Identification of Natural Gas Cooling Process Using Manual Mode of Controller Operation

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Abstract— **This paper describes an experimental identification of nonlinear process of natural gas cooler in CPS Molve III, Podravina. Recording is executed for step changes of the controller output, with different temperatures of disturbance value (regeneration gas). Step changes of controller output are enabled by putting the controller in the manual mode of operation. In that way the recordings are carried out in open loop.**

Optimal values of the transfer functions parameters for different operating points are determined using MATLAB, for transfer functions with dead time and one (FODT) and two time constants (SODT). Since determined parameters of cooler's model change significantly, elaboration and implementation of natural gas temperature adaptive controller is proposed.

I. Introduction

Developing a control system usually begins with finding mathematical description of a system to be controlled. Thereby, a number of different methods of mathematical model determination are developed, some of them analytical and some experimental [1], [2], [3].

Experimental methods have some advantages over analytical methods of mathematical model determination, most of all the simplicity and clarity of the obtained model, which can be used immediately for controller design purposes. Expressive nonlinearities as well as change of conditions and operating regimes complicate analytical procedure of mathematical model determination, making experimental methods more suitable.

The process with expressive nonlinearities (natural gas cooler) and with expressive dead time, along with experimental procedure of mathematical model determination is given and described in [4], [5]. In that papers the response on reference step change is used for determination of cooler's dynamic model and parameters, for different operating conditions. The system is in that way in closed loop, and mathematical model and parameters are determined based on the controller output signal and process output signal.

Accuracy of experimental determination of optimal parameters of cooler's model transfer functions is significantly effected by constant oscillations of cooler input gas, with amplitude around 1 °C and relatively low frequency: 2.2 mHz [4]. Influence of those oscillations on accuracy of determination of optimal parameters of cooler's model transfer functions is partially reduced by increasing controller integral time constant and gain [5].

In this paper manual mode of controller operation is applied, that is transients recording in open loop. In that way transients in cooler are slower and constant oscillations of input gas in cooler are filtered better. Therefore, accuracy of determination of optimal parameters of cooler's model transfer functions is increased.

The optimal dynamic model and parameters are determined using MATLAB [6] and *simplex* optimization method [7] for different disturbance values (temperatures of regeneration gas).

The description and construction of the natural gas cooler in CPS Molve III is given in section II. Results of determination of cooler's dynamic model and parameters in different operation conditions are described in section III. Conclusions are given in section IV, and references are given in final section.

II. Description of natural gas cooling system

CPS Molve III plant, with gas flow capacity of $5 \cdot 10^6$ $\mathrm{m}^3/\mathrm{day}$, is built for preparation of crude gas for transport in INA Naftaplin's backbone gas pipeline system, elimination of noxious substances and separation of valuable hydrocarbons. To perform this task, gas is treated with aMDEA (**M**ethyl **D**i**E**thanol **A**mine) mixture. For separation of sulphur from CO_2 current, Lo-Cat procedure is applied. Besides that, water and mercury are separated from natural gas.

After technological process of CO_2 and H_2S separation in aMDEA system, natural gas enters the cooling section. Input gas temperature in that section reduces from 60 to 32 °C. Besides input gas, a regeneration gas returns to the cooling system input (Fig. 1), with temperature varying from 30 to 270 °C. Cooler's output gas temperature control system consists of controller TIC-3404, asynchronous drive, gearbox, fan, cooler E-3401 and temperature sensor (Fig. 1).

Controller is implemented in the main programmable logic controller (PLC) *Advant Controller 450* (AC 450), from ABB's PLC family. Controller operates the speed of fan via asynchronous drive and frequency converter. Exceptional dynamic performance and accuracy of speed control is achieved by direct torque control (DTC) algorithm.

Temperature controller of the cooler's output gas TIC-3404 is implemented as PID controller via function block PIDCON in ABB Advant Controller 400 Series assembly [8].

III. Identification of natural gas cooler's model parameters

Block schematic of the natural gas cooler E-3401 temperature control system is shown on Fig. 1.

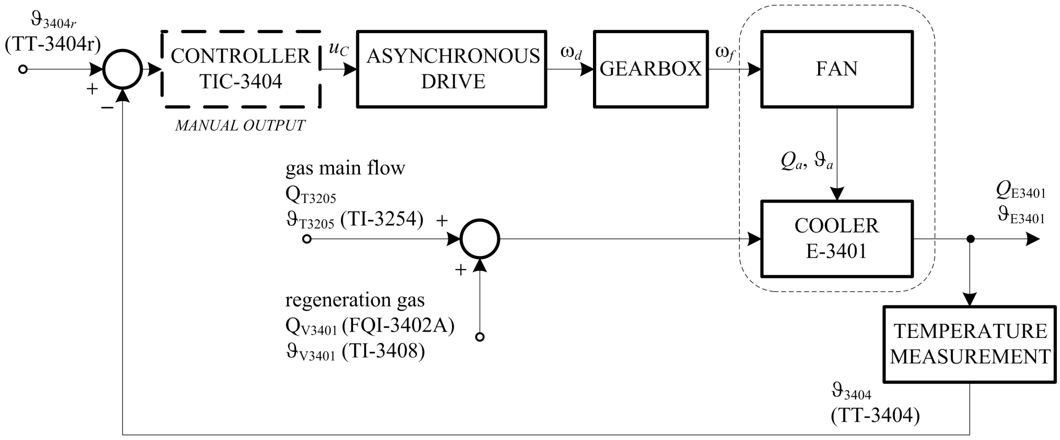

Fig. 1. Block schematic of natural gas cooler E-3401 temperature control system.

The main gas flow at the cooler input Q_{T3205} is approximately constant and equals $Q_{T3205} = 130.000\ \mathrm{m}^3/\mathrm{h}$. The temperature of the main gas flow ϑ_{T3205} oscillates around mean value 60 °C with amplitude 1 °C. Period of oscillations of the main gas flow temperature equals $t_\vartheta = 450$ s ($f_\vartheta = 2.2$ mHz).

Regeneration gas flow through cooler Q_{V3401} is approximately constant and equals $Q_{V3401} = 18.000\ \mathrm{m}^3/\mathrm{h}$, while regeneration gas temperature ϑ_{V3401} significantly changes in range of $\vartheta_{V3401} = 30 - 270$ °C.

Dynamic behavior of the natural gas cooler with asynchronous drives, fans and temperature sensor, can be satisfactorily described with transfer function with dead time T_{dt} and one time constant T_1, or two time constants T_1, T_2:

$$G_{p1}(s) = \frac{\Delta\vartheta_{3404}(s)}{\Delta u_C(s)} = \frac{K_p e^{-T_{dt}s}}{1+T_1 s}, \quad (1)$$

$$G_{p2}(s) = \frac{\Delta\vartheta_{3404}(s)}{\Delta u_C(s)} = \frac{K_p e^{-T_{dt}s}}{(1+T_1 s)(1+T_2 s)}. \quad (2)$$

Dead time T_{dt} represents the time needed for establishment of the airflow through the cooler and it depends on fan speed ω_f:

$$T_{dt} = f_4(\omega_f). \quad (3)$$

Time constant T_1 represents the cooler thermal time constant, which depends on fan speed ω_f, cooling air temperature ϑ_a and regeneration gas temperature ϑ_{V3401}:

$$T_1 = f_5(\omega_f, \vartheta_a, \vartheta_{V3401}). \quad (4)$$

Time constant T_2 represents temperature sensor's time constant:

$$T_2 = T_{TT3404}. \quad (5)$$

Gain coefficient K_c of the cooler with fan and temperature sensor depends on the fan speed ω_f, cooling air temperature ϑ_a and regeneration gas temperature ϑ_{V3401}:

$$K_c = f_6(\omega_f, \vartheta_a, \vartheta_{V3401}). \quad (6)$$

Total gain coefficient of the process unit K_p is equal to the product of asynchronous drive gain coefficient K_{as}, gearbox i, and cooler with fan and temperature sensor K_c:

$$K_p = K_{as} \cdot i \cdot K_c. \quad (7)$$

Because of the gain coefficient K_p, dead time T_{dt} and time constant T_1 dependence on regeneration gas temperature ϑ_{V3401} and air temperature ϑ_a, values of those parameters are determined experimentally from responses to step change of the controller output value u_C, for different values of regeneration gas temperature ϑ_{V3401}.

The waveforms of the cooler and heater temperatures, their controller outputs, temperatures of the main and regeneration gas, regeneration gas flow, recorded with mean value of the main gas flow $132,255\ \mathrm{m}^3/\mathrm{h}$ and mean value of the outside air temperature 0.6 °C are shown on Fig. 2.

The meanings of gauge signals, shown with different colors on Fig. 2, are displayed in TABLE I.

Recorded data about initial (0) and final (∞) values of the temperature controller output u_C, gas temperature at the cooler output ϑ_{3404} and regeneration gas temperature ϑ_{3408}, for transients shown on Fig. 2, are given in TABLE II.

Optimization of the model's transfer function parameters (1) and (2) is carried out using program package MATLAB, *simplex* optimization method [6], [7] and recorded transients of the system. Block schematic for organizing optimization of model parameters in MATLAB is given on Fig. 3. Integral square error criterion was used for optimization.

The responses of controller output change Δu_C, cooler output gas temperature $\Delta\vartheta_{3404}$, cooler's model temperature $\Delta\vartheta_{M3404}$ and error e for transfer function $G_{p1}(s)$ (1) and conditions from TABLEs II and III are shown on Fig. 4-8.

Obtained results for second order transfer function with dead time (SODT) $G_{p2}(s)$ (2), for transients shown on Fig. 2, are given in TABLE IV.

Obtained results for first order transfer function with dead time (FODT) $G_{p1}(s)$ (1), for transients shown on Fig. 2, are given in TABLE III.

The responses of controller output change Δu_C, cooler

TABLE I
EXPLANATIONS OF GAUGE SIGNALS SHOWN ON FIG. 2.

Label	Element	Description
FER02	TI-3408	regeneration gas temperature
FER03	TT-3404	cooler's output gas temperature
FER05	TT-3422	heater's output gas temperature
FER06	TIC-3404 OUT	cooler's controller output
FER07	TIC-3422 OUT	heater's controller output

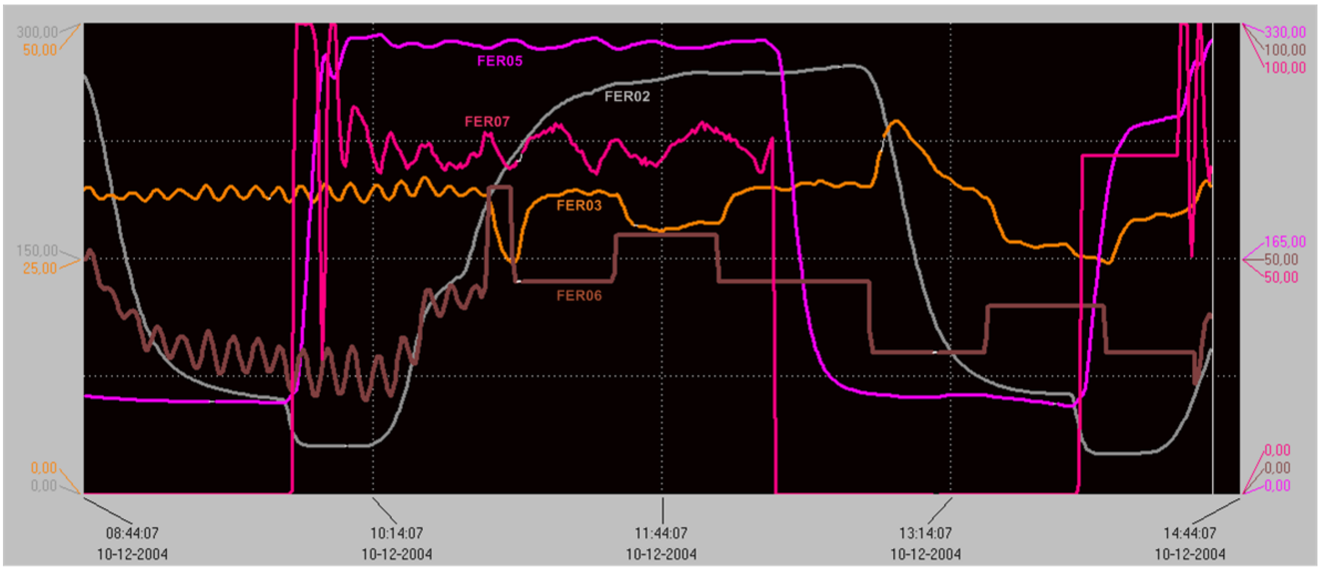

Fig. 2. Process values transient waveforms recorded with mean values of main gas flow $132,255\ \mathrm{m}^3/\mathrm{h}$ and outside air temperature $0.6\ °\mathrm{C}$.

TABLE II
CONDITIONS FOR DIFFERENT OPERATING POINTS SHOWN ON FIG. 2.

	u_C [%]		ϑ [°C]		
N^o	$u_C\,(0)$	$u_C\,(\infty)$	$\vartheta_{3404}\,(0)$	$\vartheta_{3404}\,(\infty)$	$\vartheta_{3408}\,(0)$
1	65	45	24.6	31.7	214
2	45	55	31.7	28.7	261
3	55	45	28.7	32.7	268
4	30	40	31.5	26.6	73
5	40	30	24.8	29.1	26

TABLE III
PARAMETERS OF TRANSFER FUNCTION $G_{p1}(s)$ (1) DETERMINED USING MATLAB FOR OPERATING POINTS GIVEN IN TABLE II.

N^o	K_p	T_1 [s]	T_{dt} [s]	e_m [%]	Fig.
1	−0.367	170.5	100.5	5.27	4
2	−0.326	104.7	133.7	14.3	5
3	−0.405	233.6	79.05	11.8	6
4	−0.515	166.3	121.1	11.1	7
5	−0.456	168.4	176.5	8.67	8

TABLE IV
PARAMETERS OF TRANSFER FUNCTION $G_{p2}(s)$ (2) DETERMINED USING MATLAB FOR OPERATING POINTS GIVEN IN TABLE II.

N^o	K_p	T_1 [s]	T_2 [s]	T_{dt} [s]	e_m [%]	Fig.
1	−0.367	165.6	23.93	79.61	4.59	9
2	−0.326	68.20	68.20	98.64	14.2	10
3	−0.405	233.2	6.102	73.16	12.0	11
4	−0.512	103.0	103.0	71.05	4.76	12
5	−0.442	94.37	94.37	136.4	5.69	13

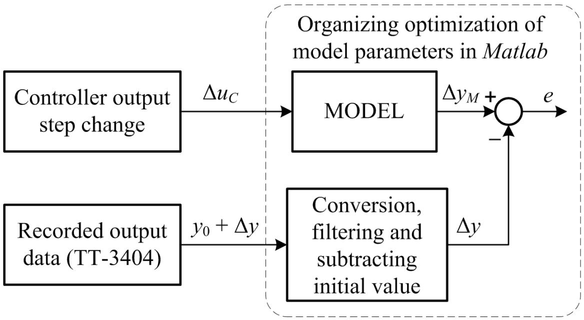

Fig. 3. Block schematic for organizing optimization of model parameters.

output gas temperature $\Delta\vartheta_{3404}$, cooler's model temperature $\Delta\vartheta_{M3404}$ and error e for transfer function $G_{p2}(s)$ (1) and conditions from TABLEs II and IV are shown on Fig. 9-13.

The jaggy responses of the error e on Fig. 4 – 13 are caused by signal quantization in the procedure of A/D conversion.

Comparison of results given in TABLEs III and IV shows that maximum error e_m is smaller for transfer function $G_{p2}(s)$ (TABLE IV) than for $G_{p1}(s)$ (TABLE III). Besides that, maximum error value in the beginning of transient is smaller for transfer function $G_{p2}(s)$ (Fig. 9 – 13) than for transfer function $G_{p1}(s)$ (Fig. 4 – 8). Therefore, transfer function $G_{p2}(s)$ approximates the dynamic behavior of natural gas cooler better than transfer function $G_{p1}(s)$.

Errors of cooler's model $G_{p1}(s)$ and $G_{p2}(s)$, which occur in the cooler after steady state establishment (Fig. 4 – 13), are caused by constant oscillations of the cooler input gas. However, those errors are smaller than in the case of recording transients in the closed loop and step change of the temperature reference value [4], [5].

IV. CONCLUSION

In this paper a procedure of experimental determination of optimal parameters of natural gas cooler dynamic model, using manual mode of controller operation and step change of controller output, is described and obtained results are presented. In that way the recording of transients is carried out in the open loop, without controller action. Thereby, the transient in the cooler is slower, resulting in better filtering of the constant gas temperature low frequency oscillations at the cooler input. In that way higher accuracy of determination of cooler's model optimal parameters is achieved, than in the case of transients recording in the closed loop.

The recording of the controller output and cooler output

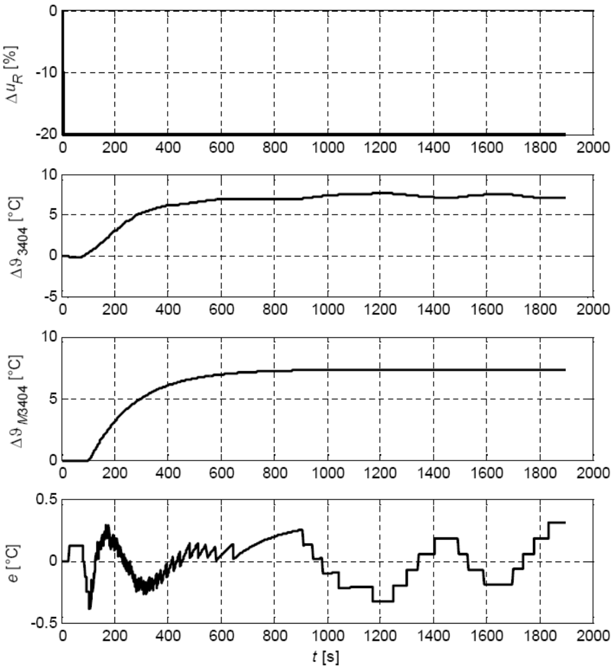

Fig. 4. Responses of change of cooler's output temperature $\Delta\vartheta_{3404}$ (TT-3404), cooler's model output $G_{p1}(s)$ $\Delta\vartheta_{M3404}$ and error e with parameters N^o 1 from TABLEs II and III.

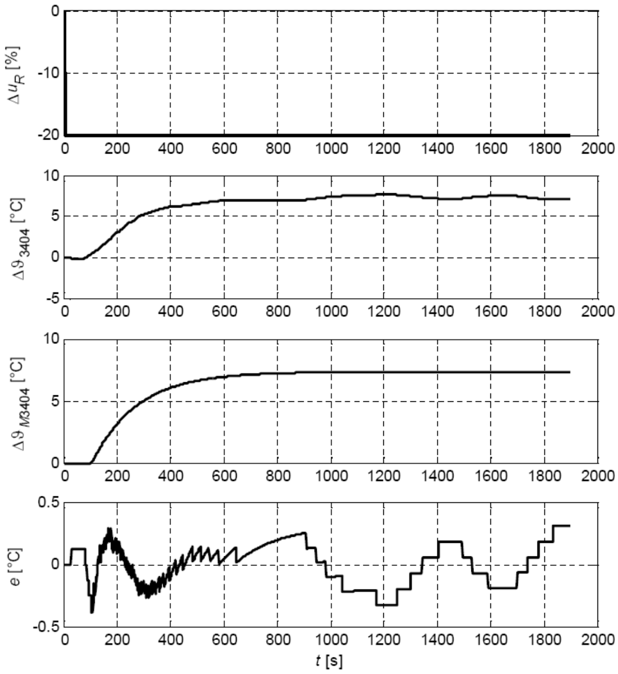

Fig. 5. Responses of change of cooler's output temperature $\Delta\vartheta_{3404}$ (TT-3404), cooler's model output $G_{p1}(s)$ $\Delta\vartheta_{M3404}$ and error e with parameters N^o 2 from TABLEs II and III.

gas temperature transients is carried out with different temperatures of regeneration gas (disturbance). Optimal parameters of cooler's dynamic model is determined using MATLAB and *simplex* optimization method.

Optimal values of cooler's dynamic model parameters are determined for transfer functions with dead time T_{dt} and one time constant T_1 (FODT) $G_{p1}(s)$ as well as with dead time T_{dt} and two time constants T_1, T_2 (SODT) $G_{p2}(s)$.

The results of experimental determination of cooler's dynamic model optimal parameters show that maximum error value e_m is smaller for the transfer function $G_{p2}(s)$ (SODT), than for the transfer function $G_{p1}(s)$ (FODT). Furthermore, with the transfer function $G_{p2}(s)$ error e is considerably smaller, that is, approximation of the real natural gas cooler in the beginning of the transient is better than with the transfer function $G_{p1}(s)$. Maximum error value of cooler's model with the transfer function $G_{p2}(s)$ occurs after the establishment of steady state and it is caused by constant oscillations of gas temperature at the cooler input.

Maximum error values of cooler's dynamic models $G_{p1}(s)$ and $G_{p2}(s)$ are in the range of $5-14\%$, so it can be considered that both transfer functions approximate cooler's dynamic beavior equally well.

Obtained results show that parameters of cooler's dynamic model $G_{p1}(s)$ and $G_{p2}(s)$ change significantly by change of regeneration gas temperature. This points out that for achieving approximately the same cooler's dynamic behavior in all operating conditions it is necessary to apply one of the adaptive control methods (gain scheduling, reference model with signal adaptation or self-tuning controller).

ACKNOWLEDGEMENT

The authors would like to thank Ivan Meandzija and Nikola Tufegdzic of the INA Naftaplin for their support in acceptance of research program. Special thanks to Mijo Sobota and Djordje Babic of the INA Naftaplin, and Josip Crnkovic for their cooperation and help in organization of process values recording and great technical support, because without them, this paper would not exist.

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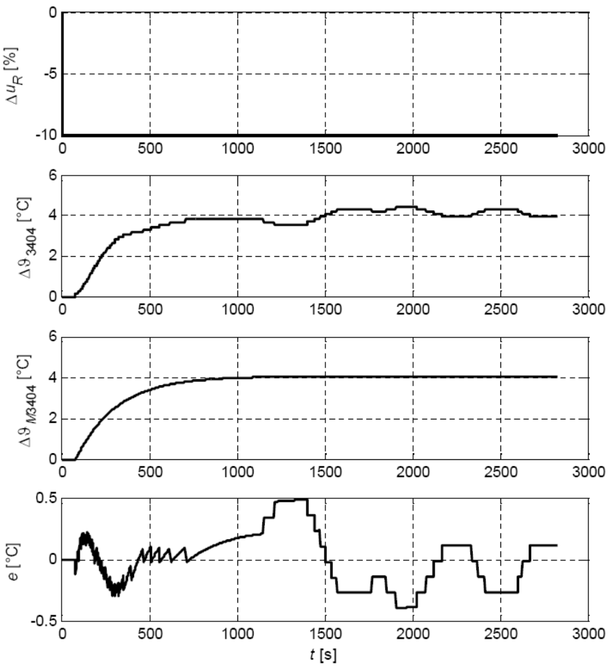

Fig. 6. Responses of change of cooler's output temperature $\Delta\vartheta_{3404}$ (TT-3404), cooler's model output $G_{p1}(s)$ $\Delta\vartheta_{M3404}$ and error e with parameters N^o 3 from TABLEs II and III.

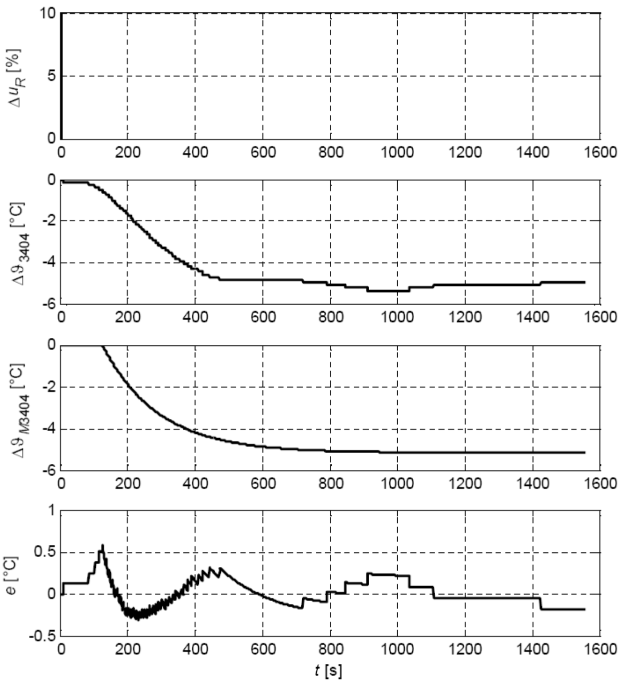

Fig. 7. Responses of change of cooler's output temperature $\Delta\vartheta_{3404}$ (TT-3404), cooler's model output $G_{p1}(s)$ $\Delta\vartheta_{M3404}$ and error e with parameters N^o 4 from TABLEs II and III.

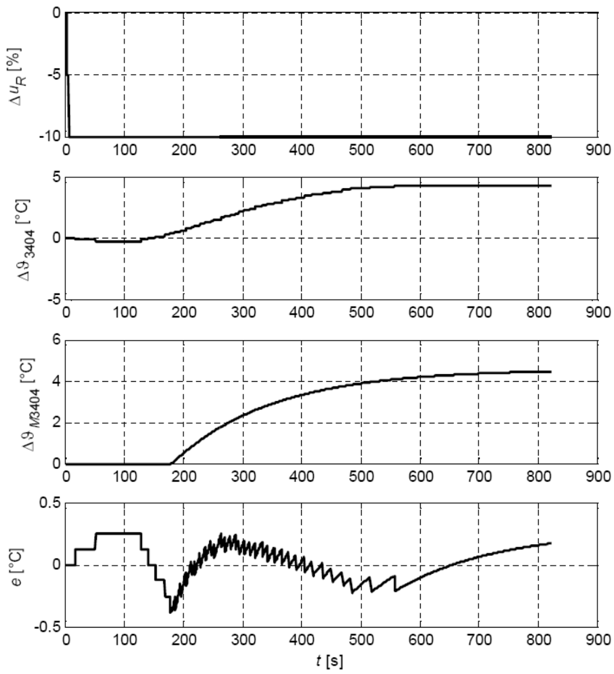

Fig. 8. Responses of change of cooler's output temperature $\Delta\vartheta_{3404}$ (TT-3404), cooler's model output $G_{p1}(s)$ $\Delta\vartheta_{M3404}$ and error e with parameters N^o 5 from TABLEs II and III.

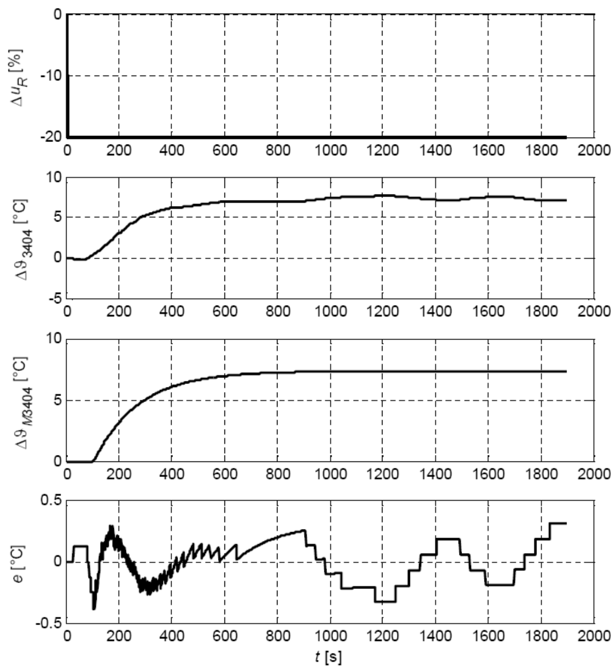

Fig. 9. Responses of change of cooler's output temperature $\Delta\vartheta_{3404}$ (TT-3404), cooler's model output $G_{p2}(s)$ $\Delta\vartheta_{M3404}$ and error e with parameters N^o 1 from TABLEs II and IV.

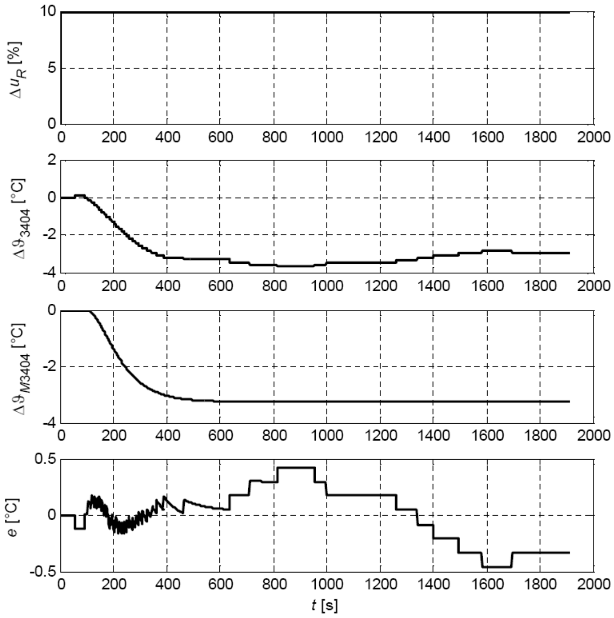

Fig. 10. Responses of change of cooler's output temperature $\Delta\vartheta_{3404}$ (TT-3404), cooler's model output $G_{p2}(s)$ $\Delta\vartheta_{M3404}$ and error e with parameters N^o 2 from TABLEs II and IV.

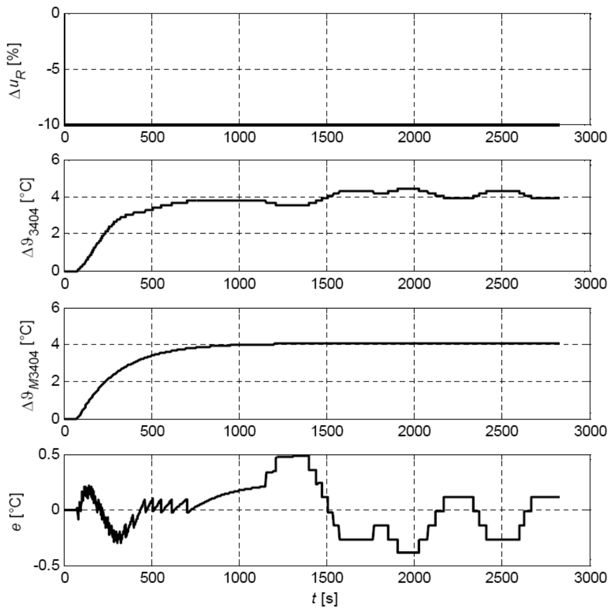

Fig. 11. Responses of change of cooler's output temperature $\Delta\vartheta_{3404}$ (TT-3404), cooler's model output $G_{p2}(s)$ $\Delta\vartheta_{M3404}$ and error e with parameters N^o 3 from TABLEs II and IV.

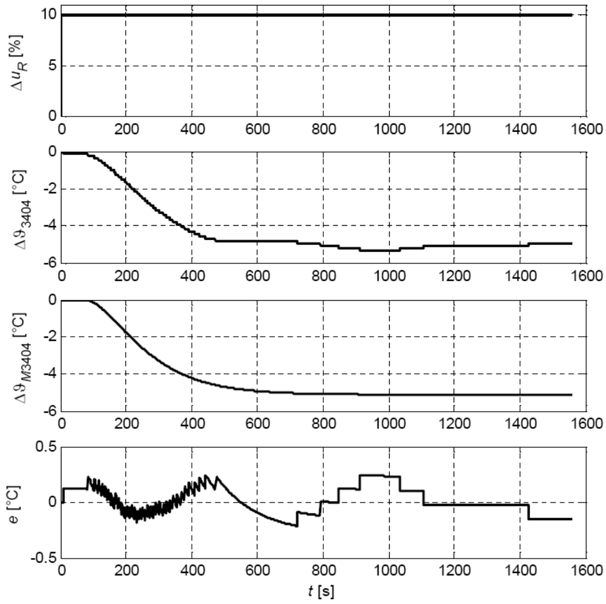

Fig. 12. Responses of change of cooler's output temperature $\Delta\vartheta_{3404}$ (TT-3404), cooler's model output $G_{p2}(s)$ $\Delta\vartheta_{M3404}$ and error e with parameters N^o 4 from TABLEs II and IV.

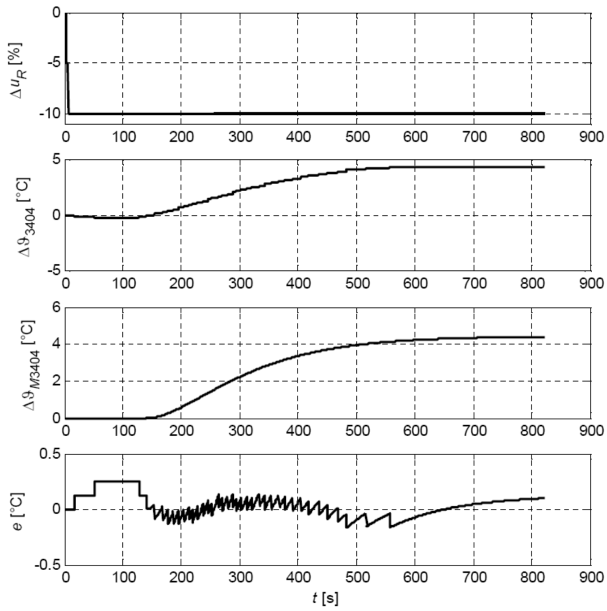

Fig. 13. Responses of change of cooler's output temperature $\Delta\vartheta_{3404}$ (TT-3404), cooler's model output $G_{p2}(s)$ $\Delta\vartheta_{M3404}$ and error e with parameters N^o 5 from TABLEs II and IV.