

# Application of an Automated Cascade Temperature Control System in a Fluidized Bed Spray Dryer

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## Abstract:

This article analyzes the temperature control in the fluidized bed of a drying plant, using a cascade automatic control system, studied in ideal and production conditions. The system provides high quality control indicators while maintaining good stability and meeting the set technological requirements. For automatic control of the fluidized bed dryer, a DeltaV - Emerson digital automatic process control system was used. The control object was approximated to a model, with the help of which numerous simulations were implemented in order to select the most effective structure and parameters of the control regulators. The adjustment of the automatic control system in production conditions improves the quality of control, allowing to track, analyze and compensate for disturbing effects. The commented system has been implemented in real operating conditions, works well and provides an opportunity to optimize the drying process, in search of the best technical and economic indicators of the specific production.

**Keywords — Cascade control system, Fluidized bed dryer, Temperature, DeltaV**

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## I. INTRODUCTION

Modern trends in the development of technological processes in industry are characterized by the introduction of new technologies aimed at increasing the efficiency of technical facilities, structures and systems. New principles, design solutions, software innovations are being sought to optimize the operation of automatic control systems. The potential capabilities of new technologies are realized in operating conditions in combination with modern regulation and control systems [3].

The main indicators that determine the quality of regulation of an automatic control system are its static and dynamic accuracy. In the classical theory of automatic control, a number of methods for optimizing the parameters of typical regulators or compensating units are known.

The main disadvantage of conventional approaches is that they are based on an

approximation of the real control object to a mathematical model, which is based on known approximations. The identification model does not always adequately represent the characteristics of a real technological process or object, for a number of reasons, such as the introduction of simplifying assumptions when choosing the model, changes in the load on the control object, the complexity of the object and the inability to take into account all interrelated parameters of the system.

In industry, drying processes are used to separate a certain amount of moisture from solid, liquid and/or pasty materials in order to improve their quality, extend the shelf life of products, as well as for the purposes of subsequent technological operations in production [4].

Spray drying is a proven, highly effective approach that has become established in practice. It is mainly used for drying various types of solutions and emulsions. From a management perspective, it is considered a single-stage continuous process in which a transportable solution is converted to a

powder with desired or optimized quality parameters [1, 5, 6, 7, 8].

The aim of this paper is to present a cascade system for automatic temperature control in a fluidized bed spray dryer. The real control object (the dryer) is represented by an approximate structural model, for which several studies have been carried out in search of the most efficient structure of the cascade system.

## II. AUTOMATED PROCESS CONTROL IN A FLUIDIZED BED SPRAY DRYER

Fig. 1 shows a schematic diagram of a fluidized bed spray dryer. The process product, which is stored in a tank, is pumped by a pump  $M_{101\_225}$ , which provides a constant pressure of the product, to a high-pressure pump  $M_{101\_300}$ . The pump  $M_{101\_300}$ , in turn, transports the product to spray nozzles in the upper part of the chamber. Drying is carried out by finely spraying the feed liquid into

the drying chamber, through which hot air passes [7].

The drying process is relatively fast due to the large surface area of the liquid droplets created by the fine atomization of the pressure nozzles [7]. Although high inlet air temperatures are often used, the product temperature remains low during the process due to rapid evaporation. To avoid powder burning in the spray zone, the system is equipped with cooling by external air supplied by a fan  $M_{103\_140}$ .

The powdered material enters the lower part of the drying chamber, where a fluidized bed is formed. The air for forming the fluidized bed is sucked in by a fan  $M_{107\_430}$ , passes through a filter, is heated by a heat exchanger (with steam) and is supplied to the lower part of the drying chamber, passing through a specially designed gas distributor. A previously prepared bonding agent is sprayed onto the fluidized bed using a double nozzle pump  $M_{108\_110}$ . As a result, the fine particles agglomerate.

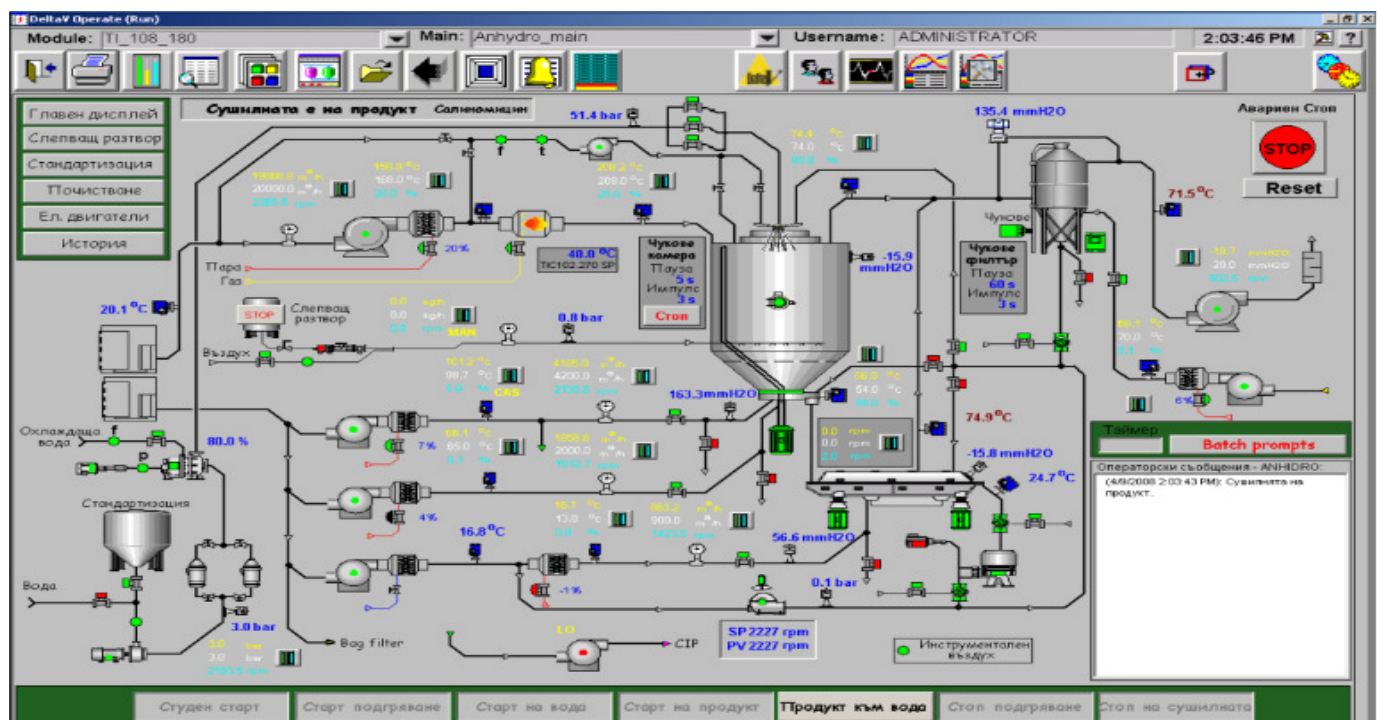


Fig.1. Schematic diagram of the spray dryer

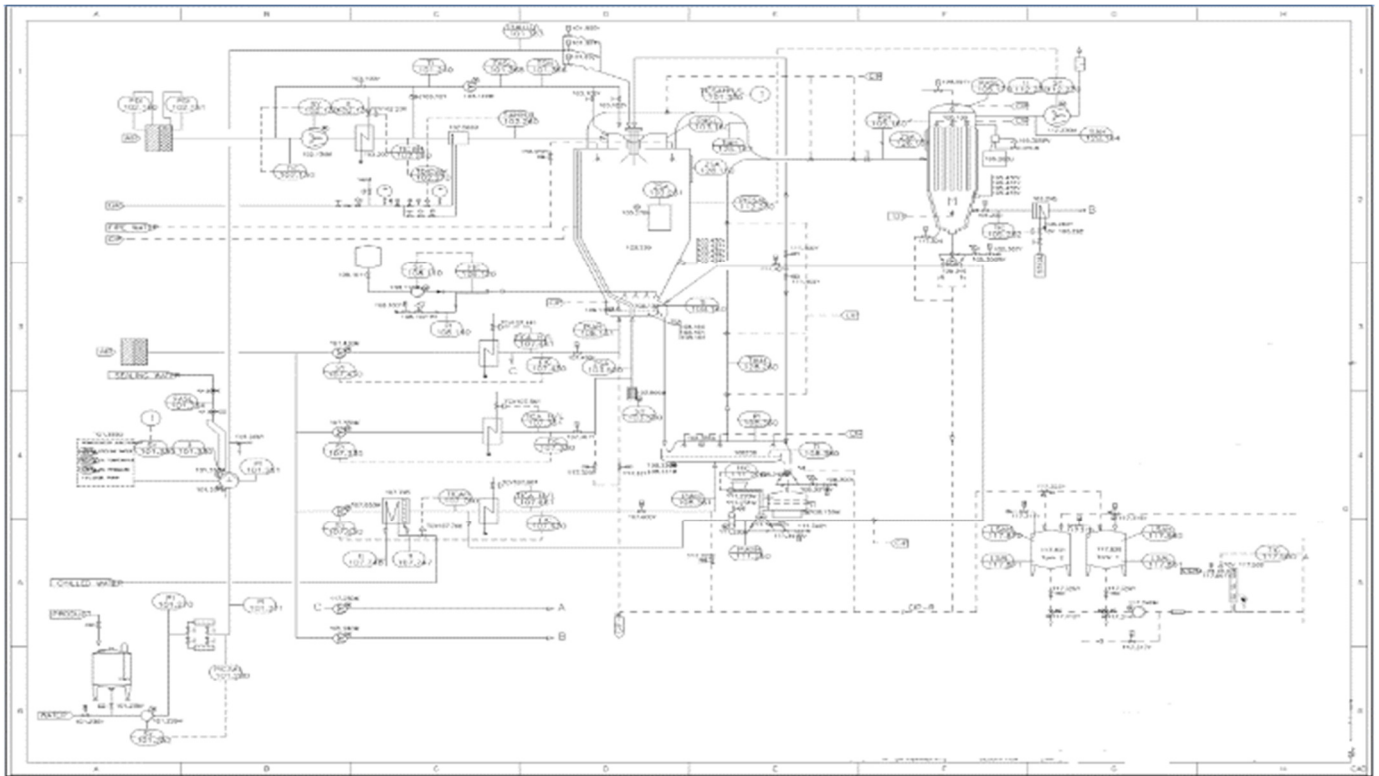


Fig.2. Structural diagram of technological equipment

The powder and fines do not leave the process until they have grown to a certain desired diameter. The grown granules pass through a valve (barrier) into an external fluidized bed, to cool the granules and improve their stability. By means of a screening machine, the product leaving the external fluidized bed is separated into three fractions: finished product, coarse and fine particles.

Fine particles are recirculated in the installation. The dried dust is separated from the exhaust air using a dust cyclone filter, which is removed from the installation by a fan  $M_{112\_230}$ . The dust produced by the cyclone filter is recirculated in the installation using circular airlocks and a cooling transport installation.

When managing the above-mentioned installation, it is necessary to control and regulate numerous variables, such as the air flow rate, the temperature regimes in the different zones of the dryer, the height of the fluidized bed, the retention time, etc. The thermodynamic state of the drying agent is of decisive importance for the course of the drying and granulation process [2]. The drying agent is a mixture of air and drying gases obtained in the

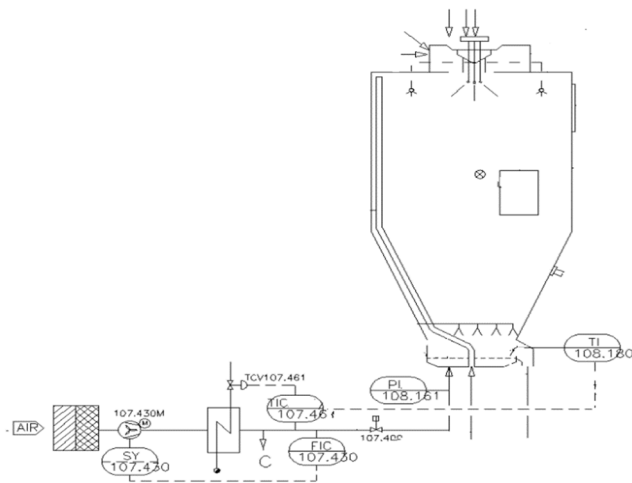
combustion chamber, where the temperature controller  $TIC_{102\_260}$  provides optimal combustion conditions. The incoming air flow is stabilized by a flow controller  $FIC_{102\_130}$ , changing the frequency of rotation of the power machine (pressure fan). The temperature of the exhaust air from the combustion chamber is regulated by a frequency controller  $TIC_{101\_330}$ , changing the amount of material supplied for drying. The controller actually changes the speed of the high-pressure pump  $M_{101\_300}$ .

The air flows under the grate, to the pneumatic broom and to the external fluidized bed are controlled by the flow controllers  $FIC_{107\_430}$ ,  $FIC_{107\_330}$  and  $FIC_{107\_630}$ , changing the rotation frequency of the respective power machine. The pressure in the chamber is maintained close to the set value by means of the  $PIC_{112\_230}$  controller, changing the speed of the outlet fan after the cyclone filter. This controller also helps to purify the air from small fractions. The temperature for heating the cyclone filter and the air to the broom are controlled by the  $TIC_{105\_262}$  and  $TIC_{107\_363}$  controllers, changing the position of the steam

valves to the respective heat exchangers, at a constant flow rate of the supply air flow.

One of the main difficulties in the automation of drying processes is the determination of the humidity of the dried material. At this stage, there is no methodology that would determine this humidity unambiguously. Therefore, it is necessary to monitor the parameters of the drying agent during the technological process, which are indirectly related to the humidity of the processed material [3].

The temperature in the fluidized bed is an indicator that to some extent characterizes the initial moisture content of the material and is therefore one of the main adjustable parameters in the system [3]. Fig. 3 shows a diagram of the cascade automatic control system used to control the temperature  $TI_{108,180}$  in the internal fluidized bed of the drying plant.



$M_{107,430}$ – rotary fan;	$TCV_{107,461}$ – actuator (valve);
$SY_{107,430}$ – rotary fan speed sensor;	$PI_{108,161}$ – pressure sensor;
$FIC_{107,430}$ – flow sensor and regulator;	$TI_{108,180}$ – temperature sensor.
$TIC_{107,460}$ – temperature sensor and controller;	

Fig. 3. Structural diagram of a cascade system for automatic temperature control in the fluidized bed

The rotary fan  $M_{107,430}$  supplies warm air to the drying installation. The temperature of this air flow is regulated by changing the amount of steam supplied to the heat exchanger. If the control system is single-circuit, depending on the deviation of the temperature in the fluidized bed from the setpoint, the regulator in the module  $TI_{108,180}$  changes the amount of steam supplied to the heat exchanger. Disturbing effects in the system such as: change in

steam pressure, unforeseen changes in the flow rate of warm air, etc., in a single-circuit system must be compensated by the regulator  $TI_{108,180}$ .

To structure a cascade control system, an additional loop with a regulator  $TIC_{107,461}$  has been added, the purpose of which is to stabilize the temperature of the warm air under the grate. The regulator  $TI_{108,180}$  changes the setpoint of the slave regulator  $TIC_{107,461}$  depending on the temperature change in the fluidized bed. In this case, whatever disturbances occur at the entrance to the object, the regulator  $TIC_{107,461}$  will be activated and will minimize the influence of the disturbing effects on the regulated value.

When optimizing the technological process of drying, it is necessary to take into account many indicators, such as the composition of the material to be dried, the flow rate and temperature of the drying agent, the temperature and composition of the fluidized bed, etc. To achieve effective indicators such as the humidity of the dried material, drying speed, maximum use of the input thermal energy, various regulating effects are applied [7]. From a technical and economic point of view, they are not at all equivalent, which turns the issue of increasing the efficiency of automatic control of the technological regime into a significant case.

### III. STUDYING THE INFLUENCE OF THE REGULATOR ON THE QUALITY OF TRANSIENT PROCESSES IN A CLOSED SYSTEM

The spray dryer described above is considered as a control object in a closed-loop automatic control system. After a number of mathematical transformations, the control object operating under low-frequency disturbances is approximated by a feedforward function of the form:

$$W_{obj}(p) = \frac{1.7e^{-\tau_{obj} \cdot p}}{35p+1} \quad (1)$$

The derived transfer function was simulated in the MatLab environment, examining the behavior of the system under proportional (P-), integral (I-) or proportional-integral (PI-) control laws, respectively.

**A. Proportional regulation law (P):**

$$W_p(p) = K_p \tag{2}$$

where  $K_p$  is the gain of the regulator.

The proportional controller synthesizes a regulating effect proportional to the regulation error. Its functioning is usually associated with the presence of a regulation error, the so-called droop.

This type of controller (P) does not increase the order of the differential equation and does not introduce phase shifts into automatic regulation systems.

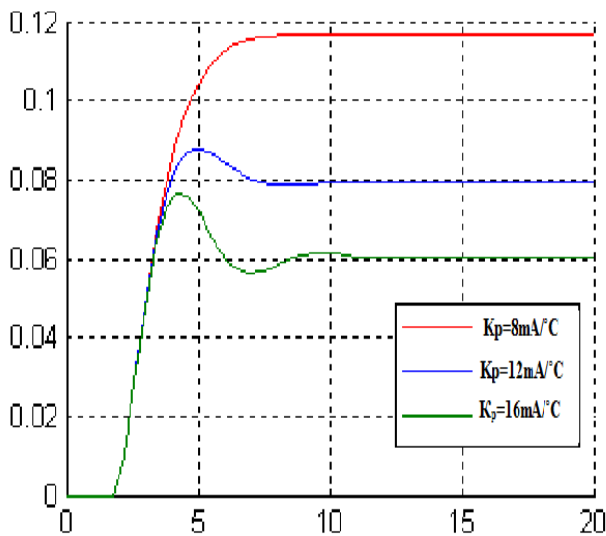


Fig. 4. Transient processes under disturbance in an automatic control system with a P controller

The influence of the proportionality coefficient  $K_p$  of the regulator on the quality of transients in the system has been studied. The simulation has been performed for three values of the proportionality coefficient.  $K_p = 8mA/C$ ,  $K_p = 12mA/C$  and  $K_p = 16mA/C$ , when applying a disturbance to the input of the control object.

It can be seen that as  $K_p$  increases, the static error in the system decreases. At the same time, the duration, overshoot, and oscillation of the transient process increase. From the transient analysis it can be argued that for the analyzed object, the proportional control law will lead to a larger static error, which can be reduced by larger values of the proportionality coefficient. But in such a case we risk a longer transient process with small stability margins.

**B. Integral regulation law (I).**

Integral regulators implement a proportional relationship between the speed of movement of the regulating element and the input effect (regulation error). The transfer function of an I - regulator has the form:

$$W_r(p) = \frac{k_p}{p} = \frac{1}{T_i p} \tag{3}$$

where  $K_p$  is the proportionality coefficient of the regulator, and  $T_i$  - integration time constant. The latter has a time dimension and represents the period for which the regulator processes at its output a quantity equal in value to the input [3].

The influence of the integration time constant and the quality of the transients was investigated at  $T_i = 8, 15$  and  $30$  sec.

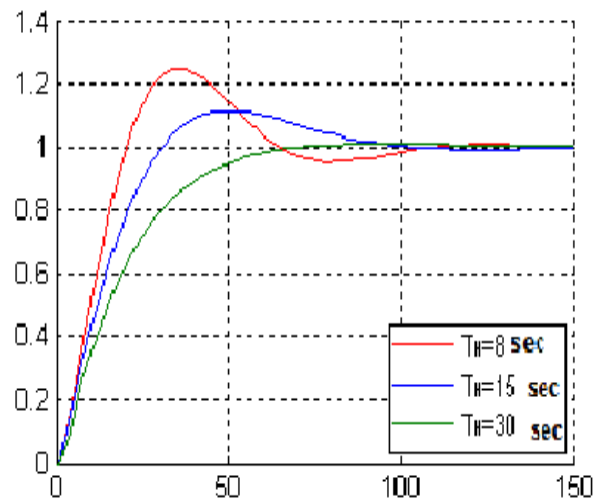


Fig. 5. Transient processes under disturbance in an automatic control system with a I controller

From Figure 5 it is seen that with increasing the value of the integration time constant, the duration of the transient process decreases. The overshoot and oscillation are also lower, compared to proportional control. With decreasing  $T_i$ , the damping coefficient decreases, i.e. the oscillation of the transient process becomes very pronounced, but the maximum dynamic deviation decreases. The absence of static error is also noted, which can be indicated as an advantage of the integral regulator.

### C. Proportional-integral (PI) control.

Proportional-integral controllers are one of the most commonly used. In this type of regulation, a signal is generated at the regulator output that is proportional to both the deviation of the regulated quantity from the set value and the integral of this deviation over time. The speed of movement of the regulating element is proportional to the sum of the regulation error and its first derivative.

The transfer function of the PI - controller has the form:

$$W_r(p) = k_p + \frac{k_p}{T_i p} = k_p \left( \frac{T_i p + 1}{T_i p} \right) \quad (4)$$

The PI controller combines the positive qualities of both the proportional and integral control laws.

Fig. 6 presents a simulation of the transients obtained at a proportionality factor  $K_p = 3 \text{ mA}^\circ\text{C}$  and time constant  $T_i = 3, 10$  and  $20 \text{ sec}$ .

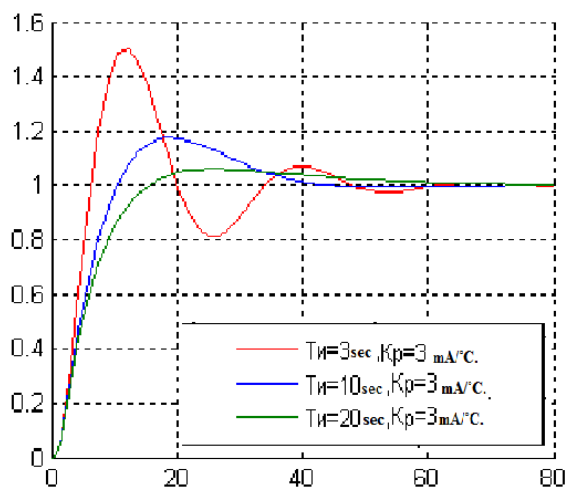


Fig. 6. Transient processes under disturbance in an automatic control system with a PI controller

As  $K_p$  increases, the maximum dynamic deviation, the oscillation frequency, and the duration of the transient process increase. While as the integration time constant increases, the values for the maximum dynamic deviation and the oscillation frequency decrease.

The presence of two tuning parameters ( $K_p$  and  $T_i$ ) provides significantly greater opportunities for improving the quality of transient processes. The PI - regulators achieve better speed of operation due to the presence of the P - component.

### IV. IMPLEMENTATION OF THE CASCADE MANAGEMENT SYSTEM

Cascade-connected systems have two regulators and one regulating body. The output effect from the first regulator  $W_{p1}(p)$ , called the main (correcting), is fed as a task to the second regulator  $W_{p2}(p)$ , called the auxiliary (stabilizing), which forms the regulating effect entering the input of the object. There are two regulation loops – internal and external. The external loop is the main one, and the internal one has an auxiliary meaning.

The adjustment of the cascade system is significantly more difficult than in single-circuit systems, because two regulators must be adjusted.

The large variety of dryers and the relatively poor knowledge of the heat and mass transfer processes in the different designs leads to the need to apply experimental identification methods [7].

In this article, the *DeltaV Tune* software product is used to study the performance of a real cascade system under operational conditions. The program is based on the *Aström-Hägglund* method and performs automatic tuning of the implemented PI-controllers based on the relay oscillation principle. *Emerson Process Management* supports the tuning algorithm with a patented technique for identifying the process time delay.

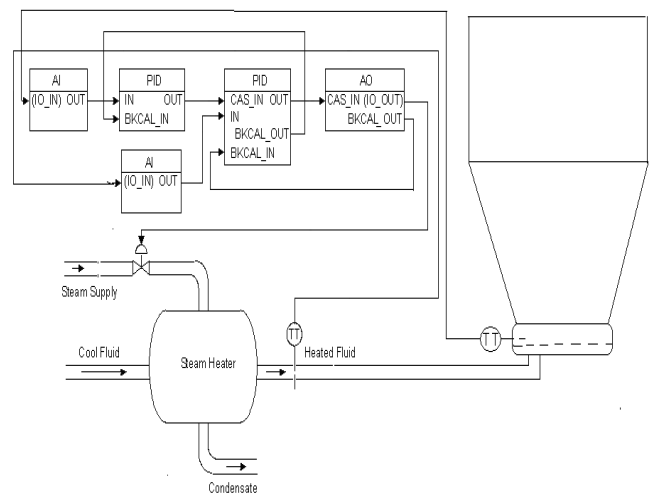


Fig. 7. Functional block diagram of the realized cascade control system

The cascade system (Fig. 7) of the real control loop is built from two modules. One TIC<sub>107\_461</sub> module, in this case a stabilization loop, consists of a temperature transmitter (TT) for the air after the



The internal loop is characterized by inertia, but relatively less than the external one. In normal operation of the installation, when the external loop is turned off, the internal loop is set and operates in automatic mode. The temperature in the external fluidized bed  $TI_{108\_180}$  is measured, resulting in an overregulation (Fig. 10), it is necessary to constantly change the setpoint of  $TIC_{107\_461}$  until satisfactory accuracy is achieved. Temperature control  $TI_{108\_180}$  through a cascade simplifies the work on the system.

Fig. 11 shows the operator display of the PID block for the inner loop. The parameters for adjustment are selected from the detailed display of the regulator.  $K_p=0.6 \text{ mA}/^\circ\text{C}$  and  $T_i=159 \text{ sec}$ , so that the process is stabilized and the installation functions sustainably.

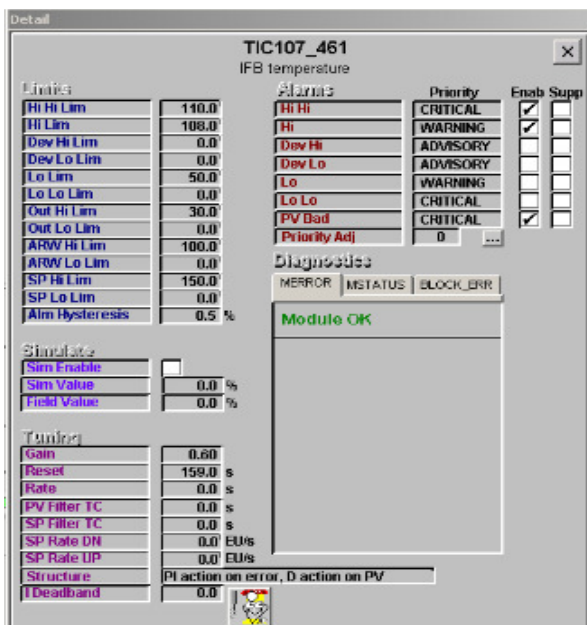


Fig. 11. Detailed display with indicated limit values, alarm levels and controller settings

The controller tuning for the respective loop is started when the current value (PV) is acceptably stable, close to the set point (SP). Disturbing influences in the experimented loop are the change in the feed steam pressure and the air flow rate. They have a significant influence on the air temperature under the grate, and therefore on the air temperature in the fluidized bed. If the controller is

unstable during tuning, the calculated parameters will be inconsistent and inaccurate [2].

The automatic tuning (Fig. 12) for the corresponding loop is started at the values of the setpoint and the controlled variable  $PV = SP = 93.9^\circ\text{C}$ .

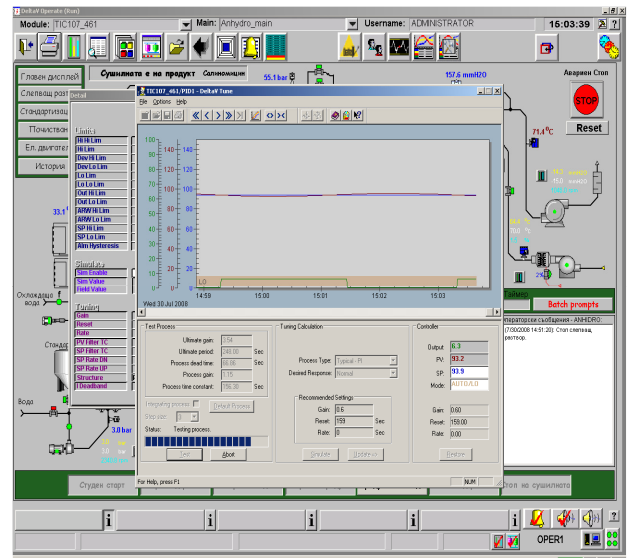


Fig. 12. Automatic tuning started

The tuning system uses the principle of relay oscillation to determine the process dynamics. During the control loop identification procedure, the mode of the corresponding block (PID) is changed to LO and the output goes through a two-state (relay) function - Fig. 13.

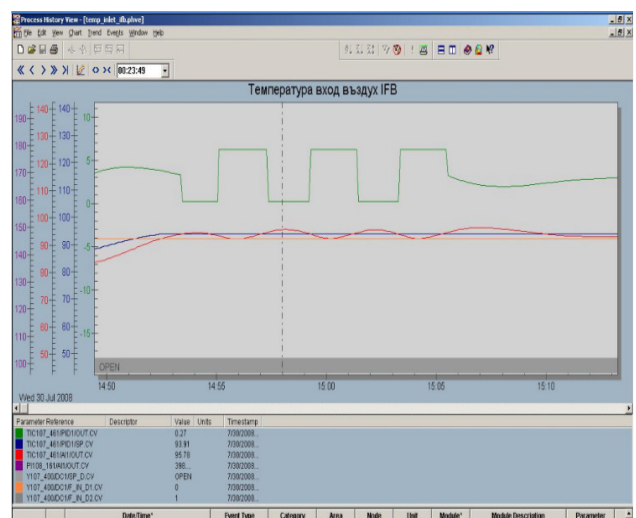


Fig. 13. Change of output and current value during adjustment

During this tuning phase, the loop is under two-state control, exhibiting a slight oscillation. Its amplitude defines the final gain and period. The rules of the modified Ziegler-Nichols method determine the necessary parameters for tuning the controllers. The recommended values for the slave PI - controller are  $K_p=0.68\text{ mA}^\circ\text{C}$ ,  $T_i=164\text{ sec}$ , and the calculated parameters for the object as follows:  $K_{obj}=1.62\text{ mA}^\circ\text{C}$ ,  $T_{obj}=221.25\text{ sec}$ ,  $\tau = 49\text{ s}$ .

To verify and enable further refinement, *Delta V Tune* provides simulated loop response, robustness plotting, and robustness-based tuning. The change in the controlled variable, the setpoint transient, and the change in the output signal to the valve can be seen - Fig. 14. At the top of the figure, a box is indicated where, by clicking, it is possible to select other values for the tuning parameters so as to obtain a transient with the desired quality.

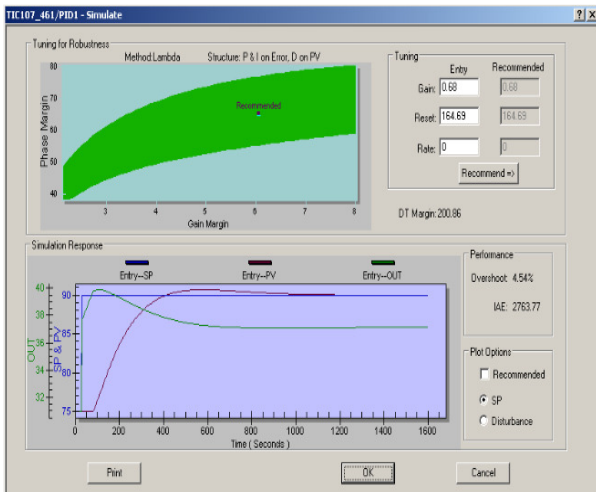


Fig. 14. Simulation response of the loop with the selected settings

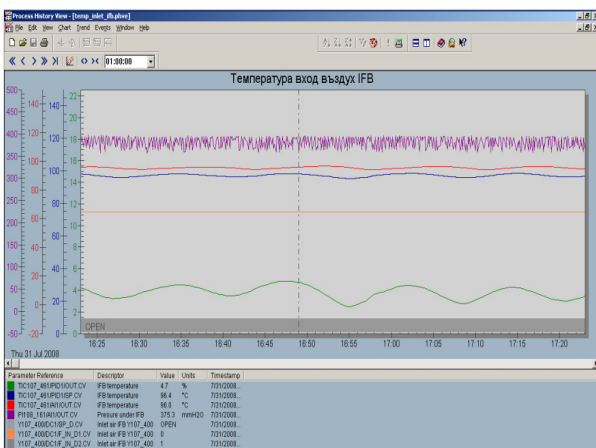


Fig. 15. Temperature TIC<sub>107\_461</sub> change after loop adjustment

From the process history, the quality of regulation in automatic mode of the regulator can be seen - Fig. 15.

The master controller is placed in cascade mode. The automatic setup of the master controller with the equivalent object is performed, analogous to the first one but with both controllers turned on. Initial parameters for the main regulator are  $K_p=1.5\text{ mA}^\circ\text{C}$ ,  $T_i=300\text{ sec}$ , and the subordinate has the already calculated  $K_p=0.68\text{ mA}^\circ\text{C}$ ,  $T_i=164\text{ s}$ . Similarly, with this regulator, the automatic adjustment is started from the detailed display - Fig. 16 and Fig. 17.

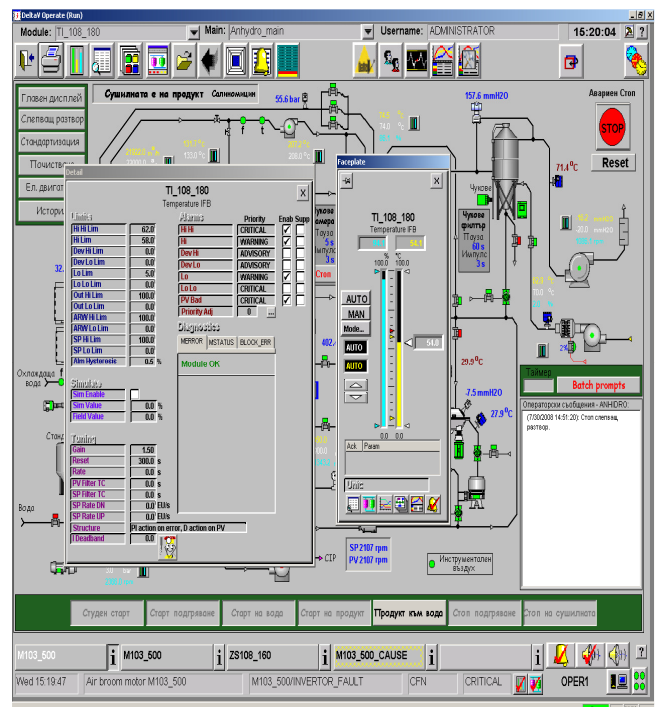


Fig. 16. Detailed display of the external controller

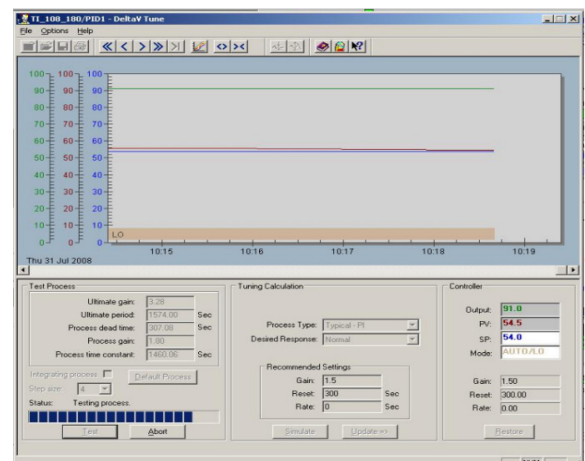


Fig. 17. Automatic adjustment for the outer contour

During the automatic adjustment for the respective loop, the values of the setpoint and the current value  $PV = SP = 54^{\circ}C$  and the output to the working element  $PO = 92\%$  are taken into account. When PV and output are stable, closed loop tuning is started.

During tuning, the output of the PID block is defined with a known function that acts as a relay with hysteresis. This relay provides two-position control and leads to a small oscillation in the process with a small amplitude - Fig. 18. From the process history, transient processes are observed during tuning of the main regulator with a selected step of 4%.

The amplitude of the relay is typically 3 to 10 percent of the controller output range. For the DeltaV control block, this corresponds to a percentage change in OUT. Typically, the process variable changes in the range of 1 to 3 % of the range.

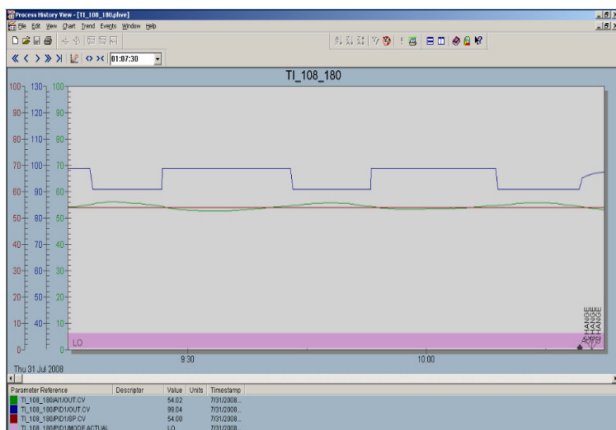


Fig. 18. Diagram of the relay output and the process variable PV during adjustment

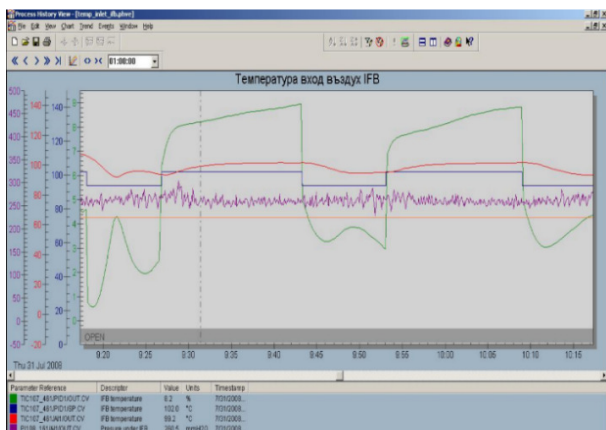


Fig. 19. Transient characteristic of  $TIC_{107\_461}$  during adjustment of the external loop

The process history program displays real-time and historical process data. The changes in the parameters ( $TIC_{107\_461}$ ) of the internal loop during the adjustment of the main controller are shown in Fig. 19.

Recommended parameters for the main PI-controller:  $K_p=0.65 \text{ mA}^{\circ}C$ ,  $T_i=1193 \text{ sec}$ . The calculated parameters of the object are:  $K_{obj}=1.87 \text{ mA}^{\circ}C$ ,  $T_{obj}=1669 \text{ sec}$ ,  $\tau = 261 \text{ s}$ .

The calculated parameters using the Ziegler-Nichols method for the regulator are as follows:

$d = 4$ ;  $a = 4^{\circ}C$  за  $K_{p,critical}=1.28 \text{ mA}^{\circ}C$ .  $T_{i,critical}=900 \text{ sec}$ .,  $K_p=0.57 \text{ mA}^{\circ}C$  and  $T_i=748 \text{ sec}$ .

The simulated contour response, robustness plot, and robustness-based tuning are shown in Fig. 19 and Fig. 20.

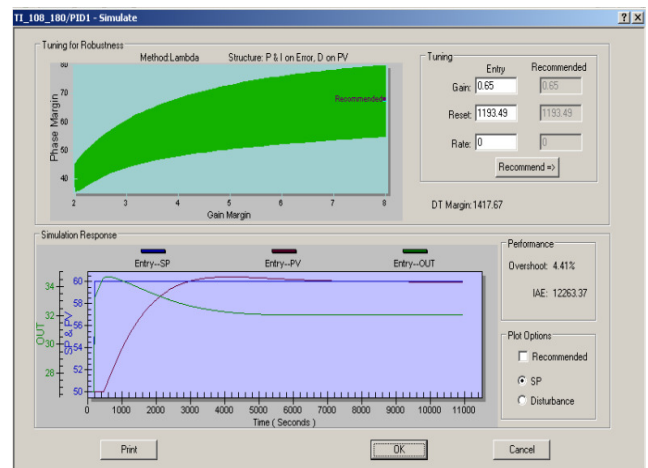


Fig. 20. Simulation response of the loop with the selected settings when acting on the setpoint

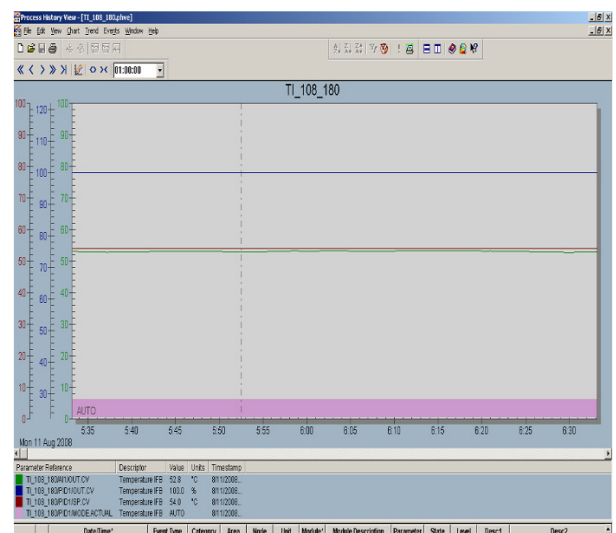


Fig. 21. Temperature change during normal operation of the facility

An experiment is conducted with the obtained recommended parameters for the two regulators and the quality of regulation is judged from the transient processes.

The control blocks integrated in the PLC perform all the necessary calculations on an iterative basis, i.e. they are not performed continuously (continuously), but periodically depending on the execution time of the PLC program cycle. At the time of scanning, the PV and SP values are quantized and digitized once, after which the three functions - proportional, integral and differential - are calculated, summed and the control signal is generated. In the next cycle, the procedure is repeated. The cascade control system is reliable, flexible and provides the necessary accuracy [7].

In powerful drying installations, such as the one discussed above, in addition to maintaining the final moisture content of the product, it is also necessary to ensure high technical and economic efficiency with minimal energy costs and maximum dry matter productivity. For this purpose, procedures for ongoing optimization of the tasks of the main regulators are included, ensuring: optimal amount of air for drying, utilization of exhaust gases and heat released from auxiliary heat sources, optimization of the parameters of the drying agent. To solve these tasks, it is necessary to develop models of drying devices valid for the entire operating range of technological factors [3].

## V. CONCLUSION

In this article, the accuracy of *PI* - controllers implemented in a cascade system for automatic temperature control in a fluidized bed is studied. The system model is synthesized using the graphical extension of *MATLAB/Simulink*. To ensure precise control of the output quantity, the influence of the controller settings and the type of disturbances on the transient processes is studied.

The basic idea in the design of control systems is that it works well when implemented on a real installation. Since the model is an approximate description of the object over time, it is reasonable to require robustness when the controller is applied to the object. Thus, the minimum requirement for a closed-loop system is its nominal robustness.

The application of the cascade system for a temperature loop from a real installation gives relatively good results in controlling the drying and granulation process. *PI* - regulators are used in the control loops. The inner loop is characterized by a higher speed of operation compared to the outer (main) one. Automatic *Delta V* adjustment is used to adjust the real loop. The regulators are designed so that the closed-loop system operates stably within certain limits for all possible disturbances. Despite the complex structure of the object, the cascade system provides good control performance and realizes stable and efficient operation of the analyzed technological process.

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