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Numerical modeling of the intelligent heating systems for living space

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Abstract. Nowadays, the intelligent solution of heating and hot water supply in residential house has become a current domain in the domain of energy efficiency analysis. It is presented the mathematical model and some numerical simulations for intelligent heating systems, ventilation, and air conditioning into a building structured on two floors, with spaces with intermittent occupancy, between certain hours. The heating system was structured into a permanent correlation with the reference temperature and the hot water consumption, corresponding to the time-period spent by the inhabitants in the living rooms. The control algorithm is a combination of fuzzy systems, anticipation systems and conventional systems. The numerical modeling analyzes both periods, the inhabited and the holidays. As input data were considered the atmospheric conditions and solar radiation, house structure, as to obtain the output data, scheduled solution of heating the building. A solution of ceiling, estimation of windows behavior, internal and external walls is presented. The air temperature is regulated via a three-way valve commanded by an actuator, whose time constant is adjustable. The experimental validation of the obtained results was tested in a building system from the metropolitan area of the city.

1 Introduction

In the actual context of raising the prices of natural gas and raw materials, for instance, coal and wood, to reduce significantly the unnecessary energy consumption in buildings is a key objective for households, SMEs, but also for large industrial consumers. A first step in achieving this objective is the development of the numerical simulations, dedicated to each practical application. It may be realized based on the necessary consumption for heating, air ventilation, and water consumption during inhabitation, and reducing their consumption during uninhabited/holidays periods. Software now commonly used in the automation conception systems for heating does not take into account an adaptive structural modeling of the residential buildings and, of their equipment. Consequently, it must be known the structure of the system needed to be modeled as well as systems of differential and algebraic equations describing the dynamic behavior of the equipment supplied by the manufacturer or their technical characteristics determined by experimental testing. In this

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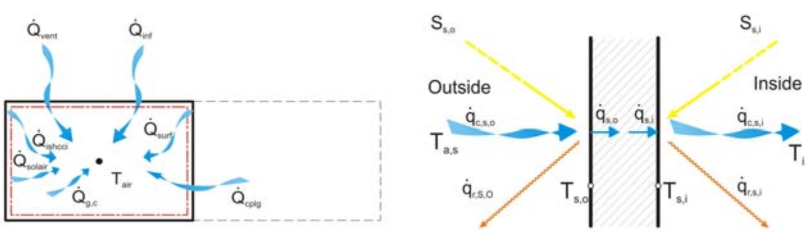
paper is modeled a living space with four rooms and intermittent occupation during the day. The numerical results are performed for a week, considered an average span. The mathematical models are taken from the simulation programs, TRNSYS and HVACSIM, interconnected with a pre-processor design of physical models for buildings. This extremely flexible software for environment is used to simulate the behavior of transient systems, such as buildings with energy consumption variation. The majority of simulations are focused on assessing the performance of thermal and electrical energy systems, with dynamic systems as biological processes. The proposed solution for numerical simulation is dedicated to buildings with mechanical system controls, the heating/cooling plant, energy management, and control system algorithms. The program uses a hierarchical, modular approach for advanced equations and solving techniques to perform dynamic simulations of building control systems.

2 Mathematical model

There are two ways to model the equipment for heating, cooling, humidification, and dehumidification, similar to the "energy rate" and "temperature level." For the first one a simplified model of the air conditioning equipment must be first implemented. In present paper was considered the second method. For the basic modeling must be specified the setting temperatures for heating and cooling, set points for humidity control, and maximum cooling and heating rates. These specifications can be different for each zone of the building. A more detailed model of the heating and cooling equipment and supplementary temperature level approach is needed, because separate components are required. The outputs from the buildings model can be used as inputs for the equipment models, which in turn produce heating and cooling-inputs to the control devices. The numerical model was developed in MATLAB/SIMULINK [1-2]. Is presented the general case, with separate equipment components, which can be coupled to the air-nodes as either internal convective gains or ventilation gains, Figure 1. The time-step simulation is not equal to the time-base on which the transfer function for the walls behavior is based. There is also briefly presented a descriptions of the optical and thermal window model, the way in which solar and internal radiation are distributed within each zone, based on geographical position of the building, the moisture balance calculations and the integrated model for thermo-active walls.



a b

Fig. 1. a- Heat balance on the air node, b- Heat fluxes and temperature through wall or window.

The Convective Heat Flux to an air node is (all terms are in kJ/h):

$$\dot{Q} = \dot{Q}_{surf} + \dot{Q}_{inf} + \dot{Q}_{vent} + \dot{Q}_{g,c} + \dot{Q}_{cplg} + \dot{Q}_{solar} + \dot{Q}_{ISHCCI} \quad , \tag{1}$$

Where $\dot{Q}_{surf}$ - gain from surfaces, $\dot{Q}_{inf}$ - infiltration gains (air from outside only), $\dot{Q}_{vent}$ - ventilation gains (air from a user-defined source), $\dot{Q}_{g,c}$ - internal convective gains (by people, equipment, illumination, radiators, etc.), $\dot{Q}_{cplg}$ - gains due to air flow from air-node i, $\dot{Q}_{solar}$ - fraction of solar radiation entering an air-node, and $\dot{Q}_{ISHCCI}$ - the absorbed solar radiation on all internal shading devices

$$\dot{Q}_{inf} = \dot{V} \cdot \rho \cdot c_p \left(T_{outside} - T_{air}\right) \tag{2}$$

$$\dot{Q}_{vent} = \dot{V} \cdot \rho \cdot c_p \left(T_{ventilation} - T_{air}\right) \tag{3}$$

$$\dot{Q}_{cplg} = \dot{V} \cdot \rho \cdot c_p \left(T_{zone} - T_{air}\right) \tag{4}$$

The coupling statement allows for an air mass flow that an air-node receives from another air-node, considered as a heat flow. The reason for this convention is to allow the user to describe cross ventilation or a ventilation circle within three or more air-nodes. In this case may be considered some possible situations:

Radiative Heat Flows (only) to the Walls and Windows

$$\dot{Q}_{r,w} = \dot{Q}_{riw} + \dot{Q}_{sww} + \dot{Q}_{long} + \dot{Q}_{wall-gain} \tag{5}$$

Here: $\dot{Q}_{r,w}$ - radiative gains for the wall's surface temperature node, $\dot{Q}_{sww}$ - solar gains through zone windows received by walls, $\dot{Q}_{long}$ - long-wave radiation exchange between this wall and all other walls and windows, and $\dot{Q}_{wall-gain}$ the user-specified heat flow.

Integration of walls and windows

In Figure 1-b is presented the heat fluxes and temperatures that characterize the thermal behavior of any wall or window, where S- radiations heat flux and q net radiative, $S_{s,i}$ - absorbed at inside surface, $S_{z,o}$ – absorbed from outside, $\dot{q}_{r,s,i}$ - heat transfer, $\dot{q}_{r,s,o}$ - transfer with all surfaces, $\dot{q}_{s,i}$ - conduction heat flux from the wall, $\dot{q}_{s,o}$ - conduction flux into the wall, $\dot{q}_{c,s,i}$ - convection heat flux to the air, $\dot{q}_{c,s,o}$ - convection heat flux to outside from the boundary ambient, $T_{s,i}$- inside temperature, $T_{s,o}$ – outside temperature.

The walls are modeled according to the transfer function relationships defined for each surface. For any internal or external wall, the heat conduction is:

$$\dot{q}_{s,i} = \sum_{k=0}^{n_{b_s}} b_s^k T_{s,o}^k - \sum_{k=0}^{n_{c_s}} c_s^k T_{s,i}^k - \sum_{k=0}^{n_{d_s}} d_s^k \dot{q}_{s,i}^k \tag{6}$$

$$\dot{q}_{s,o} = \sum_{k=0}^{n_{a_s}} a_s^k T_{s,o}^k - \sum_{k=0}^{n_{b_s}} b_s^k T_{s,i}^k - \sum_{k=0}^{n_{d_s}} d_s^k \dot{q}_{s,o}^k \tag{7}$$

These time series equations are evaluated at equal time intervals. The superscript k refers to the term in the time series. The current time is k = 0. The coefficients of the time series (a's, b's, c's, and d's) are determined considering the z-transfer function. The operating principle of the intelligent heating systems is relatively simple, because it is sufficient to increase the heat flow if a lower temperature appears in the inhabited rooms. In reality, this algorithm is not efficient for any kind of buildings, because the same amount of heat can be supplied for buildings and spaces with different energy needs.A window is considered thermally as an external wall, partially transparent to solar, but opaque to long-wave internal gains. In numerical modeling, in the energy balance calculation, the window is described as a second type node model. The method of the transfer function or response factors can be described as the method to tell the "thermal history" of the wall. The wall example consists of three layers with concrete, mineral wool, and gypsum from outside to inside. The number of time-steps (k) related to the time-base (defined by the user) shows the wall structure. If it is a heavy wall, with a high*- thermal mass (k < 20) or it is thin wall, with only a few time-steps. For walls adjacent to another air-node, internal walls, or walls adjacent air-nodes with identical conditions, the previous equations (6), (7) may be applied, but with some corrections. Finally, the total gain to air-node i from all surfaces, is the sum of the combined heat transfers:

$$\dot{Q}_{surf,i} = \sum A_s q_{comb,i} = \sum_{j=1}^{Adj.Zonessurfaceitoj} \sum_{i=1} A_s B_s T_{star,j} + \sum_{i}^{ext.surface} A_s B_s T_a + \\ + \sum_{i}^{int.walls} A_s B_s T_{star} + \sum_{i}^{knownbound} A_s B_s T_{b,s} - \sum_{i}^{surfaceinzonei} A_s \left(C_s T_{star,i} - D_s - S_{s,i} \right) \quad (8)$$

Where A_s-surface, T_{star} – external walls, B_s, C_s, D_s- coefficient staking account of wall material for external and for internal ones, type of windows [3].

3 Numerical model

The numerical simulations was performed for a building with four rooms, on two floors, with intermittent heating and inhabitants, assuming that, part of the day, nobody is at home. The hot water is produced at constant temperature by a boiler with control system programmed separately, [4], [5]. The water temperature supplies the radiators, adjusted according to the ambient temperature, solar radiation, and human occupancy status.

The modeled apartment is structured: First floor: Living- 40 m^2, Kitchen- 4.8 m^2, Bathroom 1-5.5 m^2, Lounge 1- 6.7 m^2, Second floor Bedroom 1-15.7 m^2, Bedroom 2-15.5 m^2, Bedroom 3-12.5 m^2, Bathroom 2-7 m^2, Toilet- 2 m^2, Balcony- 6 m^2, Lounge 2- 10 m^2,, Terrace: 136 m^2, Garden: 40 m^2, Total built surface- 135 m^2, room height-3.2 m.

The main steps in numerical simulation refer at input 1 – 6 and output 7-10:

1. Selection of the hemisphere and orientation (estimation of solar radiation);

2. Data input for building structure: number of rooms/surfaces, air mode ventilation and volume (for closed volumes), heat transfer coefficients; if there is not specific references will be used some implicit values;

3. Calculation of radiation data internal or/and external by another component and estimation of shading/insulation;

4. Nature of materials, constructions, schedules of the building, heating, or heating/cooling;

5. An overview of the project initialization, construction types, schedules, regime types, zones, and the geo-information of the project;

6. There is only one possibility to select in calculations or only heating or combined heating and air control. It can be selected a constant for the same temperature, day-night during the entire week, a pre-selected option considered input- I for a standard week behavior, with differences between day-night and inhabited or not, or schedule-S the most complex, with different day variations (shading factor, radiance, internal shading devices).

7. As output must be selected the air node or group, by one option: thermal air nodes, external nodes, auxiliary nodes, air links;

8. Selection of the kind of N Types: air node outputs, group of air node outputs, surface outputs, comfort outputs, balances (extremely helpful overview);

9. Evaluation of the energetic balance:

- Balance 1: how much solar radiation is blocked, or not and how much is entering, and exchanged with other area of the building

- Balance 2: how much primary solar radiation is blocked or not through an external window; it reflect the window performance, as shading devices, diffuse radiation (without reflected radiation)

- Balance 3: The system boundary for this energy balance includes the inside surface node of all surfaces of a zone; all radiative heat fluxes appear in this balance; is different from balance 2, which could only treat the Convective Heat Flux to the Air Node. The system boundary does not include the inside wall so the energy of an active layer, and the stored energy of walls is not part of this balance, but of the detailed balance for surfaces;

- Balance 4: **t**his Balance shows the moisture balance for all zones separately. Note: if humidity ratio reaches 100 %, positive water gains to the zone. This will still lead to an increasing amount of water stored in the air while actually there would be water drops somewhere on surfaces.

10. Finally, is the editing of the building performances based on the construction model.

For modeling part of the basic input data are necessary the monitored atmospheric parameters from the area of the building: temperature, humidity, solar radiation, etc. An example of these registered parameters is mentioned in Table 1, Table 2.

Table 1. Humidity variation with temperature.

T (ºC)	-30	-20	-10	0	10	20	30
U_{am} (g/m^2)	0.3	1,1	2,3	4,9	9,4	17,3	30,4

Table 2. Main monitored parameters February 2018.

Parameter	Max	Max. Time	Max. Data	Min	Min. Time	Min. Data	Average
WD (º)	359	1:00pm	2/20/17	1	5:00pm	2/13/17	225.69
WV(m/s)	60	2:38pm	2/12/17	0.12	10:00pm	2/18/17	10.57
U (%)	100	6:00am	2/19/17	8	4:00pm	2/8/17	43
T (ºC)	17.11	2:04pm	2/8/17	-10.11	9:01am	2/3/17	0.75
P(mmHg)	767.59	11:00pm	2/28/17	746.76	1:00pm	2/12/17	758.44
QP(mm)	0.55	12:00pm	2/20/17	0.31	12:00pm	2/1/17	0.40

Here: WD-wind direction, WV-wind velocity, U – humidity, T-temperature, P-pressure, QP- quantity of precipitation.

4 Simulation and results

During the modeling, it may be added a new internal wall or removed some others. The control algorithm is a combination of fuzzy systems, anticipation systems and conventional systems. The air temperature is regulated via a three-way valve, operated by an actuator whose time constant is negligible compared to the time constant of the process. The valve is placed on the hot water supply circuit, [6], [7]. The schematic components of walls internal or external, windows, building's structure are extremely useful to create a particular system of heating. Daily, weekly, or monthly schedules can be created for normalized occupancy, lighting or equipment schedules, and set points for temperature thermostats. In Figure 2 is presented the environmental temperature registered into a week from February 2018.

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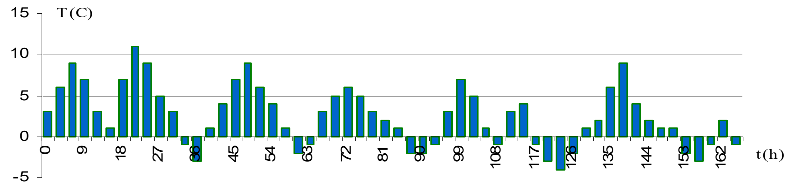

Fig. 2. The variation of the ambient temperature during one week.

The working temperature in the rooms was set differently for bedrooms, living room, bathrooms, and kitchen, depending on the level into the building, and the time period occupancy during the day. In Figure 3 is presented the variation of the interior ambient temperature, during a typical heating in weekly periods, for the Bedroom 1 in February 2018. Similar results are obtained for each chamber, bathrooms, or kitchen.

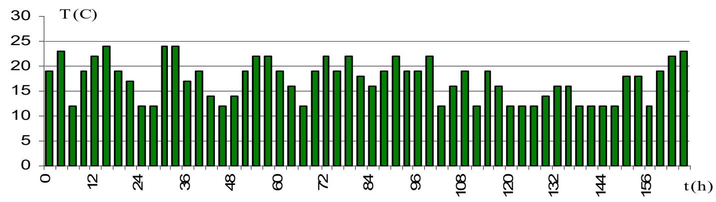

Fig. 3. Reference temperature in rooms.

In Figure 4 and Figure 5 are represented the variation of temperature of water supply and temperature in a room, during a week.

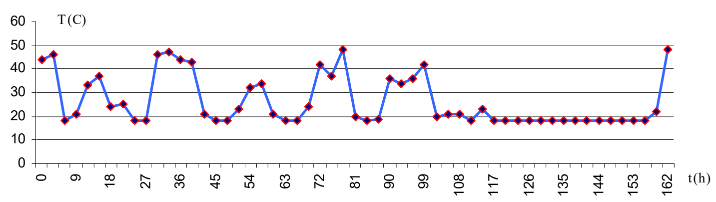

Fig. 4. Variation of temperature of the water supply during a week.

The range of the command system components may be from a simple thermostat controller to a complex multi-stage differential controller, with an on/off setting of minimum/maximum temperature, and with a tempering valve controller and an outside air reset controller. The model allows extensions concerning the possibilities of heating: the classic version with central by gas on wall, or has components for modeling solar photovoltaic (PV) and solar thermal combined (PVT). In present model was used the first solution with a wall gas central heating.

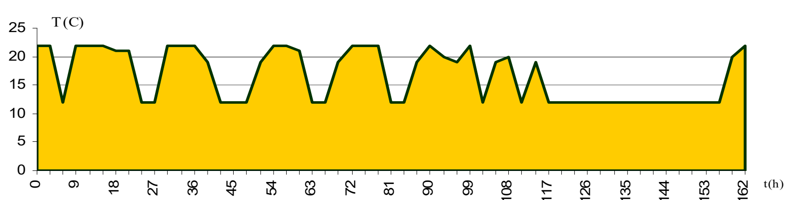

Fig. 5. Temperature variation in Bedroom 1, during a week.

The properties entered for the shading devices are effective only if the shading device is defined for the window in zone description. The heat flux depends on temperatures, type of shading device, and geometry of air volume between the shading device and window.

Table 3. Coefficients for the outside surfaces.

Outside surface	**Solar absorb. coef.**	**Outside surface**	**Solar absorb. coef.**
Roof tile		**Exterior wall**	
Rough Dark red	0,8	Smooth, dark color	0,74
Smooth, dark color	0,75	Medium bright color	0,61
Asbestos concrete	0,64	Rough, white color	0,34
Roof coating		Smooth, white color	0,2
green	0,63		
Aluminum	0,6		
Smooth white	0,22		

Finally, the convective heat transfer coefficient (without a radiative part): inside: 11 kJ/h m²K and outside: 64 kJ/h m² K. The presented example of measured data for a closed internal shading device illustrates the correlation of these variables:

- transmission = 30 %, respective I-shade = 1- = 0,7;
- absorption = 43,4%, respective reflection-shade = $\rho/(1-\tau)$=0,38;
- absorbed heating by the window 20%;
- reflected by windows 26%;
- transmitted solar radiation 54%;
- reflection by shading 14,3%;
- solar radiation transmitted through shading 16,2%;
- long wave radiation to window 15,8%;
- volume of the air within the air-node 68%;
- capacitance of total thermal of air-node, is considered as walls (furniture, etc.) 32%.

4 Conclusions

The possibility of modeling and simulating the house systems, taking into account the present real estate development, allows a project personalized for each apartment, according to the owner's options. The strategic implementation of heating creates the possibility of optimization for the primary energy consumption and enables a rapid validation of its effectiveness. However, it must be considered that the realization of a discontinuous, intermittent heating of buildings requires installation of additional systems for specific temperature control. In this way, it must be assessed realistically the entire intelligent heating system, because it requires integration of an intermittent programmer and a seasonal programmer. The compensator must be designed to provide interior comfort without self-oscillations inside the system.

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