Modeling and Control of Rectification Column

Ahmed Kula, Anna Georgieva, Georgi Ruzhekov

***Abstract*—Paper introduces modeling and control of rectification column. The modeling of process is important part of engineering, because it gives an overview of dynamics of the process. In chemical industry most of the processes are involved in purifying liquids. One way to purify liquids is to use rectification process. Rectification process is multiple distillation. Multidisciplinary system is being created for modeling and control of rectification process by desired product. The plant is realized in MATLAB. For this purp ose, is created software in AppDesigner. Simulation of process is made in Simulink and after that the parameters of the process are transferred to PLC system. The control system uses an industrial controller and SCADA system. In this work are realized two ways of control for rectifying process – PID and PID with decoupler matrix. Communication between the two products (MATLAB and PLC/SCADA) is created through industrial protocol – MODBUS. Programmer logic controller (PLC) is MODBUS master and software developed in AppDesigner is MODBUS slave.**

***Index Terms*—Multidisciplinary system, rectification, control system, PLC, SCADA, MATLAB, MODBUS.**

I. Introduction

Rectification is the process of purifying mixture by repeatedly or fractionally distilling it to remove water and undesirable compounds [1]. With using rectification process, you can reach higher purity of each product compared to distillation process. For this reason, it is most used method for splitting of mixtures in chemical, petrochemical and other industries – Fig. 1.

The principle of rectification is as follows: the vapors from the first distiller are fed directly to the second, where their partial condensation occurs. The heat released during the condensation evaporates some of the liquid in the second distiller. The residual product from the second distiller is fed into the first distiller.

Rectification columns are tall cylindrical vessels in which plates are placed one above the other, which retain a certain amount of liquid.

At the bottom part of column, usually, there is a evaporator, which evaporates part of the liquid. As it rises, the steam comes into contact with the liquid on the plates, condensing part of it while part of the liquid evaporates.

At the top part of column is located condenser, which make a liquefies of part of the steam and returns it to the column (also called reflux). The liquid descends under the action of gravity and comes into contact with the steam on each of the plates. The number of plates is important for sufficient separation of the components, a larger number of plates (higher column) leads to better separation of the components.

Typical columns for separation of mixture, gives two products (top product and bottom product).

II. Modeling of Rectification Column

For modeling of rectification column, there is a need to describe the physics process into the column with differential equation. They are described in [2]. The formula for condenser is:

$$M_D \dot{x}_n = (V + V_F) y_{n-1} - L_{x_n} - D_{x_n} \tag{1}$$

Trays are split into four section – tray above the feed flow, trays in rectifying section, tray below the feed flow and trays in stripping section.

$$\begin{aligned} M\dot{x}_n &= V(y_{n-1} - y_n) + L(x_{n+1} - x_n) + V_F(y_F - y_n), \\ M\dot{x}_n &= (V + V_F)(y_{n-1} - y_n) + L(x_{n+1} - x_n), \\ M\dot{x}_n &= V(y_{n-1} - y_n) + L(x_{n+1} - x_n) + L_F(x_F - x_n), \\ M\dot{x}_n &= V(y_{n-1} - y_n) + (L + L_F)(x_{n+1} - x_n) \end{aligned} \tag{2}$$

Equation for reboiler calculation is:

$$M_B \dot{x}_1 = (L + L_F) x_2 - V_{y_1} - B_{x_1} \tag{3}$$

Parameters in equations are:

- Vapor boilup V
- Vapor phase feed rate V_F
- Reflux flow rate L
- Diameter of the column D
- Holdup on each tray M
- Holdup in the column base M_B

In [3], the following model is created:

$$\begin{pmatrix} x_D(s) \\ x_B(s) \end{pmatrix} = \begin{pmatrix} \dfrac{12.8e^{-s}}{1+16.7s} & \dfrac{-18.9e^{-3s}}{1+21s} \\ \dfrac{6.6e^{-7s}}{1+10.9s} & \dfrac{-19.4e^{-3s}}{1+14.4s} \end{pmatrix} \begin{pmatrix} L(s) \\ V(s) \end{pmatrix} \tag{4}$$

This model represents the relation between top product, bottom product, reflux ratio and steam flow.

III. Modeling in MATLAB/Simulink

By using already shown model of the rectification column in MATLAB and Simulink, is created a multidisciplinary laboratory setting for PI control and PI with decoupling matrix control.

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https://doi.org/10.47978/TUS.2022.72.02.003

A. Continuous model characteristics

In figures bellow is presented step response of the defined continuous model of rectification column.

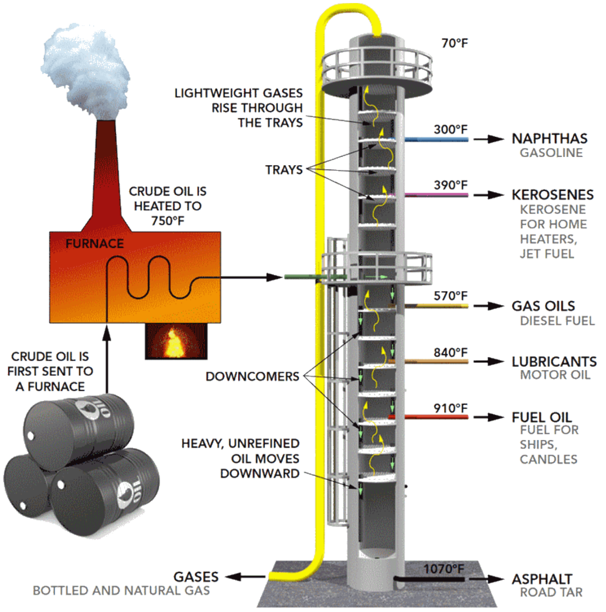

Fig. 1. Rectification column

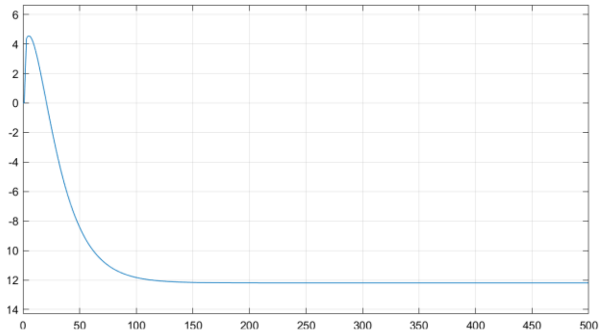

Fig. 2. Step response of Top product

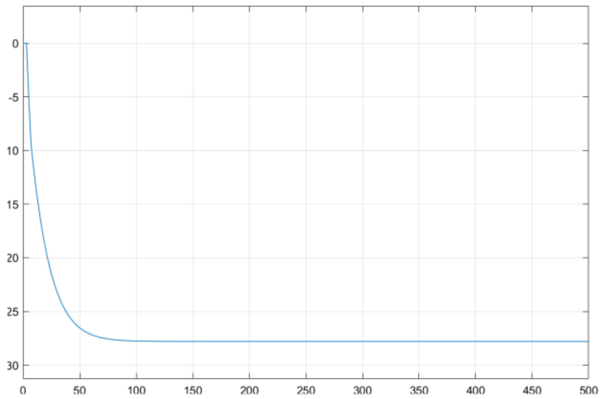

Fig. 3. Step response of Bottom product

From this step response can be seen that there is an influence between the two outputs. This is a common problem in multivariable systems.

B. PI control of continuous model of rectification column

Control of this model is realized by using four controllers, each situated in different control loop. In Fig. 4 is shown a Simulink scheme with which simulation control is implemented.

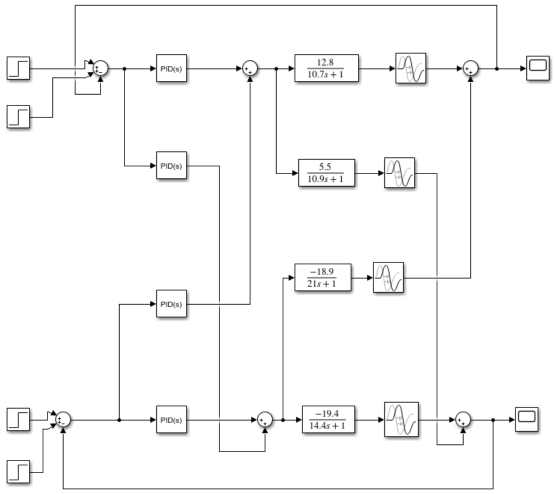

Fig. 4. PI control of continuous model of rectification column

A multivariable PI control for the rectification column is designed. The diagonal and off diagonal elements of the controller are designed in PI forms respectively. The controller is as:

$$C(s)=\begin{pmatrix} 0.17+0.02\dfrac{1}{s} & 0.009+0.0001\dfrac{1}{s}+0.1s \\ 0.1-0.007\dfrac{1}{s}+0.03s & 0.006-0.002\dfrac{1}{s}+0.1s \end{pmatrix} \qquad (5)$$

Results from PI control are exposed in the Fig. 5.

PI control works effectively, with small overshoot on both products and without oscillations. Process that shows bottom product control is slower than the other.

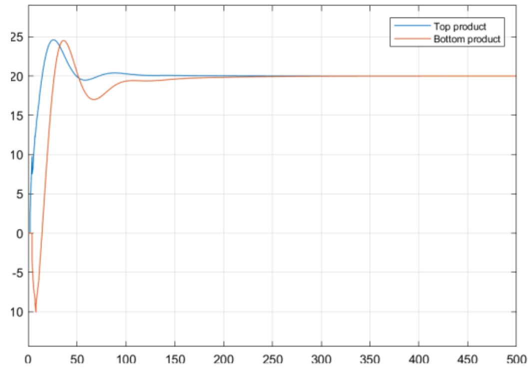

Fig. 5. PI control of continuous model of rectification column

An experiment with a change of setpoint of both products was conducted. The result is shown in Fig. 6.

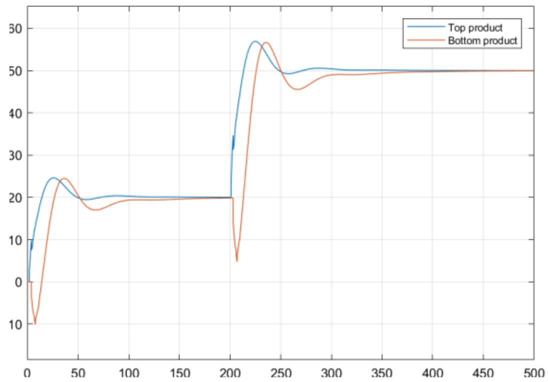

Fig. 6. PI control - change of setpoint

The control of the two outputs remains stable, despite the change of setpoint. There is a small overshoot on both products control and no oscillation. The bottom product control remains slower.

C. *Discrete model - characteristics*

Discrete model of rectification column has the following form:

$$\begin{pmatrix} x_D(z) \\ x_B(z) \end{pmatrix} = \begin{pmatrix} z^{-1}\dfrac{1.142}{z-0.9108} & z^{-3}\dfrac{-0.8789}{z-0.9535} \\ z^{-7}\dfrac{0.4821}{z-0.9123} & z^{-3}\dfrac{-1.302}{z-0.9329} \end{pmatrix} \begin{pmatrix} L(z) \\ V(z) \end{pmatrix} \qquad (6)$$

Sampling time of the system is Ts = 1s. Step response from the two of the outputs, respectively top and bottom product is shown in Fig. 7 and Fig. 8.

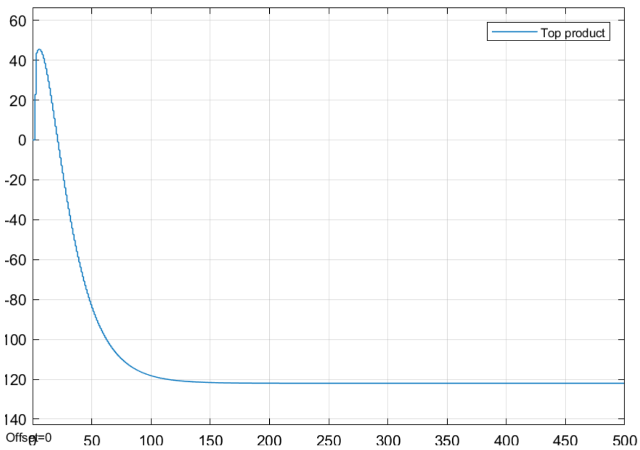

Fig. 7. Step response from discrete model of rectification column

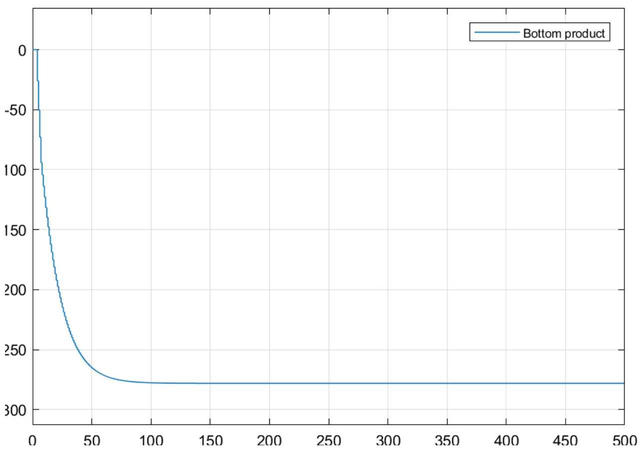

Fig. 8. Step response from bottom product of discrete model of rectification column

D. *Discrete PI control of discrete model of rectification column*

Discrete control is realized by using the same scheme in Simulink, with difference in controllers, which in this case are discrete PI controllers:

$$C(z) = \begin{pmatrix} 0.0001 + 0.0005T_s\dfrac{1}{z-1} & 0.08 + 0.0001T_s\dfrac{1}{z-1} \\ 0.001 + 0.000001T_s\dfrac{1}{z-1} & 0.002 - 0.001T_s\dfrac{1}{z-1} \end{pmatrix} \qquad (7)$$

The scheme in Simulink with which control of the discrete model of rectification column is simulated is shown in Fig. 9.

Fig. 10 illustrates the results of PI control.

PI control shows good results. The process is fast and with small overshoot on top product control (Fig. 11).

Fig. 11 shows an experimental change of setpoint of both products, the process remains stable with small overshoot and without oscillations.

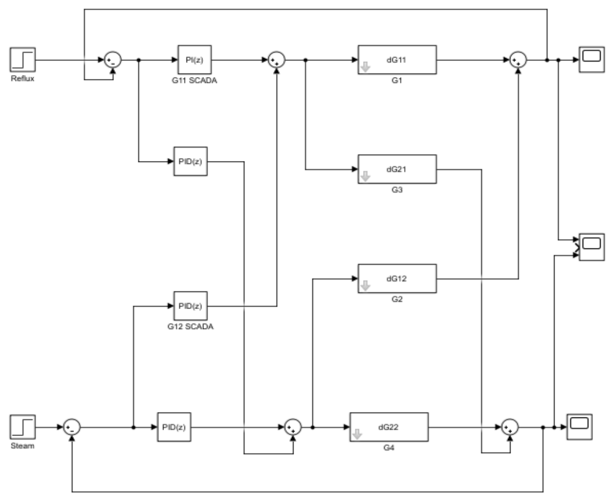

Fig. 9. Simulink scheme of discrete PI control

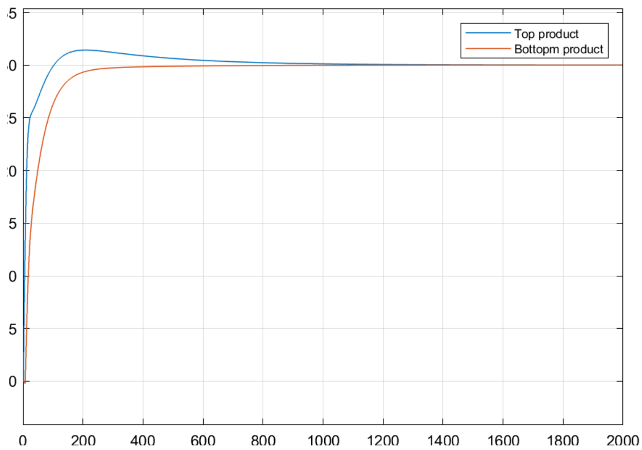

Fig. 10. PI control of discrete model

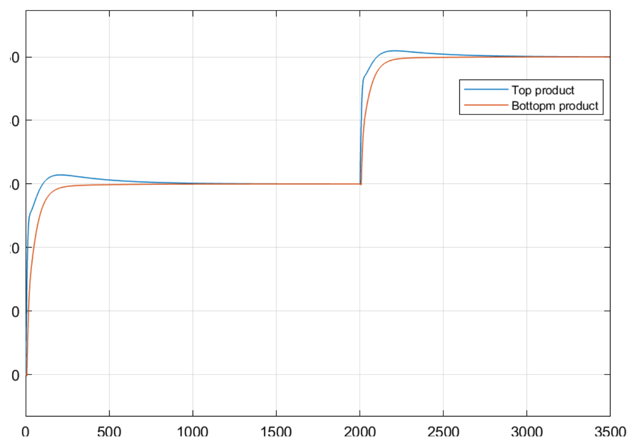

Fig. 11. PI control of discrete model – change of both setpoints

Fig.12 presents the result from change of setpoint only on top product process. The process is stable and without overshoot in top product process, but as it can be seen on the graphic there is an influence between both products and a small overshoot occurs in bottom product.

Fig. 13 shows the result from change of setpoint on bottom product. Process is still stable, despite the big influence between both variables. In conclusion from this experiment top product is more sensitive to changes in the bottom product then the opposite.

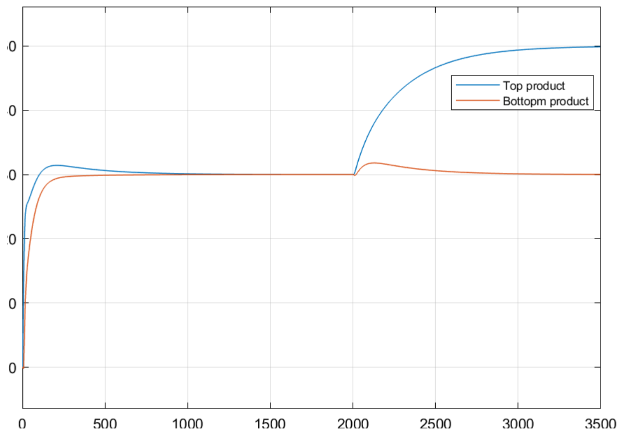

Fig. 12. PI control with change of setpoint on top product

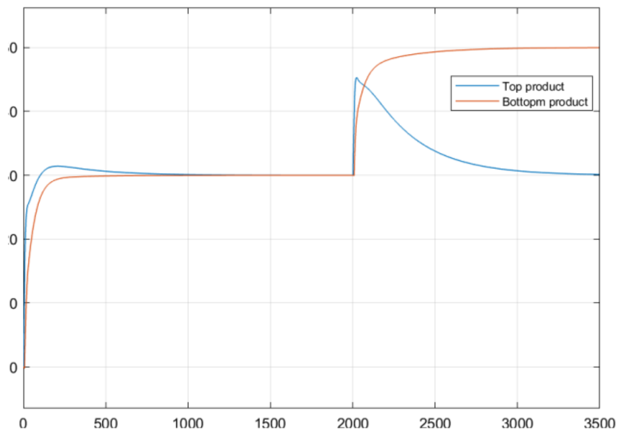

Fig. 13. PI control with change of setpoint on bottom product

E. Discrete model of rectification column with decoupling matrix

Most industrial systems are with more than one input and outputs. Often each output reaction depends on more than one input. This problem can be solved by using decoupling matrix. The main purpose of those decoupling matrix is to untangle the connections between the outputs and each output to be controlled uninfluenced by others.

Fig. 14 shows a scheme of multivariable object with decoupling matrix, which outputs can be presented with these equations:

$$\begin{aligned} y_1(s) &= G_{11}(s)u_1(s) + G_{12}(s)u_2(s) \\ y_2(s) &= G_{22}(s)u_2(s) + G_{21}(s)u_1(s) \end{aligned} \tag{8}$$

Equations for input signals are (9):

$$\begin{aligned} u_1(s) &= D_{11}(s)u_1^*(s) + D_{12}(s)u_2^*(s) \\ u_2(s) &= D_{22}(s)u_2^*(s) + D_{21}(s)u_1^*(s) \end{aligned} \tag{9}$$

$$\begin{aligned} &D_{11}(s) = 1, D_{12}(s) = -\frac{G_{12}(s)}{G_{11}(s)}, \\ &D_{21}(s) = -\frac{G_{21}(s)}{G_{22}(s)}, D_{22}(s) = 1 \end{aligned} \tag{10}$$

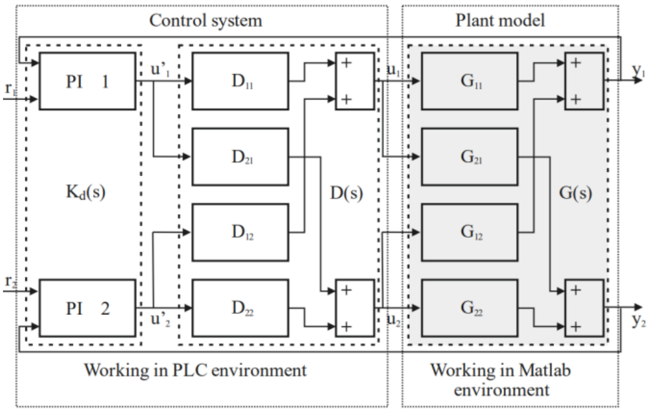

Fig. 14. Structural scheme of multivariable object with decoupling matrix

After several mathematical operations and removal of the influence of other inputs, decoupling matrix can be obtained by:

Following this method for decoupling matrix is used:

$$\begin{aligned} &D_{11}(z) = 1, D_{12}(z) = \frac{0.4447z^3 - 0.4316z^2}{0.3776z^7 - 0.3687z^6}, \\ &D_{21}(z) = \frac{0.2959z^7 - 0.2858z^6}{0.6621z^{15} - 0.6324z^{14}}, D_{22} = 1 \end{aligned} \tag{11}$$

Step response from the discrete system with decoupling matrix is (Fig. 15):

In comparison of the results of step response that already were shown, in this case it is obvious that there is no influence between both processes.

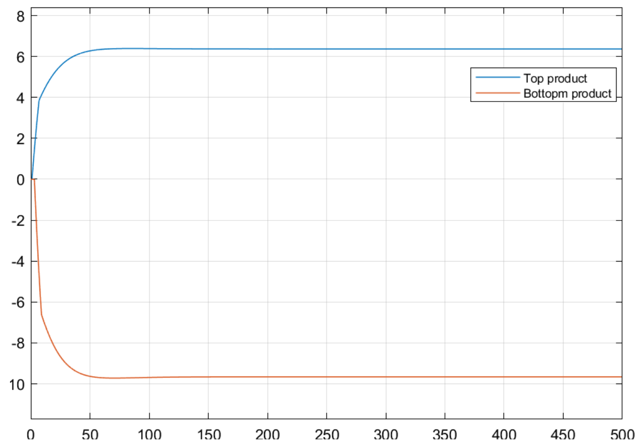

Fig. 15. Step response - discrete system with decoupling matrix

F. PI control of discrete model of rectification column with decoupling matrix

For control of this multivariable system with decoupling matrix are synthesized two PI controllers. In Simulink the structural scheme is shown in Fig. 16.

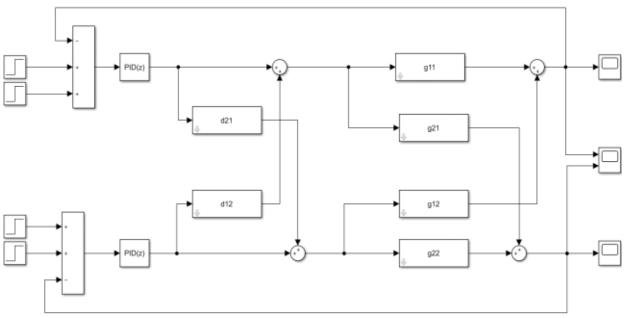

Fig. 16. Simulink scheme of PI control of multivariable model of rectification column with decoupling matrix

Parameters of the PI controllers are presented below:

$$C(z)=\begin{pmatrix} 0.1+0.04T_s\dfrac{1}{z-1} \\ 0.03-0.004T_s\dfrac{1}{z-1} \end{pmatrix} \quad (12)$$

In the graphic bellow (Fig. 17) is seen that the PI control is effective. The process is stable with small overshoot.

An experiment with change of setpoint of both process is realized in Fig. 18.

On Fig. 19 and Fig. 20 are shown two experiments of change of setpoint first only on top product process, second on bottom product process. As it can be seen the decoupling matrix is an effective method with which the problem of influence between the two process is solved. The processes remained stable.

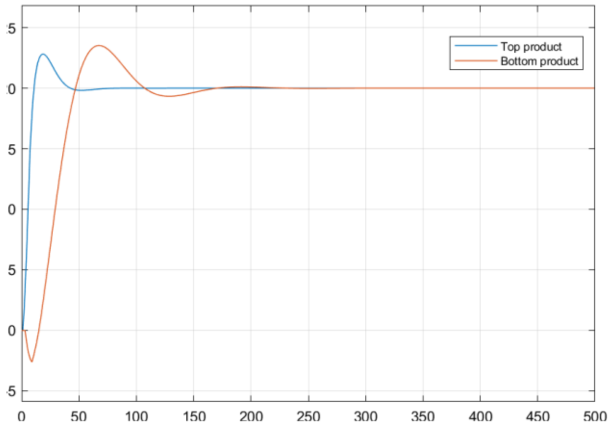

Fig. 17. PI control of discrete model of rectification column with decoupling matrix

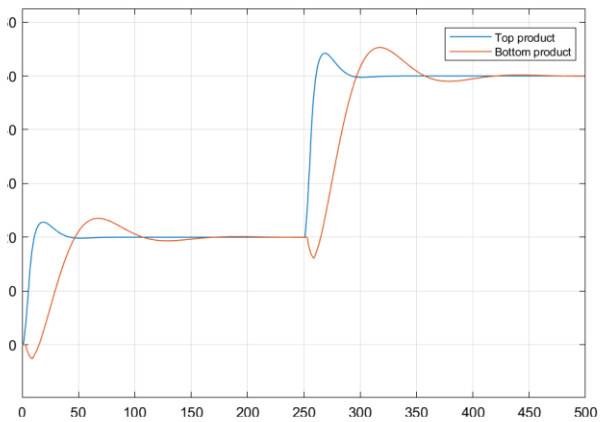

Fig. 18. PI control of discrete model with decoupling matrix - change setpoint

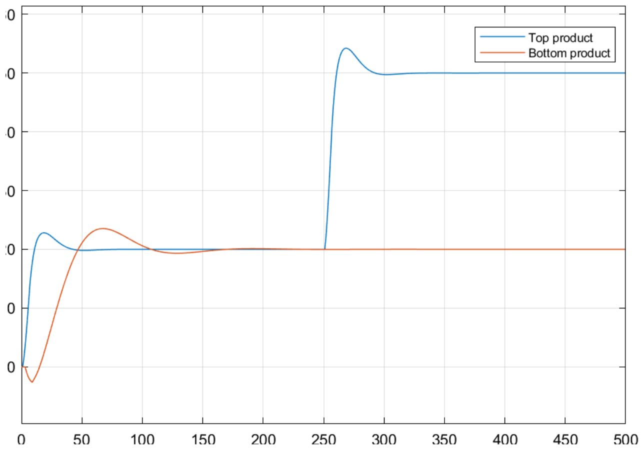

Fig. 19. PI control of discrete model of rectification column with decoupling matrix - change setpoint of top product

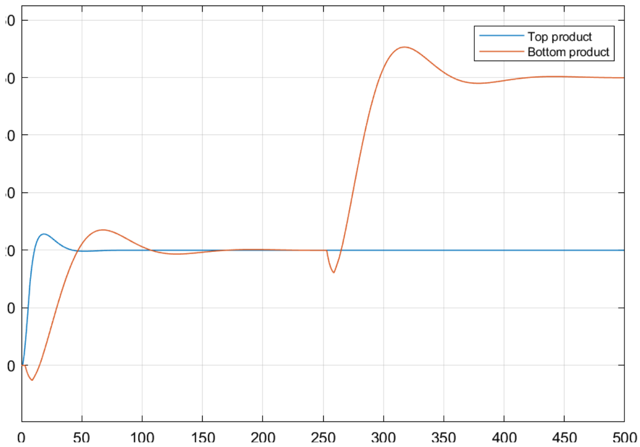

Fig. 20. PI control of discrete model of rectification column with decoupling matrix - change of setpoint of bottom product

IV. Real-Time Realization of System

Real time simulation of the model is created by using internal software in MATLAB called AppDesigner (Fig. 21). In this software you can set parameters of liquid, which user want to be used in rectification process. After submitting the values, the process is realized using the equations described in *II*. The output signal of the process is generated by using direct canonical form [4].There are two trends in which are visualized the control signal and output of the plant.

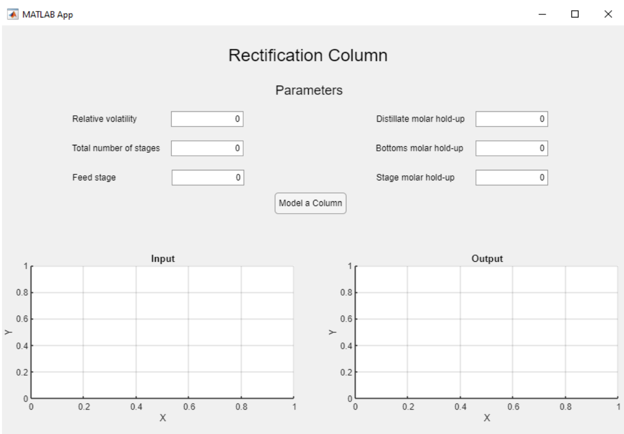

Fig. 21. Software created in AppDesigner

V. COMMUNICATION MATLAB – TIA PORTAL

Communication between the two programs which are used (MATLAB and TIA Portal) is realized by using MODBUS TCP/IP protocol.

MODBUS is an application-layer messaging protocol, positioned at level 7 of the OSI model. Modbus has its benefits in flexibility and easy implementation. It can be used for communication with microcontrollers, computers, PLC's and other devices. It can be done on serial line as on Ethernet TCP/IP networks (Fig. 22).

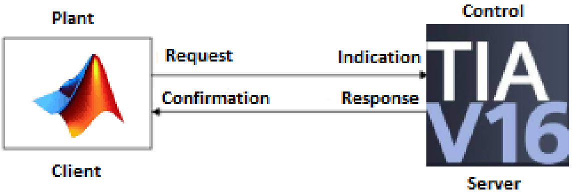

Fig. 22. MODBUS Client/Server

MODBUS communication is based on massages and not on the type of physical communication. So, it can be used on different physical communication systems, connecting old and new. MODBUS is an open protocol. The MODBUS messaging system is based on the Client/Server model between devices connected on an Ethernet TCP/IP network.

In this article the MODBUS server is situated in TIA Portal and MATLAB is the MODBUS client (Fig. 22).

The experiments performed in MATLAB, shown below in this article are realized again in real time using MATLAB respectively AppDesigner as a plant and TIA Portal as a control device, both communicating with MODBUS.

In Fig. 25 is shown the response from plant in real time simulation. As1 it can be seen the results from step response from MATLAB simulation and this from real time simulation are the same.

VI. RECTIFICATION COLUMN CONTROL IN TIA PORTAL

The control of system is made in TIA Portal (Siemens PLC). For PLC is used Siemens S7-1500 series. Simulation of the controller is with S7PLCSIM Advanced.

The control of the process, for one of the experiments, is implemented with PI Compact functional block. For other one is used decoupling matrix technology [5] for control of processes. Parameters of PI regulators and decoupling matrices are the same as this which are calculated in SIMULINK schemes bellow.

Decoupler matrix in TIA Portal is created with functional blocks. In these blocks is realized direct canonical form of discrete process in time domain [6].

SCADA system is developed for visualization and control of the processes in rectification column Fig. 23.

The SCADA system contains two trends for visualization of the process of both top and bottom products of the rectification column. IO fields for visualization of reflux, steam flow, current top product and bottom product. Popup screens for each PI controller, in which their parameters can be tuned. Slide-in screen in which all PI controllers parameters can be tuned. In these popups and slide-in PI parameter screens can be start procedure of pre tuning or fine tuning of PI parameters. Setpoint of top and bottom product can be set, also process variable of actual value of top and bottom product. Also, can be input minimum and maximum control value of controllers.

In Fig. 26 is shown a graphic of real time PI control of the rectification model in AppDesigner. As it can be seen there are four experiments that are conducted: normal PI control, PI control with change of the setpoint on both top and bottom product, PI control only on top and only on bottom product. The results from these experiments are the same with this obtained in MATLAB earlier in this article.

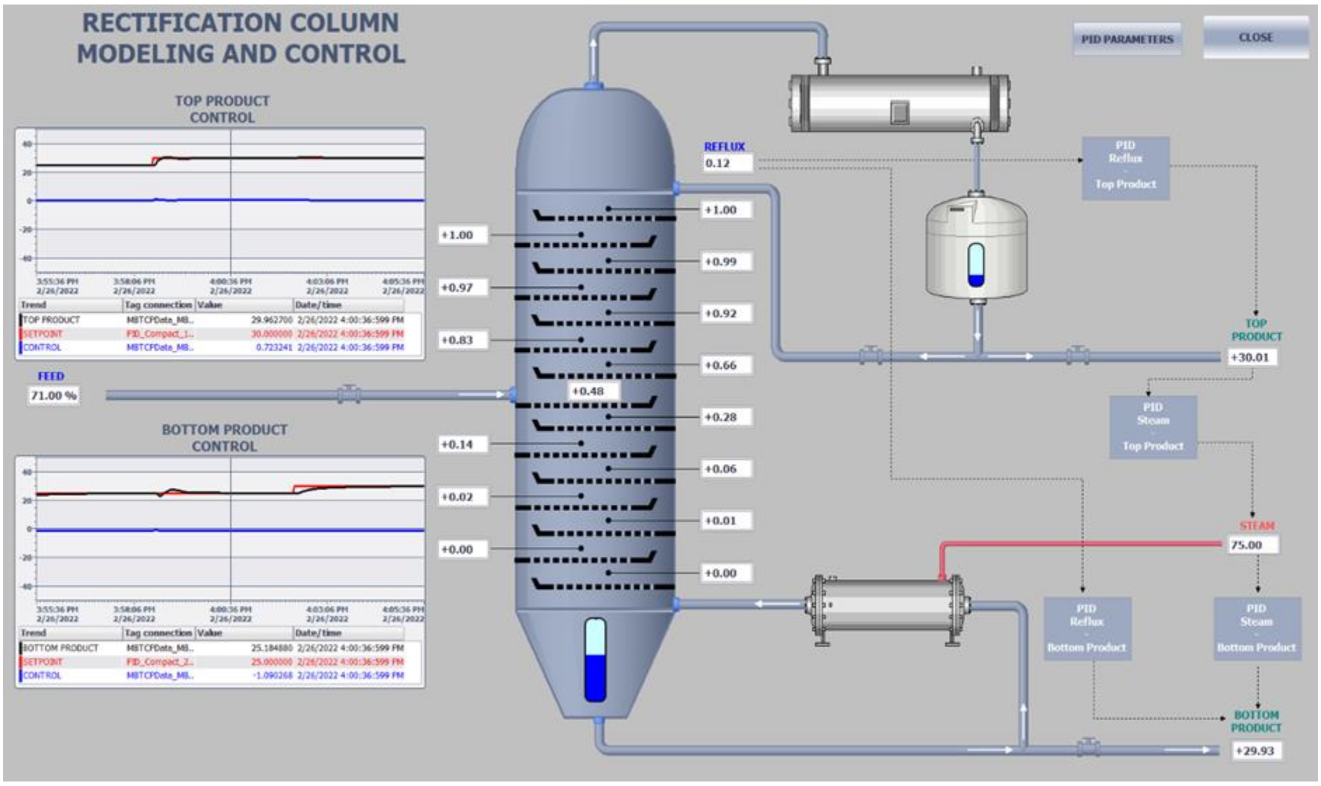

Fig. 23. SCADA system

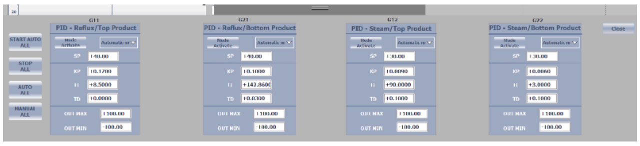

Fig. 24. Slider screen for PI parameters

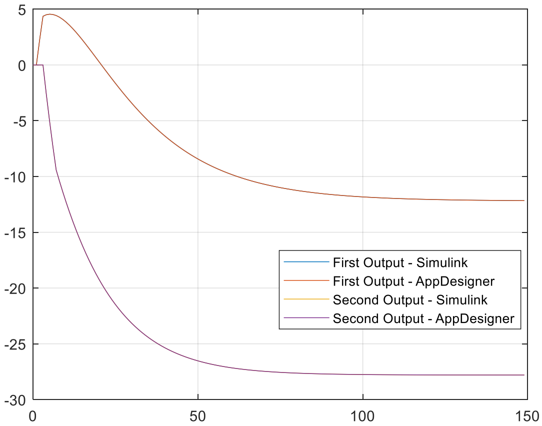

Fig. 25. Comparison between Simulink and AppDesigner

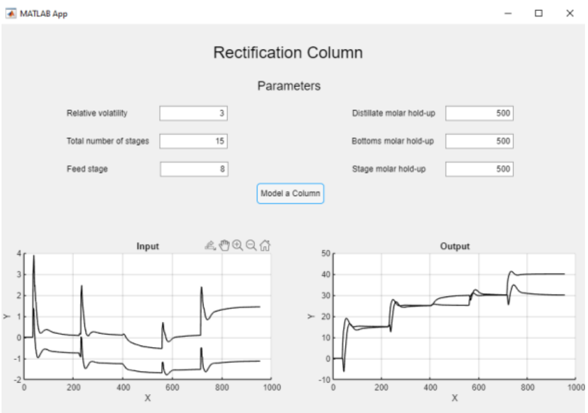

Fig. 26 AppDesigner - PI real time control of the plant

In Fig. 27 can be seen a graphic from one of the trends in SCADA screen that shows the reaction of the top product of the system during the experiments explained for Fig. 26.

In Fig. 28 is presented a graphic from the other trend in SCADA screen that shows the reaction of the bottom product of the system during the experiments explained for Fig. 26.

In Fig. 29 is represented a graphic of real time PI with decoupling matrix control of the model of rectification column in AppDesigner. Four experiments are conducted normal PI control with decoupling matrix, change of setpoint only on the bottom product, change of setpoint only on the top product and change of setpoint on both products. The results from these experiments in comparison with this obtained in MATLAB are the same. Comparing them with the one obtained only with PI control are better. There is no influence between the outputs.

In Fig.30 is shown a graphic from one of the trends in SCADA screen which shows the reaction of the top of the system during the experiments explained for Fig. 29.

In Fig. 31 is shown a graphic from the other trend in SCADA screen which shows the reaction of the bottom product of the system during the experiments explained for Fig. 29.

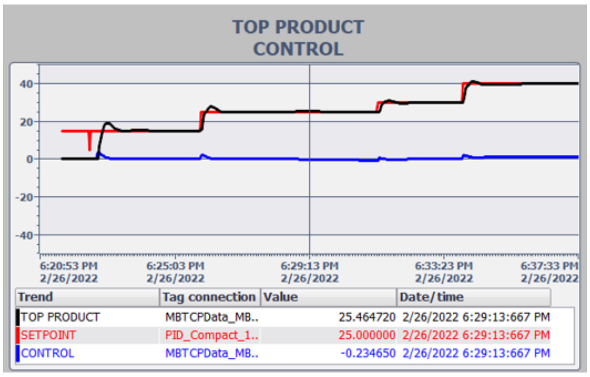

Fig. 27 SCADA - PI real time control of the top product

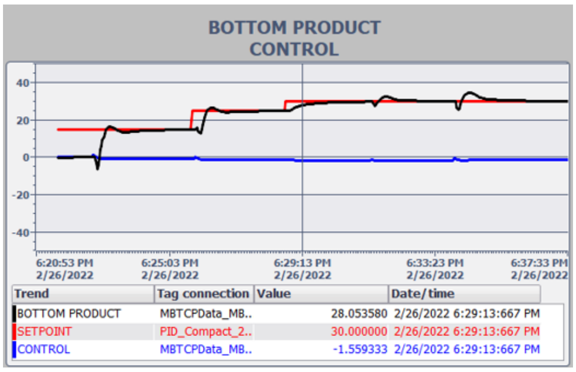

Fig. 28 SCADA - PI real time control of the bottom product

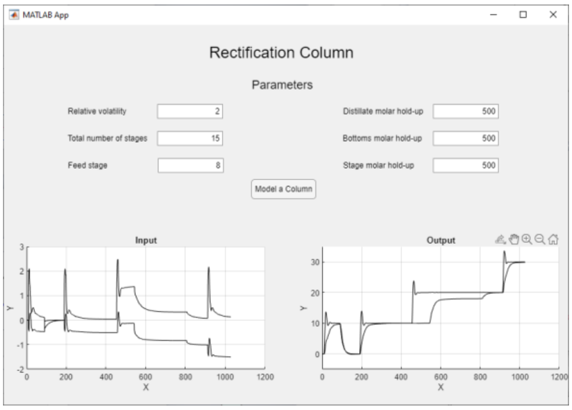

Fig. 29. Control with PI and decoupling matrix

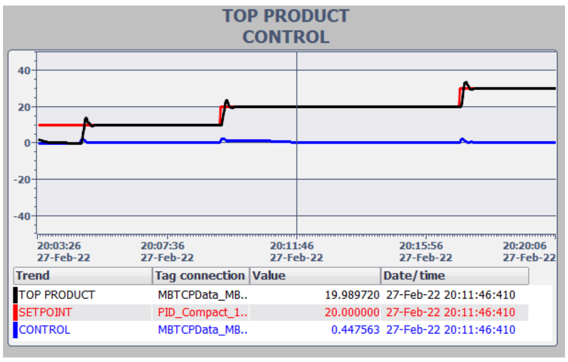

Fig. 30. Top Product control with PI and decoupling matrix

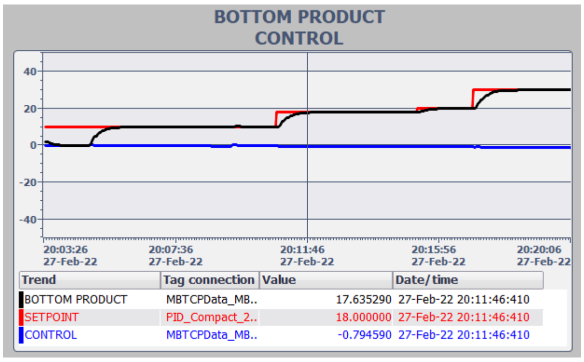

Fig. 31. Bottom Product control with PI and decoupling matrix

VII. Conclusions

The following can be said as a conclusions:

- Multidisciplinary laboratory stand of rectification column is created for experimental studies and trainings for technologists and students.
- PI control of the continuous and discrete model of rectification column is realized in MATLAB and Simulink.
- PI control with decoupling matrix of the discrete model is created in MATLAB and Simulink.
- Real time simulation is created using an internal software in MATLAB, AppDesigner.
- MODBUS communication between MATLAB and TIA Portal is realized.
- SCADA system for visualization and control of the rectification column is created.
- Real time PI control of the model of rectification column is performed using MATLAB as a plant and TIA Portal as a control unit.
- Real time PI control with decoupling of the discrete model is realized by using MATLAB as a plant and TIA Portal as a control unit.
- It is proven that the method in which decoupling matrix is used is better for control and reduces the influence between the outputs.
- Nowadays plants are becoming more complicated and difficult to control. The automation of multivariable systems is a challenge for engineers. In this article is presented a way of how one program should be tested before commissioning. First the whole program should be tested with a model of the plant and after specifying all of the parameters then to be integrated in real factories.

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