DRUM LEVEL CONTROL OF A BOILER SYSTEM

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Abstract. The present paper describes the steps and functions needed to control the drum level of a boiler system in Honeywell Experion PKS and modelling it in MATLAB, and compares the results.

Keywords: Experion, Honeywell, MATLAB, Simulink HMI, Configuration studio, Steam generation, Boiler control, Drum level control.

1. INTRODUCTION

In the process of modeling a steam boiler, the goal is to represent the phenomenon of shrinking and swelling: the increase or decrease in the boiler's steam consumption, which leads to a change in level, exactly the opposite of what is intuitively expected. If there is a sudden increase in steam consumption, the level temporarily increases due to the momentary drop in steam pressure caused by the increase in consumption. This initial drop in pressure leads to greater evaporation and an increase in the size of the steam bubbles (the swelling phenomenon), which causes the level in the drum to rise until the heat flow increases enough to restore the pressure value. On the other hand, if there is a sudden decrease in steam consumption, there will be a temporary decrease in the level in the drum (the shrinkage phenomenon). A similar phenomenon occurs when the feed water consumption changes. To model these phenomena, it is assumed that three distinct phases of water, steam, and bubbles continuously exist in the drum, which must be studied separately (Fig. 1).

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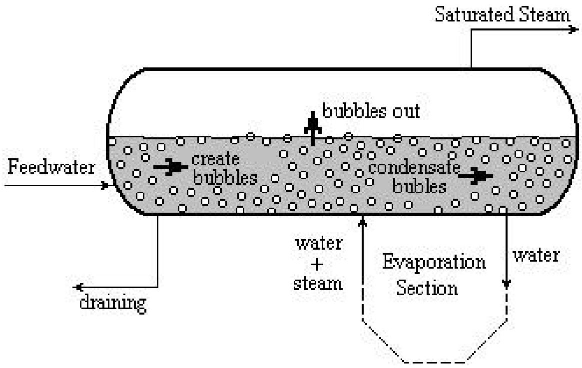

Fig. 1. Flow diagram in a boiler drum

Figure 2 illustrates the detailed process of steam generation in a drum. Its complex geometry, the number of outlet and downcomer pipes, and especially the attempt to model the three-phase flow are usually quite complex, requiring the use of partial differential equations. There are many research papers in the literature that have been devoted to the development of relatively simple physical models [1, 2, 3, 4].

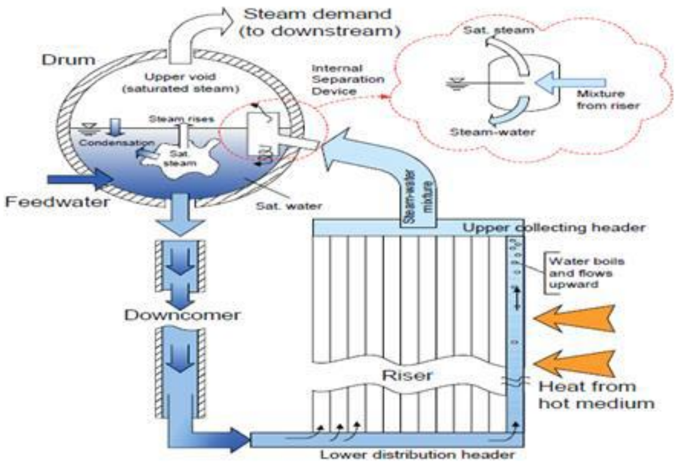

Fig. 2. Circulation cycle diagram

In this paper, the well-developed Astrom-Bell model [4] is considered. The system can be described by a 4th-order nonlinear model, defining the mass flow and energy balance using a physical mechanism introduced under the following elementary assumptions. Most parts of the system will be in thermal equilibrium, due to their direct contact with the saturated liquid/vapor mixture. The energy stored in the mixture is either absorbed or released rapidly, following the changes in the drum pressure, which means that the different metal parts of the system will adapt their temperatures in the same way [5, 6].

Equation (1) presents the mass and energy balance of the drum in terms of the feedwater flow rate qf, the steam flow rate q_s and the heat flow rate $\dot{Q}$ respectively. It describes the dynamic behavior of the pressure in the drum by calculating the properties of the liquid/vapor mixture using steam tables. The condensation of steam in the drum determines the relationship between the drum pressure P and the total water volume V_{wt} [7,8].

$$d/dt\,(\,\rho_s V_{st} + \rho_w V_{wt}) = q_f - q_s;$$

$$d/dt\left(\,\rho_s h_s V_{st} + \rho_w h_w V_{wt} - P V_{wt} + m_t c_p t_{sat}\right) \;= \dot{Q} + q_f h_{fw} - q_s h_s. \qquad (1)$$

The steam content in the tubes is determined using a model that represents the energy-mass balance resulting from the natural circulation in the closed loop in the downward direction, as seen in equation (2). The steam mass fraction, which is assumed to vary linearly from the tube inlet to the tube outlet, is characterized by the changes in the flow rate q_{dc}, the tube flow rate q_r and the heat flow rate $\dot{Q}$ respectively [7].

$$d/dt\,[\rho_s \bar{\alpha}_v V_r + \rho_w(\,1 - \bar{\alpha}_v)\,V_r] = q_{dc} - q_r; \qquad (2)$$

$$d/dt\left[\rho_s h_s \bar{\alpha}_v V_r + \rho_w h_w(\,1 - \bar{\alpha}_v)\,V_r - P V_r + m_r c_p t_{sat}\right] = \dot{Q} + q_{dc} h_w - q_r(\,h_w + \alpha_r h_c).$$

The empirical equation (3) defines the mass balance of the vapor bubbles below the water level in terms of the condensation flux q_{cd} and the vapor flux across the liquid surface q_{sd}, driven by the difference in the density of the mixture and the inertia of the flow q_r entering through the tubes. It can capture most of the dynamics of the process by properly parameterizing the vapor residence time in the drum T_d, the vapor volume of the bubbles in a hypothetical situation V_{sd}^0 and the empirical coefficient β respectively [8, 9].

$$q_{sd} = \rho_s T_d\left(\,V_{sd} - V_{sd}^0\right) \; + \alpha_r q_{dc} + \alpha_r \beta\;(\,q_{dc} - q_r)\,. \qquad (3)$$

2. DRUM BOILER NONLINEAR STATE EQUATION

To derive a state model, chosen state variables should have a good physical interpretation. Drum pressure P is chosen as it describes the total energy of the system. The accumulation of water related to the total water volume V_{wt} in the system is selected since it represents the storage of mass. Steam quality α_r in the riser tubes and steam bubbles volume under the liquid level V_{sd} are chosen as well to describe the distribution of steam under the water, thus estimating the level. The resulting nonlinear state-space model would be a 4th-order system whose states are [9, 10]:

$X = [P$ – drum pressure, V_{wt} - total water volume, α_r – steam quality, V_{sd} – steam bubbles volume]

The model actuating variables are:

$u = [q_f$ – feedwater flow rate, q_s – steam flow rate]

q_f and q_s are manipulated to control the water level and pressure in the drum, respectively, while the heat flux rate $\dot{Q}$ is considered more as a disturbance at the input of the model z due to the fact that its amount is related to the waste heat of the gas turbine, which corresponds to its electrical output.

The heat flux rate becomes a control variable in thermal power plants because it can be directly regulated by the boiler load [9, 10].

The solution of the differential equations of mass and energy balance was performed to obtain the algebraic equations of state. The derivatives of the liquid-vapor mixture functions with respect to the drum pressure are calculated using the coefficients e_{nm} [10].

$$dP/dt = e_{12}\dot{Q} + q_f\left(e_{12}h_{fw} - e_{22}\right) - q_s(e_{22} - e_{12}h_s)/e_{12}\,e_{21} - e_{11}e_{22}\,; \tag{4}$$

$$dV_{wt}/dt = 1/e_{12}\left[\; q_f - q_s - e_{11}^{*}\,dP/dt\right]\,; \tag{5}$$

$$d\alpha_r/dt = 1/e_{33}\left[\; \dot{Q} - \alpha_r h_c q_{dc} - e_{31}^{*}\,dP/dt\right]\,; \tag{6}$$

$$dV_{sd}/dt = 1/e_{44}\left[\rho_s T_d\left(V_{sd}^{0} - V_{sd}\right) - qf^{*}\left(h_{fw} - h_w\right)/h_c - e_{41}^{*}\,dP/dt - e_{43}^{*}\,d\alpha_r/dt\right]. \tag{7}$$

Equations (4), (5) determine the mass of the mixture in the drum and the energy balance, equation (6) combines the mass and energy balance in the closed loop of the downcomers into a single equation, and equation (7) considers only the mass balance of the vapor bubbles below the water level [10].

3. BOILER DRUM LEVEL CONTROL SYSTEM

3.1 SINGLE ELEMENT DRUM LEVEL CONTROL

The single-element control is the simplest method of controlling the level in the boiler drum. This type of control is the least efficient. It requires measuring the water level in the drum and controlling the valve to control the incoming water. It is mainly recommended for boilers with the simplest requirements, operating at a constant steam consumption.

The measured level is compared with a set point, and the difference is fed to the controller, which calculates the control effect. This is most often the position or position setpoint of the regulating feed valve. Figure 3 shows the diagram for the single-element control of the water level in the drum. In this configuration, only the water level in the drum is measured (hence the term “single element”).

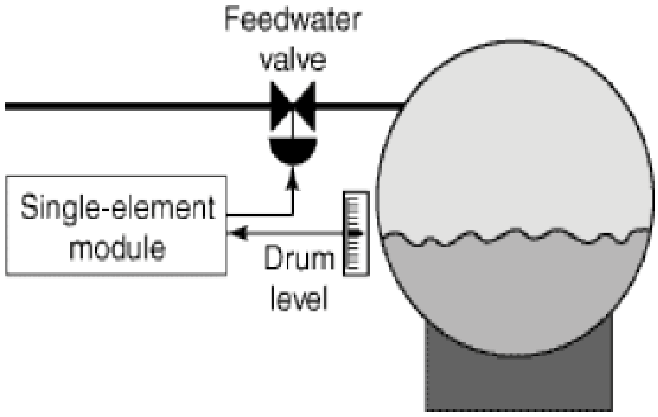

Fig. 3. Single-element boiler drum level control

3.2 TWO ELEMENT DRUM LEVEL CONTROL

The two-element drum level control system is best applied to a single-element control system where the incoming water is at a constant pressure. This requires a drum level measurement, a load requirement, and an incoming water control valve.

Level: The measured level is compared to a setpoint, and the difference is fed to the controller, which calculates the control input. This is most often the position or position setpoint of the regulating feed valve.

Steam flow: This mass flow signal is used to adjust the level setpoint, thus immediately changing the feedwater flow rate according to the changed steam flow rate, thus preempting the level change [11].

Figure 4 shows the scheme for the two-pulse drum level control. This system is suitable for moderate speed load changes. It can be applied to any size of boiler.

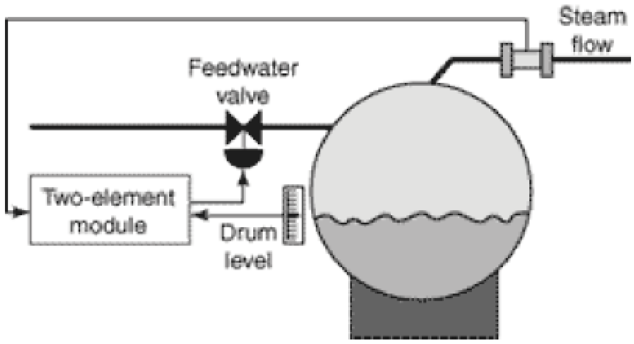

Fig. 4. Two-element boiler drum level control

3.3 THREE ELEMENT DRUM LEVEL CONTROL

This control system (Fig. 5) is ideal for cases where the boiler plant consists of multiple boilers and multiple feedwater pumps or the pressure drop across the control valve is variable. The drum level, the steam flow rate, and the feedwater flow rate must be measured. For the system to be in equilibrium (the level does not change), the steam flow rate must be equal to the feedwater flow rate. If there is a difference between the two flows, the level will either increase or decrease continuously (the object has integrating properties). The difference between the steam flow rate and the feedwater rate is fed as a correction value to the drum level setpoint. In this way, any disturbance in either flow rate is reflected in the control action before the level has changed. The efficiency of the three-element control system under transient conditions makes it very useful for general industrial and domestic steam generator applications. It handles loads with wide and rapid rates of change [10, 11].

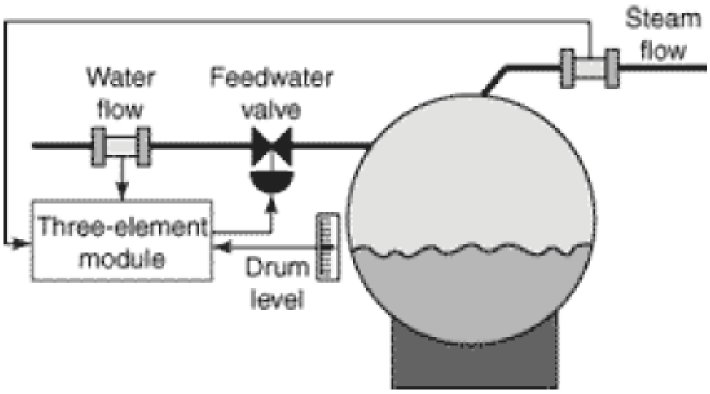

Fig. 5. Three element boiler drum level control

3.4 PID TUNNING METHODS

The mnemonic PID refers to the first letters of the names of the individual components that make up a standard ternary controller. They are: P – for the proportional component, I – for the integral component and D – for the derivative component of the controller. Conventional PID controllers are perhaps the most widely used in industry. Even complex industrial control systems can include a control network whose main control unit is a PID controller module. The PID controller calculates the three components separately - the proportional, integral, and differential components. The proportional component determines the response to the current error. The integral component is the sum of the errors in each calculation cycle [12]. The differential component depends on the rate of change of the error in each calculation cycle.

In this paper it is discussed the different methods for tuning a PID controller. Ziegler-Nichols and Tyreus-Luyben are two of the main methods for tuning a PID controller.

In addition to the conventional PID controller, an internal model control scheme, its equivalent Smith controller, fuzzy logic, and others can also be used [13, 14].

3.5 ZEIGLER NICHOLS METHOD

The method was introduced by John G. Ziegler and Nathaniel B. Nichols. In it, the coefficients K_i and K_d are first set to zero. The proportional coefficient k_p is increased until it reaches the ultimate gain k_u, at which the loop output begins to oscillate. The ultimate gain k_u and the oscillation period T_u are used to calculate the parameters, as shown in Table 1.

Table 1. ZIEGLER NICHOLS TUNING PARAMETERS

CONTROL TYPE	k_p	K_i	K_d
P	$0.5k_u$	-	-
PI	$0.45k_u$	$1.2k_p/T_u$	-
PID	$0.6k_u$	$2k_p/T_u$	$k_pT_u/8$

3.6 TYREUS-LUYBEN METHOD

The method was introduced by Tyreus-Lubyen. In this method, the coefficients K_i and K_d are first set to zero. The gain k_p is increased until it reaches the ultimate gain k_u, at which the loop output starts to oscillate. The ultimate gain k_u and the oscillation period T_u are used to calculate the parameters as shown in Table 2 [10, 11].

Table 2. TYREUS LUYBEN TUNING PARAMETERS

CONTROL TYPE	k_p	K_i	K_d
PI	$0.3125k_u$	$k_p/2.2T_u$	-
PID	$0.4545k_u$	$k_p/2.2T_u$	$k_pT_u/6.3$

3.7 INTERNAL MODEL CONTROL

The basic structure of a one-dimensional control system with an internal model is shown in Fig. 6. In parallel to the object with transfer function $W(p)$, a model of the object with a transfer function $\widetilde{W}(p)$ is included.

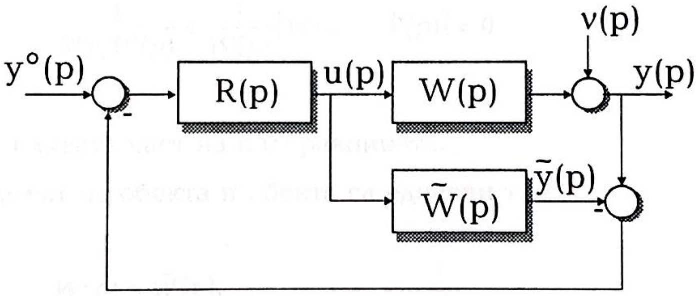

Fig. 6. Scheme of a one-dimensional control system with an internal model

The output quantity of the system with an internal model is obtained from the expression:

$$y(p) = W(p)u(p) \tag{8}$$

The regulating effect occurs in a feedback loop and has the following form:

$$u(p) = \frac{R(p)}{1 + R(p)[W(p) - \widetilde{W}(p)]}[y^o(p) - v(p)] \tag{9}$$

The adjustable quantity according to equation (9) will be [15, 16]:

$$y(p) = \frac{R(p)}{1 + R(p)[W(p) - \widetilde{W}(p)]}[y^o(p) - v(p)] + v(p) \tag{10}$$

For the system with an internal model to be stable, the poles of both characteristic equations are necessary:

$$\frac{1}{R(p)} + \left[W(p) - \widetilde{W}(p)\right] = 0 \qquad (11)$$

and

$$\frac{1}{R(p)W(p)} + \frac{1}{W(p)} + \left[W(p) - \widetilde{W}(p)\right] = 0 \qquad (12)$$

to be located on the left side of the half-plane.

If the object model and the object are the same [16]:

$$W(p) = \widetilde{W}(p), \qquad (13)$$

then the characteristic equation has the form:

$$\frac{1}{R(p)} = 0; \qquad \frac{1}{R(p)W(p)} = 0\,; \qquad (14)$$

This requires that both the object and the controller be stable.

Therefore, control systems with an internal model cannot stabilize an unstable object. If the object is unstable, it must be stabilized beforehand, using local feedback and a standard controller.

Provided that the object and the model are identical, the output quantity will be [13,15]:

$$y(p) = R(p)W(p)[y^o(p) - v(p)] + v(p) \qquad (15)$$

The regulation system will be “ideal” if the condition is met:

$$R(p) = W(p)^{-1} \qquad (16)$$

Then the output variable will follow the setpoint without error- $y(p) \; = y^o(p)$.

The ideal regulator usually cannot be realized for the following reasons: the object has a pure delay; the order of the numerator is higher than the order of the denominator; if the object is non-minimum phase, the unstable zeros turn into unstable poles of the regulator, etc.

In order for the system to be astatic, when applying a single-step effect to its input according to the previous theorem, it is necessary [13, 15, 16]:

$$\lim_{p\to 0} \frac{R(p)W(p)}{1 + R(p)\left[W(p) - \widetilde{W}(p)\right]} = 1 \qquad (17)$$

The above condition is true, only if $p \to 0$ is fulfilled:

$$1 - R(p)\widetilde{W}(p) = 0 \tag{18}$$

or

$$R(p) = \widetilde{W}(p)^{-1} \tag{19}$$

Since the regulator $R(p)$ must be stable and physically realizable. Instead of the inversion (the above equation), the following approach is used:

$$\widetilde{W}(p) = \widetilde{W}_{+}(p)\widetilde{W}(p)_{-} \tag{20}$$

where: $\widetilde{W}_{+}(p)$ contains the pure delay and all unstable zeros of the pre-function, i.e.: $\widetilde{W}_{+}(p)$ contains all non-minimum phase components of the object $W(p)$; $\widetilde{W}(p)_{-}$ - contains all and poles that are located in the left half-plane.

The gain of the object during factorization is included in $\widetilde{W}(p)_{-}$. A filter with a transfer function is added to $\widetilde{W}(p)_{-}^{-1}$ [13]:

$$F(p) = \frac{1}{(T_F p + 1)^r} \tag{21}$$

where r is chosen so that the regulator $R(p)$ is physically realizable.

Thus, the tuning of the regulator is reduced to determining the order of the filter and adjusting its time constant [14, 15, 16].

$$T_F = 1 \div 0.8 T_{ob} \tag{22}$$

4. DRUM LEVEL BOILER CONTROL DESIGN MODEL IN MATLAB

In the MATLAB programming environment, using Simulink, a model (Fig. 7) for level control in a boiler F-1011 has been built, the data for the Level block 1, 2, and Level integrator are taken from a Marathon Petroleum refinery in El Paso, USA, which is active and running. The previously mentioned boiler has been implemented in the El Paso refinery in the USA. The El Paso refinery is located approximately three miles east of downtown El Paso, Texas. The refinery was originally two facilities, with the north portion built by Chevron in 1928 and the south portion built by Texaco in 1931. The operations of both sites were modernized over the years, and the two plants were combined in 1993.

The Marathon El Paso refinery has a crude oil refining capacity of approximately 133,000 barrels per calendar day (bpcd). The refinery processes sweet and sour crudes into gasoline, distillates, heavy fuel oil, propane, asphalt and natural gas liquids, and petrochemicals, and has access to the Permian Basin shale region. Products are delivered from the El Paso refinery by truck, rail, and pipeline [17].

We have a non-minimum phase object with the following transfer function:

$$W(s) = \frac{30s - 1}{10s + 1} \frac{-2}{5s + 1} \frac{1}{30s} \tag{23}$$

It can be seen that there is an integrating unit with a 15-second integration time and a non-minimum phase part, which can be approximated with a net delay of 45 seconds. This makes the control object too complex; compensation of the non-minimum phase is necessary, which can be largely achieved by using the three-element control scheme discussed in the literature review. The equilibrium point of the exemplary simulation, at which the level is zero, is 70% steam consumption and 70% water consumption. At the input of the object with the shown transfer function, the difference between the water consumption and the steam consumption is entered. Due to the integrating properties of the object, if this difference is positive, the level will increase constantly, and if it is negative, the level will decrease constantly.

To compensate for the swelling and shrinkage of the level when changing the steam consumption or water consumption, the difference between the steam and water consumption is added to the setpoint with a weighting coefficient, which is part of the adjustment of the control scheme. When increasing steam consumption, the level increases at the first moment, and in the given model, it will start to fall after 45 seconds. This fact is sufficient for the inadequate response of the controller in a conventional control scheme, without compensation for non-minimum phase. In the present scheme, the difference between steam and water, weighted through the coefficients Gain_S and Gain_S1, is fed to the setpoint (Setpoint block). Thus, the increase in the steam consumption instantly increases the setpoint, which leads to an increase in water consumption, regardless of the fact that the level increases and does not decrease.

In other words, we compensate for the increase in level due to the pressure drop in the drum and the expansion of the steam bubbles. In a conventional scheme, this fictitious higher level leads to the stoppage of the feed water supply at a time when more water is really required. The controller used is PI. The PID is not used because there is a valve at the output of the controller that is not able to handle an output containing a differential component and may be damaged.

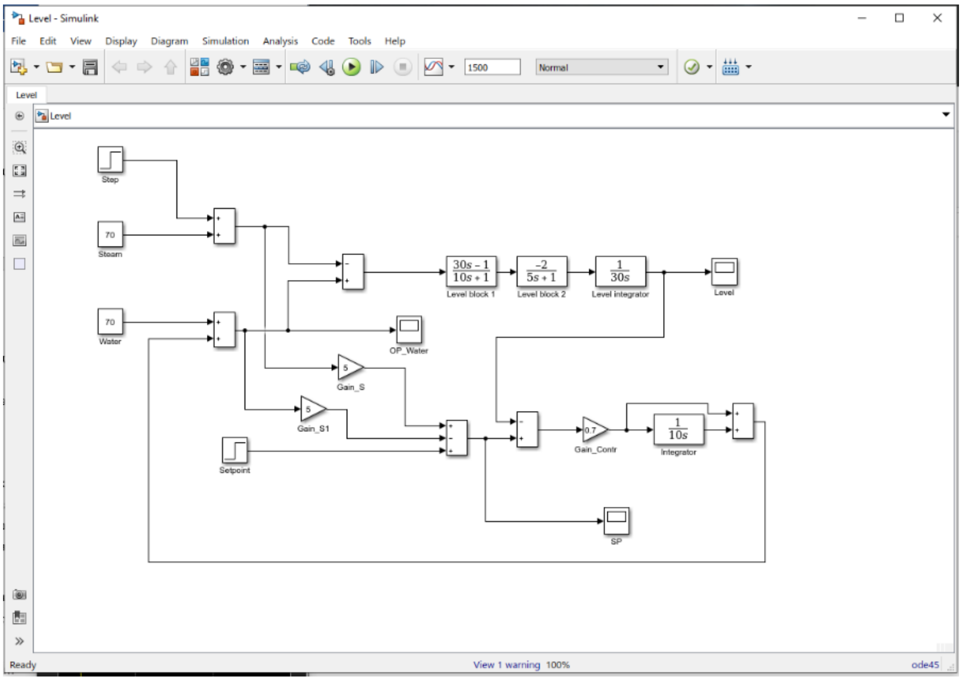

Fig. 7. Drum level boiler control of boiler F-1011(MATLAB Simulink)

5. DRUM LEVEL BOILER CONTROL SIMULATION RESULTS WITH MATLAB AND EXPERION PKS

In the control system of the plant (original configuration), boiler F-1011, which is presented in Fig. 8, a PI-regulator with a gain of 0.85 and an integration time of 7 minutes is used.

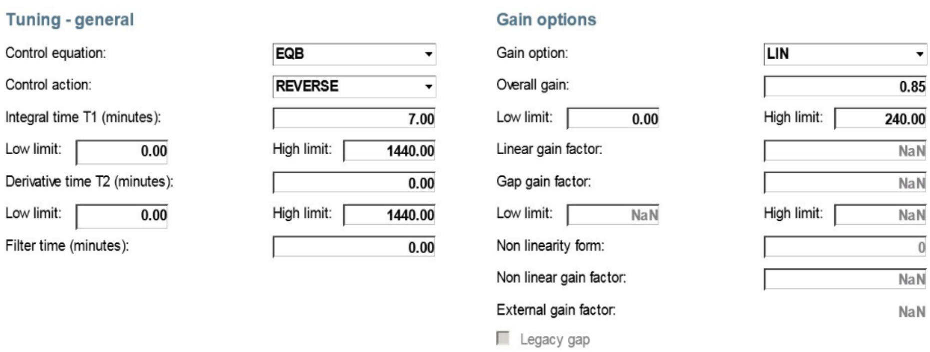

Fig. 8. Settings of level controller 10LC133 in Honeywell Experion PKS

The reason for this is that before the upgrade of the refinery, the boiler control scheme was a single-element one. It does not allow sharp adjustments of the regulator.

A three-component scheme was used with a PI-regulator, due to the presence of a slow valve, and with compensation coefficients for the difference between the steam and feedwater flow rate supplied to the setpoint.

The compensation coefficients for the difference between steam and water were determined experimentally. In the simulations conducted, they ranged from 1 to 7. The settings of the regulator are the gain factor: $K = 0.7$ and the integration time $T = 10$ seconds.

A significant difference is seen in the integration time compared to that of the plant. Figure 9 presents the results obtained.

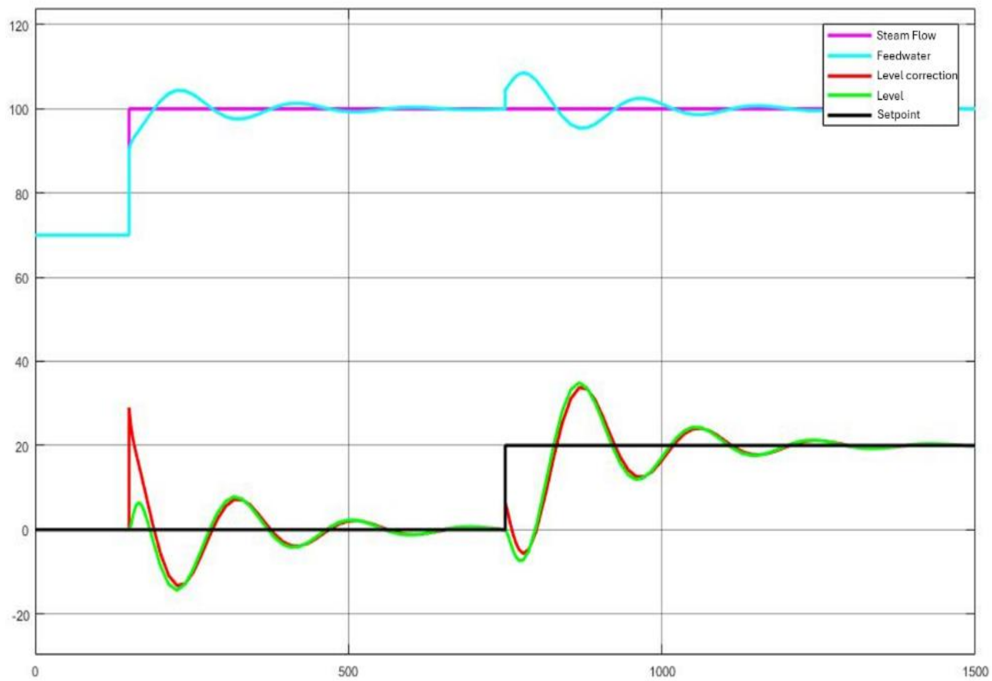

Fig. 9. a)

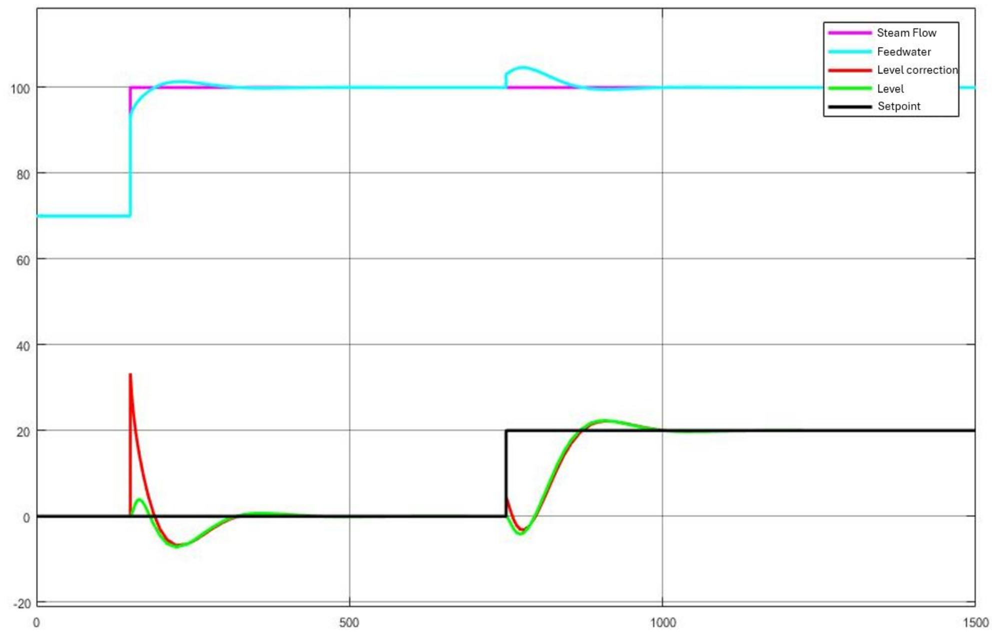

Fig. 9. b)

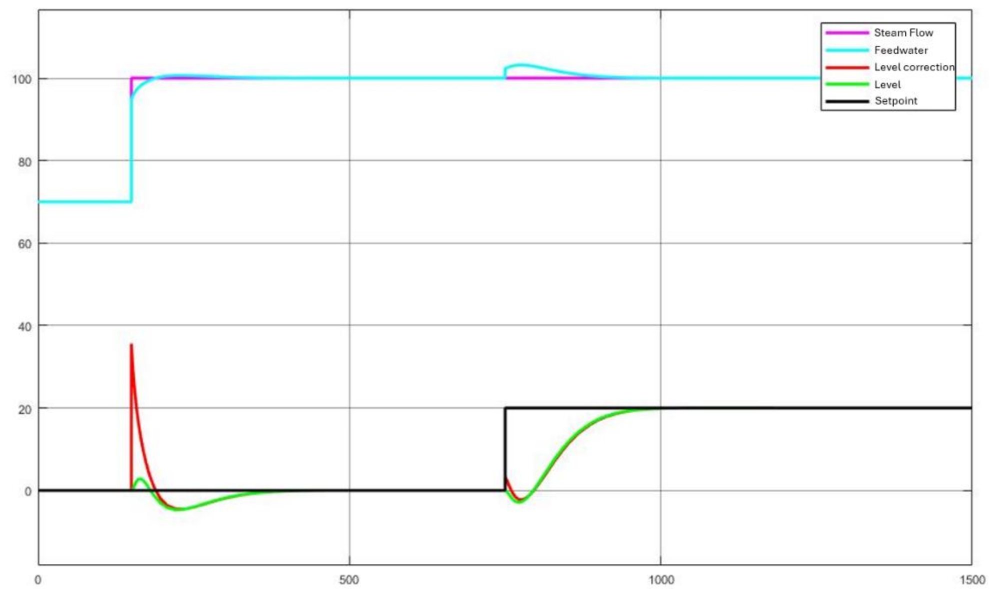

Fig. 9. c) Drum level control at different compensation coefficients
a) -at *k*=3; b) -at *k*=5; c) -at *k*=7

The best results are obtained with a weight coefficient $k = 7$. It can be seen that the correction to the setpoint is the sharpest, which leads to a stronger correction in the feedwater flow rate before the level has deviated significantly.

Figure 10 shows the open-loop scheme (the regulator output does not affect the feedwater flow rate). The scheme is used to illustrate the open system under steam and water disturbances.

Figure 11 shows the closed-loop scheme, with the disturbances being the steam flow rate and level setpoint.

The results are shown below in the text and are compared with those obtained in Honeywell Experion PKS.

Figure 12 shows the detailed display of the level control module 10LC133, from which the process can be controlled. From here, the gain, integration time, differentiation time, PID controller equation, controller limits, alarms, etc., can be changed in real time during operation.

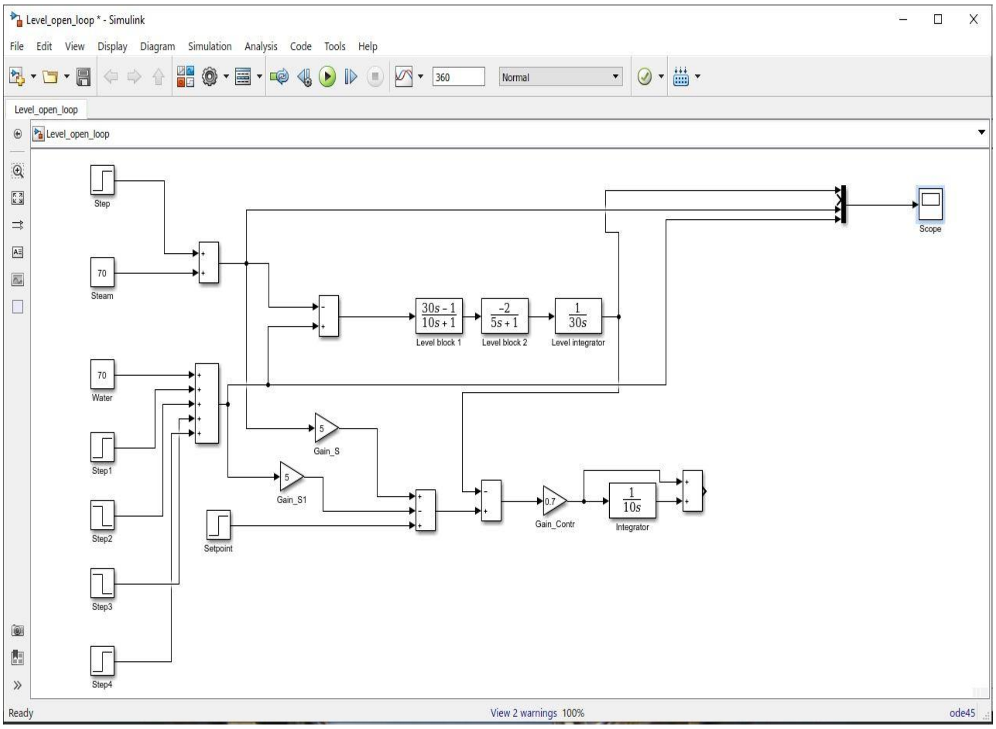

Fig. 10. Open-loop drum level control

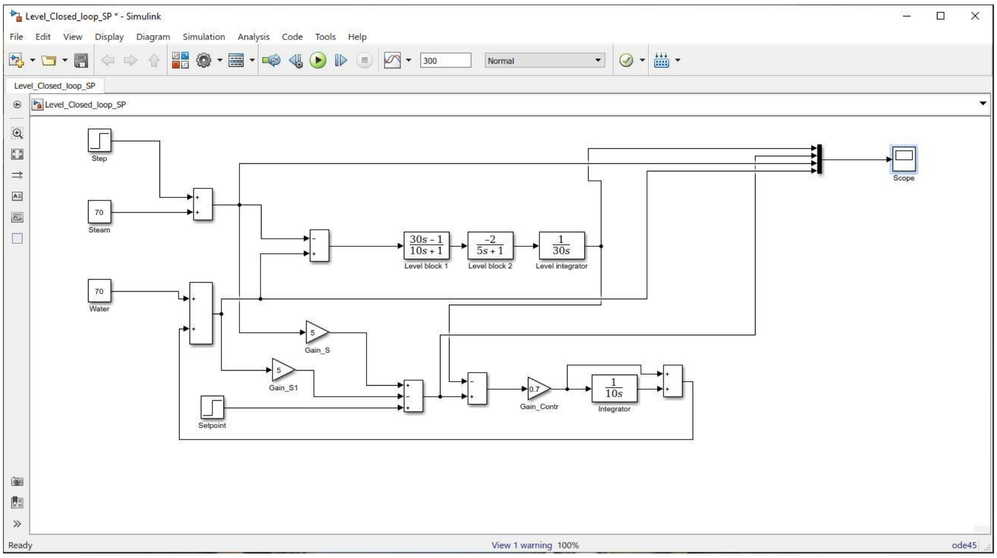

Fig. 11. Closed-loop drum level control

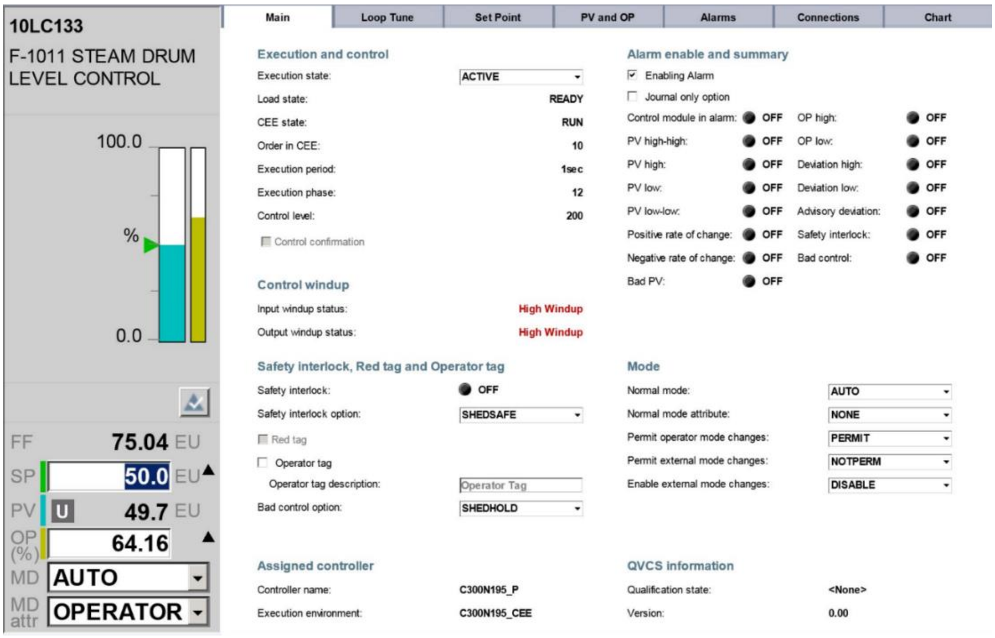

Fig. 12. Detail display of control module 10LC133

Figure 13 shows the behavior of the open and closed loop control object implemented in the Experion PKS programming environment. This programming environment is also presented and discussed in the following paper [18].

The figure is divided into three parts: the first part shows the behavior in an open loop with a working feedwater controller and a change in its setpoint. The change in the level as a result of these disturbances is shown. The non-minimum phase and integrating nature of the object is clearly visible.

The second part shows a closed-loop setpoint disturbance. The level drops as the feedwater flow rate increases and the new setpoint is reached, at which point the water flow rate becomes equal to the steam flow rate again.

The third part shows a steam flow rate disturbance (the steam flow rate decreases stepwise). The sharp correction added to the level setpoint causes the feedwater rate to immediately decrease, the value of which equals the steam flow rate when the level is restored to its previous value.

After creating the level control model in the MATLAB programming environment and implementing it in the Experion PKS programming environment, experiments were conducted to compare the behavior of the used model in the two systems. The graphs in Figs. 14 and 15 show the level change in an open loop.

Two closed-loop experiments were conducted, one with a setpoint disturbance and the other with a change in steam flow. The results of the first experiment are shown in Figs. 16 and 17. The results of the second experiment are shown in Figs. 18 and 19.

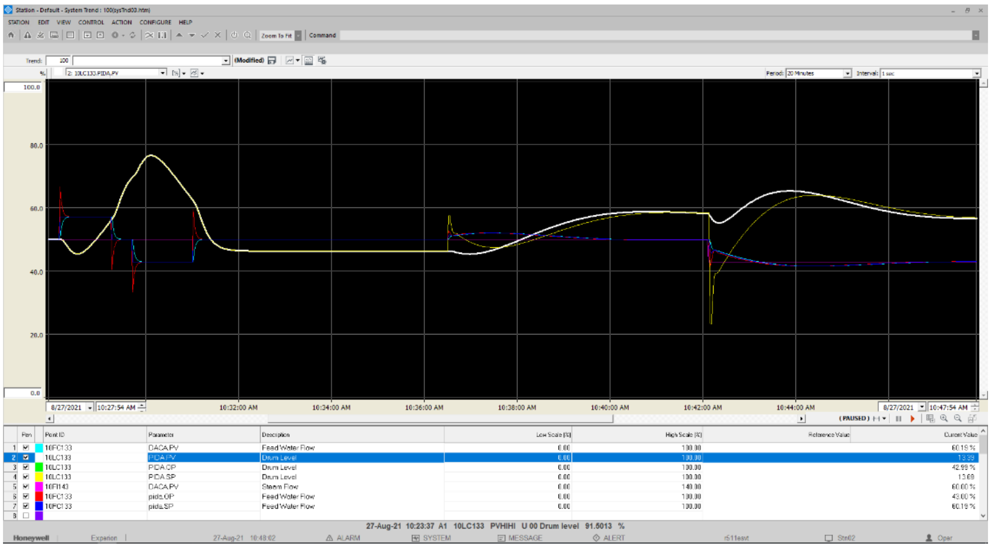

Fig. 13. Behavior of the control object in open and closed loop, implemented in the Experion PKS programming environment

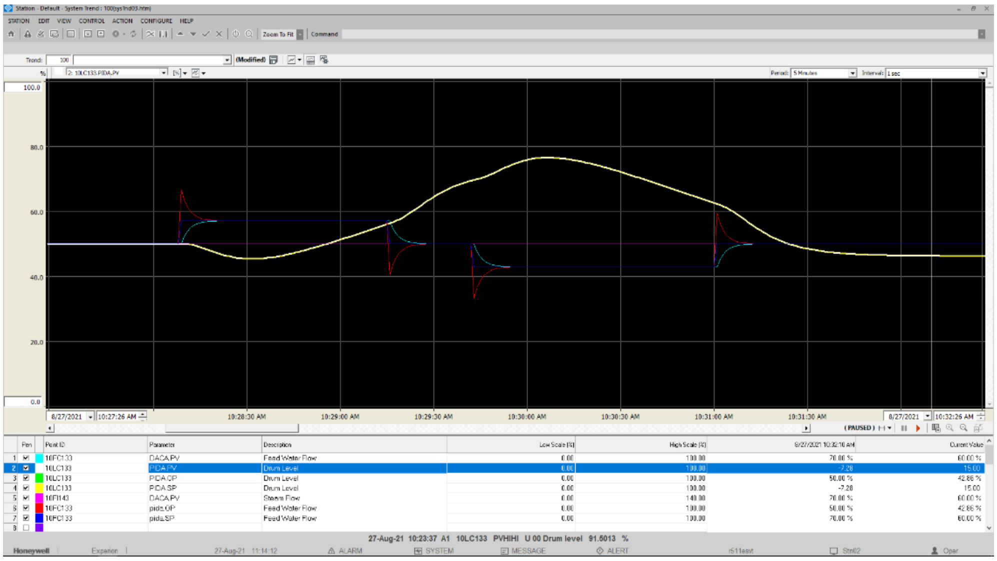

Fig. 14. Open-loop drum level behavior under water disturbance (Experion PKS)
a) 10FC133 PV (feed water) - turquoise line; b) 10FI143 PV (steam quantity) - purple line; c) 10LC133 SP (drum level setpoint matching the actual level when operating in open loop) - yellow line; d) 10LC133 PV (actual drum level) - white line

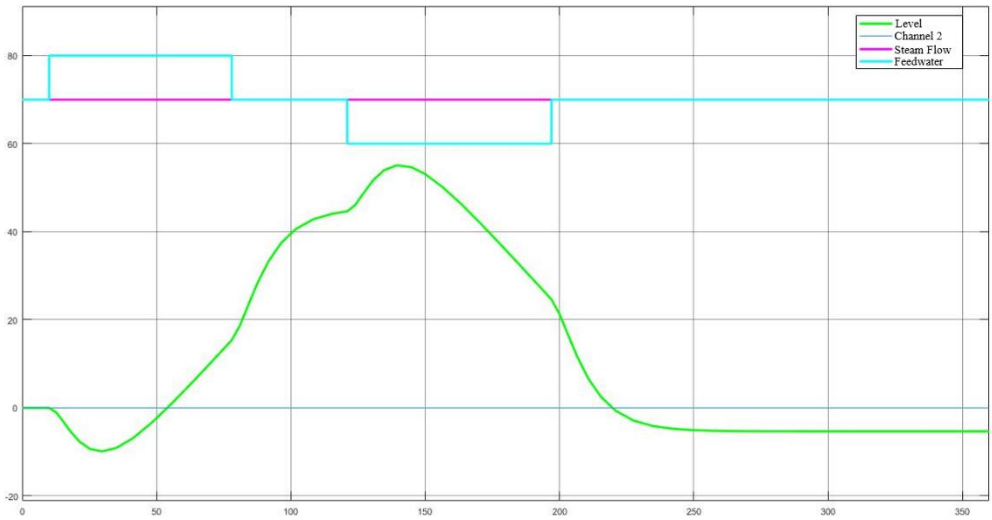

Fig. 15. Open-loop drum level behavior under water disturbance (MATLAB)
a) 10FC133 PV (feed water) - turquoise line; b) 10FI143 PV (steam quantity) - purple line; c) 10LC133 SP (drum level setpoint matching the actual level when operating in open loop) - red line; d) 10LC133 PV (actual drum level) - green line

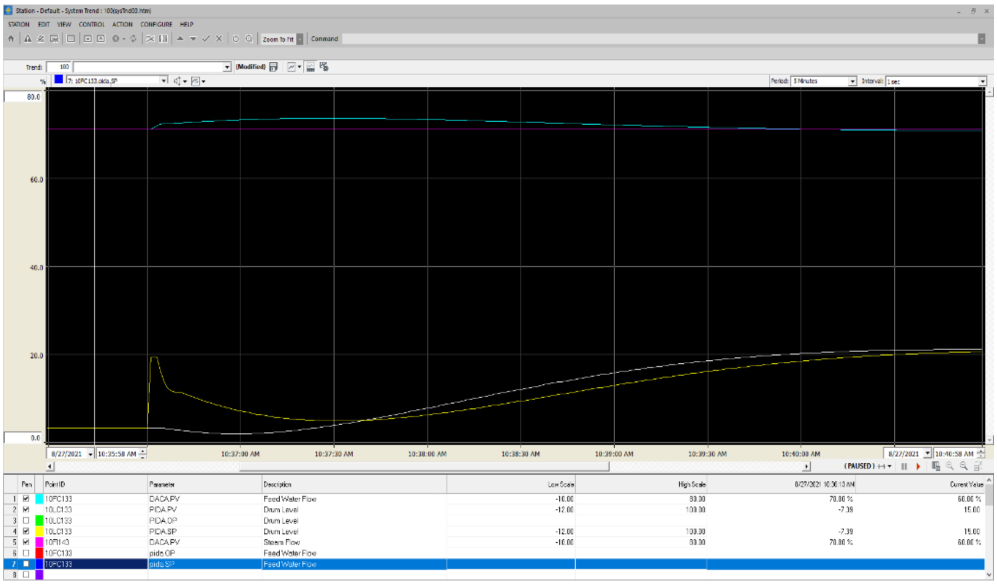

Fig. 16. Closed-loop drum level behavior under setpoint disturbance (Experion PKS)
a) 10FC133 PV (feed water) - turquoise line; b) 10FI143 PV (steam quantity) - purple line;
c) 10LC133 SP (drum level setpoint) - yellow line; d) 10LC133 PV (actual drum level) - white line

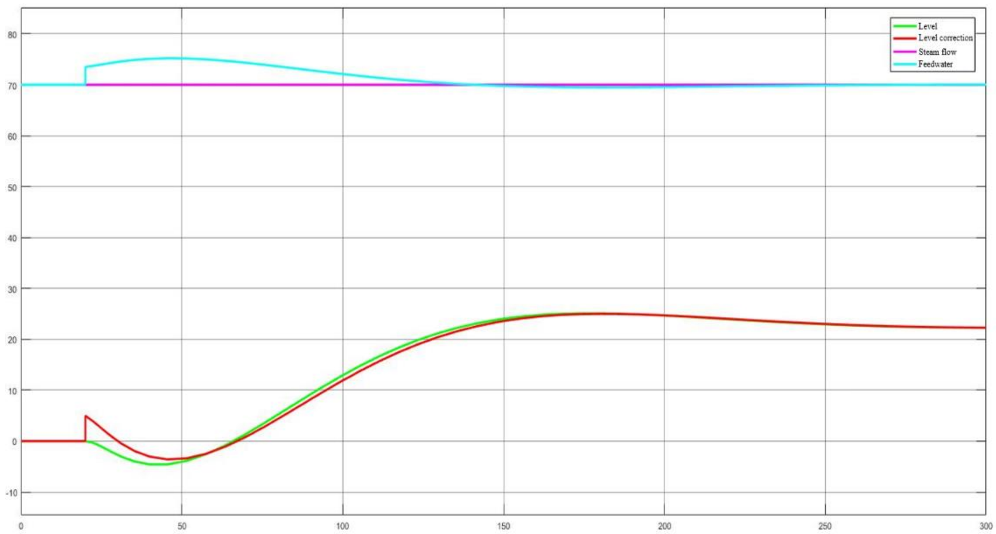

Fig. 17. Closed-loop drum level behavior under setpoint disturbance (MATLAB)
a) 10FC133 PV (feed water) - turquoise line; b) 10FI143 PV (steam quantity) - purple line;
c) 10LC133 SP (drum level setpoint) - red line; d) 10LC133 PV (actual drum level) - green line

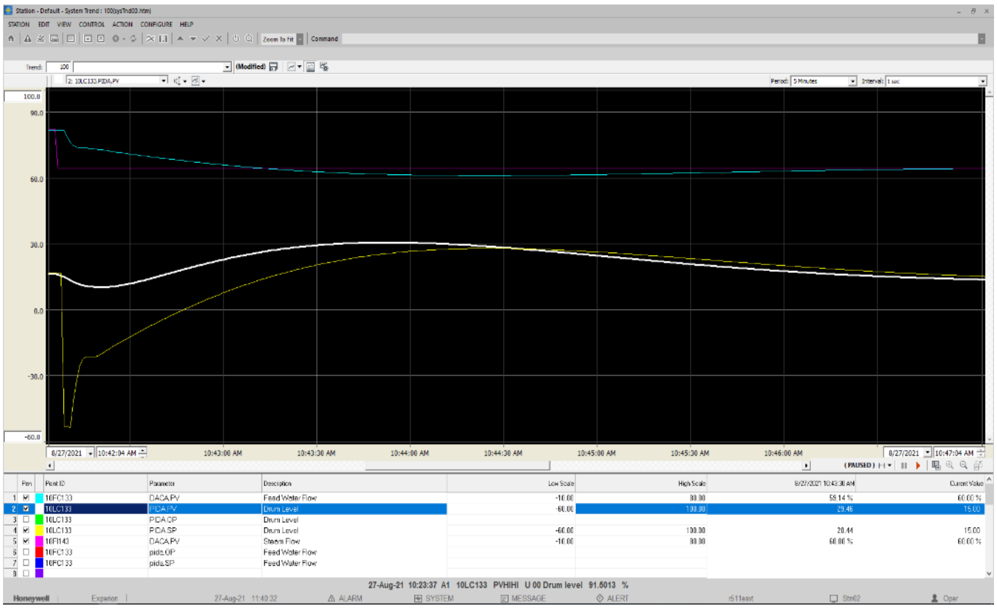

Fig. 18. Closed-loop drum level behavior under steam disturbance (Experion PKS)
a) 10FC133 PV (feed water) - turquoise line; b) 10FI143 PV (steam quantity) - purple line; c) 10LC133 SP (drum level setpoint) - yellow line; d) 10LC133 PV (actual drum level) - white line

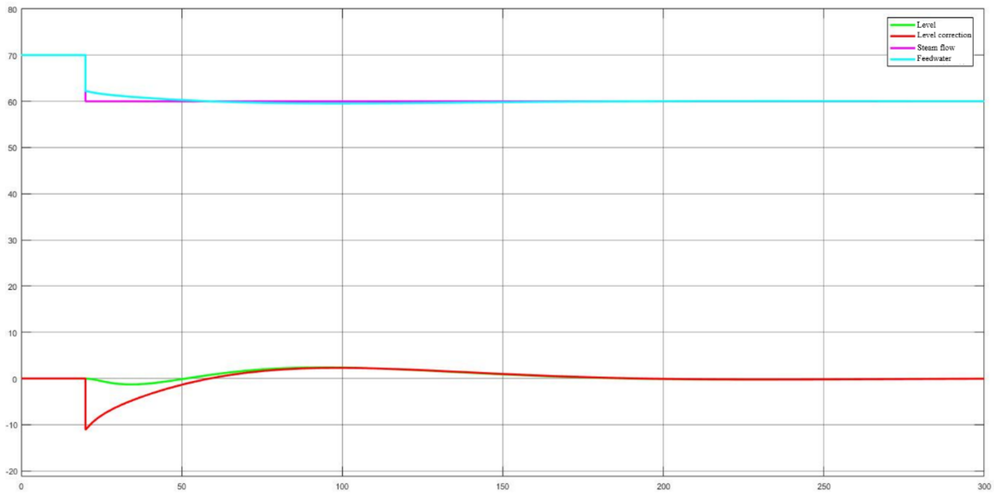

Fig. 19. Closed-loop drum level behavior under steam disturbance (MATLAB)
a) 10FC133 PV (feed water) - turquoise line; b) 10FI143 PV (steam quantity) - purple line; c) 10LC133 SP (drum level setpoint) - red line; d) 10LC133 PV (actual drum level) - green line

The simulations performed show that in MATLAB the change of the feedwater is an instantaneous process. In Experion PKS, the amount of water changes a little slower, due to the valve also being simulated. In MATLAB, a valve is not simulated, since the simulation there was conducted to verify the idea and the operability of the proposed model, which in Experion PKS is implemented in full scale.

The results obtained from this analysis prove the operability of the control scheme in real conditions.

6. CONCLUSION

This paper explains how it is possible to implement and control a boiler system using the MATLAB Simulink created model for a specific non-minimal phase system, while testing and implementing it in real time through the Honeywell Experion PKS environment. By comparing the results from MATLAB and Experion, it can be seen that the MATLAB-created control scheme is completely capable and can be used in an actual working boiler system.

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