Saving the environment by automation of crude oil distillation in a rectification column

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Abstract. The article shows the results of the development of an automated control system for the distillation of oil in a distillation column, which makes it possible to save the environment. In the theoretical part, the process of distillation of crude oil in a distillation column is described and its technological scheme is given for atmospheric distillation with a single evaporation of oil. In the calculation part, the heat and material balance of mass transfer in the rectification column has been analyzed. In the practical part, the problems of installing process control instruments, improving the emergency shutdown system reliability, expanding the automatic and automated monitoring and control functions, and improving the process control and facility performance analysis quality have been solved. The authors used the Trace Mode 6 software package to develop the SCADA of the distillation column control system. In conclusion, it was noted that the development and implementation of an automated control system for the oil distillation process provides an increase in plant productivity, as well as the quality and reliability of the process, which in turn has a positive effect on environmental conservation.

1 Introduction

The modern oil industry is a large national economic complex living and developing according to its own laws [1-3]. Oil is used in petrochemistry as a feedstock in the production of synthetic rubber, alcohols, polyethylene, polypropylene, a wide range of various plastics and finished products manufactured from them, artificial fabrics, motor fuels (gasoline, kerosene, diesel and jet fuels), oils and lubricants, boiler and furnace fuels (fuel oil), building materials (bitumen, tar, asphalt), and some protein preparations used as additives in livestock feed to stimulate its growth [4]. To meet the growing demand for petroleum products, new high-capacity crude oil distillation units should be put into operation annually [5]. Also, the capacity of operating units should be increased through intensifying processes by improving their technologies and implementing the latest highly efficient equipment and automation [6-8].

Crude oil distillation units play an important role in oil refineries [9]. The efficiency of downstream processes such as purification, gas separation, catalytic cracking, coking, etc., depends on their performance indicators [10, 11].

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2 The study goal and objectives

The study is aimed at increasing the productivity of crude oil distillation in a rectification column and improving the process quality and operation reliability through designing (developing) and implementing an APCS and the use of equipment reserves.

The study objectives are installing process control instruments, improving the emergency shutdown system reliability, expanding the automatic and automated monitoring and control functions, and improving the process control and facility performance analysis quality (gathering data, calculating economic indicators, and analyzing the work of operating personnel in static, transitional, and emergency process modes).

As a control object, the rectification column loop has been taken, where the crude oil is distilled after treatment.

3 Brief theoretical part

The demineralized oil from the crude desalter unit (CDU) is fed to the atmospheric-vacuum distillation unit abbreviated as AVDU (at Russian refineries – AVT, atmospheric vacuum tube still). This name is given since before fractioning, the crude is heated in the coils of tube furnaces by the heat of fuel combustion and flue gases. AVDU is subdivided into two units - atmospheric and vacuum distillation [12].

Atmospheric distillation serves to recover light oil cuts – gasoline, kerosene, and diesel, boiling up to 360 °C, the potential yield of which is 45-60 % of crude. The atmospheric distillation residue is fuel oil. The process constitutes fractioning crude oil, preheated in a furnace, in a rectification column - a cylindrical vertical vessel where contact structures (trays) are placed, through which vapor flows upward and liquid downward. Rectification columns of various sizes and configurations are used at almost all oil refineries, and the number of trays in them varies from 20 to 60. Heat is supplied to the column's bottom and removed from the top, therefore, the temperature in the vessel gradually decreases from the bottom to the top. As a result, the gasoline cut is taken from the column's top in the form of vapor, the kerosene and diesel vapors are condensed at and removed from the corresponding column's trays, and the fuel oil remains liquid and is pumped out of the column's bottom [13].

To separate the oil into components, several basic conditions should be met: it should be heated to a temperature ensuring not only heating but also partial vaporization of oil, i.e. flash vaporized, and the heat of the products obtained should be utilized to heat crude oil [14]. For this purpose, tubular heaters, heat exchangers, and rectification columns are used.

The oil can be distilled in atmospheric units in several ways [15]:

1. Flash vaporization in a tubular furnace and fractioning in a single rectification column. Such oil distillation flowsheet, as a rule, is applicable for oils with a low content of light petroleum products and an insignificant content of dissolved hydrocarbon gas and hydrogen sulfide.

2. Double vaporization and fractioning in two rectification columns – the preliminary vaporization column with the recovery of light gasoline cuts and the main column. In this case, the total system pressure and that in the main rectification column decrease, which improves the recovery of light petroleum products from the oil and their fractioning in the column.

When operating according to the second flowsheet, the furnace should provide a higher heating temperature as compared to the single-stage vaporization scheme due to the separate vaporization of low-boiling and heavier cuts. All modern atmospheric units mainly operate according to the double vaporization flowsheet.

The main cuts recovered in the crude oil distillation are [16]:

1. Gasoline cut - an oil distillate with a boiling range from the initial boiling point (individual for each crude oil) to 150-205 °C (depending on the technological purpose of obtaining motor, aviation, or other specific gasoline). This cut is a mix of alkanes, naphthenes, and aromatics. All these are C5-C10 hydrocarbons.

2. Kerosene cut - an oil distillate with a boiling range from 150-180 °C to 270-280 °C. This cut contains C10-C15 hydrocarbons. It is used as a motor fuel (tractor kerosene, diesel fuel component), for domestic needs (lighting kerosene), etc.

3. Gas oil cut - an oil distillate with a boiling range from 270-280 °C to 320-350 °C. This cut contains C14-C20 hydrocarbons. It is used as diesel fuel.

4. Fuel oil - the residue after the distillation of the aforementioned cuts with a boiling point above 320-350 °C. Fuel oil can be used as boiler fuel or further processed, i.e., either distilled under reduced pressure (vacuum) with the recovery of lube cuts or a wide vacuum gas oil cut (which, in turn, is a catalytic cracking feedstock to obtain a high-octane gasoline component) or cracked.

5. Tar - an almost solid residue after the distillation of lube cuts from fuel oil. It is used to obtain the so-called residual oils and bitumen, which is oxidized to produce asphalt used in road construction, etc. Tar and other secondary residues can be coked into coke, which is used in the metallurgical industry.

The single-column atmospheric distillation flowsheet is shown in Fig. 1. Crude oil from CDU is pumped by a feed pump through heat exchangers and a tubular furnace into a rectification column. Flash vaporization of oil occurs in the column's crude intake section. Oil vapors are then fractioned by rectification into target cuts, and low-boiling ones are also recovered from the liquid by rectification.

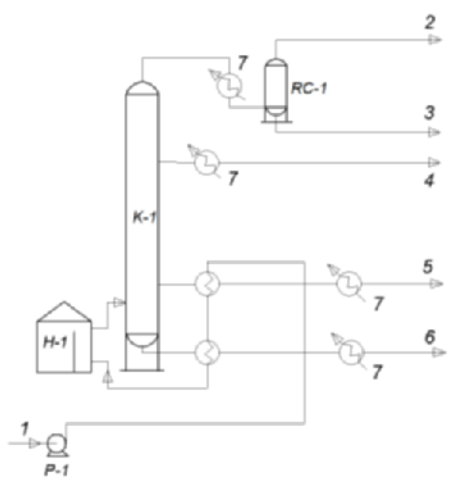

Fig. 1. Atmospheric Distillation Flowsheet with Single Vaporization of Oil: 1 - oil; 2 - gas; 3 - gasoline; 4 - kerosene; 5 - diesel; 6 - fuel oil; 7 - water; P-1 - pump; H-1 - oven; K-1 - rectification column; RC-1 – condenser.

The process products are:

a) C1-C4 hydrocarbon gases containing hydrogen sulfide are sent for purification and separation,

b) wide gasoline cut with an IBP of 150 °C is sent to hydrotreating and separation into narrow cuts for further processing,

c) 150-250 °C kerosene cut is sent to the mixing unit,

d) 250-360 °C diesel cut is sent to hydrotreating,

e) fuel oil (residue > 360 °C) is sent to vacuum distillation or secondary processing.

4 Research results

4.1 The process problems to be solved

When automating atmospheric distillation processes, the following problems should be solved:

1. Automated monitoring of the equipment conditions [17]: a) temperature, flow rate, pressure; b) their system parameters; c) the state of the nodes; d) operation time and downtime of process mechanisms.
2. Automated control [18]: a) stabilizing process parameters; b) optimizing the performance.

To successfully solve the process automation problems, special preparation of equipment is required [19, 20].

For the analysis, one of the main process modules of the crude oil distillation stage – rectification column K-1 was chosen (Fig. 2). Before entering the first rectification column, also called a flash column, oil is heated only in heat exchangers, passing through them in one, two, or more parallel streams. The first column top product is light gasoline with a small gas content. Other unit distillates, as well as fuel oil, are obtained in the second column. The column's operation procedure provides for control over steam flow rate, oil consumption, temperature, pressure, and level.

When analyzing the column as a control object, the main disturbances, possible control actions, and outputs can be identified. Since the initial product enters the column from the upstream process vessels, fluctuations in the feedstock flow rate, composition, and temperature, as well as column pressure and temperature, are the main disturbances in the crude oil distillation. Possible sources of uncontrolled disturbances include environmental heat losses, etc. control actions include flow rate and pressure of oil and steam entering the rectification column. The key disturbances are the column pressure (P_k) and temperature (T_k) and the column feedstock temperature (T_1, T_2), pressure (P_1, P_2), and volumetric flow rate (F_1, F_2), i.e., parameters significantly affecting the control object. In this case, the basic controlled parameter is the flow rate of steam fed to column K-1.

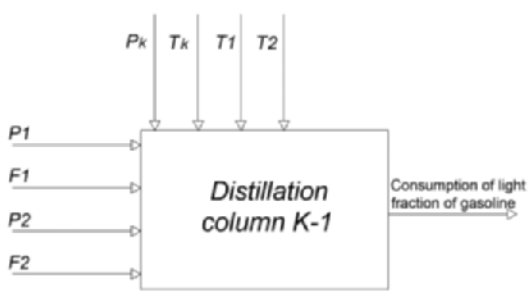

Fig. 2. The Control Object Analysis.

To calculate the automated control system, the column steam feed flow rate stabilization loop has been chosen.

Thus, the problem of control over the crude oil distillation in the K-1 rectification column is generally formulated by a vector of control actions compensating for disturbances at the unit's input and a vector of process mode parameters ensuring the planned (or maximum) yield of the finished product at the unit's output.

4.2 Heat and material balance analysis

Fig. 3 shows the rectification module flowsheet.

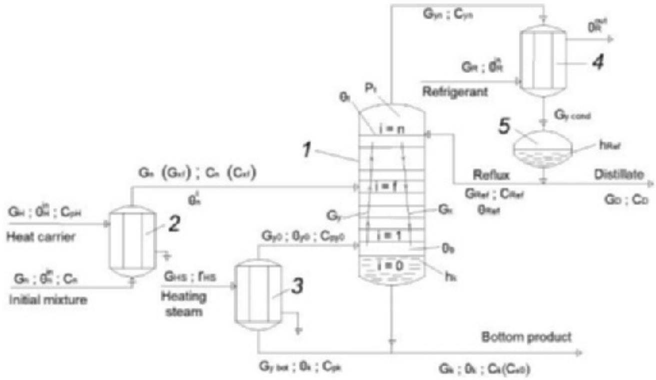

Fig. 3. Rectification Module Flowsheet: 1 - rectification column; 2 - feedstock heater; 3 - boiler; 4 - condenser (reflux condenser); 5 - reflux drum.

Mass transfer occurs on the trays of the rectifying (upper) and exhausting (lower) column sections as a result of the interaction of liquid and vapor phases counterflowing in the column. The initial mix $G_n(G_{xf})$ is heated in the feedstock preheater 2 to the boiling point θ_{n0} and is fed to the feed plate of column 1 (i=f). The initial mix flows down the trays in the lower column section as a liquid flow G_x into the column bottom, participating in the mass transfer with a steam flow G_y. The bottom product G_{bot} is discharged from the column bottom. Part of the bottom product is fed to boiler 3, where it evaporates to form a vapor stream G_{y0}, which is fed down the column. The vapor stream flows upward the column, contacting the liquid stream while being enriched with the target component. The vapor stream G_{yn} enriched with the target component is discharged from the column top and fed into the reflux condenser 4, where it is condensed. The condensate is collected in the reflux drum 5. Two streams are taken from the reflux drum: the target product – distillate stream G_D and reflux flow G_{Ref} – the liquid phase used to reflux the column top. The process efficiency indicator is distillate concentration C_D. The process control goal is to ensure $C_D=C_{Din}$.

Let us determine the material balance for the entire substance.

The dynamics and statics equations will have the form, respectively:

$$\rho_k \cdot S_k \cdot \frac{dh_k}{dt} = G_{x1} - G_k - G_{y0}, \qquad (1)$$

$$G_{x1} = G_k + G_{y0}, \qquad (2)$$

where ρ_k is the bottom liquid density, kg/m^3; S_k is the column bottom section, m^2; h_k is the bottom liquid level, m; G_{x1}, G_k, G_{y0} are the mass flow rates in the column bottom.

Formulas (1) and (2) allow considering:

$$h_k = f(G_k, G_{y0}). \qquad (3)$$

Then G_k will be the preferred control action.

The column top heat balance will be determined by the equality $\theta_t = \theta_b$.

The dynamics and statics equations will have the form, respectively:

$$M_{xn} \cdot C_{pxn} \cdot \frac{d\theta_t}{dt} = G_{yn-1} \cdot C_{pyn-1} \cdot \theta_{yn-1} - G_{yn} \cdot C_{pyn} \cdot \theta_t + $$
$$+ G_{Ref} \cdot C_{\mathrm{p}Ref} \cdot \theta_{Ref} - G_{xn} \cdot C_{pxn} \cdot \theta_t, \qquad (4)$$

$$G_{yn-1} \cdot C_{pyn-1} \cdot \theta_{yn-1} + G_{Ref} \cdot C_{pRef} \cdot \theta_{Ref} = \\ = G_{yn} \cdot C_{pyn} \cdot \theta_t + G_{xn} \cdot C_{pxn} \cdot \theta_t, \quad (5)$$

where M_{xn} is the mass of the vapor phase at the column top; C_{pyn}, C_{pyn-1}, C_{pRef}, C_{pxn} are specific heat capacities of the vapor and liquid phases on the n-th tray; G_{yn-1}, G_{yn}, G_{xn} are the flow rates of the vapor and liquid phases on the n-th tray.

Formulas (4) and (5) allow considering:

$$\theta_t = f(G_{Ref}, G_{yn}, G_{yn-1}, G_{xn}). \quad (6)$$

In this case, G_{Ref} will be the preferred control action.

The dynamics and statics equations for the heat balance by the vapor phase will have the form, respectively:

$$\frac{V \cdot M_t}{R \cdot \theta_t} \cdot \frac{dP_t}{dt} = G_{yn}(P_t) - G_{yk}(G_R), \quad (7)$$

$$G_{yk}(G_R) = G_{yn}(P_t). \quad (8)$$

The vapor phase heat balance has some specifics:

1. The solution to the dynamics equation for P_t gives an equation for the integral link.
2. When considering the equation $G_{yn}=f(P_t)$, then we obtain an aperiodic link of 1st order.
3. When considering the equation $G_{yk}=f(G_R)$, based on the condenser's heat balance, we can obtain: $G_{yk} \cdot r_{yk} = G_R \cdot C_{pR} \cdot \Delta\theta_R$.

Formulas (7) and (8) allow considering:

$$P_t = f(G_R). \quad (9)$$

The demineralized oil is pumped in two parallel flows through a group of heat exchangers, where it is heated to 200-220 °C, and enters the middle section of the column. The rectification column operates at an overpressure reaching 0.45 MPa at some units. Light gasoline vapors (in some cases, the end boiling point of this cut is 85 °C, and in others – 140 or 160 °C) at the column output are condensed in an air cooler. Condensate and associated gases are further cooled in a water cooler and separated in a gas separator. Light gasoline is then pumped to the stabilization and secondary distillation section (module). Part of the light gasoline is returned to the column as reflux. From the column bottom, partially skimmed oil is pumped to the tubular furnace coil. The oil heated in the furnace coils enters the main rectification column in a vapor-liquid state. Part of the oil after the furnace recirculates to one of the column's lower trays as a hot stream. Superheated steam is fed under the bottom trays of stripping columns.

The process mode is given in the table of process parameters (Table 1).

Table 1. Mass Transfer Process Mode.

Parameter	**Value**
Oil heating temperature in heat exchangers	200-230 °C
Skimmed oil heating temperature in the tubular furnace coils	330-360 °C
The temperature of vapors leaving the pre-flash column	120-140 °C
The pre-flash column bottom temperature	240-260 °C
The pre-flash column pressure	0.4-0.5 MPa

4.3 Information support composition and arrangement

The data processing system (DPS) is an integral part of the oil refining control system, designed to automatically calculate the consumption and determine the parameters of oil and its components. The DPS information support is based on a distributed database. The DB contains data describing the process object. Process objects of metering stations are described in the DB as a set of monitoring and control elements. Each monitoring and control element is described by a specific data structure. Monitoring and control elements comprise analog and discrete inputs and outputs [21, 22].

The DPS DB structure is determined by the Daniel FloBoss S600 flow computer software by Emerson Process Management (USA), as well as SIMATIC S7 400 and the PCS operator's AWS with SCADA by Siemens (Germany). The DPS distributed database comprises Daniel FloBoss S600 flow computer DB, SIMATIC S7 400 controller DB, and PCS operator's AWS DB. The Daniel FloBoss S600 flow computer DB comprises the flow computer configuration, algorithms for calculating oil consumption, processing the oil composition data, and calculating physical and chemical parameters according to the regulatory documents in force, and instantaneous values of parameters. The PCS operator's AWS database comprises the operator's AWS configuration and data processing algorithms, parameter values read from the flow computer, and archived data of process parameters, events, and alarms [23].

The DPS database is built based on the following principles: one-time data input with its repeated use; ensuring data protection from unauthorized access; providing data to the user in a form convenient to solve the problems set. The information support data medium types and the data distribution between them are determined by the software and hardware of the controller used. The DPS information support is distributed between hard disk drives (HDD), optical drives (OD), random access memory (RAM), and programmable read-only memory (PROM).

For the Daniel FloBoss S600 flow calculator, the HDD stores files of compiled C programs and ladder logics with the *.abs, *.lad ext. For the operator's AWS, it stores project database files in the C:\Program Files\Siemens\PCS\ directory, license files in the C:\Program Files\Siemens\License directory with the *.lic ext., and message log files in the C:\Program Files\Siemens\Common directory with the *.AEH ext. ODs are used to store software configuration copies. Time-critical real-time tasks use RAM to store data: the Daniel FloBoss S600 flow computer has 4 MB RAM; the SIMATIC S7 400 controller has 4 MB RAM; the operator's AWS has 1 GB RAM; PROM (flash memory) ensures reliable storing static data. This data medium is used to store data remaining unchanged during the system operation. Flash memory stores resident software, user software, constants and coefficients, and instrument and system parameters of controllers.

4.4 Arranging the data acquisition and transmission

Data of flow, pressure, and temperature transducers installed on the metering lines of the site metering stations is fed to the Daniel FloBoss S600 flow computer inputs via current channels (4-20 mA), digital channels based on the standard HART protocol, as well as digital channels based on custom protocols [24, 25]. The Daniel FloBoss S600 computer processes data according to configured data processing functions and algorithms implemented by the computer software. The Daniel FloBoss S600 computer data is transmitted to the site operator's AWS via the RS485 serial interface using the Modbus RTU protocol. The Daniel FloBoss S600 computer data can be transmitted via Ethernet (Modbus TCP protocol) to the higher-level APCS systems of oilfields by routers located in the control panels [26].

The state of monitoring elements is identified by the color of displaying them. The monitoring element state identification is shown in Table 2.

Table 2. Table captions should be placed above the tables.

Indication Color	**Status, Abnormality**
Green	Normal parameter value
Yellow	Exceeding the parameter warning limits, activation of the warning alarm
Red	Exceeding the parameter alarm limits, actuation of the alarm
Crimson	Invalid parameter value, malfunction

Warning and alarm signaling attract the operator's attention with not only color and sound but also pulsating light.

The DPS is arranged as a two-level functionally distributed hierarchical structure with two dedicated monitoring and control levels: lower and upper. The lower level ensures automated (and command-by-command from the upper level) equipment control, i.e., automatic data measurement, calculation, and output (flow rate and operating parameters) based on the FloBoss S600 flow controllers, automated monitoring and control based on the Simatic controller integrated into the APCS. The upper level acquires data on the equipment state by interrogating the lower level, controls the measured parameter ranges, remotely controls the equipment, visualizes the equipment state, and generates and prints reporting documents.

The lower control level ensures the data acquisition, processing, and accumulation, as well as process control and its automatic protection. The upper APCS level is implemented based on servers, operator (AWS) and engineering stations and fulfills the tasks of automated control and regulation, equipment start and shutdown, logical command control, and emergency shutdowns and protections.

The upper level of the main system ensures the interaction of process operators and engineers with controlled process equipment, arranges the system operation, and prepares data arrays for use by non-operational administrative and technical personnel. Also, the upper level ensures the interaction of the APCS engineer with the serviced software and hardware complex. The upper level is represented by the operator-technologist's and the APCS engineer’s AWS computers (the system maintenance AWS).

4.5 SCADA system development

The rectification column operation should strictly adhere to the process mode and avoid its overflow or excessive level lowering. A too low level may cause the load-drop of the fuel oil pumps. Insufficient heating of the processed crude oil leads to the reduced yield of light petroleum products and deteriorates the quality of side cuts and fuel oil. Increasing pressure in the columns reduces the yield of lighter cuts. With the pressure decrease, the cuts obtained become heavier. Process personnel should continuously control pressure vessels [27].

The operator's control level is arranged using the Trace Mode SCADA with data output to the operator's AWS. APCS provides for round-the-clock, continuous control. The system operates in three modes: automated, remote, and local. The automated mode is the system’s basic control mode. In this mode, all actuators are controlled automatically according to the introduced settings, programs, and algorithms built in the system, while various automated control parameters are adjusted by the chief dispatcher from the chief dispatcher’s AWP keyboard or the process site control panel. Operator control panels allow implementing a simplified automated control mode, when only the basic control parameters can be changed

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using the panel keyboard. This mode should provide an operator with an opportunity to control and change the control parameters in the automated control mode while being in the process zone. Operator control panels ensure changing control loop settings, forced termination of the key phases of the software logic control, monitoring of the controlled parameter values, settings, and limits, the current state of the control object, and switching modes. In the remote mode, the APCS control over actuators is blocked. The display system is operational. Automated control loops operate at the settings configured in the automated control phase until manually adjusted. This mode is used for debugging and repair. The local control mode is an auxiliary one since it is used to debug each actuator individually. Actuators are controlled by local control stations (operator panels).

The SCADA project was developed to ensure the rectification column operation, which most closely simulates the real unit's work, as well as comply with modern data processing techniques. This project has the following specifics: it runs stably without errors, polls the system sensors with an optimal frequency, converts the sensor signals with the required discreteness, displays the process in an operator-understandable form, signals the process and equipment operating modes, effectively controls actuators, and can change the control tasks.

Complicating processes and productions set the tasks of creating distributed hierarchical systems and their pass-through programming, which explains the emergence of new computer technologies for integrated systems integrating all the production levels.

A SCADA intended to design and operate distributed automated control systems has been taken as a basis, which usually serves for supervisory control and data acquisition. However, its latest versions have significantly expanded functionality. In particular, the domestic manufacturer AdAstra Research Group LTD has released the 6th version of the Trace Mode SCADA offering powerful tools to create distributed hierarchical APSC with up to three hierarchical levels: the lower controller level, the upper operator AWS level, and the administrative level.

The external view of the rectification column control is visualized in Fig. 4.

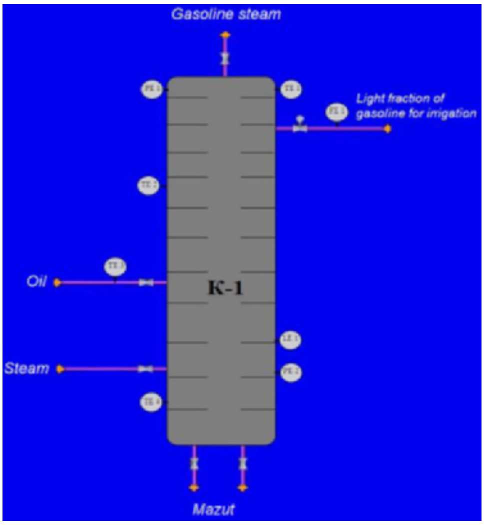

Fig. 4. Rectification Column Control Logic.

Thus, the rectification column is controlled and supervised according to the logic developed. Customized color indication allows viewing and promptly eliminating process failures and errors and, if required, switching from automated control to remote or manual one, as well as, where appropriate, adjusting the operation of a specific process module.

5 Conclusion

Thus, designing and implementing an APCS for crude oil distillation at the GK-3 unit and, in particular, developing a SCADA to control the rectification column process in the Trace Mode 6 package have solved problems such as installing process control instruments, improving the emergency shutdown system reliability, expanding the automatic and automated monitoring and control functions, and improving the process control and facility performance analysis quality (gathering data, calculating economic indicators, and analyzing the work of operating personnel in static, transitional, and emergency process modes). The authors have achieved an improvement in the crude oil distillation unit performance and the process quality and reliability by designing (developing) and implementing an APCS with the use of equipment reserves.

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