Automatic Thermal Control System with Temperature Difference or Derivation Feedback

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Abstract: Automatic thermal control systems seem to be non-linear systems with thermal inertias and time delay. A controller is also non-linear because its information and power signals are limited. The application of methods that are available to on-linear systems together with computer simulation and mathematical modelling creates a possibility to acquire important information about the researched system. This paper provides a new look at the heated system model and also designs the structure of the thermal system with temperature derivation feedback. The designed system was simulated by using a special software in Turbo Pascal. Time responses of this system are compared to responses of a conventional thermal system. The thermal system with temperature derivation feedback provides better transients, better quality of regulation and better dynamical properties.

***Keywords*: Thermal system, heated system, heating plant, automatic control of temperature, simulation of thermal system, model of heated system.**

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1. Introduction

The heating system consists of the heated system (controlled object) that contains the heating plant and the control unit (control system, controller). It forms the thermal system. If the control unit is working automatically, we can speak about an automatically controlled thermal system. These systems can have various configurations and structures. System configurations can include an electrical, hydraulic, hot air and/or similar system. The heating plant and its power consumption depend on the size of the heated system, on its inner temperature and on the outer temperature. The energy source is usually a burner (natural gas, oil, coal, etc.) or an electric heater (heating resistor, arc furnace, Peltier cell, etc.) [14].

2. Material and Methods

Linear model of heated system

The heated system is a certain space (heated space) where we need to keep a certain inner temperature with a certain range of outer temperature [1], [2]. The heating plant supplies thermal energy to the heated space. The heated space is separated from the other environment by a temperature insulation wall. This configuration may have various sizes, from big (hall, house, room, etc.) up to small (heated containers, furnaces, dryers, etc.). The linear mathematical model of the controlled system is created by transfer functions with three inertial blocks and a block with time delay. The transfer function G(s) of this object is as follows:

$$G(s) = \frac{X_0(s)}{U_1(s)} = \frac{K}{(1+T_{1s})\cdot(1+T_{2s})\cdot(1+T_{3s})} \cdot e^{-sTd} \quad (1)$$

The linear mathematical model of this configuration is a linear 3rd order system with time delay. The transfer function of the heating plant is part of the transfer function G(s):

$$G_{hp}(s) = \frac{C_2(s)}{U_1(s)} = \frac{C_7 \cdot K_4}{(1+T_{1s})\cdot(1+T_{2s})} \cdot e^{-sTd} \quad (2)$$

where:

$G_{hp}(s)$ – transfer function of the heating plant;
$U_1(s)$ –standard control signal from the controller to the heater;
$U_2(s)$ –standard value of the thermal power from the heater to the overall part of the heating plant;
$C_2(s)$ – temperature of the heating medium;
C_7–gain of the heater;
K_4–gain of the overall part of the heating plant;
T_1–time constant of heat transfer between the heater and the heated medium;
T_2–time constant of heat transfer in the heated medium;
T_d– time delay, the result of heat transfer by the overflow of the heated medium;
s – Laplace transformation operator.

The transfer function of the heated space is the second part of the transfer function G(s):

$$G_{hs}(s) = \frac{X_0(s)}{C_2(s)} = \frac{K_3}{(1+T_{3s})} \quad (3)$$

where:

G_{hs}–transfer function of the heated space;
X_0–temperature of the heated space without outer influence;
C_2–temperature of the surface of the heating body in the heated space;
K_3–transfer function's gain of the heated space;
T_3–time constant of the heated space (between the temperature of the surface of the heating body and the temperature of the heated space).

The following conditions are valid for total gain K and transfer function G(s) in Eq.1:

$$K = C_7 \cdot K_4 \cdot K_3 \quad (4)$$

$$G(s) = G_{hp}(s) \cdot G_{hs}(s) \quad (5)$$

The temperature of the heated space C_3 is also gained by outer temperature U_4 with time constants T_3 and T_4. The last time constant depends on temperature insulation properties of the wall around the heated space. The transfer function of disturbance (outer temperature U_4) $G_d(s)$ is the following:

$$G_d(s) = \frac{X_6(s)}{U_4(s)} = \frac{1}{(1+T_{3s})\cdot(1+T_{4s})} \quad (6)$$

The following condition is valid for the total value of the heated space temperature $C_3(s)$:

$$C_3(s) = X_6(s) + X_0(s) \quad (7)$$

The meaning of particular values variables is presented in the following chapters, and their interconnections are shown in Fig. 1.

Note: The indices in text and in the figures do not match the letter case. Turbo Pascal language does not permit to write subscript indices. Figure indices match the Turbo Pascal syntax. Example C3 in text is the same as C3 in figure etc.

Non-linear model of heated system

The real heated system is anon-linear system. It is presented in Figure 2. together with all parts of the system of automatic space temperature control. We consider that the linear gain C_7 (in non-linearity N_3) of heater is valid only within a limited range. The standard output of thermal power has a value from 0 to 1 for variable value U_1within the same range. The value of output saturation in non-linearity N_3 is constant. The value of input U_1 for the output U_2 to reach the saturation depends on gain value C_7.

The second feedback non-linearity N_4 (see Figure 2.) is the protection circuit that is activated when the temperature of the heated medium is equal to or higher than the allowed value K_1. We can say that the model of heated system consists of the non-linear model of the heating plant and the linear model of the heated space.

The heated system in Fig.2. has two inputs (U_1– standard control signal from the controller to the heater, eventually desired input; U_4– outer temperature, eventually disturbance input) and two outputs (C_3– the temperature of the heated space with disturbance influence; C_4– temperature derivation value).

3. Results and Discussion

Design of automatic heating control system with temperature derivation loop

Figure1. shows an example of technical solution implementation. The management system of media temperature in an enclosed space with the loop of temperature difference is the media temperature

management system 9 in the enclosed space of a vessel 8 (i.e. in the controlled system); its structure is of a cascade control loop of temperature. The main controlled variable is the media temperature data transmitted by link 22, and the auxiliary controlled variable is the data of temperature difference of media transmitted by link 18. The cascade controller of the system (units 1 to 6, block 7, 25 and 26) generates the manipulated variable (link 15) arising from the processing of temperature data (link 19, link 21, link 22), and the media temperature difference (link 18) for selected time ranges. Following generated manipulated variable provides an optimum time course of media temperature and stable value (output) of media temperature. To such a feedback of the control circuit is integrated the differential block of scanned output value (the difference of heated media temperature), which consists of a differential block 26 and delay block 25. The data of output temperature value from the media temperature sensor 6 (link 21) is provided to this block and also the same data after passing through delay member 25 (member of delivery-delay) by link 20. At the output of the differential block 26 (link 18) is the difference between the present and the previous media temperature (measured temperature difference, link 18). This data enters the central management member containing the main differential blocks 1 and 3, the main member of the temperature controller 2, a central member of the temperature difference 4 and actuator 5. Its output is connected to the input of the regulated system, i.e. the assembly of the heating element 6, vessel 8 containing media 9. The body of the temperature sensor 7 is part of the controller. Manipulated variable (link 15) exiting from the controller provides the optimal time course and stable value (of output) media temperature. Thereby, it is possible to achieve the objectives of regulation (desired media temperature transmitted by link 10) at optimal time, while consuming minimal energy sources [1],[2],[3].

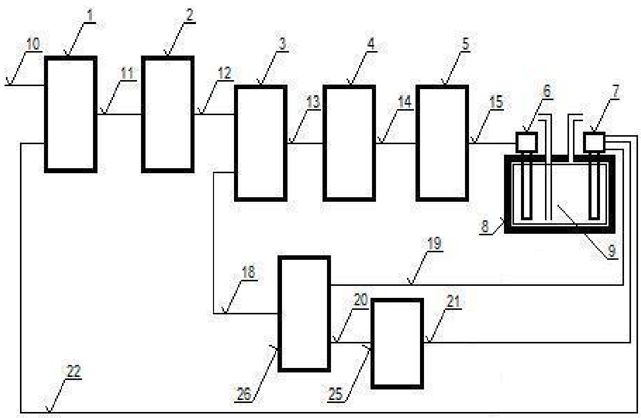

Figure 1. Thermal system with temperature and temperature difference feedback

The described heated system is a controlled system with linear 3rd order part, time delay and two non-linear blocks. The automatic control of this system is not very simple.[4] Experience with electromechanical systems of similar types of controlled system lead us to solve this problem by analogous methods [3]. This case allows us to solve this problem by using the temperature feedback loop and by using the temperature feedback loop derivation. This parameter describes the temperature change rate and thus provides the state information to controller faster than by providing only output temperature. The temperature change rate feedback loop creates possibility to control the output temperature in better and faster manner [2],[3].

The block diagram of the temperature control system with temperature derivation feedback is shown in Fig. 2. The controller consists of the PI controller of space temperature and P controller of space temperature derivation. This controller (N_2) is also non-linear because the output values of the real parts of controller are within limited range. The proportional part of the temperature PI controller N_1 is also non-linear. The integrator block has windup phenomena and its output value is also limited. The parameters in Fig.2. have the following meaning:

U_0– desired value of space temperature (input, control input);

U_1– standard control signal from the controller to the heater;

U_2– standard value of thermal power from the heater to the overall part of the heating plant;

U_3– output value of the proportional part of temperature PI controller;

U_4– outer temperature (input, disturbance input);

C_2– temperature of the heated medium;

C_3– temperature of the heated space (output) with disturbance influence;

C_4– temperature derivation value;

C_6– gain of the temperature derivation controller;

C_7– gain of the heater;

C_8– gain of the integration part of temperature PI controller;

C_9– gain of the output temperature sensor;

K_0– gain of the proportional part of temperature PI controller;

K_3–transfer function's gain of the heated space;

K_4– gain of the overall part of the heating plant;

K_6– input to the temperature derivation controller, difference between XX_8 and temperature derivation proportional value;

K_7– temperature derivation proportional value;

K_9– gain of the temperature derivation sensor;

T_d– time delay, the result of heat transfer by the overflow of the heated medium;

T_1– time constant of heat transfer between the heater and the heated medium;

T_2– time constant of heat transfer in the heated medium;
T_3– time constant of the heated space (between the temperature of the surface of the heating body and the temperature of the heated space);
T_4– time constant depending on temperature insulation properties of the wall around the heated space;
X_8– output from the integration part of temperature PI controller;
XX_8– addition X_8 (output from the integration part of temperature PI controller) and C3 (temperature of the heated space);
X_0– output space temperature value (without disturbance influence);
XD_0– temperature derivation value;
XD_8– error, input to the space temperature PI controller [4],[5].

When we are using the temperature as an output value, the linear part of the heated system has a 3rd order denominator of transfer function. The course of its Nyquist diagram begins in the positive part of the real axis and its end is in zero after crossing of three quadrants. Two of these quadrants are in the left side of the complex plane. The gain of the controller must be low because the Popov line must be on the left side of the Nyquist diagram curve. This Popov line has a large distance to an imaginary axis [6],[10].

When we are also using temperature derivation as one from two output values, the linear part of the heated system has a 2nd order denominator of transfer function. The course of its Nyquist diagram begins in the positive part of the real axis and its end is in zero after crossing of the two quadrants. Only one of those quadrants is on the left side of the complex plane. The gain of the controller may be high because the Popov line on the left side of the Nyquist diagram curve has a small distance to an imaginary axis. The high gain value of the controller improves the properties of the feedback system [8],[9].

The gain size of the controller can be calculated quickly if we are using the Popov criterion. We need only to draw the curves of Nyquist diagrams of the linear part of the heated system. This drawing is not so simple without using the PCif time delay Td has a plumbless value.

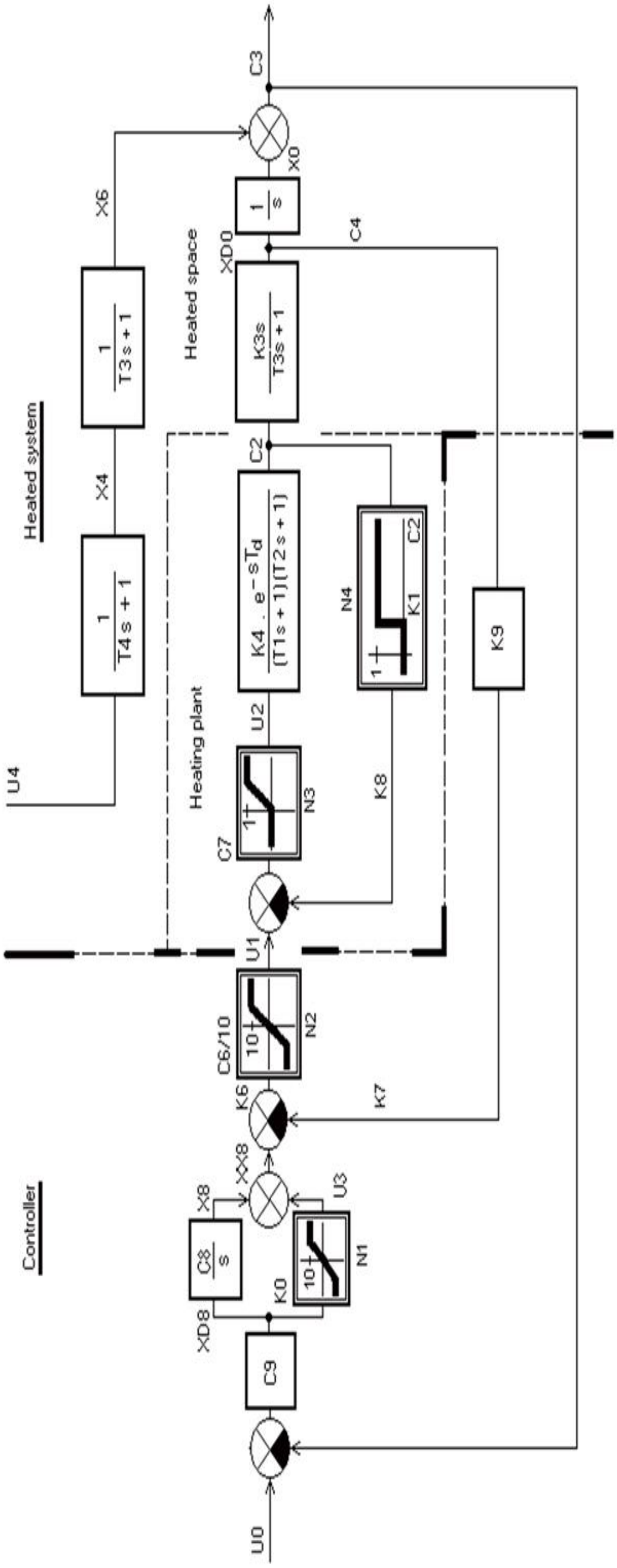

Figure2. Thermal system with temperature and temperature derivation feedback

4. Results of the simulation

The PC simulation of the thermal system in Figure 2.was made by using aspecial SDS software (Simulator of Dynamic Systems) in Turbo Pascal. This original program gives possibility to simulate linear and non-linear continuous systems with and without time delays.

The parameters of simulated systems are following:

U_0 = 20 °C – desired value of space temperature;
U_4 = 0 and −25 °C after 15 hours – outer temperature;
C_6 = 1– gain of the temperature derivation controller;
C_7 = 1– gain of the heater;
C_8 = 1–gain of the integration part of temperature PI controller;
C_9 = 0.1 – gain of the output temperature sensor;
K_0 = 5 –gain of the proportional part of temperature PI controller;
K_1 = 80 – the maximal permitted temperature of heating medium;
K_3 = 0.78 –transfer function's gain of the heated space;
K_4 = 98 – gain of the overall part of the heating plant;
K_9 = 0.3 – gain of the temperature derivation sensor;
T_d = 0.1 hour – time delay, the result of heat transfer by the overflow of the cooling medium;
T_1 = 0.2 hour – time constant of heat transfer between the heater and the cooling medium;
T_2 = 1 hour – time constant of heat transfer in the cooling medium;
T_3 = 2 hours – time constant of the heated space (between the temperature of the surface of the heating body andthe temperature of the heated space);
T_4 = 10 hours – time constant dependingon temperature insulation properties of the wall around the heated space.

Simulation was made for two cases, without the temperature derivation loop (K_9 = 0) and with the temperature derivation loop (K_9> 0). The desired value of space temperature U_0 changed by step from 0 to 20 °C. Outer temperature U_4 had value 0 and after 15 hours −25 °C by step change.

The results of simulations are demonstrated by the following output parameters:

U_1– standard control signal from the controller to the heater, controller output;
U_2– standard value of thermal power from the heater, actuating variable;
U_4– outer temperature (disturbance input);
C_2– temperature of the heating medium;
C_3– inner temperature, the temperature of the heated space (output) with disturbance influence;
XX_8 – output from the temperature PI controller, controller output.

The results of the simulation of the system without the temperature derivation loop (K_9 = 0) are shown in Figure 3. We can see that the course of outputs has damped oscillations and overshoots. The results of the simulation of the system with the temperature derivation loop (K_9= 0.3) are shown in Fig.4. We can see that the outputs have more fluent course, and damped oscillations have little overshoots. The number of overshoots is minimized. Quality control and control speed are improved after application of the temperature derivation feedback.

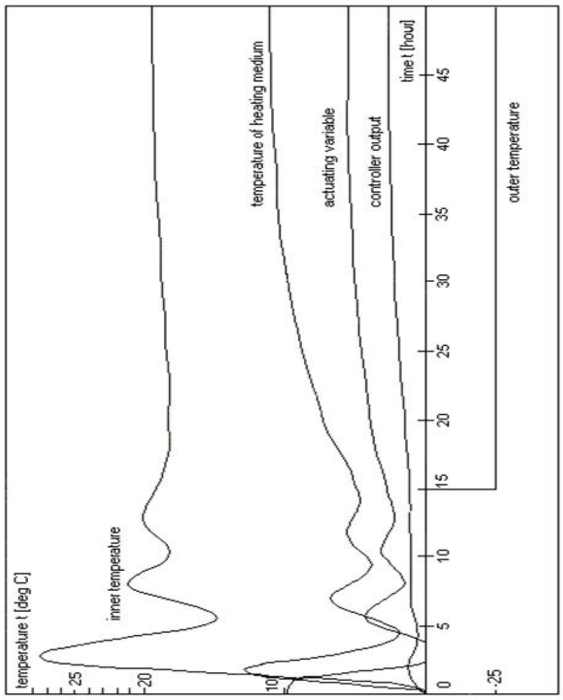

Figure 3. Time responses of the thermal system without temperature derivation loop

Note: It is necessary to multiply the values of variables in relation to the value of the vertical axis scale by the following constants: inner temperature – 1 (°C), temperature of the heating medium – 5 (°C), actuating variable – 0.1 (1), controller output – 2 (V), outer temperature – 1 (°C). This note is valid also for Figure 3.

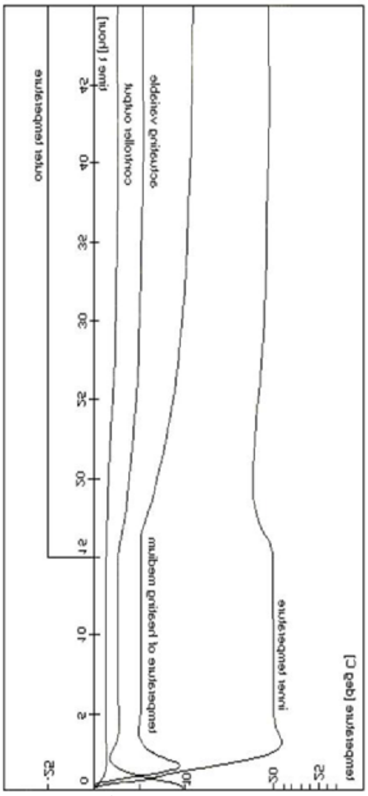

Figure 4. Time responses of the thermal system with temperature derivation loop

5. Conclusion

The paper describes the model and the simulation of the thermal heating system. Thermal systems with automatically controlled temperature represent non-linear systems with thermal inertias and time delay. The controller is also non-linear because its information and power signals are limited. The application of methods that are available to non-linear systems with time delay gives the possibility to reach a suitable solution.

The paper provides a new look at the heated system model and also designs convenient structure of the thermal system. The model of thermal system consists of the model of the heated system and controller with temperature feedback and temperature derivation feedback.The implementation of temperature derivation feedback improves the dynamic properties of the thermal system. The computer simulation and the mathematical modelling of this system give us an opportunity to acquire important information about the researched system. The system was simulated by using the original special software in Turbo Pascal. Time responses of this system are compared to the responses of the conventional thermal system. The thermal system with temperature derivation feedback provides more stability, more convenient transients, better quality of regulation and better dynamical properties. This system has a suitable level of invariance against outer thermal disturbance [5], [6], [7].

The acquisition of temperature derivation signal is a negotiable problem. In case of digital controller, it is a result of subtracting two following samples of temperature signal. The analogous controller needs a special double temperature sensor, where the successive samples of temperature signals are made by temperature insulation of one temperature sensor. Other ways of solution of this sensor are possible and were carried out [15],[16].

The measuring process is usually influenced by effects of measurement settings, so consideration on experimental arrangement and characteristics of samples that can determine the data reliability is necessary. Data reliability can be improved by performing comparison measurements using various methods. Comparison measurements are the key strategy to improve the data reliability. There is also a relation between the real and the ideal experimental arrangement [11],[12],[13].

Acknowledgement

This work is formulated for common use in the area of thermal systems. The main direction of considerations was focused on heating (or cooling) of special portable containers to be used in food industry, medical equipment and the like.

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