t) - \Phi_i(t) \\ &= \frac{1}{R_{ls}}(T_{ls}(t) - T_i(t)) - \frac{1}{R_i}(T_i(t) - T_e(t)) \end{aligned} \tag{4}$$

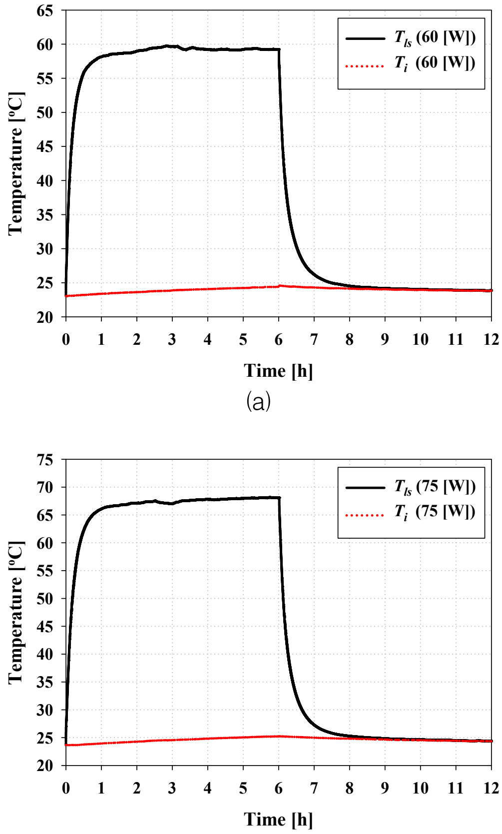
where, U is the energy J, Q is the quantity of heat J, W is the work of system J. The indices ls and i are, respectively, the lighting system and the building internal zone. C is the global thermal capacitance J/℃ (the product of mass and specific heat). Tls is the lighting system temperature ℃, Ti is the building zone air temperature ℃, and Te is the exterior temperature ℃ of the zone. Pls is the supplied power to the lighting system W (heat flux of the lighting system), Φls is the heat flux W consequence of the temperature difference Tls and Ti, and Φi is the heat flux W consequence of the temperature difference Ti and Te.

2.2 Parameter Identification

Thermal parameters of the presented model can be identified using experiments and numerical parameter identification methods. In this study, the input and output of the system were measured and an optimization process based on the interior reflective Newton method [9] was used in order to estimate the model parameters.

The used building zone is a small-scale laboratory that is well-insulated with the dimensions 4 x 2.4 x 2.4m^3. The wall of the room is made of polyurethane and stainless steel sheeting. It has one door (length: 0.9m, height: 1.9m) of the same material as the wall and a small window (length: 0.3m, height: 0.5m). A lighting system is installed within the room. 60W and 75W bulbs were prepared to investigate the heat gain of the lighting system. The electric power consumed by the lighting system is entirely converted to heat flux by heat transfer.

The room is also equipped with a temperature acquisition device and K-type thermocouples to measure the lighting system temperature, the indoor air temperature, the indoor surface temperature, the outdoor surface temperature and the outdoor ambient temperature. These data were measured each 1s and were stored in a computer. For each experience with 60 and 75W bulbs, the measurements were respectively carried out over a period of twelve hours. During the first period (six hours), the bulbs were turned on and they generated 60 and 75W for each time. Sequentially, they were turned off during the next six hours. The experimental results are shown in Fig. 1. The temperature of the lighting system Tls and the temperature of average indoor air Ti are figured. Fig. 1 (a) shows the results obtained when a 60W bulb is used for the lighting system while Fig. 1 (b) illustrates the case of 75W consumption of the bulb.



(a)

(b)

Fig. 1. Measured temperature Tls and Ti

At each case during the first periods, Tls increases for transient-state after which it reaches steady-state. In this state there is no longer effect of a thermal capacitance from the lighting system but only heat transfer between the lighting system and the building zone. Consequently, Ti increases during the first period due to the heat flux generated by the lighting system. After turning off the lighting system, Tls and Ti decrease and become spatially and temporally uniform through thermal equilibrium.

From this thermal behavior of the lighting system, the thermal parameters of the model can be estimated. Both transient-state and steady-state during the first period were used for the parameter identification. The parameters are determined via the interior reflective Newton method and listed in

Table 1. Based on the obtained parameters, Tls is simulated and is compared to the measured one as shown in Fig. 2.

Table 1. Estimated thermal parameters

	Rap ℃/W	Cap J/℃	τap s
60W	0.578	1081	626
75W	0.565	1267	716

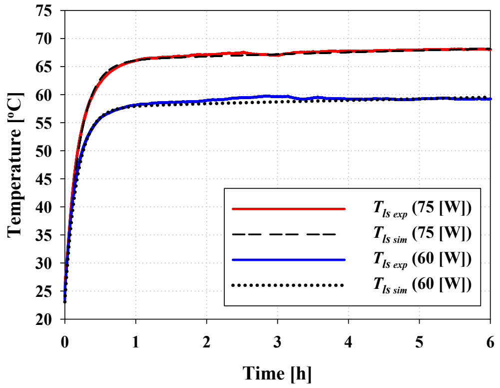


Fig. 2. Comparison of measured data and simulated data

To validate the model and its parameters, the mean of the sum of square errors (MSE) are calculated as follows:

$$MSE = \frac{1}{N}\sum_{k=1}^{N}[T_{ls_{\exp}}(k) - T_{ls_{sim}}(k)]^2 \quad (5)$$

where N is the number of samples, Tls exp is the measured data and Tls sim is the simulation result. The obtained values of MSE for each system of 60 and 75W are, respectively, 0.005 and 0.004 ℃ and the model is thus validated within the accepted ranges.

The thermal time constant τap (product of Rls and Cls) that determines the dynamics of the model is differently defined despite the fact that the lighting system used is the same for two cases and only the bulbs used differ. The ratio is 0.87 and the difference is about 90s. This could be driven by differently varied Te and unpredicted noise during the measurements.

3. Thermal Influence of the Lighting System

3.1 Description of Building Simulation

The obtained model of a lighting system is then integrated into a low energy building model in order to investigate the thermal influence of the lighting system in detail using the proposed dynamic model. There are two main reasons to adopt a dynamic model such as this instead of a static model, which only takes into account the power consumption profile or the power density of the system. First, heat gains within a low energy building affect more the thermal behavior of the building since its thermal insulation is reinforced. Second, a more accurate thermal analysis of building energy simulations is demanded and the time interval of the simulation therefore is shortened. Consequently, a more sophisticated model is required. The building model used is designed as a low energy building with lower U-values of less than 0.10W/(m^2 · K). The building energy simulations were conducted on the SIMBAD (SIMulator of Building And Devices) toolbox, which works within Matlab/Simulink® platform [10].

3.2 Simulation Results

Thermal behaviors of the building considering the usage of a lighting system were studied during a winter period under severe weather conditions simulation. A lighting system turned on from 06:30-9:00 and 17:00-23:30 while the building is occupied, and a heating system operated according to its pre-defined usage profile are as listed in Table 2.

Table 2. Setting profile of the heater

Mode	Temperature ℃	Usage Time
Comfort	18-20	05:00-08:30 11:30-13:30 17:00-23:00
Sleep	16-18	23:00-05:00
Eco	10	08:30-11:30 13:30-17:00

The lighting system integrated in the living room of the building is modeled by a dynamic model (DM, Pls=150W, τls=660s, DM) and a static model (SM, Pls=150W). The thermal gains of the lighting system obtained by the dynamic model and the static model are illustrated in Fig. 3. Since the dynamic model has its own thermal characteristics, the heat gains of the two models are differently presented. While the SM of the lighting system dissipates the heat gain instantly, the heat gain of the DM is charged in the system and discharged to the building after the light system is turned on and off, respectively. Consequently, the thermal influences of the two models of the lighting system are different based on the thermal behavior of the building.

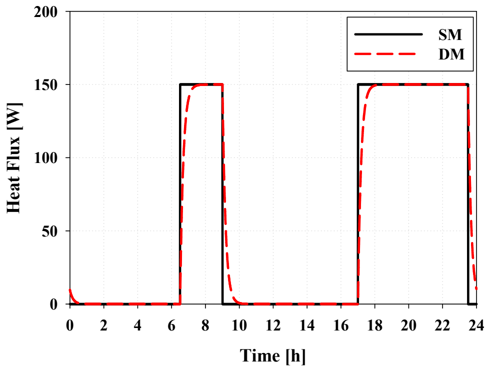


Fig. 3. Comparison of heat gains of a dynamic model and a static model

As a factor describing the thermal behavior of the building, the indoor temperatures of the living room were observed. The temperature related to the usage of the lighting system modeled using a dynamic model was calculated and was compared with two other cases: with a static model of a lighting system and without any lighting system, respectively. The results are shown in Fig. 4.

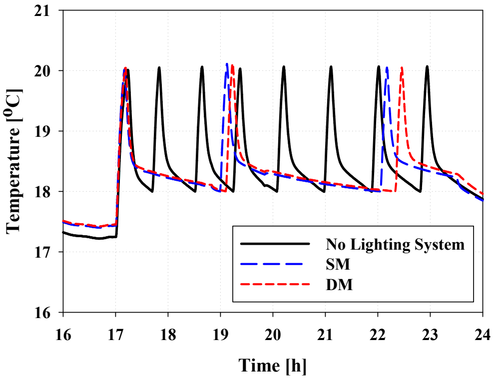


Fig. 4. Comparison of indoor temperature

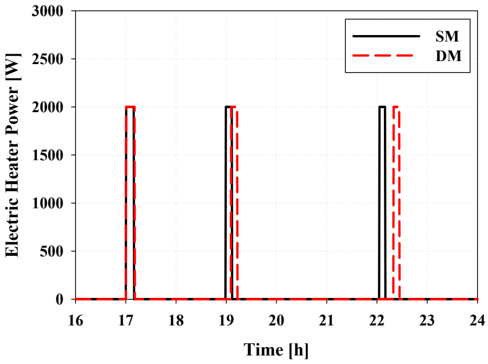


Fig. 5. Comparison of electric heater profiles

When there is no lighting system, indoor temperature is frequently regulated to the setting reference thanks to the function of the heater. However, for cases of SM and DM, temperature increase and decrease are rare due to the dissipated heat of the lighting system. This compensates for the heating energy demand of the heater. Moreover, since the thermal characteristics and the heat dissipation of each model are defined differently, temperature variations are not also super-positioned between the cases of SM and DM. Thermal delay on both heat gain and temperature are observed. The corresponding electric heater power profiles are also presented in Fig. 5.

As stated above, the thermal delay of the heat gain leads the different thermal behavior of the building, so that the heaters function at different times. For example, at 17h the heaters of the two cases turn on at the same moment. However, the heater having the thermal influence of DM turned off 2min after that of SM turned off. It prompts another thermal delay in the chain. Finally, it causes different heating energy demands (Eheat) in the building for a time. In this study, the heating energy demands of the living room during the winter are calculated as follows: Eheat_DM=13.11kWh/m^2/period and Eheat_SM=13.08kWh/m^2/period. The difference of the heating energy demand could be accumulated and significant while the numerical calculation is accomplished for an annual analysis.

As a result, the presented dynamic thermal model of a lighting system can be applied to any other type of lighting systems and be used for more accurate building energy simulation. However, this study does not take into account ventilated lighting systems. Further study that takes into consideration of the ventilating procedure will confirm that the heat gain of lighting systems and its thermal influence within a building is reduced. For a more energetically efficient and thermally comfortable building, investigation of the global management of the lighting systems and their linked ventilation systems in summer and winter will be of interest.

4. Conclusion

This paper aims to study the heat gain of a lighting system, which is the most used in buildings, and its thermal effect within a low energy building. To this purpose, a dynamic thermal model of a lighting system was first established based on the first principle of thermodynamics. Second, thermal parameters of the proposed model were estimated by experiment and an optimization process. The obtained model and the parameters of the system were then validated comparing simulation results to experimental one. Sequentially, the presented model was integrated into a low energy building model in order to quantify its thermal influence within the building. Thermal gains of the lighting system, thermal behavior of the living room, and its heating energy demand were obtained and presented. This contributes to the understanding of the thermal dynamics of lighting system and to further apply lighting systems for the energy management of low energy buildings.

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Biography

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