Modelling and Simulation of the Temperature Control System in the Heating Installations from Nonresidential Buildings

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Abstract: The article addresses specific issues of the automated heating systems for non-residential buildings, which aim to ensure thermal comfort with low energy consumption. The specialized automatic system maintains constant the indoor temperature when the heat input in building equals the heat loss through the building envelope. The specialized automatic system consists of several subsystems. The model for each subsystem is obtained considering the particularities of the heating processes from buildings and requirements for the thermal comfort. By simulating the operation of the specialized automatic system is obtained the time behavior for the main physical values that characterizes the system, relevant to the quality of the heating temperature control in the building. The operation of the automatic controller and the control valve are analyzed by simulation, in a comparable time interval with transient regime of the automatic heating system of the real building. The validation of the model is done by comparing the results obtained by simulation with results of experimental measurements in the real automatic system, implemented in the building chosen for study.

1 ENSURING THE THERMAL COMFORT IN NONRESIDENTIAL BUILDINGS

The automation of heating systems in buildings can be made differently from one building to another, depending on the size of the building, the thermal comfort imposed, the rooms destination in the building, the number of persons in the building, the heat source used, the building materials used, etc. (Popescu and Ciufudean, 2012; Popescu, 2004; Clements-Croome, 1996; Castilia et al., 2014; Arguello and Velez, 2002; Balan, Stan and Lapusan, 2009; Balan et al., 2009; Chmielnicki, 2011; Liao and Dexter, 2004; Ma et al., 2011; Kim and Ahn, 2013).

In an individual dwelling are easly to impose the requirements for indoor thermal comfort: is chosen a room "witness" (reference) for imposed thermal comfort and, into the room, is placed the transducer that measure the indoor temperature adjusted (Popescu, 2014; Castilia et al., 2014). Choosing a room as being the reference for indoor thermal comfort is not recommended for non-residential buildings because: the number of building occupants is high and the thermal comfort exigencies differ from one person to another, even if performing the same task (Clements-Croome, 2011; Wagner and Schakib, 2011); also, heated spaces in the building may have different destinations and a good labor productivity impose adequate thermal comfort for the activity carried (Oancea and Caluianu, 2012; Clements-Croome and Li, 2000; Seppanen et al., 2006; Clements-Croome, 2006; Wargocki, 2006).

Heating systems in non-residential buildings have a heat source and contain multiple independent thermal-hydraulic circuits, in which the water temperature is adjusted to the corresponding values. The desired water temperature in a heating circuit is established using the selected heating curve for that circuit (Mira et al., 2010; Ilina et al., 2010); flow temperature changes correlated with outdoor temperature values.

Ensuring the thermal comfort in a zone of building that is heated with an own heating circuit, depends on the correct choice of heating curve for that zone. The graph must lead to a heat input in building that is

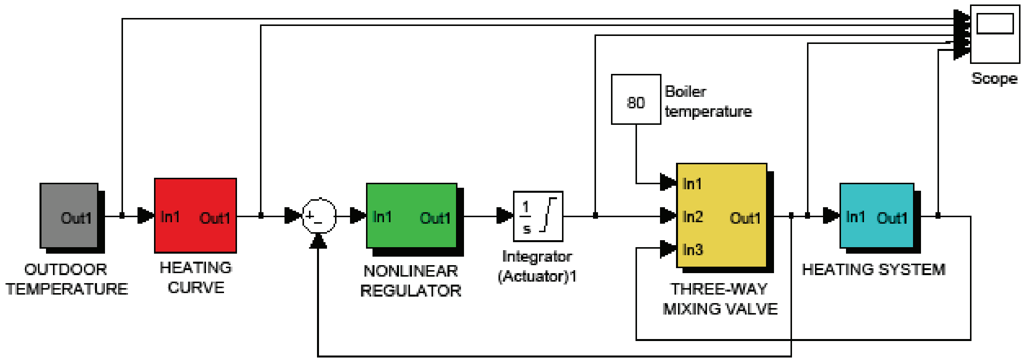

Figure 1: Model of the automatic system that adjusts the water temperature in a heating circuit.

able to compensate the heat loss through the building envelope in the heated zone; indoor temperature in the building is maintained constant.

Heating automation in a non-residential building involves:

- an automated system that adjusts the temperature of the heat source (boiler) to a constant value, usually 80^0C;
- distinct automatic systems that independently adjust the temperature of the water in each heating circuit.

2 MODELLING OF THE AUTOMATIC SYSTEM FOR ADJUSTING THE WATER TEMPERATURE IN A HEATING CIRCUIT

The model of the automatic system was developed in Simulink from Matlab and is composed of several subsystems, interconnected as shown in Figure 1.

Automatic adjustment of water temperature in the heating circuit of the building is done using a combined control loop, i.e. a control that supervises the value of deviation (error), simultaneously with a control that supervises the dominant disturbance. Heating curve of the building establishes the required flow temperature in the heating circuit; the flow temperature increases (decreases) at the decrease (increase) of the outdoor temperature, which represents the dominant disturbance. Heat input in the building is automatically adjusted and, therefore, the indoor temperature is maintained constant.

3 MODEL OF THE HEATING SYSTEM

The building chosen for modeling the automatic system for temperature control of the thermal agent in the heating installation, belongs to the Faculty of Building Services Engineering from Bucharest. In this building were conducted experimental research, which had the purpose of ensuring the thermal comfort by automatically controlling the quantity of heat that is lost through building envelope (Popescu, 2008; Popescu and Ciufudean, 2008; Popescu, Ciufudean and Ionescu, 2009; Popescu and Ciufudean, 2012). One of the three independent heating circuits with which it is equipped the building was experimentally identified (Popescu, Ciufudean and Ghiaus, 2009) and the transfer function of the heating installation for this circuit is

$$H_F(s) = \frac{0{,}586 \cdot e^{-19{,}7s}}{53{,}6s + 1} \tag{1}$$

The dead time $T_M = 19{,}7$ and the inertial time constant $T_F = 53{,}6$ are expressed in minutes.

The HEATING SYSTEM model, in Simulink, is shown in Figure 2.

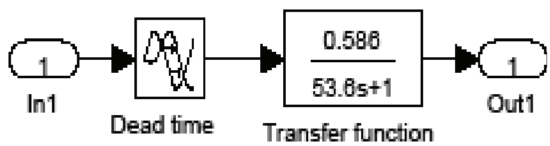

Figure 2: Model of the HEATING SYSTEM.

4 MODEL OF THE OUTDOOR TEMPERATURE SUBSYSTEM

OUTDOOR TEMPERATURE subsystem generates outdoor temperature values (dominant disturbance), which changes similar to the outdoor temperature. The subsystem is designed to provide a sinusoidal signal with a period of 24 hours. Sinusoidal signal is centered on an average outdoor temperature of -10^0C and the outdoor temperature extremes variations in 24 hours range between 0^0C (day) and -20^0C (night). Values for the outdoor temperature have been chosen particularly lower, similar to those actually recorded in Romania at the beginning of the year 2015, temperatures that pose particular problems in maintaining thermal comfort in the building.

OUTDOOR TEMPERATURE model is shown in Figure 3.

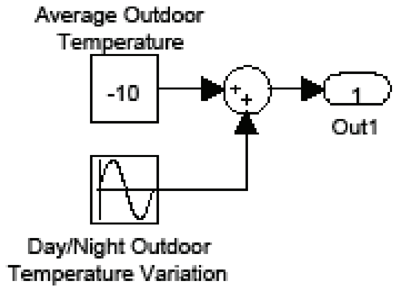

Figure 3: Model of the OUTDOOR TEMPERATURE.

5 MODEL OF THE HEATING CURVE SUBSYSTEM

HEATING CURVE subsystem generates the flow temperature setpoint in the heating circuit of the building. Water temperature dependence on the outdoor temperature is set by heating curve, which is a line with a slope of 1.5. Slope value was chosen adequate for the studied zone in the heated building.

Automation equipments used for heating buildings allow choosing the slope of the heating curve within the range 0.5 ... 4.0, as shown in Figure 4. Heating curves are taken from the technical documentation of automation equipments and the temperatures are given in Celsius degrees.

Temperatures in the HEATING CURVE subsystem are expressed in Kelvin degrees.

The heating curve used in model was designed based on the heating curve, in Celsius degrees, with a slope of 1.5, from the set of heating curves shown in the Figure 4. The ranges of temperatures are equal, regardless of unit Kelvin or Celsius chosen for temperatures, so we can write

$$\Delta\theta(^0C) = \Delta T(K) \qquad (2)$$

Therefore, the variation of flow temperature in the heating installation is $\Delta\theta_{ft}(^0C) = 80^0C - 20^0C = 60^0C$ ($\Delta T_{ft}(K) = 60K$) and the outdoor temperature variation is $\Delta\theta_{ot}(^0C) = -20^0C - 20^0C = -40^0C$ ($\Delta T_{ot}(K) = -40K$).

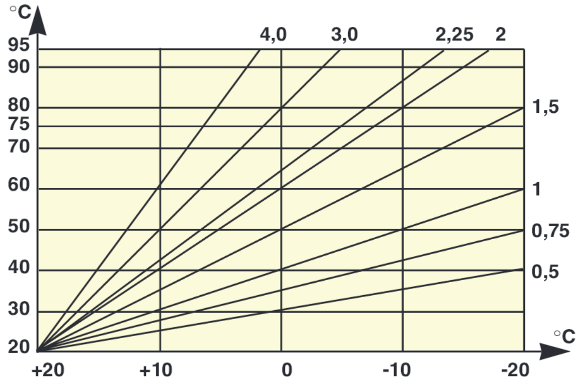

Figure 4: Heating curves for a three-way mixing valve.

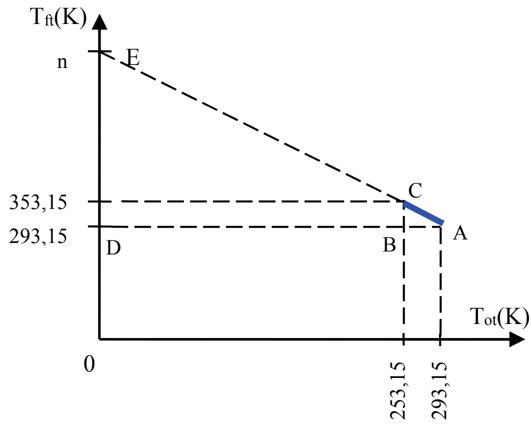

Figure 5: Heating curve used in the model.

The heating curve used in the model is the straight segment noted AC (figure 5), which has the general equation

$$y = m \cdot x + n \qquad (3)$$

With the values written on the graph axes is calculated the slope $m = \frac{\Delta T_{ft}(K)}{\Delta T_{ot}(K)} = \frac{60K}{-40K} = -1{,}5$.

Using the resemblance of triangles ABC and ADE, we can write

$\frac{353{,}15K - 293{,}15K}{n - 293{,}15K} = \frac{293{,}15K - 253{,}15K}{293{,}15K - 0K}$, from where shall be determined the value $n = 732{,}87K$.

Heating curve has the equation

$$T_{ft}[K] = -1{,}5 \cdot T_{ot}[K] + 732{,}87K \qquad (4)$$

Equation (4) represents the basis for HEATING CURVE subsystem from Figure 6.

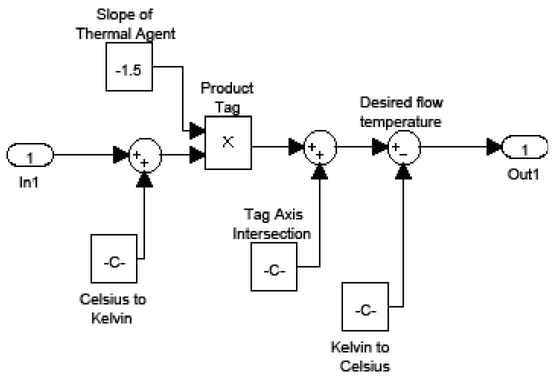

Figure 6: Model of the HEATING CURVE.

Choosing a heating curve with slope value greater than 1.5 will lead to overheating of the building; a value of the slope less than 1.5 will lead to insufficient heating of the building.

If the outdoor temperature reaches extreme values, -20...-30^{0}C, the set temperature at the boiler must be fixed at values higher than 80^{0}C, in order to not negatively affect the indoor temperature in the building. Practical experience in the heating of buildings has shown that a set temperature at the boiler higher than 80^{0}C is rarely needed and for small time intervals. The boiler automation equipment allows to establish the working temperature at maximum 95^{0}C.

6 MODEL OF THE NONLINEAR REGULATOR SUBSYSTEM

NONLINEAR REGULATOR subsystem is a three-point regulator to which the switching thresholds and the dead zone were established in the static characteristic of the regulator. The model of the regulator was realised by authors and this regulator ensures a good precision in operation.

This type of nonlinear regulators can be successfully used for the automation of the heating installations, due to the high thermal inertia for buildings (Arguello and Velez, 2002).

7 MODEL OF THE THREE-WAY MIXING VALVE SUBSYSTEM

The boiler has its own automatic control loop that maintains the temperature of boiler at the constant value 80^{0}C

The three-way mixing valve send the thermal agent in the heating installation at a temperature obtained by mixing the thermal agent taken over from the boiler with the thermal agent taken over from the return of the heating installation. The angular position of the three-way mixing valve is variable between -45^0 and +45^0. The temperature of the thermal agent at the output of the control valve is comprised between the temperature in the heating installation return (minimum value for the angular position -45^0) and the boiler temperature (maximum value for the angular position +45^0). Temperature regulated with mixing valve depends linearly on the angular position of the valve; for angular position 0 degrees, the valve takes over thermal agent in equal proportions from the boiler and from the heating installation return.

Model of three-way control valve was realised by authors in Simulink.

8 SIMULATION OF THE AUTOMATIC CONTROL SYSTEM

The simulation was performed during 50 hours (180,000 seconds), which is relevant for thermal comfort in the building studied. The results obtained by simulation are shown graphically in Figure 7.

The first graph is for the outdoor temperature. The evolutions in time for the next graphs must be analyzed in correlation with the graph for the outdoor temperature.

Flow temperature values imposed for the heating installation (ranging between 50^{0}C and 80^{0}C) are in accordance with the values of the outside temperature (ranging between 0^{0}C şi -20^{0}C) and with the heating curve with slope 1,5.

The values of angular position for three-way control valve indicate a greater amount for thermal agent taken from the boiler, compared to the amount of thermal agent taken from the heating return. For the angular position of 40^0, the flow temperature reaches 77 ... 78^{0}C; for the angular position of 45^0, the flow temperature should reach a maximum value of 80^{0}C. The error comes from the nonlinear regulator.

The temperature in the heating installation return varies due to the changes of the flow temperature and through the exchange of heat between the installation and building. The difference between flow temperature and return temperature of the heating installation is maintained approximately in the range 20 ... 30^{0}C, which indicates that the installation heats efficiently the building (Ilina et al., 2010).

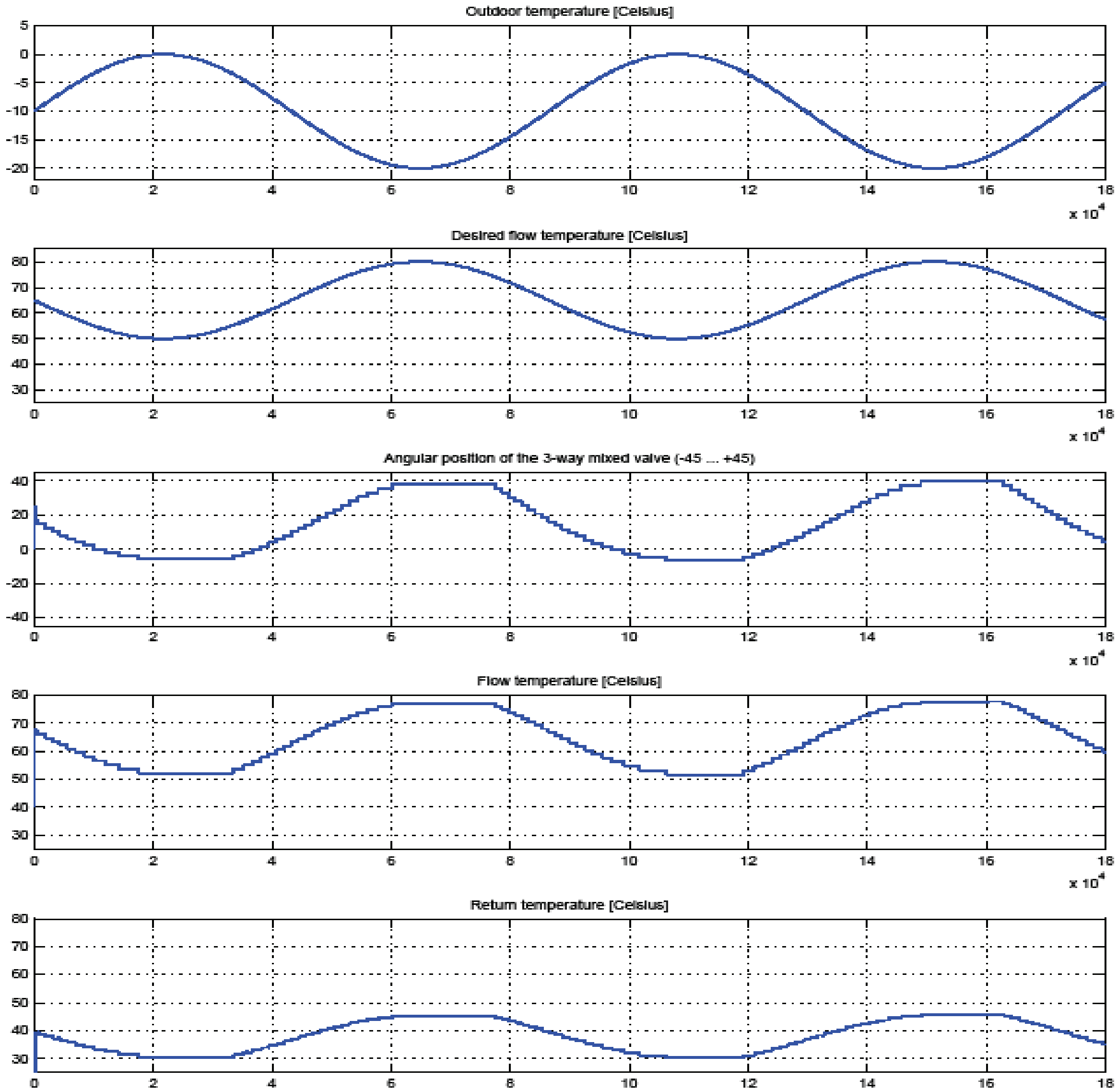

Figure 7: Results obtained by simulation of the automatic control system.

Correct operation of the automatic regulator and the control valve can be evaluated using the graphs from Figure 8, during the transitional regime.

The 300 seconds simulation time is relevant to analyze the transitory regime of the automatic heating system used in non-residential buildings.

The error adjusting decreases to the value 2,5K, which is very good if we take into account that relates to temperature in heating installation and not to the indoor temperature of the building.

The regulator commands, for adjusting the angular position of the control valve during the transitory regime, are generated at time intervals from 10 to 100 seconds. These values are large enough to find that the actuator of the control valve is not overloaded by repeated orders during transitory regimes. Furthermore, in the operation of the heating installation of a building, transitory regimes follow each other at intervals of tens of minutes or even larger, usually when the outdoor temperature changes.

9 VALIDATION OF THE MODEL FOR AUTOMATIC CONTROL SYSTEM

Faculty of Building Services Engineering from Bucharest is the non-residential building equipped

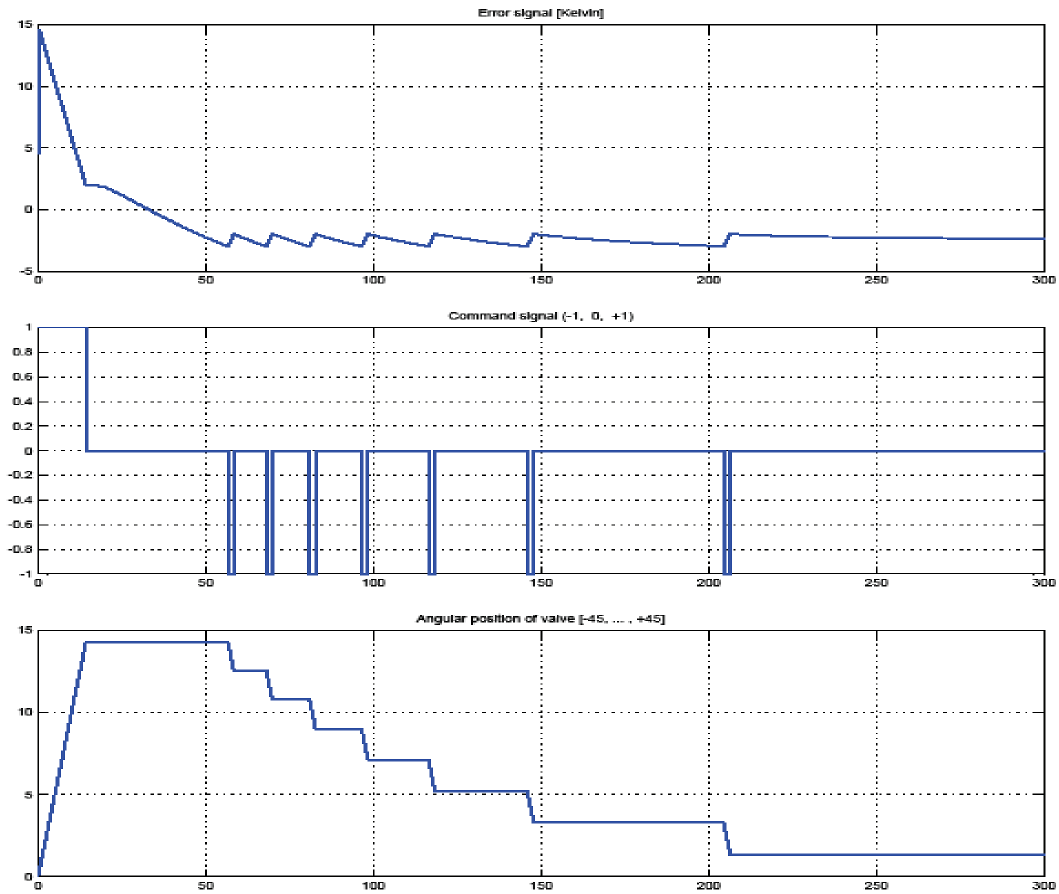

Figure 8: Results obtained by simulation automatic control system in transitional regime.

with automatic heating system which formed the basics for the model presented this article. It was monitored the operation of the automatic heating system of the building during two days, in the first part of January from 2015, when outdoor temperatures were extremely lower. Were measured and were recorded hourly the values for outdoor temperature, indoor temperature in the building and flow temperature in the heating installation. The graphs for the three temperatures are plotted in the Figure 9.

Outdoor temperature variation experimentally measured is approximately sinusoidal; the deviation from sinusoidal form in the model is due to the particular weather conditions existing in Bucharest in period chosen for experimental measurements. Experimentally measured flow temperature on the heating installation has evolved over time by following outdoor temperature values, according to the heating curve with slope 1.5, selected in the control cabinet of the boiler.

The experimental measurements have also included indoor temperature in an office of the building. Indoor temperature variations were between 18,1^{0}C and the 19,9^{0}C; these values are acceptable for activities in an office of the building in cold winter days.

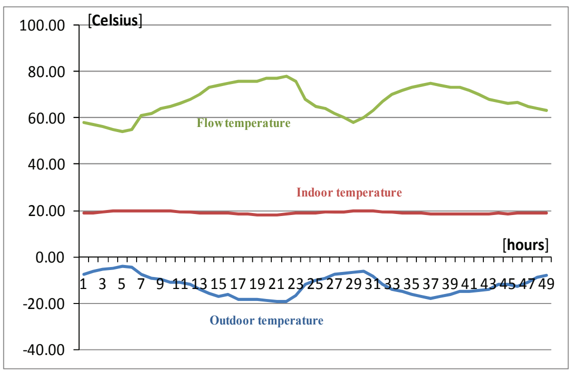

Figure 9: Graphs for experimentally measured temperatures.

The comparative analysis of values and graphs for significant temperatures, obtained by simulation and experimental measurements in the building, show that the model of automatic system was done correctly and accurately.

10 CONCLUSIONS

The finite duration of the transitory regime show the stability of the automatic system modeled and a large reserve of stability.

The accuracies for temperature control of the thermal agent have close values in the case of the simulation and the case of the operating for real system in building.

The nonlinear regulator and the three-way mixing valve are suited for the purpose.

There are no overloads for the three-way mixing valve caused by the transitory regimes of the automatic system.

The change of the angular position during operation at the three-way mixing valve takes place within the domain of variation thereof, from -45^0 to $+45^0$. Consequently, are not producing saturations of the regulator commands which would reduce the adjusting performances.

Slope value for heating curve must be adapted to the particularities from the building heated zone.

The model for the automatic system can be used as an auxiliary tool in design of automatic heating systems for non-residential buildings; it is necessary to know prior the mathematical model of the heating process.

The model of the automatic heating system is validated by comparing the significant temperatures obtained by simulation and experimental measurements in the studied building.

The article presents how the temperature of the thermal agent is controlled in the heating installation from a non-residential building. Thermal comfort depends on the indoor temperature of the building, which in turn depends on the temperature of the thermal agent in the heating system. Adding a subsystem called the heated space to the automatic system model, provides a better solution to ensure the thermal comfort inside the building.

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