Methods for control of crude oil refinery unit

L G Tugashova

Almetyevsk State Oil Institute, 2, Lenina Str., Almetyevsk, Republic of Tatarstan, 423450, Russia

E-mail: Tugashova@yandex.ru

Abstract. We have reviewed the features of the oil rectification process in the low-power crude oil refinery unit. The features of heat removal by intermediate pumparound in comparison with a large-capacity unit have been distinguished. The input and output parameters of the object have been selected. The possibility of representing a multi-loop controlled object as single-channel objects using the EOTF method of effective transfer functions has been reviewed. To improve the quality of unit control, it has been proposed to use the model in practice. For this purpose, a dynamic Hammerstein model for the low-power crude oil refinery unit has been developed to identify the nonlinear part. The proposed model allows studying the influence of various effects (live reflux consumption, diesel oil consumption and superheated steam consumption) on the controlled parameters (points of the temperature profile of the atmospheric tower). The Matlab/Simulink software has been chosen as the tool for implementing the model.

1. Introduction
Control of oil refining units as nonlinear multidimensional objects should be carried out when the requirements for the quality of the produced petroleum products are met and when the technological parameters are maintained at the specified values under the influence of disturbances.

Research by Russian and foreign scholars A. P. Verevkin [1], S. Skogestad, M. Morari [2], A. A. Stopakewich, I. B. Furtat etc., has been devoted to the synthesis of multi-loop systems for controlling the rectification process:

Standard controllers are used in domestic oil rectification unit control systems, and improvements are achieved by using multi-loop automatic control systems. Advanced control systems such as Profit Controller (Honeywell), exaSMOC (Yokogawa), and etc. are used to control large oil refineries based on predictive models. The process control objective while meeting the abovementioned requirements is also relevant for low-capacity oil refining units.

The problem of building robust control systems for the rectification process of a binary mixture in the industrial-type column is solved in the work [2], in order to increase the efficiency of the separation process under uncertainty caused by changes in the composition of the supply stream, the temperature of the streams, etc.

The article [3] proposes a system for controlling quality indicators of primary crude oil processing products with fuzzy process controllers. Models of virtual analyzers have been obtained in a number of works to determine the quality indicators of distillation column products.

To stabilize the product quality of primary oil refining units, two-loop circuits of rectification process regulation are used.
When controlling refinery facilities (distillation columns, heat exchangers, furnaces, etc.), along with a typical solution that involves one-loop and cascade automatic control systems (ACS), control using mathematical models is used.

A review of foreign articles has shown that dynamic control object models are often represented in the State Space [4], in the form of a system of ordinary differential equations [5], by an artificial neural network.

When controlling the rectification process, Internal model controllers (Internal model control - IMC) are used. The controller is an inverted model of the control object, which is not always possible to get. The Skogestad IMC (SIMC) method [6] sets the desired type of transition characteristic of a closed-loop control system, described by an first order inertial element The SIMC-method setting is the expected time constant of this element.

The use of a reference model is proposed in a number of works on distillation column control. A method for controlling small refineries using the model in conditions of variable consumption and composition of raw materials is proposed in the article [7] by narrowing down the issue of controlling a petroleum product sampling to controlling the temperature conditions of the installation and stabilizing intermediate parameters.

The possibility of using disturbance compensators for the consumption and composition of raw materials and cross-link compensators for controlling the distillation column has been reviewed in the article [8]. When using compensators, practical implementation is a challenge, and there can be quite a lot of disturbances in the system.

The application of the EOTF (effective open-loop transfer function) method has been reviewed in the work [9] for an object containing two inputs and two outputs. This method is applicable for converting a multi-loop control object to a set of single-channel objects.

The object of the study is the atmospheric tower with auxiliary equipment that operates as part of a low-power oil refining unit (up to 500 thousand tons). The main factors that cause difficulties in controlling the object: multi-connectivity of parameters, functioning under the influence of disturbances, the presence of nonlinear static characteristics.

To avoid multi-connectivity of parameters, we set the task to determine the main control and disturbance channels and try to apply the EOTF method and the disturbance suppression method.

In order to register the nonlinear characteristics of an object, first of all you need to identify their structure and parameters, and then to apply object controlling according to the model. We propose to use a nonlinear Hammerstein model to improve the quality of object control process.

A distinctive feature of a low-capacity oil refining unit is the arrangement of pumparounds and petroleum product sampling. Standard heat removal schemes with intermediate pumparound (as in large-capacity units) are not used, and we take into account this fact when selecting the parameters of the object of study.

2. Materials and methods
For an atmospheric tower with auxiliary equipment operating as part of a low-power oil refining unit (up to 500 thousand tons), the following input and output parameters are selected: top reflux rate \( LT \), superheated steam flow rate \( VB \), diesel fraction flow rate taken from the atmospheric tower \( DT \), tower overhead temperature (naphtha) \( T_1 \), diesel fraction temperature \( T_2 \), column bottom temperature (fuel oil) \( T_3 \), raw material consumption \( F \).

Let us define the main control and disturbance channels. Testing dynamic characteristics on a production facility can be a quite difficult experiment. The dynamic model of the oil rectification process at a small oil refinery is presented in the work [10], built on the basis of a system of material balance and heat balance equations. Adequate accuracy of the built dynamic model is shown. Therefore, we consider this circumstance to be the basis for its application as a source for obtaining experimental data of the control object.

The parametric sensitivity of the object has been studied using a dynamic model of the rectification process [10]. By the relative sensitivity coefficient, the sensitivity of the temperature profile has been
determined from $T_1$, $T_2$, $T_3$ column height to $LT$, $VB$, $DT$ controlling actions, and the dynamic control channels has been selected.

As a matter of convenience in the further implementation of the object mathematical model, the controlling actions are combined into the $u$ vector, disturbances – into the $d$ vector, the intermediate parameters into the $x$ vector, and outputs into the $y$ vector:

$$\{LT, DT, VB\} \in u; \{f(LT), f(DT), f(VB)\} \in x; \{F\} \in d; \{T_1, T_2, T_3\} \in y.$$

Thus, it has been determined that an atmospheric tower with auxiliary equipment operating as part of a low-power oil refining unit is a multi-dimensional MIMO (Multiple Input Multiple Output) object with three control inputs, three controlled outputs, and one disturbance.

The $EOTF$ method is applied to a linear object model. The formula that determines the effective transfer function of an open loop is following [9]:

$$W(p)_{EOTF} = \frac{W_{ii}(p)}{DRGA_{ii}},$$

where $DRGA$ is a dynamic relative gain array; $W_{ii}(p)$ is the object's transfer functions for the control channel; $i$ is the channel number.

The effective transfer functions of the $W(p)^{EOTF}$ object has been determined using the formula (1) for the case of 3 inputs – 3 outputs for the following control channels: "reflux rate – overhead temperature", "diesel fraction flow rate – diesel fraction temperature", "superheated steam flow rate – bottom temperature".

The controlled disturbance is the consumption of raw materials supplied to the atmospheric oil rectification unit. The "virtual experiment" was used to identify parameters of object models using disturbance channels: "raw material consumption - temperature of naphtha", "raw material consumption - temperature of diesel fuel", "raw material consumption - temperature of fuel-oil residue (bottom)". As a result of step disturbance the curves of the transition characteristics for the above-mentioned channels has been obtained.

Models of disturbance compensators are determined by formulas known from the classical theory of automatic control.

Dependencies for non-linear parts for each control channel has been derived in the form of static characteristics. The model presented as a system of material and heat balance [10] is difficult to apply in unit controlling. In order to implement the dynamic model in the controller and single out the non-linear part, the model of the rectification process [10] has been transformed to a suitable form for implementation. The Hammerstein model which containing nonlinear and linear parts is used for this purpose.

To determine the type of nonlinearity for each control channel, the following "experiment" has been performed on a dynamic model. To measure static characteristics, they raised the control signal, they waited for a stable temperature setting, and then the input step was increased sequentially with a constant increment. Therefore, as a result of the abovementioned steps, a step change in the controlling action in time and a change of the output parameter in time has been obtained.

With adequate accuracy, the static characteristics are approximated by a truncated cubic parabola:

$$x_i = k_1 \cdot u_i + k_2 \cdot u_i^3.$$

After determining the type of nonlinearity (2), an Input-Output model is recorded for each channel. In the image area, the description is performed using transfer functions (TF) for each channel.

For the case of a MIMO system, each output is defined as follows:

$$y_i(t) = \frac{B_{i1}(z^{-1})}{A_{i1}(z^{-1})} \cdot x_1(t) + \frac{B_{i2}(z^{-1})}{A_{i2}(z^{-1})} \cdot x_2(t) + \frac{B_{i3}(z^{-1})}{A_{i3}(z^{-1})} \cdot x_3(t),$$

where $A_{i1}, A_{i2}, A_{i3}, B_{i1}, B_{i2}, B_{i3} –$ polynomials; $z^{-1} –$ first-order lag operator.
Then the parameters of the linear part (3) has been determined, for which the ordinary least squares method (OLS) is applied. The input of the linear model is fed to the output of the nonlinear model for each channel, and the delay should be taken into account as well.

3. Results of experiments
For the case of 3 control inputs – 3 controlled outputs according to the formula (1) using Matlab, the $TFW_1(p)^{EOTF}$, $TFW_2(p)^{EOTF}$, $TFW_3(p)^{EOTF}$ have been defined. As a result of identification using OLS method, coefficients of mathematical models of the object have been obtained for the $Wd_1(p)$, $Wd_2(p)$, $Wd_3(p)$ channels of disturbances. For example, figure 1 shows the result of identifying model parameters using the "raw material consumption – diesel fraction temperature" channel in comparison with the "experimental" curve. The experimental values are indicated as separate readings, and the model values are indicated as a solid line.

![Figure 1](image1.png)

**Figure 1.** Approximation using the "raw material consumption – diesel fraction temperature" channel.

Figure 2 shows the structure of the ACS that contains the effective transfer function $W(p)^{EOTF}$, naphtha recovery temperature controllers, diesel fraction, $P_1$, $P_2$, $P_3$ fuel oil residue; $WK_1(p)$, $WK_2(p)$, $WK_3(p)$ disturbance compensators; the transfer function of the object for the $Wd_1(p)$, $Wd_2(p)$, $Wd_3(p)$ disturbance channels; $SP_1$, $SP_2$, $SP_3$ controller setting values.

![Figure 2](image2.png)

**Figure 2.** ACS containing effective transfer functions
The $W(p)^{EOTF}$ functions we got are of high order. The Pade approximation was used to exclude lagging elements which also have led to an increase in the order. There is a pade function for this in Matlab.

Due to the complexity of the obtained expressions, we conclude that it is difficult to apply the EOTF method to a multidimensional multiloop system containing 3 control inputs and 3 controlled outputs.

Arrays of controlled parameter and control action values have been formed from the "experimental" values of the dynamic model of the oil refining unit atmospheric tower [10]. The structure and parameters of the Hammerstein model’s linear and nonlinear parts have been determined.

Static characteristics that are visually nonlinear have been built. The $k_1$, $k_2$ coefficients for the cubic parabola for each control channel have been calculated.

Table 1 shows the coefficients obtained for the cubic parabola (formula 2) for each control channel.

| Control channel                           | $k_1$  | $k_2$  |
|-------------------------------------------|--------|--------|
| Reflux rate – overhead temperature        | 77.11  | -3.344 |
| Diesel fraction flow rate – diesel fraction temperature | 21.46  | 2.355  |
| Superheated steam flow rate – bottom temperature | -390.3 | 31.23  |

After finding the parameters of the Hammerstein model nonlinear part, the type and coefficients of transfer functions of the linear part of the model have been determined.

The objective of finding coefficients using the OLS method is to minimize the mismatch between the output signal of the model and the experimental one at any time. As a result of identification, the Hammerstein model has been presented in the following way:

$$
T_1 = W_{11}(p)f(LT) + W_{12}(p)f(DT) + W_{13}(p)f(VB);
T_2 = W_{21}(p)f(LT) + W_{22}(p)f(DT) + W_{23}(p)f(VB);
T_3 = W_{31}(p)f(LT) + W_{32}(p)f(DT) + W_{33}(p)f(VB);
$$

(4)

where $W_i(p)$ is the transfer function from the $j$-th input to $i$-th output; $f(LT)$, $f(BT)$, $f(VB)$ are nonlinear static characteristics; $T_1$, $T_2$, $T_3$ – temperatures at the draw-off trays

4. Discussion of results and conclusions

An attempt to use the EOTF method for controlling an object containing three inputs and three outputs has resulted in an almost unrealizable form of effective transfer functions.

When conducting experiments using the Matlab software, we have managed to identify the Hammerstein model’s linear and nonlinear parts. The maximum percentage error of the produced Hammerstein model (4) is 4.8% against "experiments".

Thus, on the basis of an accurate dynamic model of the oil rectification process using the proposed algorithm, the Hammerstein model is produced, which allows isolating the nonlinear part of the model and, importantly, use the model to control the oil rectification process over a larger range of input parameters.

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