BUIILDING THERMAL MODELING BASED ON ENERGY CONSUMPTION AND AMBIENT TEMPERATURE

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ABSTRACT

Nowadays, building's power consumption represents the most important portion of the global consumption (about 60% - 70%). Building's energy management is more and more required in order to ensure better energy management and human comfort in buildings. This requires thermal models that are accurate enough. The aim of this paper was to make a thermal model to describe the form of temperature variation within buildings. This would then be used to gain information about the buildings physical properties. It consists on combining physical models and experimental measurements in order to have adapted model. This modeling process will be applied to the Smart building Platform in International Research Institute MICA in Vietnam in order to illustrate the proposed modeling process.

PROBLEM STATEMENT

The energy issue is one of the major challenges of the 21st century. Building related energy consumption accounts for a large part of the total energy bill. Researchers are therefore developing continuous performance monitoring, automatic diagnoses and home energy management systems to improve building consumption. Nevertheless, all these upcoming applications require reduced order models of the building envelop that can be tuned online.

Many models have been proposed in scientific literature to represent the thermal behavior of the buildings. Linear regressive models such as ARX (Auto Regressive model with exogenous inputs) have been compared with time scaled identification methods [1] and ARMA (Auto Regressive Moving Average) models for fault detection purposes [2]. The structures of these models are very general and take into account neither the actual physical relations between variables, nor the existing links between parameters. These kinds of models may be used in real-time for a given context, using no other information than input-output data, considering the system as a black box. Using black box approaches is not relevant for GMBA-BEMS purpose.

A physical analogy of thermic with electric circuits has been widely used in literature [3,4]. Most of these building models are based on a heat balance equation. By means of this equation, building thermal parameters such as thermal resistance and thermal capacitance plus indoor/outdoor and adjacent zones temperatures, metabolic heat of occupancies and electric appliances can be adapted to the electric circuit components such as resistor, capacitor, voltage and current source. These models may be used to estimate the internal temperature and the heating/cooling energy demand of buildings [5].

The work in [3] proved that a second order RC network with 3 resistors and 2 capacitors (3R2C) is sufficient to capture the fine conductive dynamic interaction between two spaces connected through a single wall for simulation purpose. [5] suggested a 1R1C lumped parameter circuit which presents a building thermal model using thermal-electric analogy. In order to avoid opinions about model structures and to get tangible conclusions dependent of model usage, a modeling process is going to be defined.

The paper focuses on models for Global Model Based Anticipative - Building Energy Management System (GMBA-BEMS) such as GHomeTech [6] but results can be extended to any usage that requires parameter estimation procedure for physical models by contrast with black box model not directly related to physics.

STUDIED THERMAL ZONE DESCIPTIONS

Advantages and difficulties related to the modeling process in this paper will be detailed through a defined use case of a Smart Platform (SP). SP is located on the 9th floor of building B1 of Hanoi University of Science and Technology (HUST). This thermal zone is surrounded by 6 other adjacent thermal zones: visitor room, store, radio frequency (RF) platform, corridor, outside, speech communication department (SC department – high zone) and direction room (down zone) (see Fig.1).

This platform is highly instrumented and all energy flows are measured using different sensor technologies. The SP is equipped with two DAIKIN air conditioners model FTXD71FVM/RXD71BVMA to maintain comfort temperature inside.

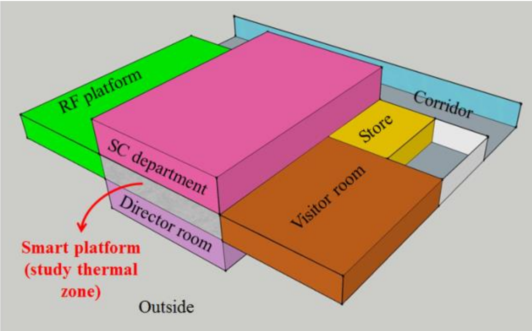

Fig. 1. Location of SP inside the building B1 of HUST

BUILDING ENVELOPE MODELING

Because our aim is to configure a GMBA- BEMS whose sampling time is 1 hour, dynamics lower than one hour would not appear. Before finding a model is suitable for a given goal, the quality of a model has to be defined:

- a good model has to explain relations between observed phenomena according to expected precision i.e. estimation error has to be small enough, especially during the validation process
- for BEMS, a good model has links with physics in order to be able extrapolate behaviors like modification of the ventilation
- the parameters of a good model has to be identifiable

A methodology to make reduced order physically explicit models is proposed in this section. It relies different steps. First step consists in calculating parameters with bounds from physics and to propose a relevant model structure according to the expected usage (GMBA-BEMS). The second step relies on a nonlinear optimization algorithm that both minimizes the error between estimations and measurements but also keeps parameters close to the values calculated using physics in order to avoid weird values.

There exists a well-known duality between heat transfer and electrical phenomena. Any heat flow can be described as a "current", and the passing of this heat flow through a thermal "resistance" leads to a temperature difference equivalent to a "voltage". Thermal resistances are enough for describing steady-state behavior, but dynamic behavior is important, and this requires thermal "capacitances" as well. Thermal capacitances imply that even if the power flow changes instantaneously, there is a delay before the temperature changes and reaches steady state. The thermal resistances and capacitances together lead to exponential rise and fall times characterized by thermal RC time constants similar to the electrical RC constants. The equivalent electric model represented in Fig. 3 has been selected.

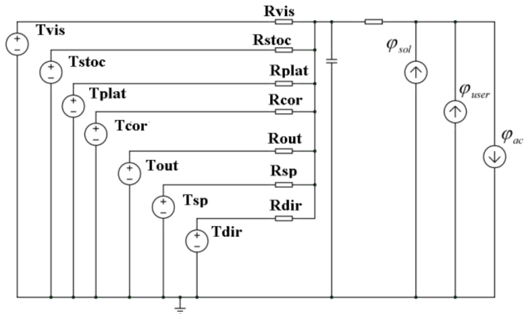

Fig. 3. Electric equivalent model for Smart Platform

Reduced order physically explicit model is given by the following formulas (1).

$$\begin{cases} \dfrac{\partial T_w}{\partial t} = A.T_w(t) + B.u(t) \\ T_{in}(t) = C.T_w(t) + D.u(t) \end{cases} \tag{1}$$

$$A = \frac{-1}{C_w}\left(\frac{1}{R_{vis}} + \frac{1}{R_{stoc}} + \frac{1}{R_{plat}} + \frac{1}{R_{cor}} + \frac{1}{R_{out}} + \frac{1}{R_{sc}} + \frac{1}{R_{dir}}\right)$$

$$B = \frac{1}{C_w}\begin{bmatrix} \frac{1}{R_{vis}} & \frac{1}{R_{stoc}} & \frac{1}{R_{plat}} & \frac{1}{R_{cor}} & \frac{1}{R_{out}} & \frac{1}{R_{sc}} & \frac{1}{R_{dir}} & 1 & 1 & -1 \end{bmatrix}$$

$$C = 1$$

$$D = R_w[0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1 \quad 1 \quad -1]$$

$$u(t) = \begin{bmatrix} T_{vis} & T_{stoc} & T_{plat} & T_{cor} & T_{out} & T_{sc} & T_{dir} & \varphi_{sol} & \varphi_{elec} & \varphi_{ac} \end{bmatrix}^T$$

Analytical calculation of parameters

In order to calculate parameter values based on physics, 6 interfaces have been defined, each interface is decomposed of parts. Thermal conduction, convection and radiation have been taken into account for each layer of a part within an interface but thermal bridges have been neglected. They can be calculated by the formulas (2).

$$\begin{aligned} R &= \frac{e}{\lambda.S} \\ C &= \rho.e.S.C_p \end{aligned} \tag{2}$$

Dimensions and physical characteristics of materials of each interface between the SP and the adjacent thermal zone as followings:

- The SP/corridor interface (35.12 m2): masonry wall part (25.84 m2), windows and doors part with glass layer and aluminum frames (9.28 m2).
- The SP/outdoor interface (35.12 m2): masonry wall part (15.12 m2), windows and doors part with glass layer and aluminum frames (20 m2).
- The SP/RF platform interface (37.04 m2), the SP/store interface (15.36 m2) and the SP/visitor interface (21.24 m2): masonry wall part.

- The SP/SC department interface (81 m2) and SP/director room interface (81 m2): floor part with concrete layer, air layer and plastic layer.

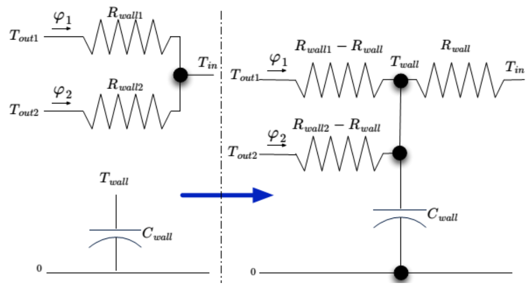

Fig. 2. Model transformation used to adapt calculated parameter values

Nevertheless, calculated parameters cannot be directly used in the selected model. The transformation illustrated in Fig.2 has been used to obtain model parameters. This transformation relies on the idea that heat fluxes have to remain identical if T_{in} and T_{out} are identical. Consequently, the resistor R_w has to be determined. Assuming symmetricity, we used:

$$R_w = \frac{1}{\frac{2}{R_{cor}} + \frac{2}{R_{plat}} + \frac{2}{R_{vis}} + \frac{2}{R_{stoc}} + \frac{2}{R_{out}} + \frac{2}{R_{sc}} + \frac{2}{R_{dir}}}$$

$$C_w = C_{cor} + C_{plat} + C_{vis} + C_{stoc} + C_{out} + C_{sc} + C_{dir}$$

Because of the uncertainties about the materials and some dimensions, instead of searching average values, surrounding values have also been searched taking into account the minimum and maximum possible values for dimensions and physical characteristics of materials as in Table 1.

Table 1. Model transformation used to adapt calculated parameter values

Parameters	*calculated*	*min*	*max*
R_{cor}	1.06 10-3	0.53 10-3	1.59 10-3
R_{plat}	0.0056	0.0012	0.0084
R_{stoc}	0.0097	0.0019	0.01455
R_{vis}	0.0134	0.067	0.0201
R_{out}	3.74 10-4	1.87 10-4	5.62 10-4
R_{sc}	4.77 10-4	2.385 10-4	7.16 10-4
R_{dir}	4.77 10-4	2.385 10-4	7.16 10-4
R_w	1.22 10-4	0.62 10-4	1.83 10-4
C_w	4.12 107	2.06 107	6.18 107

As stated previously a key contribution to the model of temperature variation involves the inclusion of various heat sources from within the compartment. One such source, likely to be important is that of the buildings heating/cooling system. The simplest model relating the power input of the heating system to that of the generation of heat within a compartment will be that of a time dependent source generating heat uniformly across the compartment. It should be noted that this model neglects factors like air movement or position of the source. The primary aim of this model is to act as a first order approximation of the effect of a source delivering power on the temperature. Generation of heat by the source may be described according to (4). The theoretical COP for an air conditioning system is expressed by Carnot's theorem, reduced to the following equation (5).

$$\frac{\partial \varphi_{ac}}{\partial t} = COP.P(t) \tag{4}$$

$$COP = \frac{T_C(t)}{T_H(t) - T_C(t)} \tag{5}$$

Parameters estimations using nonlinear optimization

By using a 16 days dataset from 19 Aug 2015 to 3 Sept 2015, an interior point optimization algorithm has then been used that both minimizes the error between estimations and measurements. The optimization criterion has been used is given in equation (6)

$$J = \sqrt{\sum_k (T_{\text{int}}^{calcul} - T_{\text{int}}^{measured})^2} \tag{6}$$

Thanks to this objective, the optimization will modify a parameter value only if it reduces the optimization error. The optimization process led to estimated parameters as in Table 2.

Table 2. Model transformation used to adapt calculated parameter values

Parameters	*initial value*	*estimated value*
R_{cor}	*1.06 10-3*	**1.2 10-3**
R_{plat}	*0.0056*	**0.0016**
R_{stoc}	*0.0097*	**0.0020**
R_{vis}	*0.0134*	**0.01339**
R_{out}	*3.74 10-4*	**3.7 10-4**
R_{sc}	*4.77 10-4*	**7.16 10-4**
R_{dir}	*4.77 10-4*	**2.5804 10-4**
R_w	*1.22 10-4*	**1.83 10-4**
C_w	*4.12 107*	**4.1237 107**

VALIDATION RESULTS

Thanks to the identified parameters, the inside temperature of the SP for the 2 other days (22-23 Aug 2015) can be estimated as shown in figure Fig.3 (blue curve), we can see that the temperature curve calculated from obtained model ($T_{in}^{calculated}$) correspond very well with the temperature measured curve ($T_{in}^{measured}$).

The figure Fig.4 shows the average absolute error between the calculated temperature and the temperature measured is about 0.12°C. The largest error, about

0.48°C, caused by the impacts of users' behaviors during daytime.

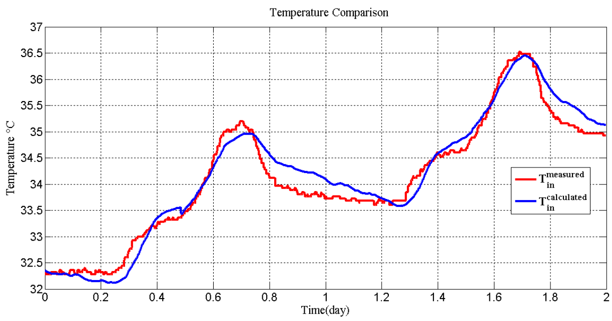

Fig. 3. Measured and calculated temperature for T_{in}

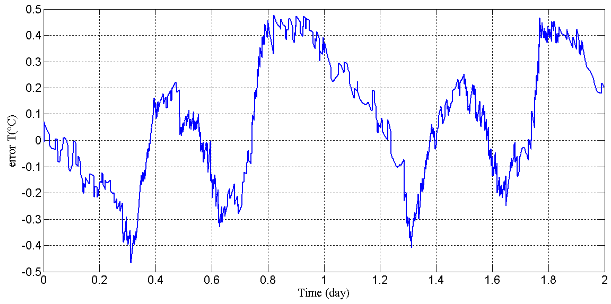

Fig. 4. The error between calculated temperature and measured temperature of inside temperature of SP.

CONCLUSIONS

This paper proposes a methodology to make a reduced order physically explicit model. It relies different steps. First step consists in calculating parameters with bounds from physics and to proposed a relevant model structure according to the expected usage for GMBA-BEMS. The second step relies on a nonlinear optimization algorithm that both minimizes the error between estimations and measurements but also keeps parameters close to the values calculated using physics. Physically explicit parameter values have been found but it turns out that it is still difficult to identify some parameters. Some methodologies have to be developed in order to taking into account the impacts of users' behavior and impacts of solar radiation to the studied thermal zone.

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NOMENCLATURE

T_w : average temperature of the SP walls [K/W]
T_{vis} : average temperatures of visitor room [K/W]
T_{stoc} : average temperatures of store [K/W]
T_{plat} : average temperatures of RF platform [K/W]
T_{cor} : average temperatures of corridor [K/W]
T_{out} : average temperatures of outside [K/W]
T_{sc} : average temperatures of speech communication department [K/W]
T_{dir} : average temperatures of direction room [K/W]
C_w : equivalent thermal capacitance of the walls[J/K]
φ_{ac} : heating/cooling power provided by the AC [W]
φ_{sol} : power provided by the solar radiation [W]
φ_{user} : power provided by the user behavior [W]
e : thickness of material [m]
S : surface of material [m^2]
λ : thermal conductivity [W/m.K]
ρ : volumetric mass density [kg/m^3]
C_p : specific heat [J/kg.K]
COP : coefficient of performance of air conditioning
$P(t)$: the electric power consumption [W]
$T_C(t)$: cold temperature, for space cooling, the cold temperature is inside the space [K]
$T_H(t)$: the hot temperature [K]

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