

## Bond Graph Modeling and Control of A Single-Zone Building in a Semi-Arid Region for Thermal Comfort

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### ABSTRACT

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To analyze the thermal behavior of our studied local; a model of the bond graph of a single-zone construction taking into account influences of the outside/inside climate has been developed and validated. Using a thermoelectric analogy, the thermal model is thus represented by a second-order RC network. Data from experimental input-output measurement sequences collected at the laboratory ENERGARID of the University of Bechar in southwest Algeria are used to identify and validate model parameters. This allowed us to obtain a good behavioral model of our site. For the well-being of occupants and with greater energy efficiency, the internal climate management was dedicated to the use of a PID controller. Its parameters are optimized by the Newton Raphson algorithm so we have achieved satisfactory results illustrated by simulation.

#### Keywords:

Building; Energetic efficiency;  
Thermal Comfort; Bond Graph;  
Modelization; experimental  
Measurement; optimization;  
Simulation; PID

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## 1. Introduction

Efforts to reduce energy consumption in the residential building sector become technological and environmental concern justifying advanced scientific research [1]. These lead to use of models to describe the thermal behavior and evaluate the energy consumption of buildings [2]. The evolution of the internal temperature in a building is one of the most influential framers on the dynamics of the building [3].

This evolution of the temperature comes from the thermal interaction between the indoor climate and the outside, either through conduction (walls) or convection (air) [4].

These models are usually grouped into three categories: black box, white box and gray box models. Comparison among the three models show that the gray box models are the most effective for managing energy consumption of buildings [5]. These models combine the physical sense and

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spirit of simple models; also they are very suitable for the modeling of elementary heat transfer problems.

Gray box models are based on the analog circuit model of semi-physical laws as the equivalent electrical circuit (RC). The most popular modeling framework is using resistors and capacitors to model this interaction. Order RC array model with 2 resistances and 1 capacitor is sufficient to capture the conductive dynamic interaction between two spaces connected by a single wall [6]. So it is possible to model the conductive interaction in a multi-local building using RC networks as simple as building blocks. The resulting model of the building consists of an electrical network of resistors and capacitors.

In this sense, many researchers have studied the question of global modeling of building energy via the use of energy conservation laws, thermo-electric analogy, neural networks, etc. and via many simulation methods: Trnsys, Simulink, bond graph (BG), etc.

The Bond Graph approach (makes part of gray box models) is little used in the modeling of thermal systems; this approach makes it possible to describe energy exchanges in a physical system [7]. Energy is represented by a force and a flux whose product is homogeneous to a power. The particularity of the graph bonds is due to the fact that this theory is based on the representation of energy transfer phenomena within the system [8]. So we can say that the BG model seems quite appropriate to represent the thermal behavior of the building.

The balance between occupant thermal comfort and energy efficiency is the main goal of temperature control strategies in heating and cooling systems in buildings [9]. There is a multitude of control tools ranging from classical PID to intelligent methods such as fuzzy logic and genetic algorithms.

So our objective in this work is to look for processes to improve thermal comfort and reduce consumption through a mathematical modeling (BG model) of a building where we find that most researchers have developed the BG models via the energy conservation law; but in our case study we will develop it via thermoelectric analogy (2R1C), and controlled by an optimized PID.

The organization of this paper is as follows: In section 2, we find a description of the experimental studied site followed by a collected data base of outside climate and indoor microclimate of the local building. Section 3, intended to define the BG methodology and explain its usefulness followed by the RC model and BG model of the local. In Section 6 an approach for designing the control system using PID-based feedback system. Section 7, the simulation results for a temperature control system is discussed. Conclusions are discussed in Section 8.

## **2. Mono-zone Building Model**

### **2.1 Presentation of Case Study**

The considered building is a research laboratory "ENERGARID" at the University Tahri Mohamed Bechar (Algeria) with 210 m<sup>2</sup>; see Figure 1.

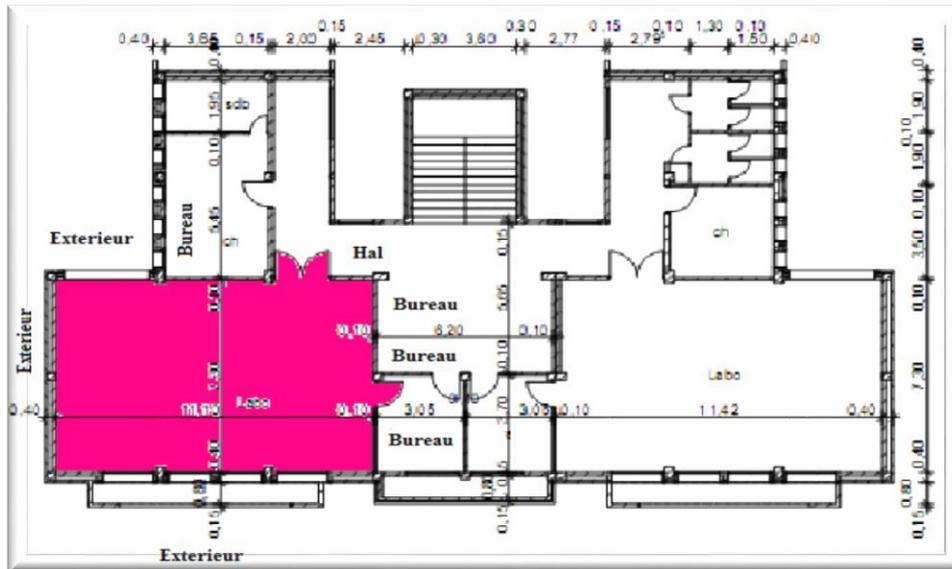


Fig. 1. Localization of local laboratory building

## 2.2 Acquisition of Measured Meteorological Data

The parameters identification of the thermal balance by means of measurements performed by a very accurate data logger and sensors for temperature ( $PT100 \pm 0.1^\circ C$ ), for horizontal global radiation (Pyranometer  $\pm 5 \text{ Wm}^{-2}$ ) and a commercial building climate control computer. The experiment was carried out in the month Mars 2018. Measurements from this experiment are used in the modeling procedure ( $T_o$ ,  $T_i$ ,  $Q_s$ ,  $W_s$ ) as shown in Figure 2-5. The following variables were measured at a sample time of 10min.

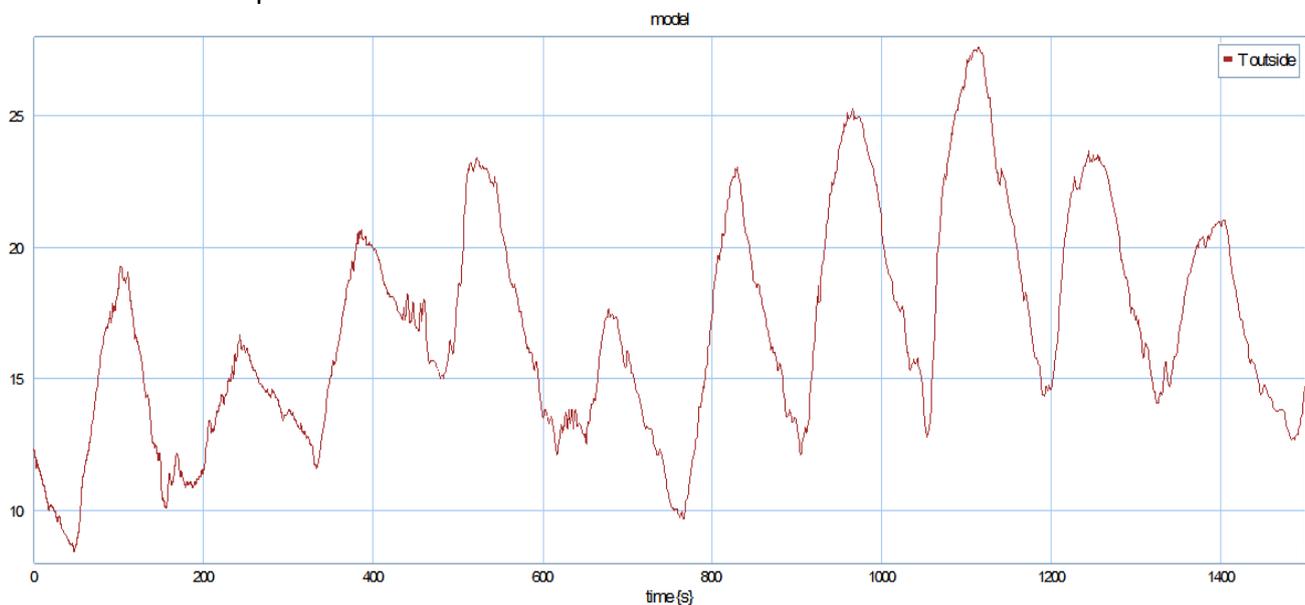
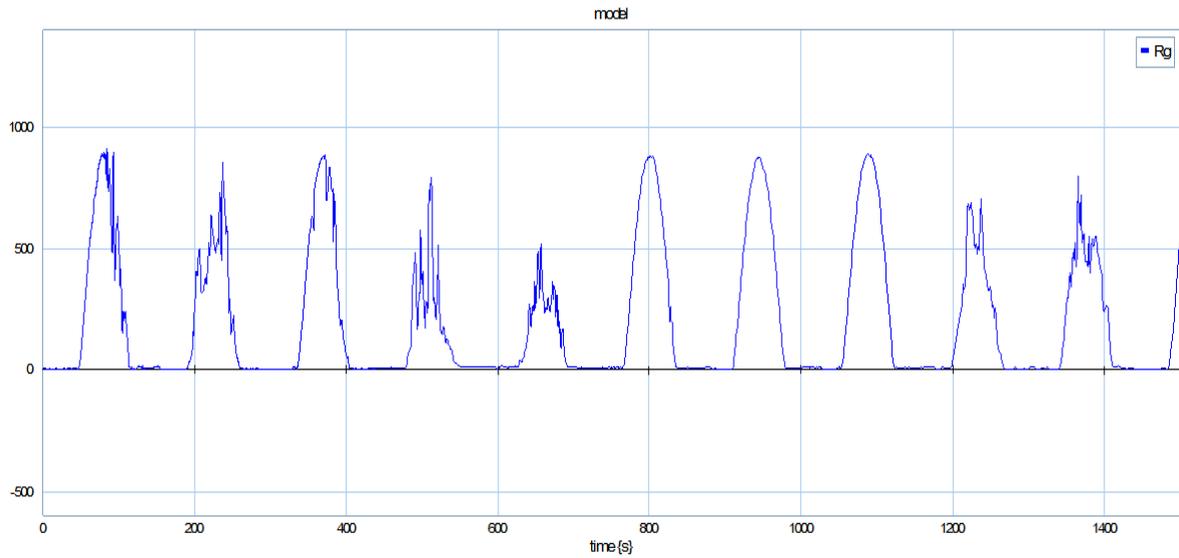
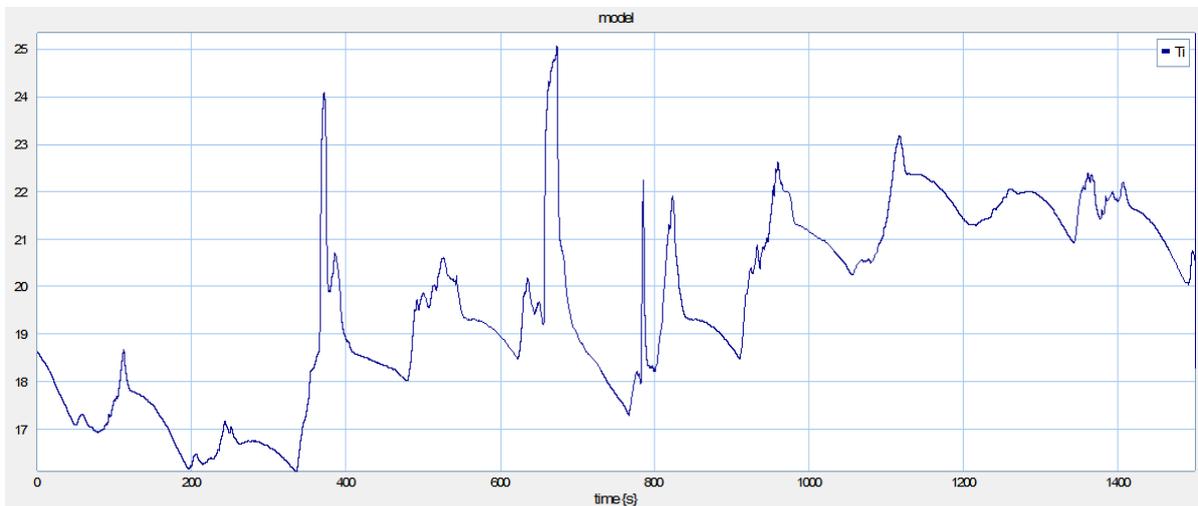


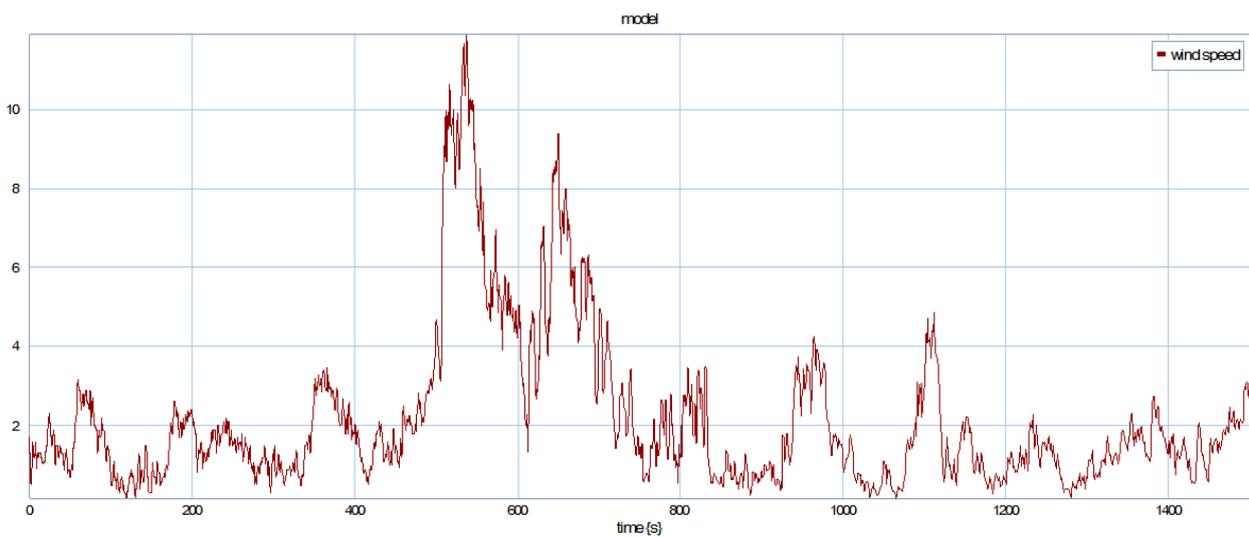
Fig. 2. The measured outdoor temperature,  $T_o$



**Fig. 3.** The measured solar radiation,  $Q_s$  ( $R_g$ )



**Fig. 4.** The measured indoor temperature,  $T_i$



**Fig. 5.** The measured wind speed,  $W_s$

### 3. Bond Graph Approach Presentation

It is a tool based on the concept of transfer of energy or power. It is fast developing and provides a systematic method and structured design of the model [10]. Among its many benefits include

- i. The possibility to apply to many fields of physics,
- ii. Modular design patterns,
- iii. The achievement of a "complex" model through interconnectivity of several basic models,
- iv. The systematic development of numerical models from graphical models.

The fundamental principle of description is based on the energy exchange between the sub-parts of a system. The exchange of power between two elements A and B of a system is represented as shown in Figure 6 by a half arrow (called "link" or "jump") which carries two variables called "power variable", with a generic name "effort" and "flow", the product  $e * f$  represents the instantaneous power carried by this link.

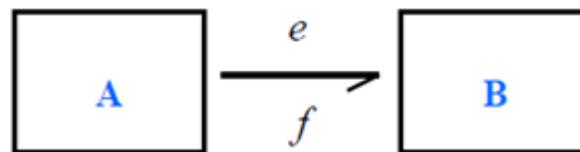


Fig. 6. Power Transfer Link [11]

The choice of power depends on variables of the physical system to study. In heat, the effort is the temperature  $T$  and flow variable is the  $S$  entropy flow. However, since it is difficult to measure the entropy flow, the researchers introduced a variable flow named heat flow  $Q$  (pseudo-Bond Graph) [12].

So, Bond Graph representations consist of

- i. Active elements (sources of effort noted  $Se$  and sources of flow noted  $Sf$ ) which provide power to the system and which can be modulated (noted  $MSe$  and  $MSf$ );
- ii. Passive elements (storage noted  $C$  and dissipators noted  $R$ ) which receive the power; and junction elements materializing power balances to common effort (noted  $0$ ) or common flow (noted  $1$ ) [12].

Thermal modeling of our building local is obtained either by electrical analogy ( $RC$ ) or via the energy conservation law.

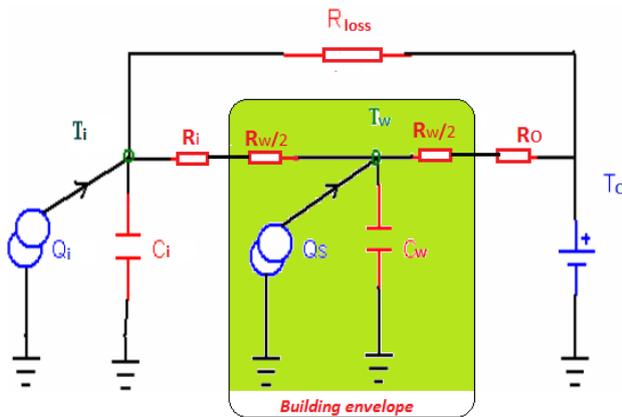
#### 3.1 Obtaining the Model with $RC$ Network

Most researchers have developed the BG models via the energy conservation law. The latter allows us to calculate the temperature of each node from the different heat flows exchanged; but in our case study we will use the thermoelectric analogy as it is illustrated on Figure 7(a) and (b). We assumed that the outer walls, roof and floor are in a single node with temperature in the interior of the homogeneous area. For our study we chose a  $2R1C$  model, with the set of  $C_i$ ,  $C_w$ ,  $R_1$ ,  $R_2$ ,  $R_{loss}$  parameters.

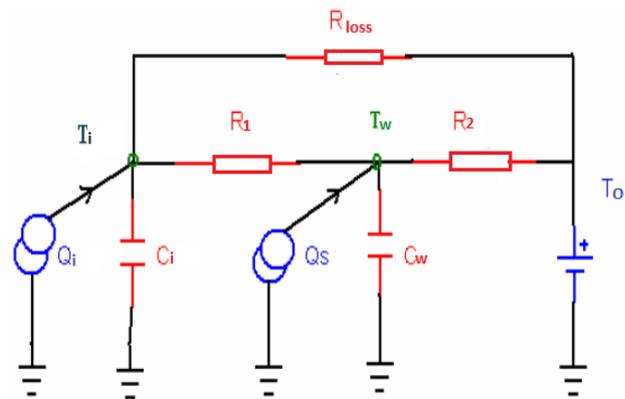
The  $R_{loss}$  Resistor represents the Losses due to the leakages from outside. The resistors  $R_1$  and  $R_2$  are composed with conductive and convective parts:  $R_1 = R_i + R_w / 2$  and  $R_2 = R_o + R_w / 2$  as shown by Figure 7(b).

They give more or less importance to the interaction between the interior and the outside environment, with the contribution of the strongest capacity of the model, as well as the capacity of

structure Solar flow  $s$  is injected directly into the node of the wall. The power is the internals contributions (air-conditioning, heating, lighting, electric apparatuses and occupants) also injected into the node which represent the indoor temperature  $T_i$ .



**Fig. 7. (a)** Electrical 2R1C analogy of the building thermal model of local



**Fig. 7. (b)** Simplified electrical 2R1C building thermal model

Applying nodes and mesh law [13], the heat dynamics can be expressed as a system of ordinary differential equations.

The dynamics of the indoor temperature,  $T_i$

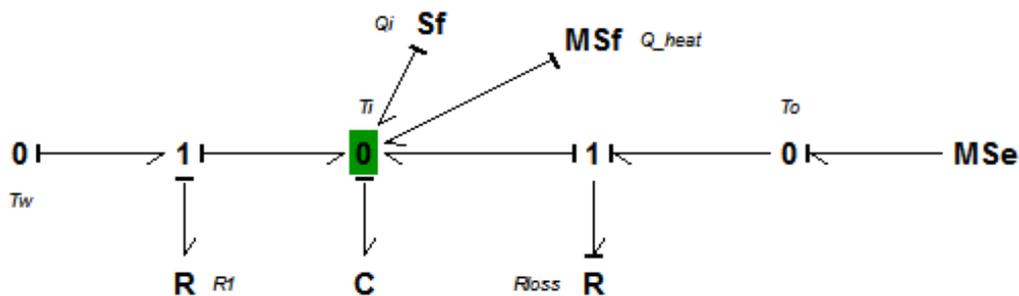
$$\frac{dT_i}{dt} = \frac{1}{C_i} \left( \frac{T_o - T_i}{R_{loss}} + \frac{T_w - T_i}{R_1} + Q_i + Q_{heat} \right) \quad (1)$$

The dynamics of the envelope temperature,  $T_w$

$$\frac{dT_w}{dt} = \frac{1}{C_w} \left( \frac{T_i - T_w}{R_1} + \frac{T_o - T_w}{R_2} + Q_s \right) \quad (2)$$

### 3.2 Obtaining the Model with BG

The thermal equilibrium applied to the air in the room is expressed taking into account the infiltrations due to the convective exchange between the outside and the inside, convective exchange between envelope and the interior and the convective exchange between envelope and the outside; as shown in Figure 8 and 9.



**Fig. 8.** Bond Graph representation of indoor air

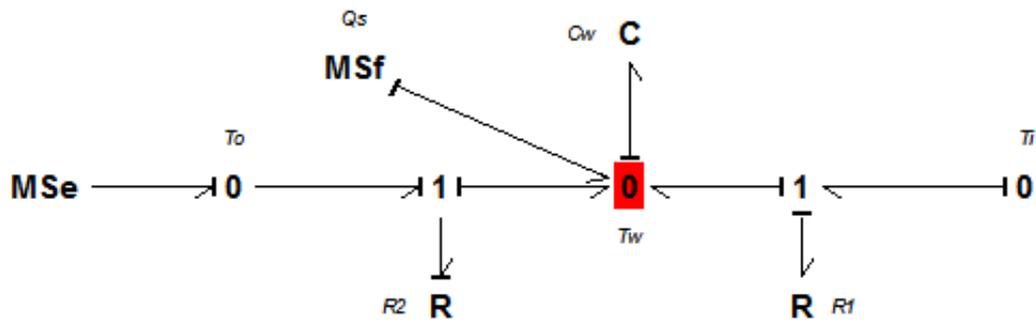


Fig. 9. Bond Graph representation of the wall

By grouping the different nodes, we give below a complete Bond Graph representation of the thermal model of the building, as shown Figure 10.

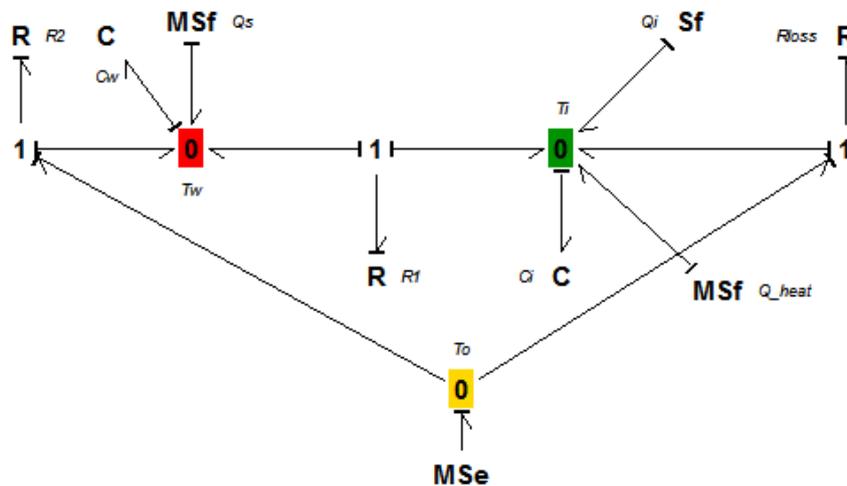


Fig. 10. Bond Graph representation of the global thermal model

#### 4. Identification and Validation of the Model

The experimental inputs outputs data symbolizing sequences of March 2018 climate of semi-arid region (Bechar) are applied to our bond graph model Figure 11.

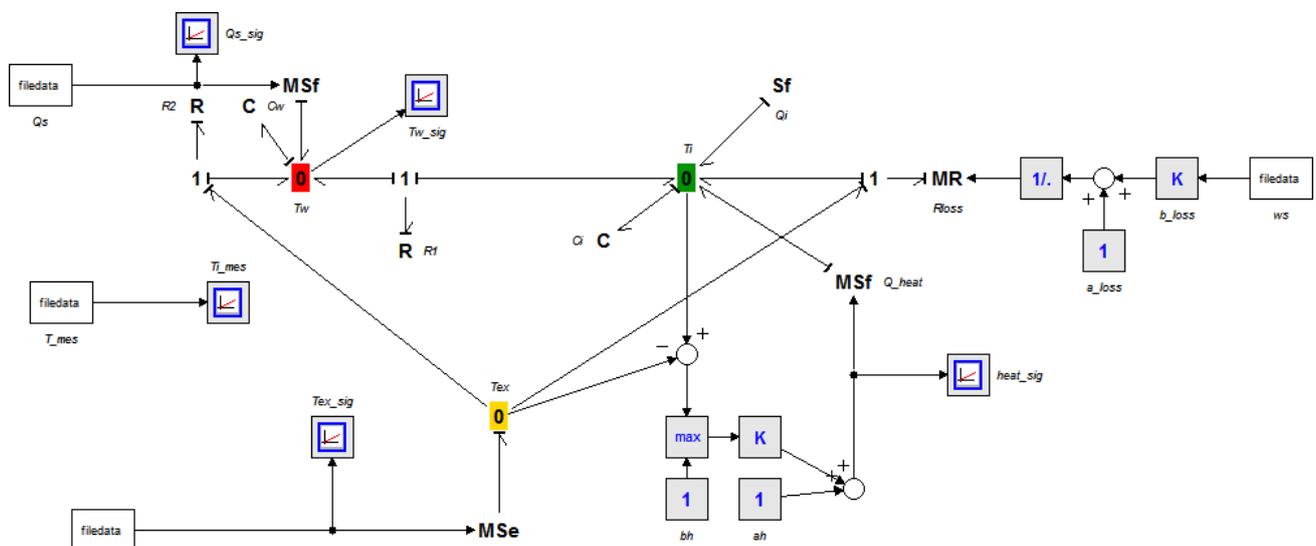


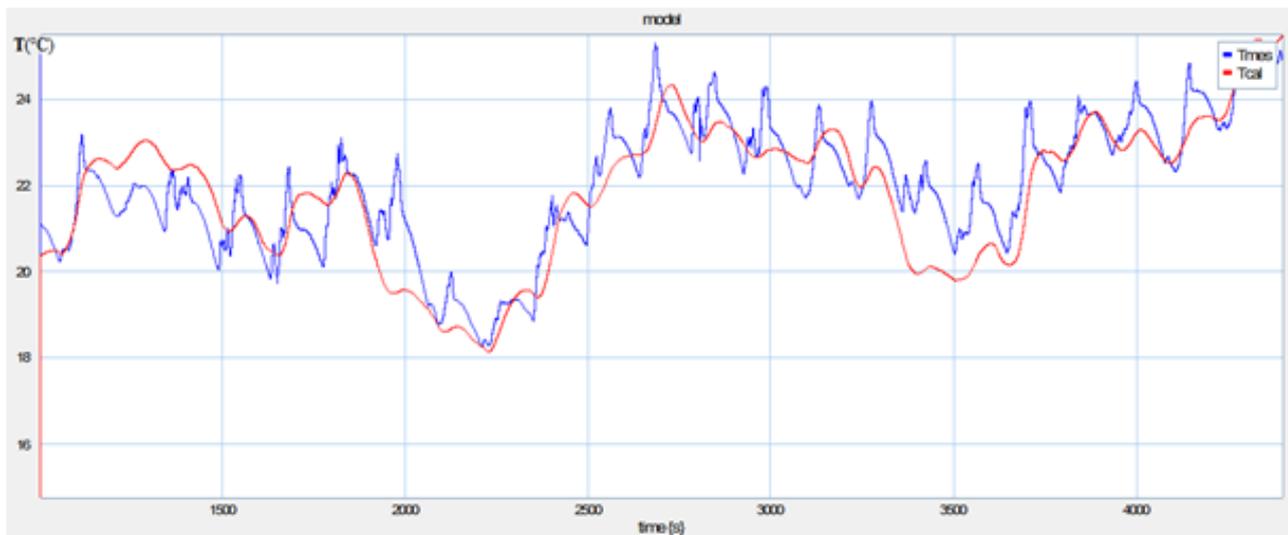
Fig. 11. Bond Graph representation of the global thermal model with input-output

These parameters were manually adjusted (see Table 1). The variance of the values obtained is due to bad weather recognized in this month of our region.

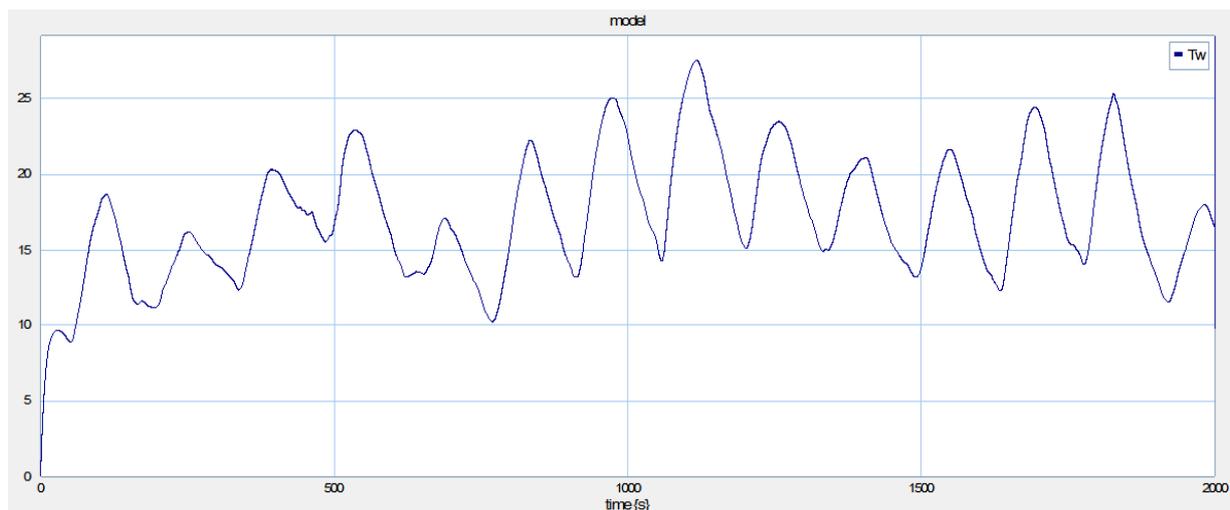
**Table 1**  
 Parameters value of BG model

Parameter	Rloss	R1	R2	Ci	Cw	Qi	A	B	K	Aloss	Bloss
Value	0.02	0.15	0.001	100	300	800	5	5	500	4000	4000

The internal temperature obtained from the laboratory local ( $T_i$ ) in comparison with the measured values are shown in Figure 12. Likewise, the temperature of the envelope ( $T_w$ ) calculated by the model BG is represented on Figure 13.



**Fig. 12.** Evolution of internal temperatures measured and calculated for the month of March 2018



**Fig. 13.** The temperature of the envelope ( $T_w$ ) calculated by the model BG

The simulation results allow us to observe the evolution of the temperatures of the thermal nodes throughout the month of MARCH 2018 (see Figure 12). These temperature values seem quite likely.

## 5. Optimization Method

In this study, the model parameters will be optimized using Newton -Raphson optimization. It is the most widely used method for solving nonlinear algebraic equations. This method consists of introducing a sequence ( $x_n$ ) of successive approximations of the equation  $f(x) = 0$ .

- i. We start from a close  $x_0$  of the solution.
- ii. From  $x_0$ , we compute a new term  $x_1$  of the following kind: we draw the tangent to  $f$  in  $x_0$ . This tangent intersects the abscissa axis in  $x_1$  as indicated in the Figure 14.
- iii. This process is repeated by calculating  $x_2$  by replacing  $x_0$  with  $x_1$ , then  $x_3$  by replacing  $x_1$  with  $x_2$  and so on. . . . [14]

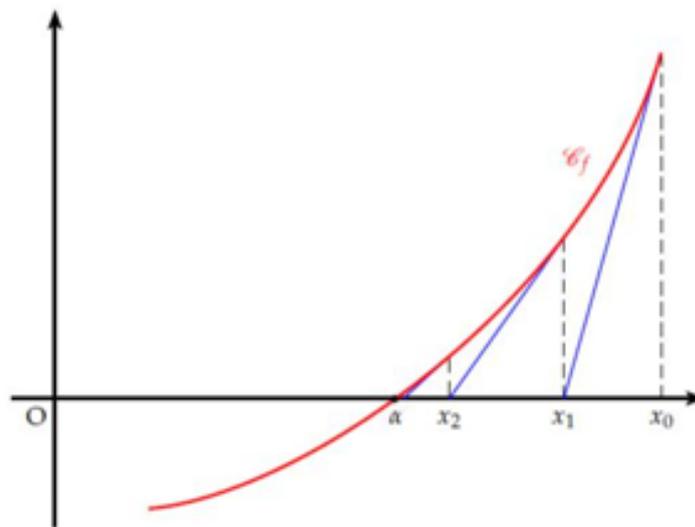


Fig. 14. Calculation principle by the method of Newton - Raphson [14]

## 6. PID Controller Design

Heating or cooling control is to provide the necessary heat or cool to the building to ensure a comfortable temperature in the most economical manner. For this, a PID controller is the best choice in terms of energy efficiency and ease of use. In Figure 15, inputs are the set point temperature, outside temperature, solar flux  $Q_s$  and overall internal gains  $Q_i$ . The output generated by the controller is a given power of the amount of heating / cooling needed to reach the level of desirable comfort.

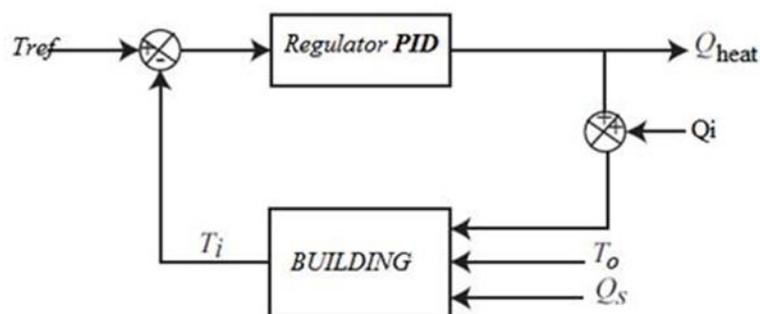


Fig. 15. Closed loop model of the building [15]

## 7. Result of the Control

In this section we will present the simulation results control of the comfort level in the building room, i.e. the heating and air conditioning control loop, then we will study the impact of this control on the thermal comfort in the room.

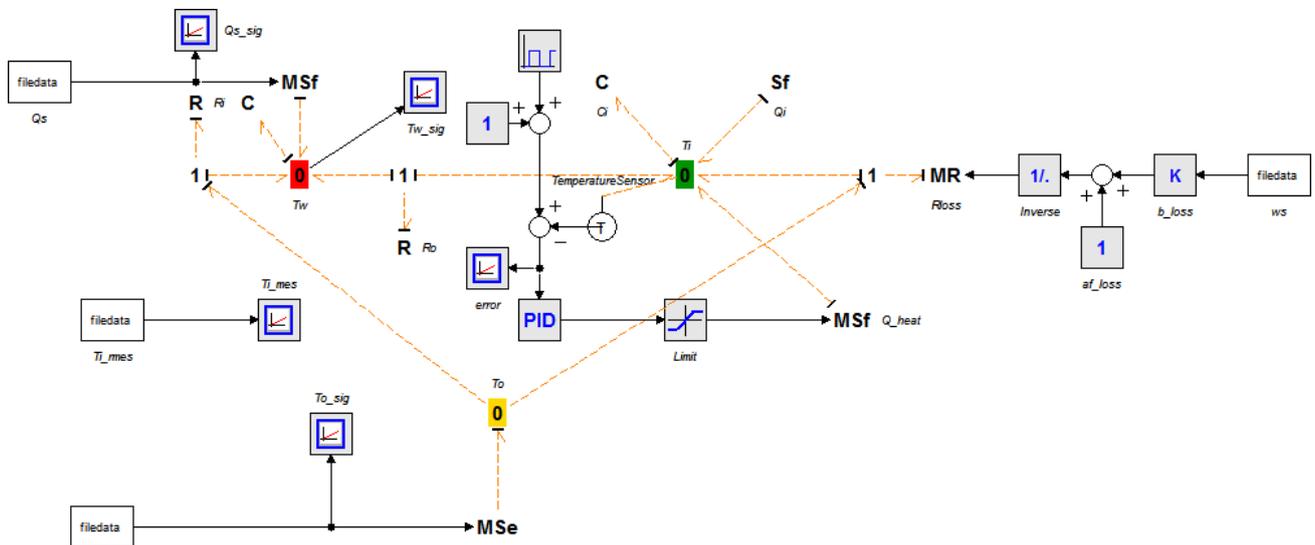
The values of the parameters of the manually optimized PID controller by Newton -Raphson are brought to the Table 2.

**Table 2**

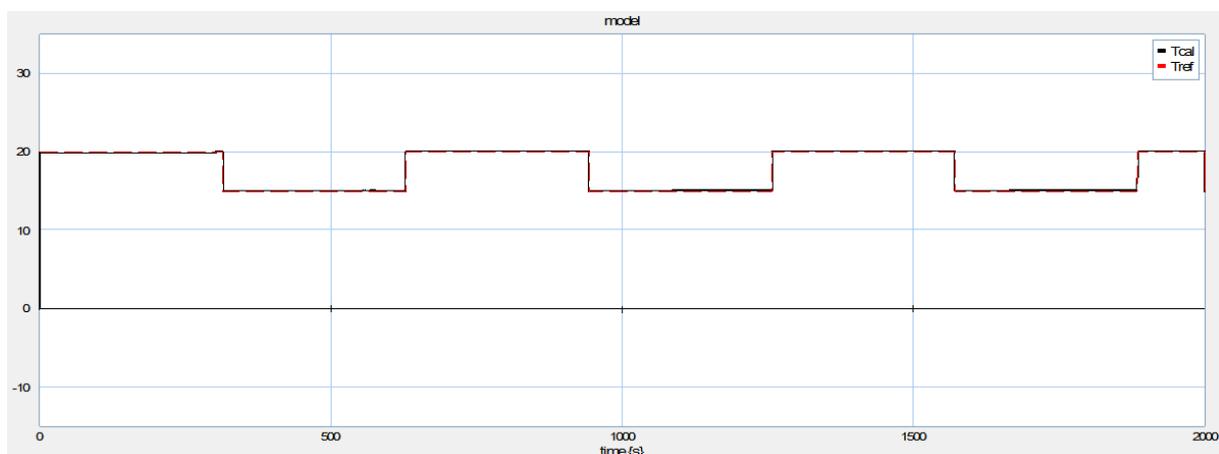
Parameters value of PID controller

Parameter	KP	$\tau D$	$\beta$	$\tau I$
Value	500	1	0.1	0.5

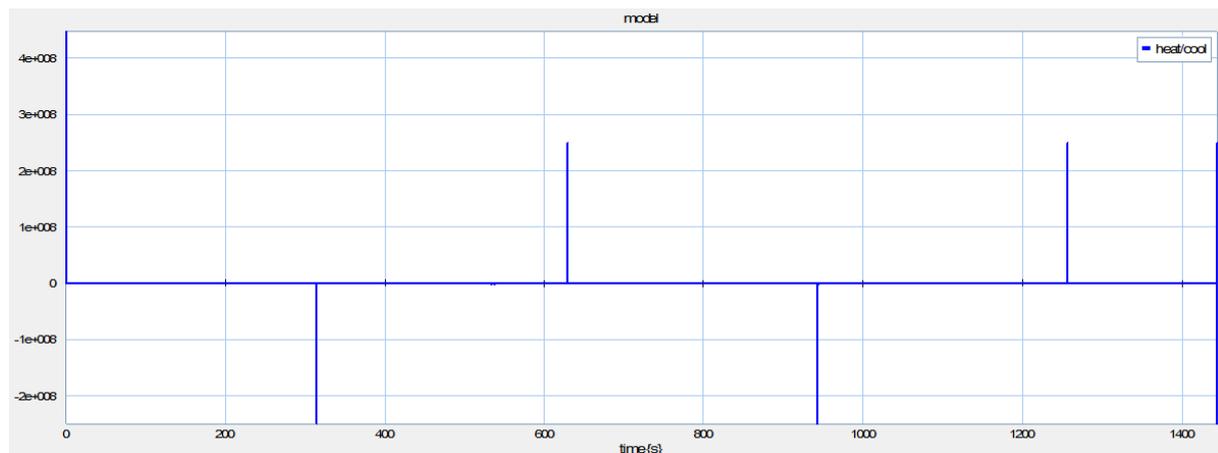
After simulation of the BG model with the PID controller (see Figure 16); we have obtained an internal temperature which follows suitably the reference temperature (without constraint) as shown in Figure 17, and a signal of flux heating /cooling of great values (see Figure 18).



**Fig. 16.** Bond graph building Model control with a PID (with and without constraint)



**Fig. 17.** Internal temperature in tracking mode (without constraint)



**Fig. 18.** Generated flux heating and cooling by PID

Whereas in the case with constraint, the results are less satisfactory in the presence of the heating or cooling signal alone.

## 8. Conclusion

A gray model was developed to represent and analyze the thermal behavior of a single-area building (laboratory ENERGARID). The Bond Graph methodology, so far little used in the modeling of thermal systems, was used. In this work, the validation of our model is done with simulation [16,17]. The results showed a good correlation between the internal temperature  $T_i$  and the set point temperature  $T_{ref}$ . The climatic management of the internal environment of the laboratory room was done by a PID. The actuator constraints were taken in consideration during the simulation.

The Bond Graph modeling tool facilitated by offering a behavioral approach and to guaranteeing the conservation of energy between components. The Bond Graph model seems entirely appropriate to represent the thermal behavior of the building.

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