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Optimal Regulation Criteria for Building Heating System by Using Lumped Dynamic Models

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Abstract

Energy efficiency of buildings has gained an important role with respect to possible energy saving policy measures, mainly for space heating demand which represents the dominant energy end-use. The present contribution addresses the problem of estimating building heating energy consumptions by using numerical models able to simulate the dynamic interaction between the building and the heating system. A dynamic numerical code in the Engineering Equation Solver (EES) is developed to simulate both building and heating system and the influence of heating system regulation criteria on different parameters (mainly energy saving and internal comfort) is investigated in an optimization perspective.

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Keywords: building, energy consumption, heating/cooling system, numerical simulations

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1. Introduction

European building sector is responsible of about 40% of the total energy consumption representing the largest sector in all end-users area in Europe [1]. The growing trend in heating and cooling energy demand causes a relevant issue on the adequate development of energy systems and energy policies [2].

Using new existing technologies allows significant energy savings compared to current practice for new buildings in all climatic zones. Moreover, the energy consumption depends more on how the various energy-using devices (pumps, motors, fans, heaters, chillers, etc.) are put together as a system, rather than on the efficiencies of the individual devices.

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Nomenclature

Roman letters

A	Area [m^2]
C	Thermal capacitance heat capacity [J K^{-1}]
c_p	Water specific heat [J kg^{-1} K^{-1}]
h	heat transfer coefficient [W m^{-2} K^{-1}]
Q	Heat flux [W]
R	Thermal resistance [K W^{-1}]
T	Temperature [K]

Greek letters

α	Parameter of mixing valve
β	Parameter of thermostatic valve
τ	time [s,h]

Subscripts

A	ambient
e	external
HS	heating system
i	internal
M	flow water
P	wall
W	water

In this context, software able to predict the heating and cooling energy demand are useful to find the best solution to increase energy efficiency. Following this aim, several numerical models were developed over the years to simulate the energy performances of buildings. Generally, steady state approaches [3,4] are commonly used to estimate the building consumption in the preliminary stage of the design or for scenario analyses. On the other hand, new technologies based on the building thermal inertia (e.g. free cooling [5], phase change materials [6]) can be modeled only by transient thermal models. Moreover, transient simulations are fundamental role to propose optimal energy saving solutions, especially in the short time regulation criteria which assume an important role in the global energy performance of energy integrated systems [7].

For these purposes, several approaches have been developed and tested in the last years, which are now implemented in the most famous dynamic tools, e.g. TRNSYS, EnergyPlus, etc. (an overview of their capabilities is reported in [8]). However today, there is a massive availability of mathematical packages, which allow creating, with a relative low strength, in-house custom tools for evaluating the energy demand of building without excessive computational costs. Recently, a simplified numerical model for building, called BEPS and implemented in Matlab/Simulink, was developed and validated in different dynamic conditions [9,10]. The validation showed that BEPS was able to predict the heating and cooling energy demand accurately for the tested configurations in all climatic conditions, guaranteeing a very high degree of flexibility and customization for the analysis of specific problems.

In this context, the present paper describes a simplified method for building modeling which permits to obtain detailed information about the building energy consumptions and the heating/cooling system operation in dynamic conditions. The model is implemented in the Engineering Equation Solver (EES) environment and it is based on the lumped capacitance approach coupled with a thermal network. Both building and heating/cooling systems are modeled, permitting a high level of customization in terms of the main components design. Several simulations have been performed in order to observe the model behavior whit different types of building thermal inertia and different thermostatic valve regulation criteria.

2. Methodology

In order to perform a general analysis the building is modeled considering a unique isothermal volume (Figure 1a) which exchanges heat with the internal wall layer and it receives heat by heating elements and by internal free gain by source (person, equipment, and lighting). All the geometric data concerning the considered building are reports in Table 1.

Table 1. Main data of the benchmark building

Internal volume	13889	m^3
Wall mass	$4.582 \cdot 10^3$	ton
Wall specific heat (heavy configuration)	879	kJ/m^2-K
Wall specific heat (light configuration)	610	kJ/m^2-K
Wall transmittance	1.9	W/m^2-K
Wall external total surface	6290	m^2
Wall internal total surface	5661	m^2
External convective heat transfer coefficient	0.023	kW/m^2-K
Internal convective heat transfer coefficient	0.015	kW/m^2-K
Internal total wall mass	131.7	ton
Internal total wall surface	2124	m^2
Heater element total mass	17.9	ton
Heater element specific heat	0.8	kJ/kg-K
Heater element total surface	327	m^2
Nominal boiler outlet temperature	80	°C
Boiler efficiency	0.94	

The transient energy balance equation for the internal node can be written as in Eq. 1, where Q_{HS} and $Q_{A,P}$ represent the heating input thermal power and the heat losses through the external wall P respectively. Also the heat stored in the internal walls ($Q_{A,I}$) and the internal heat sources (Q_{source}) are considered.

$$(MC)_A \cdot \frac{dT_A}{d\tau} = Q_{HS} - Q_{A,I} - Q_{A,P} + Q_{source} \tag{1}$$

All the external walls are modelled as a unique node temperature with the related thermal capacitance. Two different layers are considered: the internal layer, which exchanges heat with the internal mass of air, and the external one, which is subjected to the combined effect of external air convection and solar irradiation (Figure 1b). The transient energy balance equations for opaque external walls can be written as follows:

$$(MC)_P \cdot \frac{dT_P}{d\tau} = \dot{Q}_{P,i} - \dot{Q}_{P,e} \tag{2}$$

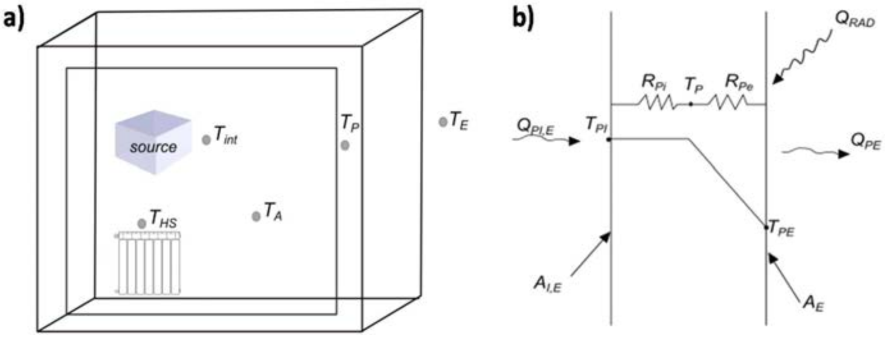

Figure 1: a) Schema of the internal volume modelling. b) Schema of the wall modelling.

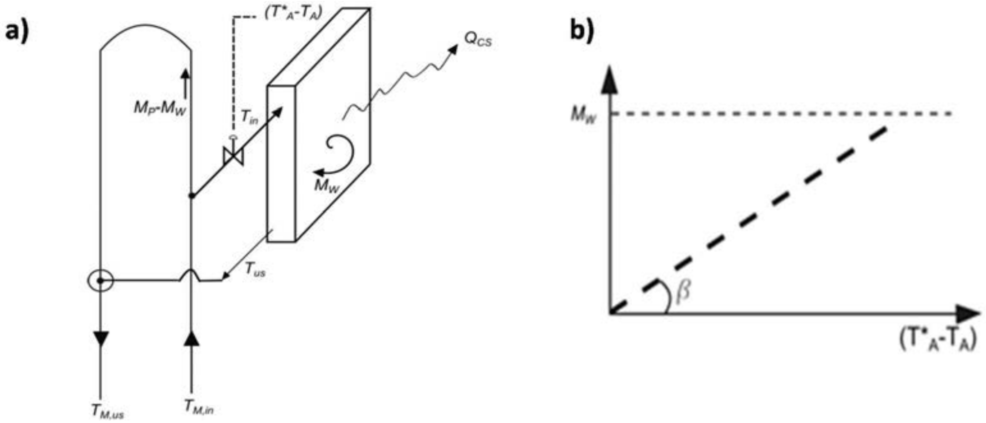

Figure 2: a) Model of the heater body. b) Variation of the mass flow rate against parameter β due to the action of the thermostatic valve.

where the internal and external heat flow rate can be expressed using a steady state energy balance approach on the respective internal and external node temperatures. As for instance, the energy balance equations for the external wall node temperature can be expressed using the following equations:

$$Q_{P,e} = A_e \frac{T_P - T_{P,e}}{R_{P,e}} \tag{3}$$

$$Q_{P,e} + Q_{RAD} - Q_{PE} = 0 \tag{4}$$

The heater bodies are modelled considering a single unit element and with a thermal capacitance defined as the sum of all elements in the building (Figure 2a). According to this assumption, an energy balance equation can be written as follows:

$$(MC)_{HS} \cdot \frac{dT_{HS}}{d\tau} = Q_W - Q_{HS} \tag{5}$$

A thermostatic mixing valve is installed in the heater element with the aim to vary the mass flow rate flowing in the element according to measured internal air temperature (Eq. 6). The dynamic response of the thermostatic valve is determined by varying the parameter β in the calculation of δT_A, according to Eq. 7. The variation of the mass flow rate as function of β is shown qualitatively in Figure 2b.

$$\dot{M}_W = \max\left[0; \dot{M}_{W,rif} \cdot \frac{1}{\sqrt{(1+\delta T_A)}}\right] \tag{6}$$

$$\delta T_A = \max\left[\frac{1}{\Delta M^2_{\max}} - 1; \beta(T_A - T^*_A)\right] \tag{7}$$

The heating system considered in the present work is an instantaneous response boiler with an ON/OFF regulation criteria. The water temperature at the exit of the heating unit TC is considered to be constant and equal to 80°C. The main components considered in the system model are show in Figure 3a. The control system is performed by a mixing valve based on the external temperature, with a setting curve shown qualitatively in Figure 3b, defining the flow temperature T^*_M required by the system as function of the temperature difference between a reference temperature (20°C) and the external temperature.

$$T^*_M = Min\left(T_C; \overline{T_A} + \alpha \cdot (\overline{T_A} - \overline{T_E})\right) \tag{7}$$

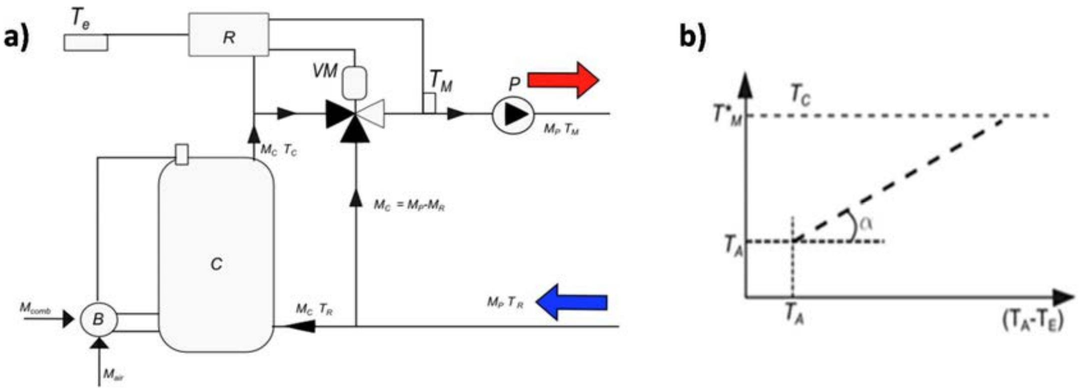

Figure 3: a) Schema of the heating system and b) mixing valve characteristic profile.

3. Preliminary results

Several analyses have been conducted in order to test the behaviour of the numerical model using a standard building block as benchmark building. In order to highlight the dynamic effects related to the building envelope inertia, two different types of the wall structure are considered: heavy and light configuration. The two configurations differ by the thermal capacitance and the superficial mass of vertical walls and roof, as reported in Table 1.

To perform detailed simulations about energy building energy performance, several climatic data are necessary. In the present work, hourly profiles of external temperature and solar radiation related to January 2013 recorded by the meteorological station located at the Department of Civil, Chemical and Environmental Engineering (DICCA) of the University of Genoa (44° 24' N; 8° 58'E; Altitude 40 m) [11] are used. The station can measure several climatic parameters (such as air temperature, solar radiation, pressure, humidity, rain height etc.) which are recorded in a database with time intervals of 30 minutes.

Figure 4 reports the temperature profiles obtained for the two wall configurations. Generally, higher thermal capacity tends to reduce the energy consumption of a building, if the building needs a constant and continuous heating [9], as in this benchmark building. As it is possible to note, a greater inertia of the building envelope has the effect to reduce the peaks in the internal temperature profile T_A (Figure 4a) and, consequently, in the heating system operating conditions reflected mainly by temperatures T_{HS}.

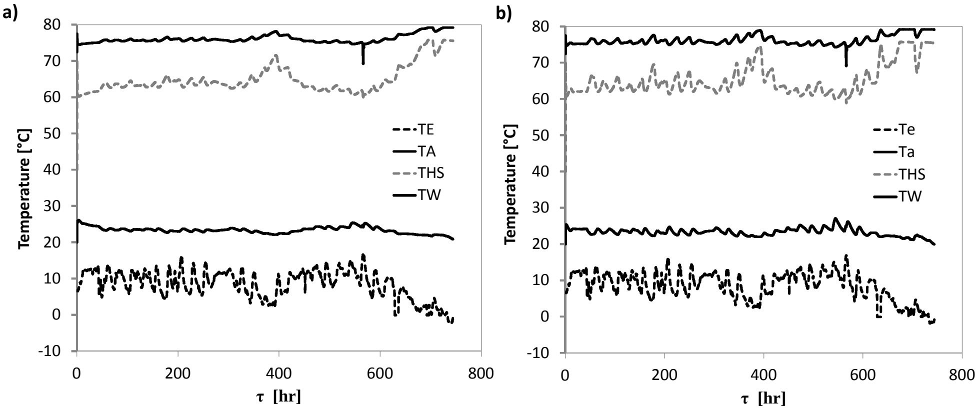

Figure 4: Temperature profiles obtained for the a) heavy wall and b) light wall configurations. Parameter: α=10, β=2.

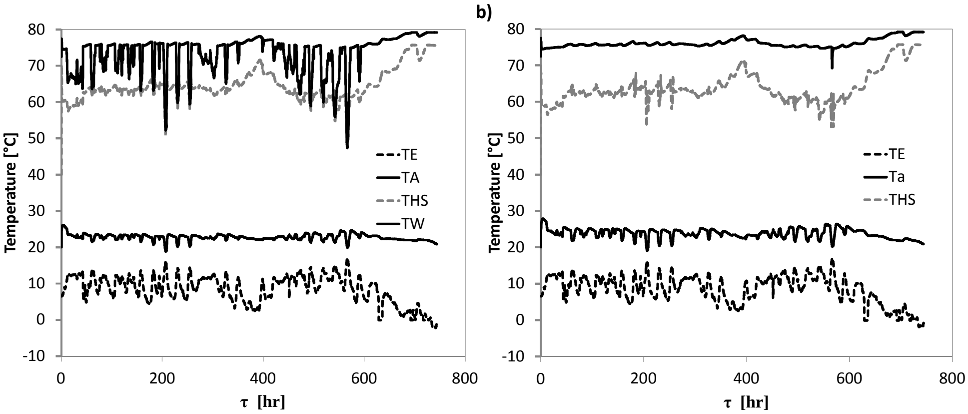

Figure 5: Temperature profiles obtained for the heavy wall configuration using a) α=5, β=2; b) α=10, β=30

In order to investigate the effect the regulation criteria provided by the mixing valve and thermostatic valve, a parametric analysis is conducted by varying the parameter α and β for the heavy wall configuration. Figure 5a reports the results obtained by varying the parameter α: as it was expected, a strong effects occurs on the output boiler temperature profile which shows greater peaks due to the strong variation of the mixing valve operating conditions. Moreover, also the internal air temperature profile is affected by these peaks, as it is possible to observe comparing Figure 4a with Figure 5a. Finally, Figure 5b shows the temperature profiles obtained by increasing the parameter β. As it is possible to note, a greater value of this parameter affects the heating element temperature profile and, consequently, the internal air temperature profile.

4. Conclusions

A simplified method for modeling the building and the heating system is described. Several simulations have been performed in order to observe the model behavior with different types of building thermal inertia and different thermostatic and mixing valves regulation criteria. The results show that a strong variation in terms of output boiler and internal air temperature profiles occurs if the mixing valve characteristic is changed. On the other hand, varying the characteristic of the thermostatic valve affects mainly the internal air temperature. Further analyses are on work in order to analyze the impact of the regulation criteria in terms of heating energy demand.

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