

# OPTIMIZATION OF RECTIFICATION PROCESS USING MOBILE CONTROL ACTION WITH ACCOUNT FOR CRITERION OF MAXIMIZING SEPARATION QUALITY

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## Abstract

The use of mobile control action allows the improvement of technical-economical characteristics of the rectification process and allows for operation regimes that can't be achieved with traditional control approaches. Mobility lies in the ability to choose the movement law of compound source and energy in the spatial region of apparatus.

Mobile control over the rectification process can be realized by changing the column feed point. An optimal number of feed trays must be determined with consideration of cost and output performance, and also the quality of the target product.

The work aimed to develop a method for calculating optimal control action, including mobile ones, on the rectification process with additional account for the criterion of maximizing quality of target product, and also, comparison of static column profiles that are optimal by different criteria.

Mathematical modeling of the rectification column for separation of water-methanol mixture revealed that increasing quality requirements to target products decreases the number of the optimal feed tray. A method was described for process optimization by the normalized criterion that accounts for separation quality and power consumption. The method was used to determine optimal values of traditional (flows of heat into the column's cube and phlegm) and mobile (feed tray number) control actions that provide the best technical-economical parameters of the rectification column.

A proof is presented for the existence and uniqueness of solutions for this optimization problem and the effectiveness of using mobile actions for different requirements to target. The optimal temperature profile of the culms was studied and their characteristic features that correspond to different specific and normalized optimization criteria were found.

**Keywords:** optimization, rectification, mobile control, normalized criterion, temperature profile, feed tray.

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DOI: 10.21303/2461-4262.2020.001503

## 1. Introduction

As a control object, the rectification column is characterized by high power consumption and cost of produced product, a large number of parameters, their relation, distribution, significant delay, and inertness of control channels [1].

Following control systems for rectification columns can be outlined: robust [2], adaptive [3, 4], supervised [5], optimal [6, 7], control systems involving neural networks [8], fuzzy logic [9], non-linear prediction process model [10, 11]. The quality and effectiveness of such systems can be improved with the use of distributed [12] or mobile [13, 14] control actions. The difference between the later lies in the ability to choose the intensity and coordinates of the object's influence point, which allows for operation regimes that are unachievable with traditional approaches.

Mobile process control actions lie in a change of column's feed point. The basis of static process optimization with the use of the cations is reviewed in [15, 16]. The solution to the problem is obtained with simultaneous use of criteria of maximizing performance and minimizing power consumption based on the required concentration of the target component in the final. However, a given limitation must be corrected according to changes in process conditions. The optimal static characteristics of the column have not been presented.

A relevant scientific problem is the development of methods for calculating optimal control actions for the rectification process, including mobile, with account for criteria of maximizing quality of target product and comparison of static column profiles that are optimal by different criteria.

## 2. Method for optimizing the rectification process using mobile control actions and additional account for the criterion of maximization of separation quality

Because dependencies that tie process value and optimization criteria can't be represented in explicit form, the problem of static optimization of rectification is solved bathed nonlinear programming. Column's material load, technical-economical values, and values of control actions have limitations in the form of inequalities:

$$V_{j, \min} < V_j < V_{j, \max}; \quad (1)$$

$$L_{j, \min} < L_j < L_{j, \max}; \quad (2)$$

$$D_{\min} \leq D_{opt} \leq D_{\max}; \quad (3)$$

$$Q_{w, \min} \leq Q_{w, opt} \leq Q_{w, \max}; \quad (4)$$

$$N_{f, \min} < N_{f, opt} < N_{f, \max}, \quad (5)$$

where  $D$  – molar distillate flow, kmole/h;  $L$  – molar liquid phase flow, kmole/h;  $N_f$  – feed tray number;  $Q$  – heat flow, kJ/h;  $V$  – molar vapor phase feed, kmole/h. Low indices:  $j$  – contact device number;  $opt$  – optimal value;  $w, 0$  – evaporator product, column's evaporator cube product parameter.

When solving optimization problems with a few criteria, they are normalized and converted to arbitrary units.

Well-known methods for optimization of the rectification process [14, 15] based on the normalized criterion which accounts for process performance and power consumption:

$$\lambda_{\{2\}} = \lambda_D + \lambda_Q = \frac{D - D_{\min}}{D_{\max} - D_{\min}} + \frac{Q_{w, \max} - Q_w}{Q_{w, \max} - Q_{w, \min}}, \quad (6)$$

where  $\lambda$  – normalized optimization criterion. Lower indices:  $\{2\}$  – number of specific criteria considered in normalization;  $D$  – maximum performance criterion;  $Q$  – power minimization criterion.

In contrast to known optimization methods, limitation in the form of inequality on the concentration of the target product in the distillate is introduced:

$$x_{d,nz,\min} \leq x_{d,nz,opt} \leq x_{d,nz,\max}, \quad (7)$$

where  $x$  – molar concentration of the component in the liquid phase, kmole/kmole. Lower indices:  $d, N$  – distillate parameter, column's top;  $nz$  – number of the target component.

This allows additional consideration of the criterion of target product quality maximization for calculation of the optimal regime of column work and control actions that provide it. It is supposed application of the normalized criterion, which defined by equation:

$$\lambda_{\{3\}} = \lambda_D + \lambda_Q + \lambda_{xd} = \lambda_{\{2\}} + \frac{x_{d,nz} - x_{d,nz,\min}}{x_{d,nz,\max} - x_{d,nz,\min}}, \quad (8)$$

where lower indices:  $\{3\}$  – number of specific criteria considered in normalization;  $x_d$  – quality maximization criterion.

The optimization problem is as follows: to define such values of traditional  $Fl_{opt}$ ,  $Q_{w,opt}$  and mobile  $N_{f,opt}$  control actions, quality of target product  $x_{d,nz,opt}$ , which provide maximum value of normalized criterion  $\lambda_{\{3\}}$  (8), considering limitations (1)–(5), (7):

$$N_{f,opt}, Fl_{opt}, Q_{w,opt}, x_{d,nz,opt}, D_{opt}, \bar{L}, \bar{V}, \bar{x}_i, \bar{y}_i, \bar{t} = \\ = f(\bar{N}_f, F, \bar{x}_f, \bar{t}_f, \bar{P}_f, t_{fl}, \bar{P}, \bar{\eta}_i, D_{\min}, Q_{w,\max}, x_{d,nz,\min}), \quad (9)$$

where  $F$  – molar feed flow, kmole/h;  $Fl$  – molar phlegm flow, kmole/h;  $P$  – pressure, MPa;  $t$  – temperature, °C;  $y$  – molar concentration of the component in liquid vapor, kmole/kmole;  $\eta$  – Murphy's effectiveness of the column's contact device. Lower indices:  $f$  – feed parameter;  $fl$  – phlegm parameter;  $i$  – number of mixture components.

The proposed method of rectification process optimization consists of the following steps:

1) Limit values of technical-economical process variables in (6) and (8) are determined by solving optimization problems using each particular criterion alone.

Maximum possible distillate output  $D_{\max}$  is calculated for given quality  $x_{d,nz}$ , considering experimental dependency  $D - Q_w$ .

The sought value of minimum heat consumption in evaporator  $Q_{w,\min}$  at minimum performance  $D_{\min}$  provides necessary quality  $x_{d,nz}$ .

The maximum concentration of target component  $x_{d,nz,\max}$  is achieved at minimum performance  $D_{\min}$  and is determined considering external dependency  $x_{d,nz} - Q_w$ .

Dependencies  $D - Q_w$ ,  $x_{d,nz} - Q_w$  are monoextreme within regions set by inequalities (1)–(5), (7). Coordinates of extreme points are found by the secant method.

2) The initial approximation of target component concentration in the distillate is taken and the problem of optimization by the criterion of maximizing performance and minimizing power consumption is solved by the method described in [15]. As such, for each requirement to distillate quality, there are defined values of normalized criteria (6) and (8).

The optimal value of mobile control action (the number of column's feed tray  $N_{f,opt}$ ) is determined when calculating  $\lambda_{\{2\}}$  via the scan method.

3) Coordinate of the extreme point of dependency  $\lambda_{\{3\}} - x_{d,nz}$  are found using the secant method which lies in determining zero rates of change in a given function.

Each requirement of distillate quality corresponds certain value of normalized criterion (8). Static characteristics of apparatus and optimization criterion are calculated based on initial approximation of target component concentration  $x_d = x_{d,nz}$ :  $\lambda_{\{3\},1} = f(x_d - \Delta x_d)$ ,  $\lambda_{\{3\},2} = f(x_d)$  and  $\lambda_{\{3\},3} = f(x_d + \Delta x_d)$ .

Iterative search is conducted according to the equation:

$$x_{d,nz} = x_{d,nz} - \Delta x_{d,nz} \cdot \frac{\lambda_{\{3\},3} - \lambda_{\{3\},2}}{(\lambda_{\{3\},3} - \lambda_{\{3\},2}) - (\lambda_{\{3\},2} - \lambda_{\{3\},1})}. \quad (10)$$

Actions are repeated until the condition is satisfied:

$$\left| \frac{\lambda_{\{3\},3} - \lambda_{\{3\},2}}{\Delta x_{d,nz}} \right| \leq \varepsilon, \quad (11)$$

where  $\varepsilon$  – set calculations precision.

Results were obtained from mathematical modeling using a nonlinear model of the rectification process of the binary methanol-water mixture. Calculation of static characteristic lies in solving systems of a multidimensional nonlinear algebraic equation, known as MESH-equations [17], which describe each contact device separately.

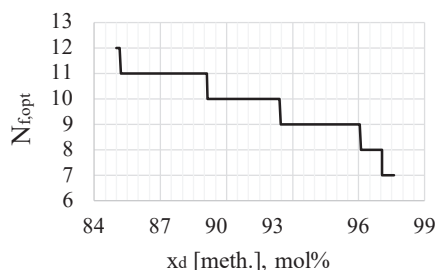
Studied columns consist of 18 contact devices, external boiler, and dephlegmator. Methanol concentration in feed 0,273 mol. parts. Parameters that define normal operation of the column:  $N_f=9$ ,  $Q_w=6.4$  GJ/h,  $D=62.8$  kmole/h,  $x_{d,nz}=0.973$ ,  $F=229.3$  kmole/h,  $P_f=P_{j=0}=P_{j=18}=1$  atm,  $\beta_x=3060.5$  kmole/(m<sup>2</sup>·h),  $\beta_y=142.82$  kmole/(m<sup>2</sup>·h), feed, phlegm and distillate are at boiling temperature, methanol is target component, product – distillate.

Because the goal is to improve technical-economical parameters of the process, the limit values of distillate output and heat consumption in evaporator corresponds to normal values:  $Q_{w,max}=6.4$  GJ/h,  $D_{min}=62.8$  kmole/h. For a demonstration of obtained results, the minimum acceptable concentration of methanol in distillate was chosen as  $x_{d,nz,min}=0.85$  mol. part.

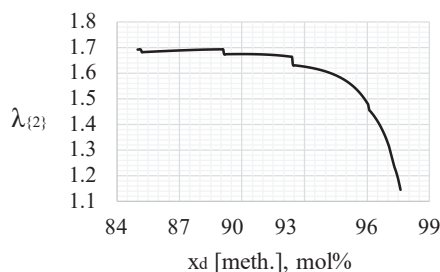
### 3. Results for optimizing the rectification process using mobile control actions and additional account for the criterion of maximization of separation quality

Results were obtained from solving the problem of static optimization with account for criteria of maximizing performance and minimizing power consumption at the different limitation of quality of distillate  $x_{d,nz}$ .

law was established for movement of control action along with the column's height with the change of the value of given limitation, and extreme values of normalized criterion  $\lambda_{\{2\}}$  for each regime (**Fig. 1, 2**) were calculated.

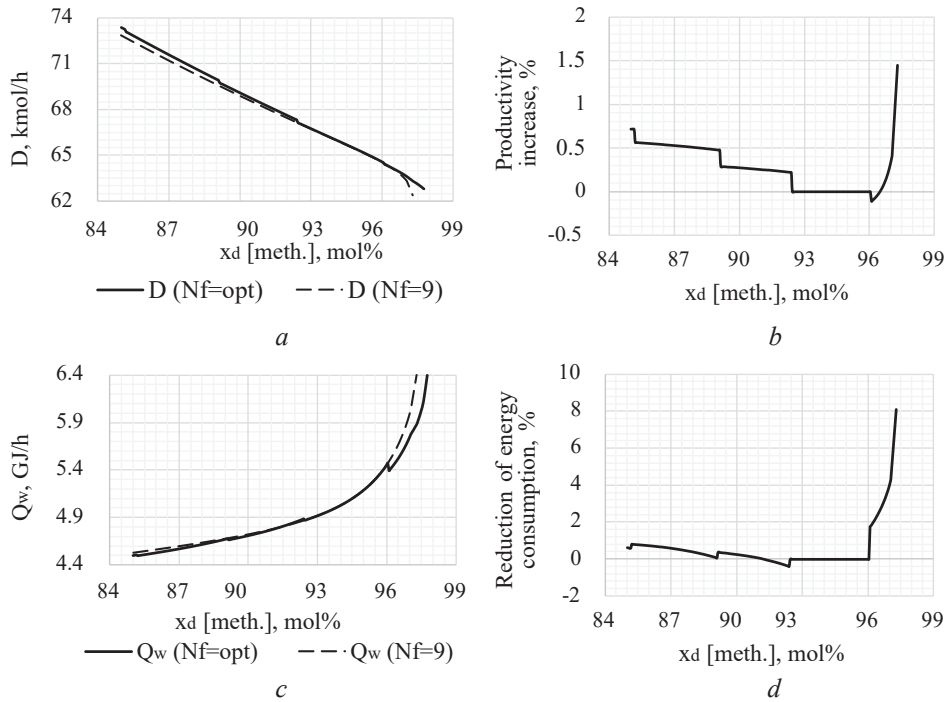


**Fig. 1.** Movement of point of applied control action along with the column's height with a change of requirements to distillate quality



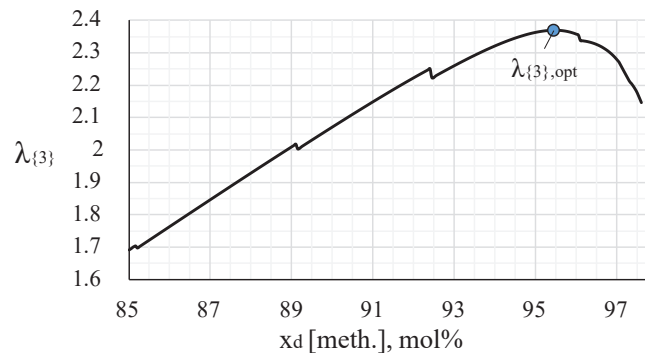
**Fig. 2.** Values of normalized optimization criterion with a change of requirements to distillate quality

The supply of feed was modeled for tray 9 and calculated optimally. The effectiveness of control actions of different requirements to distillate quality (**Fig. 3**) was studied.



**Fig. 3.** Effectiveness of mobile control actions on rectification process for different requirements to distillate quality: *a* – optimal distillate flow for feed supplied to standard and optimized trays; *b* – productivity increase due to mobile control actions; *c* – optimal heat flow in the column’s for feed supplied to standard and optimized trays; *d* – decrease of energy consumption due to mobile control actions

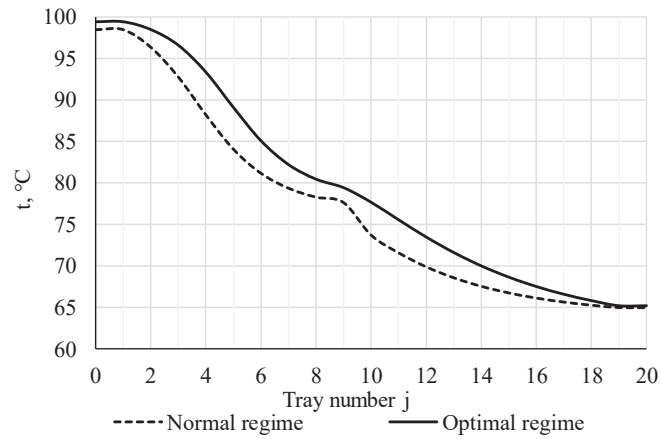
Maximum possible methanol concentration in distillate  $x_{d,nz,max}$  is determined by solving the optimization problem of the target product and is 0.9776 mol. part. This limitation along with calculation results for the effectiveness of two-criteria optimization  $\lambda_{\{2\}}$  allowed to conduct calculations (8). The results are presented in **Fig. 4**.



**Fig. 4.** The dependency of normalized optimization criterion on requirements to distillate quality and solution to rectification process optimization problem according to criteria of maximum quality, performance, and minimum power consumption

The static characteristics of the studied process that correspond to optimal and normal operation regimes of the column were calculated (**Fig. 5**).

In order to find limited values of technical-economical parameters in (8), optimization problems were solved with the use of maximum performance, quality, and power consumption minimization criteria. Solutions from normalized criteria (8) and (10) were also obtained. This allowed studying optimal static profiles with the column that corresponds to different criteria (**Table 1**).



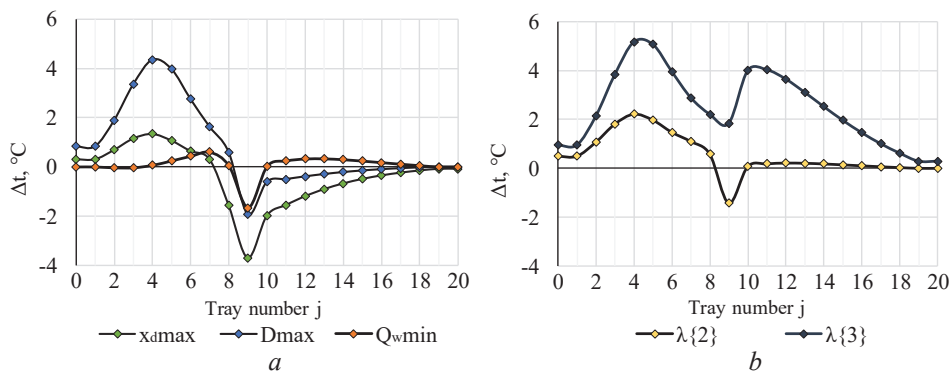
**Fig. 5.** Temperature profile corresponding to normal and optimal stationary operation regimes of rectification column for criterion

**Table 1**

Values of control actions and temperatures of the column's top and bottom, the composition of final products that provide and correspond to optimal characteristics of the process according to different criteria

Regimes	$Q_{w,opt}$	$Fl_{opt}$	$N_{f,opt}$	$D_{opt}$	$t_0$	$t_N$	$x_{w,nz}$	$x_{d,nz}$
Normal	6.4	114.2	9	62.8	98.44	64.9	0.898	97.3
$x_{d,max}$	6.779	125.1	7	62.8	98.75	64.83	0.712	97.791
$D_{max}$	6.947	128.6	7	63.64	99.27	64.9	0.408	97.3
$Q_{w,min}$	5.512	89.06	7	62.8	98.44	64.9	0.898	97.3
$\lambda_{\{2\}}$	5.881	98.89	7	63.3	98.93	64.9	0.604	97.3
$\lambda_{\{3\}}$	5.289	79.89	9	64.99	99.39	65.19	0.339	95.449

The difference between temperature profiles that correspond to normal and optimal by different criteria of column operation is shown in Fig. 6.



**Fig. 6.** Temperature change at contact devices of rectification column when changing from standard to optimized operation regime: *a* – by specific criteria; *b* – by normalized criteria

A comparison of temperature profiles allows outlining feature of optimal stationary rectification regimes.

#### 4. Discussion of results obtained from optimizing the rectification process using mobile control actions and additional account for the criterion of maximization of separation quality

The wrong choice of tray 9 as the feed tray reflects on the column's static profiles in a significant temperature increase in the given cross-section (Fig. 5). Disturbance, which introduces by

the feed is too significant for this part of the apparatus and deforms the profile. The feed point should be shifted to lower parts of the column, which corresponds to higher temperatures. This conclusion is also supported by the results of solving optimization problems and correlates the results of other investigations [15, 16].

The goal of control systems, regardless of the optimization criterion chosen, is to lower temperature in the enrichment section of the column and increase in the depleting section. This is because of the necessity of lowering the amount of high boiling component in distillate in the lower part of apparatus, and low boiling – in the lower part and evaporator residue.

The highest temperature of evaporator residue and the lowest concentration of the low boiling product is achieved in case of maximum performance.

The operation regime that corresponds to minimum power consumption (**Fig. 6**) is characterized by the same output and quality of target product when compared to the normal regime. This is because of the coincidence of first and last profile points – the temperature of the column's top and bottom and lowest changes in static profile.

Lowering requirements to the quality of the final product results in an increase of temperature parameter at all contact devices of the column.

The effectiveness of the proposed method for optimization depends significantly on the width of  $x_{d,nz,min} - x_{d,nz,max}$  range, in which for which calculations are conducted. The maximum concentration of the target component is calculated and set value  $x_{d,nz,min}$  should have an economical or technological basis. The existence of extreme (8) depends on the modeled operation regime and value  $x_{d,nz,min}$ . The main advantage of the proposed method, compared to [11–13, 17] is the easiness and correct determination of the optimal statistic parameters of the rectification column.

Investigation limitations are follows:

1) Results were obtained under limitation of the concentration of the target product in the distillate. Maximal possible concentration is calculated value, but set data  $x_{d,nz,min}$  must be justified with economical or technological reasons. Existence of the extremum (8) can depends on modulated regime of column work and value of  $x_{d,nz,min}$ . But proof or refutation of this fact requires further research.

2) Results have been investigated for binary rectification process. But proposed optimization method requires further improving for application to processes of multicomponent and complex rectification.

Disadvantages of the investigation:

1) For optimization the technological-economical parameters of rectification processes (productivity, energy consumption, quality) were used. At the same time, no economic criteria were used. Effectiveness of mobile control action in the monetary equivalent has not detected.

2) The need for use of mobile control actions arises under quite significant change of working regime of the rectification column. Under minor disturbances the number of optimal tray for feed matches with regulated one and effectiveness of mobile control action system and traditional control system is equivalent.

## 5. Conclusions

Studies conducted for the rectification column for separation of methanol-water mixture show that increasing requirements to the quality of the target product decrease the number of the optimal feed tray.

Normalized optimization criterion extremely dependant on limitations on the quality of the target product. Solving the problem of static optimization of the rectification process according to the developed method allows to provide such concentration of target component in the final product and calculate the number of feed tray at which maximum performance along with minimum heat consumption in the evaporator is achieved.

For the calculated operation regime, tray  $N_f=9$  is the optimal tray for feed. Maximum value  $\lambda_{(3)}$ , equal to 0.9545 mol. parts, is provided at following technical-economical process parameters:  $D_{opt}=65$  kmole/h,  $Q_{w,opt}=5.29$  GJ/h. An increase in performance relative to normal operation is 3.5 %, with a decrease in power consumption by 7.34 %. This is achieved by lowering methanol concentration in distillate by 1.9 %.

When compared to the optimal operation regime, calculated without considering quality maximization criterion ( $D_{opt}=63.305$  kmole/h,  $Q_{w,opt}=5.88$  GJ/h), the performance increase is 2.68 % with a decrease in power consumption by 10.03 %. This is achieved by lowering methanol concentration in distillate by 1.9 %.

Results of the conducted studied can be used for the design of new and optimization of existing rectification columns, creation of automated control of the rectification process.

Further development in the given direction lies in the study of dynamic operation regimes of rectification columns when using principles of mobile control, use of continuous mobile control actions.

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Received date 10.05.2020

Accepted date 06.11.2020

Published date 30.11.2020

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