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| Research Article

Development of an Intelligent System for Managing the Oil Rectification Process

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Abstract
The article presents an intelligent control system for the oil rectification process based on the hybrid application of a genetic algorithm (GA) and gradient optimization methods. The developed system ensures the automatic maintenance of optimal process parameters for the rectification column, such as temperature at different sections, phlegm ratio, pressure, and level in the cube, in order to minimize energy consumption while maintaining the required quality of the separation products. Experimental studies on a simulation model of a rectification column showed that the proposed GA+GD hybrid system reduces energy consumption by 12-18% compared to classical PID controllers, while providing higher accuracy in maintaining the composition of target fractions. The system automatically adapts to changes in the composition of raw materials and external conditions, which is confirmed by the results of transient mode simulations.

Keywords: Oil Rectification, Intelligent Control, Genetic Algorithm, Gradient Descent, Energy Consumption Optimization, Rectification Column, Phlegm Ratio, Separation Product Quality, and Hybrid Optimization Algorithms

1. Introduction

The rectification process is one of the most energy-intensive processes in the oil refining industry. Crude oil is separated into fractions (gasoline, kerosene, diesel, and fuel oil) in rectification columns, which are complex process apparatuses characterized by nonlinear dynamics, interconnected variables, and significant lag times [1].

Traditional control systems for distillation columns are based on PID controllers and cascade schemes. However, these approaches have several limitations. Firstly, classical controllers are not capable of effectively handling the strong nonlinearity of the process, especially when the composition of the feed or the load on the feed changes. Secondly, the mutual influence of control channels (for example, a change in the phlegm number affects both the quality of the distillate and the temperature in the column) creates problems for independent PID controllers [2]. Thirdly, setting the parameters of PID controllers to an energy-efficient mode requires a deep understanding of the process model.

Modern trends in the automation of chemical and technological processes are associated with the implementation of intelligent control methods, including neural networks, fuzzy logic, and evolutionary algorithms [3]. Genetic algorithms (GA) have shown their effectiveness in solving multi-parameter optimization problems, where traditional gradient methods face the problem of local minima and the овражности of the objective function [4]. Gradient methods, on the other hand, provide fast local convergence, but require a good initial approximation.

This work proposes an intelligent control system for the oil rectification process, which combines a genetic algorithm for global search of optimal process parameters and gradient descent for their local adaptation in real time. This hybrid approach allows to combine the advantages of both methods and provides automatic adaptation to the changing conditions of the column operation.[5]

The purpose of the study is to develop an intelligent control system for the oil rectification process that minimizes energy consumption by automatically optimizing key process parameters (phlegm ratio, cube temperature, and column pressure) using a combination of genetic algorithms for global search and gradient descent for local adaptation in real time.[6][7]

To achieve this goal, the following tasks must be completed:

- to carry out an analysis of the rectification column as an object of control, to identify the main controlled and managed variables, to determine the ranges of their change and the nature of the mutual influence of the control channels;

- to develop a target function reflecting the compromise between the energy consumption of the process and the quality of the products obtained, taking into account technological restrictions (prohibition on liquid carry-over, permissible temperatures and pressures);

- create a hybrid optimizer in which a genetic algorithm provides a global search in the space of mode parameters, and gradient descent provides precise local tuning;

- build a nonlinear dynamic model of a rectification column taking into account mass and heat transfer to verify the developed control system;

- perform a series of comparative tests for the traditional PID controller and the proposed intelligent GA+GD system under various scenarios of changes in the composition of raw materials and technological disturbances;

- evaluate the energy efficiency of the developed system, the quality of regulation, the time of adaptation to disturbances, and the computational complexity.[8]

2. Methodology

1. The management object.

A rectification column is considered as a control object for separating an oil mixture into gasoline (light) and fuel oil (heavy) fractions. The main parameters of the column are:

Parameter	Meaning
Number of plates	40 (rectification part 20, distillation part 20)
Type of plates	cap-shaped
Raw material capacity	50 t/h (nominal)
Pressure in the column	1.2–1.5 ati
Cube temperature	320–360 °C
Top temperature	100–140 °C

Control actions:

- R - phlegm number (the amount of distillate returned to the distillation column);
- Q_b - heat load of the boiler (flow rate of the heating steam);
- P - pressure in the column (controlled by the flow rate of cooling water in the de-flogger).

The main disturbances are:

- F - the flow rate of the raw material;
- z_i - the composition of the raw material (concentration of light and heavy components);
- T_f - the temperature of the raw material at the inlet to the column.

The controlled variables are:

- x_D - the concentration of the light component in the distillate;
- x_B - the concentration of the heavy component in the residue;
- T_top, T_bot - the temperatures of the top and bottom.

2. The target function.

Optimization of the rectification column operation mode is aimed at minimizing energy consumption while ensuring the required quality of the separation products. The objective function is as follows:

$$J(R,Q_b,P)=w_1\cdot\frac{Q_b}{Q_{b,\text{ном}}}+w_2\cdot\frac{R}{R_{max}}+w_3\cdot P_{enalty}(x_D)+w_4\cdot P_{enalty}$$

where:

- Q_b - heat load of the boiler (the main indicator of energy consumption);
- R - phlegm number (affects the energy consumption of the deflagrator);
- P_{enalty}(x_D) - penalty for deviation of the quality of the distillate from the set;
- P_{enalty}(x_B) - penalty for deviation of the quality of the cube residue;
- w_1, w_2, w_3, w_4 - weighting factors.

The penalty functions are designed so that when the quality exceeds the acceptable limits, the objective function increases dramatically:[9]

$$Penalty(x)=\begin{cases} k\cdot(x-x_{max})2 & \text{when } x>x_{max} \\ 0 & \text{when } x_{min}\le x\le x_{max} \\ k\cdot(x_{min}-x)2 & \text{when } x<x_{min} \end{cases}$$

3. Result and Discussion

Three series of computational experiments were conducted:

- Basic scenario - control using a classical PID controller with fixed settings (set to medium mode).

- GA-optimization - only genetic algorithm (re-optimization every 30 minutes).

- GA+GD (proposed system) - a hybrid system with global and local optimization.

The following operating modes are considered:

- Nominal mode (F=50 t/h, z=0.5);

- Disturbance in the composition of the raw material (increasing the proportion of light fractions to 0.65);

- Disturbance in the consumption of raw material (stepwise change from 40 to 60 t/h).

Table 1. Energy consumption in different operating modes

Operating mode	Heating steam flow rate (t/h)	Saving GA+GD vs PID	Saving GA+GD vs GA
Nominal	PID: 9.8; GA: 8.9; GA+GD: 8.4	14,3%	5,6%
Raw material composition z=0.65	PID: 11.2; GA: 9.8; GA+GD: 9.2	17,9%	6,1%
Flow rate F=60 t/h	PID: 12.5; GA: 11.0; GA+GD: 10.5	16,0%	4,5%
Flow rate F=40 t/h	PID: 7.6; GA: 6.9; GA+GD: 6.5	14,5%	5,8%
Average	—	15,4%	5,5%

Analysis: The developed system demonstrates a steady decrease in energy consumption by 12-18% compared to the PID controller. The highest efficiency is achieved when the composition of the raw material changes (17.9%), as the system adjusts its operation mode to adapt to the new mixture being separated.[10]

Table 2. Quality of separation products

Indicator	Requirement	PID	GA	GA+GD
x_D (gasoline), % mass	≥92	91,7 ± 0,8	92,4 ± 0,4	92,6 ± 0,3
x_B (fuel oil), % mass	≥96	95,2 ± 0,6	95,9 ± 0,3	96,1 ± 0,2
Time for quality after disturbance, min	—	45	38	26
Number of defects during disturbances, t/day	—	18,5	10,2	6,8

Analysis: The proposed system provides more stable product quality (the root-mean-square deviation is 1.5-2 times lower than that of PID). This is because GA+GD not only minimizes energy consumption but also optimizes quality by introducing penalty functions in the objective function.[11]

Table 3. Dynamic characteristics of the control system

Parameter	PID	GA	GA+GD
Regulation time during disturbance, min	42	38	26

Maximum deviation x_D during disturbance, %	2,8	1,6	1,1
Overregulation by cube temperature, %	18	12	7
Number of control valves switching/h	42	18	12
Time to reach the optimal mode after start, min	—	120	45

Analysis: The hybrid algorithm outperforms both PID and a separate GA in terms of dynamic performance. The regulation time is reduced by 38% compared to PID, and the overshoot is reduced by 2.5 times. This is achieved by the GA+GD constantly monitoring and adapting the operating mode.[12]

Table 4. Efficiency under different optimization strategies

Strategy	Power consumption, % of nominal	Quality stability (σ)	CPU costs, s/h
PID (base)	100%	0,85	0,1
GA (global only)	89%	0,45	180
GD (local only)	93%	0,60	60
GA+GD (hybrid)	84%	0,30	210
Adaptive PID with GA tuning	91%	0,50	45

Analysis: Hybrid GA+GD demonstrates the best energy efficiency-quality stability ratio at acceptable computational costs. Note that only local gradient descent (GD) is capable of improving the performance, but does not reach the global optimum.[13]

The figure (descriptively) shows the convergence of the genetic algorithm during the optimization of the rectification mode:

Generation	The average value of J	The best value of J
0	1,45	1,38
5	1,28	1,15
10	1,18	1,05
20	1,09	0,98
30	1,02	0,94
40	0,97	0,91
50	0,94	0,90

Convergence is achieved by the 30th-40th generation, with the final value of the objective function being 38% better than the initial value.

Comparison with known methods of rectification column control confirms the effectiveness of the proposed approach [14]:

Control method	A source	Savings achieved
PID controller	Basic level	—

Neural network control (NARMA-L2)	Al-Dunainawi, 2017 [2]	8–12%
GA-PID tuning for HIDiC	Tahir et al., 2025 [7]	10–15%
GA-BP surrogate model	Ye et al., 2023 [6]	6% (reduced TAC)
GA+GD (suggested)	The present article	12–18%

4. Conclusion

As a result of this work, an intelligent control system for the oil rectification process was developed and experimentally tested, using a combination of a genetic algorithm (for global optimization of process parameters) and gradient descent (for local adaptation in real time). The main scientific and practical results are as follows:

1. Scientific novelty: A three-level architecture of intelligent control of a rectification column is proposed and substantiated, combining a genetic algorithm (periodic global search) and gradient descent (continuous local correction). The effectiveness of numerical differentiation for estimating the gradients of the objective function under conditions of a non-analytical process model is shown.

2. Quantitative results: The developed GA+GD system provides a 12-18% reduction in energy consumption compared to a classic PID controller. The specific consumption of heating steam is reduced by 1.0-1.5 t/h for a column with a capacity of 50 t/h of raw material. The GA-based system offers an additional 4-6% improvement.

3. Control quality: The root-mean-square deviation of the concentrations of target products has been reduced by 1.5–2 times compared to the PID controller. The time to reach the setpoint after changing the composition of the raw materials has been reduced from 45 to 26 minutes (by 42%), which significantly reduces the amount of substandard products.

4. Adaptive properties: The system automatically adjusts the column's operating mode based on changes in raw material quality and productivity. When the proportion of light fractions in the raw material increases from 0.5 to 0.65, the GA+GD system finds a new optimal mode within 28 minutes, reducing steam consumption by 6% compared to a fixed-settings column.[15]

5. Practical feasibility: The system's computational costs are 210 s/h (less than 6% of the operating time), which is acceptable for implementation on modern industrial controllers. The proposed approach does not require replacing the main equipment and can be implemented as part of the control system's modernization.

Limitations and development prospects:

In the present work, a two-product column with a binary mixture was considered. Further research is aimed at:

- Adaptation of the proposed approach for multicomponent rectification columns with side-pumps.

- Implementation of predictive control models to account for transport delays.

- Application of ensemble machine learning methods to build more accurate column surrogate models.

- Development of a methodology for automatically determining the optimal weights of the objective function.

Recommendations for the industry: The implementation of an intelligent oil rectification control system is recommended for installations with a capacity of 30 t/h of raw material. The initial setup of the GA requires a single test (4-6 hours) and can be performed by in-house personnel. The expected payback period for the system is 6-12 months due to reduced heat energy consumption.

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