Mathematical model of large-tone pyrolysis installations in production of ethylene

D V Arapov¹, S G Tikhomirov², S L Podvalny³ and V A Kuritsyn⁴

¹,²Faculty of Management and Informatics in Technological Systems, Voronezh State University of Engineering Technologies, Voronezh, Russia
³Faculty of Information Technology and Computer Safety, Voronezh State Technical University, Voronezh, Russia
⁴CJSC Engineering Systems of Automation in Industry, Voronezh, Russia
E-mail: ¹arapovdv@gmail.com, ²tikhomirov_57@mail.ru, ³spodvalny@yandex.ru, ⁴vakuricin@gmail.com

Abstract. The model has a modular structure and includes a stochastic model of changing the composition of gasoline raw materials and the balance model of its preparation site, nonlinear models of pyrolysis of liquid and gaseous hydrocarbons, quenching of pyrogas, coke deposits, fuel combustion and coke burning.

1. Introduction
Lower alkenes (ethylene, propylene, butylene, etc.) and arenes (benzene, toluene) are widely used in the production of most petrochemical synthesis products. These intermediates are obtained by thermal cracking of liquid or gaseous hydrocarbon feedstocks in pyrolysis furnaces of large unit capacity. Usually in different countries the structure of raw materials is different. In Russia this is straight-run gasoline (naphtha) 56% by weight; liquefied gas (propane, butane) 30% by weight; ethane 8% by weight; or kerosene-gas oil fraction 6% by weight. As a rule, pyrolysis installations are universal and can work with any specific kind of raw with minor changes in the mode parameters. Much work has been devoted to mathematical modeling of the pyrolysis process. Most researchers adhere to the theory of a free-radical chain mechanism and the resulting models are very complex with a large number of parameters to be identified. In this connection, simplified models are of interest. The most interesting works published in recent years are [1–4], in which pyrolysis and gaseous raw materials are considered, such as naphtha, ethane and ethane-propane fraction. The first developed simplified model of pyrolysis of naphtha SRT-VI [3] in the furnace takes into account the physical properties of the raw materials, such as density and acceleration by Engler. On their basis, the molecular weight of the feedstock, the indices of its aromaticity and paraffininess, the ratio of carbon to hydrogen, the total concentration of hydrogen atoms associated with the secondary and tertiary carbon atoms are calculated. Pyrolysis outputs products depend on the temperature and pressure of pyrolysis at the furnace outlet, on the pressure drop across the coil and on the calculated raw material values. [2, 4] describe mathematical models of pyrolysis of gaseous raw materials based on the radical-chain mechanism of thermal cracking of hydrocarbons, including the models of cokes education in the coil of the furnace. [1, 5, 6] describe a kinetic model of the process in a separate pyro-
arsenic, which was obtained by replacing free-radical chain mechanism by a sequential-parallel reaction scheme in which are excluded intermediate elementary stages involving free radicals. The appropriateness of this approach was shown by the analysis of chemical transformations in the pyrolysis of gasoline, performed on the basis of experimental data and modeling results. The analysis of chemical transformations, performed on the basis of experimental data and modeling results, showed the validity of this approach in the pyrolysis of gasoline. It is established that the error of such a replacement is commensurable with the error of chromatographic analysis of the composition of pyrolysis gas at the outlet of the coil [7]. The efficiency of using the genetic algorithm to identify the kinetic model of pyrolysis is shown in [8] and [1]. A common disadvantage of most publications on the modeling of pyrolysis of hydrocarbon raw materials is that they do not consider auxiliary processes and apparatuses, such as coke firing in pyro-arrows, combustion of fuels in furnaces, coking of quenching-and-evaporation apparatus (QEA), generation in QEA high-pressure steam that form a series-parallel structure. In this regard, the development of a mathematical model of large-tone pyrolysis installations (LPI) is relevant, since it allow to optimize the mode of operation of the main pyrolysis process and auxiliary processes.

2. Materials and methods
The mathematical model of the LPI has a modular structure that repeats the structure of the pyrolysis installations. The model include (figure 1) a stochastic model changing the compositions of individual types of gasoline raw materials (block 1), balance model of the raw material preparation siteby mixing its individual species (block 2), nonlinear models of pyrolysis of liquid and gaseous hydrocarbons [1,3] in pyrolysis furnace of large unit capacity (block 4), quenching of pyrogas (block 7), coiling of coils and QEA (blocks 5,6), combustion of fuel in furnace (block 3), coke burning (block 8) and also allows to simulate the pyrolysis regime in separate coils of a large-capacity furnace (block 9). The input parameters of the model are determined experimentally the mathematical expectations of the amounts of normal isocyclane ($\lambda$) and their variance ($S^2_\lambda, S^2_\nu$), as well as the set values of the ratio in the raw mix of the amount of refined gasoline to the straight-run gasoline ($\lambda$), the oxygen content in the flue gases ($F^o$), raw material costs and steam in the furnace ($F^r, F^s$), study time ($\tau^s$), the temperature of the refrigerant supplied to the QEA ($T^coo$), the pressure of the pyrolysis gas at the outlet of the QEA ($P^o$) the temperature of the pyrolysis products, or the coke burning at the exit from the furnace ($T$), the time of burning of coke in coils ($\tau_{dc}$).

The output parameters of the model are the content of hydrocarbon in the straight-line, refined and mixed gasoline ($C^p, C^c, C^\nu$), the fuel gas flow into the furnace ($F^fu$), the temperature of the flue gases in the furnace ($T^{sm}$), the output of product $i$ and the amount of coke deposited in QEA ($Q_i$), the outlet temperature QEA ($T_Q$), the pressure at its outlet ($P_Q$) after the furnace ($B_i, B_{pr}$), the thickness of the coke film at the outlet $m$ of the coil ($\delta_m$), the high-pressure steam produced by this apparatus ($F^{hs}$), the carbon dioxide content in the coke combustion products ($B_{CO_2}$), the coil wall temperature ($T_w$), temperature of the cracking gas at the outlet $m$ and the pressure of raw materials at its entrance ($T_{m}, P_{m}$).

The peculiarity of the LPI model and the difference from the known dependencies is that it describes the entire interconnected complex of technological processes and regimes of the pyrolysis separation in the production of lower alkenes from the viewpoint of the system approach. Modeling of disturbances by composition of raw materials is carried out as follows. First, a normal random variable corresponding to the total content of normal and isoalkanes in gasoline is calculated. The calculation is based on the formula: $C^3 = \left( \frac{\sum_{i=1}^{K} x_i - 0.5K}{\sqrt{K/12}} \right)$, where $x_i$ is uniformly distributed random number $0 < x_i < 1$; $K$ is number of used values $x_i$; $\overline{C^3}$ are the required average content of hydrocarbons
Figure 1. Structure of the mathematical model of the LPI.

Uniformly distributed random numbers are determined using the method of degree residues. Then, according to the above formulas, the content of the constituent components in the raw material is determined. The stochastic model is used to simulate the real conditions of the functioning of the LPI in developing algorithms, control systems, and also in training technological personnel. The resulting content of $\nu$ class of hydrocarbons in pyrolysis raw materials after mixing gasoline (straight-run and refined) in the raw material preparation unit is determined from the material balance and is calculated according to the formula in block 2 (figure 1).

To create a model for the pyrolysis of liquid and gaseous hydrocarbons in a large-capacity furnace (block 4), a kinetic model of this process was developed in a separate pyromet, obtained by replacing the radical chain mechanism with a sequential-parallel reaction scheme. The group composition of gasoline serving as the pyrolysis feedstock includes n-, iso-, cycloalkanes, aromatic
hydrocarbons, higher alkenes. In the mathematical model, n-alkanes are approximated by n-hexane (C₆H₁₃) isoalkanes-isooctane (C₇H₁₈), cycloalkanes-cyclopentane (C₇H₁₄), aromatic hydrocarbons by ethylbenzene and xylene (C₈H₁₀).

The content of higher alkenes in raw materials is insignificant and is not taken into account in the model. The content of higher alkenes in raw materials is insignificant and is not taken in the model.

The adopted kinetic scheme includes 20 primary cracking reactions of the components of the gasoline raw material and 50 secondary reaction reactions of pyrolysis products. Thus, the system includes 70 elementary molecular reactions (direct and reverse) flowing between 21 components.

The rates of thermochemical reactions are equal: for monomolecular is \( r_i = k_i \left( \frac{E_i}{T} \right) \); for reactions for bimolecular reactions are \( r_i = k_i \left( \frac{E_i F_j F_k}{T^2} \right) \) or \( r_i = k_i \left( \frac{E_i}{T} \right)^2 \); for three-molecular reactions are \( r_i = k_i \left( \frac{E_i F_j F_k F_m}{T^3} \right) \) or \( r_i = k_i \left( \frac{E_i}{T} \right)^3 \), where \( r_i \) is reaction rate constant; \( F \) is the mole fraction of the reaction component, \( \text{mol/s} \); \( F_j \) is total mole consumption of participants in the reactions, \( \text{mol/s} \); \( P_i \) is partial pressure, \( \text{Pa} \); \( R \) is universal gas constant \( R = 8.3144, J/(mol \cdot K) \); \( T \) is temperature, \( K \); \( k_i \) is reaction rate constant, \( k_i = k_{10} \exp(-E_i/RT) \); \( k_{10} \) is PRE-exponential \( i \) reaction factor, \( s^{-1} \); \( m^3/\text{mol} \cdot s, m^6/\text{mol}^2 \cdot s \); \( E_i \) is activation energy of the \( i \) reaction of the kinetic scheme, \( J/mol \).

The material balance is made on the basis of the kinetic scheme, described by a system of differential equations of the first order, which is supplemented by balance equations of thermal and kinetic energy, taking into account the design features of the pyrolysis furnace:

\[
\frac{dF_j}{dt} = \sum_{i=1}^{70} \left( \alpha_{ij} \cdot r_i \right) - \frac{\pi d_{in}^2}{4},
\]

\[
\frac{dT}{dt} = \frac{\chi \cdot \alpha(F, T) \cdot \pi \cdot d_{in} \cdot (T_w(l) - T(l)) - \sum_{j=1}^{21} \left[ \frac{dF_j}{dt} \right] \cdot \Delta H_j(T)}{F^s \cdot C_p(T)_s + \sum_{j=1}^{21} F_j \cdot C_p(T)_j};
\]

\[
T_w(l) + \frac{\alpha(F, T)}{C} \cdot T_w(l) - (T^m)^4 - \frac{\alpha(F, T)}{C} \cdot T(l) = 0
\]

\[
\frac{dP}{dt} = \frac{R \cdot T(l) \cdot P(l) \cdot v_{mas}(l) \left[ \frac{dV(F)}{dt} \cdot M_{sum}(F) + \left( \frac{1}{RT(l)} \cdot \frac{dF}{dt} + \theta(T) \right) \right]}{R \cdot T(l) \cdot v_{mas}(l) - M_{sum}(F) \cdot P(l)}
\]

initial conditions are \( F_j(0) = F_j^0; F_j(0) = 0; T(0) = T_0; P(0) = P_0 \), where \( j = 1...21; i = 1...70, F_i^0 \) molar consumption \( \nu \) of raw material component, \( \text{mol/s} \); \( F_j \) is molar consumption of \( j \) product, \( \text{mol/s} \); \( \alpha_{ij} \) is stoichiometric coefficient of molecular reaction; \( d_{in} \) is internal diameter of pyrolysis coil, \( m \); \( l \) is current section of coil, \( m \); \( \chi \) is coefficient of uneven heating; \( \alpha(F, T) \) is coefficient of heat transfer from the coil wall to the flow; \( C_p(T)_j \) is heat capacity \( j \) the reaction mixture component, \( J/(kg \cdot K) \); \( C_p(T)_s \) is specific heat of steam, \( J/(kg \cdot K) \); \( F^s \) is steam consumption, \( \text{mol/s} \); \( T_w(l) \) is coil wall temperature at current point, \( K \); \( \Delta H_j(T) \) is the heat of formation of the \( j \) reaction component, \( J/kg \); \( \theta(T) \) is coefficient of hydraulic friction flow on the wall of the coil \( M_{sum}(F) \) is molecular mass of cracking gas, \( kg/mol \); \( v_{mas}(l) \) is mass velocity of cracking gas at the current point of the coil, \( kg/(s \cdot m^2) \); \( V(F) \) is volume of cracking gas, \( m^3/kg \); \( C \) is the emission factor of the flue gases in the furnace is equal to \( C = c_0 \cdot \varepsilon \cdot \varepsilon_w \cdot \varphi; c_0 \) is coefficient of radiation of an absolutely black body, \( \varepsilon \) is blackness of flue gases, \( \varepsilon_w \) is blackness of pyrometrical walls \( \varphi \) is coefficient that takes into account the intensity of heat exchange

5
between the reactor section and the source of heating, depending on the location of the burners [1]; \( T_0 \) is temperature of raw materials at the entrance to the coil, \( K \); \( P_0 \) is pressure of the mixture at the inlet of the reactor, Pa. Accepted: \( \varepsilon_w = 0.8 \); \( \varepsilon = 0.8 \). The coefficient of heat transfer from the coil wall to the moving flow in the system of equations (1)–(4) is determined by the following dependence:

\[
\alpha (F, T) = \left( \frac{d_{m}(l)}{Nu(T) \cdot \lambda(F, T)} + \frac{\delta_{w}(l)}{\lambda_{w}} + \frac{\delta_{m}}{\lambda_{c}} \right)^{-1},
\]

where \( Nu(T) \) is Nusselt number; \( \lambda(F, T) \) is thermal conductivity of a gas-vapor mixture, \( J/(m \cdot s \cdot K) \); \( \delta_{w} \) is wall thickness of the pyrolysis coil, \( m \); \( \lambda_{w} \) is thermal conductivity of pipe material, \( J/(m \cdot s \cdot K) \); \( \lambda_{c} \) is thermal conductivity of coke deposits, \( J/(m \cdot s \cdot K) \).

Evaluation of the combustion process in the pyrolysis furnace (block 3), describing the temperature dependence in the furnace from the qualitative and quantitative composition of fuel and its consumption:

\[
T_{\text{in}} = 275.599 + 0.468 \cdot \left( Q_{\text{net}} \cdot \eta - \frac{Q_{r}}{F^8 a} \right) + 1.6 \cdot 10^{-8} \cdot \left( Q_{\text{net}} \cdot \eta - \frac{Q_{r}}{F^8 a} \right)^2
\]

where \( \eta \) is efficiency of the combustion chamber, \( Q_{r} = f(F^8, F^8, T, T_0) \) are the amount of radiation heat involved in the process, \( J/s; Q_{\text{net}} \) is net calorific value of fuel, \( J/kg \).

Mathematical dependencies (1)–(6) allow the correct calculation of the profile of the reaction kinetics, physicochemical parameters of the components and furnace design. A detailed description of the components of equations (1)–(6) is given in [1].

Block 5 presents an equation for calculating the thickness of a coke film during pyrolysis of naphtha; for a gas feed, the rate of coke formation is described by the equation described in [9]. The rate of coke removal for gasoline raw materials is developed on the basis of experimental data [10] and is a dependence on the composition and conversion of gasoline, process temperature and the ratio of raw materials:

\[
W_k = a_0 \cdot \left[ Con \cdot (a_1 + a_2 Con) + a_3 Con \cdot \Delta T \cdot \left( 1 + a_4 Con + a_5 Con^2 \right) + a_6 Con/\phi \left( 1 + a_7 Con \right) + a_8 Con \cdot \Delta T/\phi \cdot \left( 1 + a_9 Con + a_{10} Con^2 \right) + a_{11} Con \left( \Delta T + a_{12}/\phi + a_{13} \Delta T/\phi \right) \cdot \left( 1 + a_{14} Con + a_{15} Con^2 \right) + a_{16} Con \cdot \phi/\Delta T + a_{17} Con/(\Delta T - a_{18})^3 + a_{19} Con \cdot \phi^{a_{20}} \cdot \left( \frac{BMCI}{K_W} + \rho^8 \right) \right],
\]

where \( Con \) is gasoline conversion, % mas.; \( \Delta T = 0.01 T \); \( \phi \) is ratio steam gas; \( BMCI, K_W \) are accordingly, the indices of aromaticity of gasoline and its paraffinity [11]; \( \rho^8 \) is relative density of naphtha at 15.6°C; \( a_0 - a_{20} \) are coefficients. The equations (in block 5 and (7)) describe the coke deposition model on the walls of coils of a tubular furnace during the pyrolysis of liquid raw materials. It is used to determine the thickness of the coke film on the inner surface in simulating the LPI.
3. Results and discussion

Software implementation of the mathematical model was developed in the programming language C# on MS Visual Studio 2010, where the system of differential equations (1)–(4), in view of its rigidity, is solved by the Runge-Kutta method of the sixth order of accuracy [12], in contrast to [13], where the solution is fulfilled by the classical Runge-Kutta method. Parametric identification of the mathematical description is carried out by the genetic algorithm [14], the required constants are the pre-exponential factors or (and) activation energies in the Arrhenius equation. In the genetic algorithm, increments of the desired parameters are randomly generated in the population. In the absence of changes in the objective function over 300 generations, the generation step is reduced by an order of magnitude and the increments are summed with the model parameters. Then the cycle repeats to the specified accuracy. To exclude the loss of effective increments, all individuals participate in the crossing. Then 85% of the worst target values of individuals are removed from the population, and the remaining ones are transferred to the next generation. The percentage of mutation in crossing the generated individuals is 10.

An analysis of the perturbation in the composition of the gasoline raw material showed that the change in composition over time is random. Using regression and correlation analysis [7], it was found that there is a relationship between individual groups of hydrocarbons, which is described by the following linear expressions:

1) for straight run gasoline is $C_{ni}^n = -12.81 + 0.6744C_{ni}^m; C_{ni}^m = C^m - C_{ni}^n; C_{ni}^v = 89.87 - 0.9784C_{ni}^m; C_{ni}^a = 100 - C_{ni}^n - C_{ni}^m - C_{ni}^v$;

2) for refined gasoline is $C_{ri}^r = -74.13 + 1.491C_{ri}^r; C_{ri}^n = C^r - C_{ri}^r; C_{ri}^v = 64.09 - 0.6235C_{ri}^r; C_{ri}^a = 100 - C_{ri}^r - C_{ri}^n - C_{ri}^v$, where $n, r$ are superscripts of straight-run and refined gasolines; $C_{ni}^m, C_{ri}^r$ is total content in rectilinear or refined gasoline of cyclones of normal and iso-structure, %;
\( C_n^{r}, C_i^{n,r}, C_c^{m,r}, C_a^{u,r} \) is accordingly, the content of n-alkanes, isoalkanes, cyclones and arenes in the feedstock.

The analysis also showed that the content of normal and isoalkanes in gasolines obeys the normal distribution law with characteristics: 1) raw material-straight-run gasoline \( \overline{C}^n_{\text{c}} = 62.13; S^n_{c} = 7.017; \mu_3^n = 12.212; \mu_4^n = 4740 \);

2) raw material-refined gasoline \( \overline{C}^r_{\text{c}} = 80.43; S^r_{c} = 5.37; \mu_3^r = -23.4; \mu_4^r = 2378 \), where \( \overline{C}^n_{\text{c}}, \overline{C}^r_{\text{c}} \) are sample mean; \( S^n_{c}, S^r_{c} \) are variances; \( \mu_3^n, \mu_4^n \) are the third and fourth moments of the random variable \( C^{n,r} \).

The obtained conclusions about the normal distribution law were verified using Pearson’s agreement criterion, whose calculated value is equal to: for naphtha is \( \chi^2 = 1.756 \), for raffinate gasoline is \( \chi^2 = 0.1213 \). The table value of Pearson’s criterion for significance level 0.05 is equal \( \chi^2_{0.05} = 3.8 \). The values found from the samples \( \chi^2 \) are less than the table values \( \chi^2_{0.05} = 3.8 \), then the Pearson criterion allows the observed distributions to be considered normal.

The results of modeling the process of pyrolysis of gasoline in the coil of a large-capacity furnace are shown in figure 2. The temperature of the cracking gas at the outlet of the coil is 1138 °K, the inlet temperature is 923 °K, the flow rate of naphtha into the coil is 0.4282 kg/s, the steam/feed ratio is 0.6. From the presented graphs it can be seen that the target products (ethylene, propylene, butadiene) pass through a maximum. The methane output rises with a rise in temperature, the conversion of gasoline drops almost to zero. The modeling error for the main products is 4-5 % rel.

The range of the dependence (7) is 20.00 ≤ \( Con \) ≤ 99.99; 1013 °K ≤ \( T \) ≤ 1138 °K; 0.56 ≤ \( \phi \) ≤ 0.8. The average relative error of the model is 5.8 %. Figure 3 and figure 4 shows the 3D profiles of the change in coke rate, depending on the conversion, temperature and steam/naphtha ratio.

![Figure 3. Dependence of the rate of coke deposition in the pyromast from the conversion of naphtha and steam/naphtha ratio to temperature 1073 °K.](image-url)
Figure 4. Dependence of the rate of coke deposition in the pyromast from the conversion of naphtha and \textit{steam/naphtha} ratio to temperature 1138 °K.

With increasing temperature and conversion of naphtha, the rate of coke deposition increases, and with increasing ratio of \textit{steam/naphtha} decreases. When the concentration of arenes increases in the raw material, the index of its aromaticity \textit{BMCI} grows and the coke rate increases, with increasing alkane content the paraffin index \textit{KW} increases and the coke rate decreases. From the density of raw materials, the rate of coking is directly proportional. The coefficients of the model (7) are presented in Table 1, the coefficient \(a_0 = 1.0\). This coefficient serves to adjust the model for the process of coke deposition in a particular industrial furnace.

| Coefficient | Value          |
|-------------|----------------|
| \(a_1\)     | 0.378043 \times 10^{-1} |
| \(a_2\)     | -0.28734588 \times 10^{-2} |
| \(a_3\)     | 0.43591933 \times 10^{-3} |
| \(a_4\)     | 1.0187825 |
| \(a_5\)     | -2.2261572 \times 10^{-3} |
| \(a_6\)     | -6.5941521 |
| \(a_7\)     | -0.112935 \times 10^{-1} |
| \(a_8\)     | 0.590875 |
| \(a_9\)     | -0.104533 \times 10^{-1} |
| \(a_{10}\)  | -0.213502 \times 10^{-4} |
| \(a_{11}\)  | -0.254395 \times 10^{-4} |
| \(a_{12}\)  | 0.349 \times 10^{6} |
| \(a_{13}\)  | -0.373769 \times 10^{5} |
| \(a_{14}\)  | -2.366965 \times 10^{-2} |
| \(a_{15}\)  | 0.224272 \times 10^{-3} |
| \(a_{16}\)  | 0.785859 |
| \(a_{17}\)  | 1.1420155 |
| \(a_{18}\)  | 8.261034 |
| \(a_{19}\)  | -0.2405377 |
| \(a_{20}\)  | 0.7149104 |

4. Conclusions

Thus, a mathematical model of the whole complex of technological processes of LPI is developed, which can be used for simulation and control. A model for the pyrolysis of hydrocarbon raw materials in a large-capacity furnace coil has been developed, which includes 23 nonlinear differential equations of the first order of the process kinetics, the balance of thermal and
mechanical energy. Based on the research on the kinetic model, a mathematical model for process control is obtained that takes into account the physical characteristics of the raw materials and the coking of the furnace units QEA. Models have been developed to manage the auxiliary processes of the LPI preparing gasoline raw materials, quenching cracking gas in QEA, burning coke in coils, burning fuel in furnaces. The adequacy of regression models to the object has been verified using the Fisher criterion.

References

[1] Bityukov V K, Tikhomirov S G, Arapov D V and Savvin S S 2015 Modeling of the Process of Pyrolysis of Naphtha Using Genetic Algorithm Vestnik Voronezhskogo Gosudarstvennogo Universiteta Inzhenernyh Tehnologii 3 65 pp 79–84
[2] Cowperthwaite E V 2014 Mathematical Model for Ethane Pyrolysis in Anindustrial Furnace Masters thesis, Queens University Kingston Canada
[3] Kuritsyn V A, Arapov D V, Ekimova A M and Yakupov A A 2008 Modeling of Pyrolysis of Straight-run Naphtha in a Large-Capacity Type SRT-VI Furnace Chemistry and Technology of Fuels and Oils 44 3 pp 180–189
[4] Meisong B E Yan 2000 Simulation and Optimization of an Ethylene Plant Masters thesis, Texas Tech University
[5] Seifzadeh Haghighi S, Rahimpour M R, Raeissi S and Dehghani O 2013 Investigation of Ethylene Production in Naphtha Thermal Cracking Plant in Presence of Steam and Carbon Dioxide Chemical Engineering Journal 228 pp 1158–1167
[6] Towfighi J, Modarres J, Omidkhah M and Niaei A 2004 Estimation of Kinetic Parameters of Coking Reaction Rate in Pyrolysis of Naphtha. IJE TRANSACTIONS B: Applications 17 4
[7] Kuritsyn V A 1987 Development of a System for the Automation of a Large-Capacity Pyrolysis Plants Kand. Diss. Russia
[8] Keyvanloo K, Sedighi M, Towfighi J 2012 Genetic Algorithm Model Development for Prediction of Main Products in Thermal Cracking of Naphtha: Comparison with Kinetic Modeling. Chemical Engineering Journal 209 pp 255–262
[9] Magaril R Z 1976 Theoretical Bases of Chemical Processes of Oil Refining Chemistry Moscow
[10] Kumar P, Kuzrun D 1987 Coke Formation During Naphtha Pyrolysis in a Tubular Reactor Canadian Journal of Chemical Engineering 65 pp 280–285
[11] Mukhina T N, Barabanov N L, Babash S E, Men’shchikov V A and Avrech G L 1987 Pyrolysis of Hydrocarbon Feedstock Chemistry Moscow
[12] Luther H A 1968 An Explicit Sixth-Order Runge-Kutta Formula Mathematics of Computation 22 102 pp 434–436
[13] Kuritsyn V A, Arapov D V and Gorilchenko R L 2012 Optimization of Circulation Water Cooling Process in Forced-Draft Towers Chemistry and Technology of Fuels and Oils 48 2 pp 97–108
[14] Holland J H, Langton C and Wilson S W 1992 Adaptation in Natural and Artificial Systems. An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence 1st MIT Press ed. London