Selection of the Strategy for Process Control of the Diethylene Glycol Rectification

Sergey E. Abramkin[1], Sergey E. Dushin[2],
Yuriy N. Serditov[3], Valeriya A. Cherkasova
Department of Automation and Control Processes
Saint-Petersburg Electrotechnical University "LETI"
St. Petersburg, Russia
[1]abrsergey@yandex.ru, [2]dushins@yandexl.ru, [3]ura-nikolaevic@yandex.ru

***Abstract*— The article presents dynamic mathematical models of devices providing the process of DEG rectification. The parameters influencing the technological process are revealed. The results of analysis of various strategies for controlling the process of rectification are presented. The strategy of automatic control of the process of DEG rectification has been developed.**

***Keywords*— rectification column; evaporator; air cooling unit; mathematical model; mass exchange; heat exchange; control strategy**

I. Introduction

The technological process (TP) of rectification of diethylene glycol (DEG) is essentially a process of rectification the pseudobinary mixture "DEG-water". The basis of this process is the separation of the initial mixture into two practically pure components. Separation is carried out in the rectifying column (RC) due to the multiple bi-lateral heat and mass exchange process when water vapor and DEG move in countercurrent. In this case, the DEG flows along the surface of the nozzle in the form of a film (film flow regime), and the vapor phase rises upwards in the form of a continuous stream through the free volume of the nozzle.

Researches of processes in the RC have special features as the input section of saturated absorbent is divided into two parts. The upper part of the column is called enriching, and the lower part is called the fractionation section. The structure of the enriching section includes a condenser, and in the fractionation section there is an evaporator. Fractionation section of the RC provides getting a high-boiling component – regenerated absorbent (RDEG) nearly to its vapor purified, while the enriching section of RC provides low-boiling component (reflux).

The technological process of rectification is described in details in the literature [1]–[7].

The main tasks of automatic rectification process control are to achieve the specified accuracy of separation of the initial mixture, maximum intensity and economy of the process [2], [7].

It should be noted that the intensity and effectiveness of the TP of the regeneration of the DEG depend on the magnitude of RC load, as well as on degree of separation selected. As a rule, the work of the RC at maximum load is effective. Under these conditions, mass and heat transfer in the "vapor – liquid" system will be best.

The organization of automatic control of TP regeneration is a complex engineering task. This is due to the large number of interrelated regulated parameters, as well as the complex dynamics of the process which are not cleared up enough.

The aim of the research is to find a strategy for controlling the technological process of DEG rectification. To achieve this goal, the following tasks are defined:

- development of dynamic mathematical models (MM) to analyze the behavior of the object;
- determination of the parameters influencing the process of DEG rectification;
- analysis of strategies for automatic control of the rectification process;
- formation of a strategy for automatic control of the process of DEG rectification.

II. Mathematical models of the system "DEG rectification"

To solve the problem of studying the dynamics of the process, we worked out for the system "DEG rectification" following models: MM "Rectification" (rectification column), "Evaporation" (evaporator) and "Air cooling" (condenser). Such a choice of objects is determined by the dominant influence of these subsystems on the process of dehydration of natural gas [1].

A. Mathematical model of heat and mass exchange processes in the RC

The dynamic nonlinear MM of the mass-and heat-exchange processes interconnected by the vapor temperature of the "Rectification" subsystem is represented by a system of partial differential equations [2], [8]:

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$$\frac{\partial C_{tc.v}}{\partial t}=v_v(\theta_v)\frac{\partial C_{tc.v}}{\partial z}+R_v[C_{tc.v}-C_{tc.v}^{ec.c}(C_{tc.r})];$$
$$\frac{\partial C_{tc.r}}{\partial t}=-v_r\frac{\partial C_{tc.r}}{\partial z}-R_r[C_{tc.v}-C_{tc.v}^{ec.c}(C_{tc.r})];$$
$$\frac{\partial \theta_v}{\partial t}=-v_v(\theta_v)\frac{\partial \theta_v}{\partial z}-R_{\theta v}(\theta_v-\theta_r);$$
$$\frac{\partial \theta_r}{\partial t}=v_r\frac{\partial \theta_r}{\partial z}+R_{\theta r}(\theta_v-\theta_r);$$
$$\frac{\partial C'_{tc.v}}{\partial t}=v'_v(\theta_v)\frac{\partial C'_{tc.v}}{\partial z}+R'_v[C'_{tc.v}-C'^{ec.c}_{tc.v}(C_{tc.DEG})];$$
$$\frac{\partial C_{tc.DEG}}{\partial t}=-v_{DEG}\frac{\partial C_{tc.DEG}}{\partial z}-R_{DEG}[C'_{tc.v}-C'^{ec.c}_{tc.v}(C_{tc.DEG})];$$
$$\frac{\partial \theta'_v}{\partial t}=-v'_v(\theta_v)\frac{\partial \theta'_v}{\partial z}-R'_{\theta v}(\theta'_v-\theta_{DEG});$$
$$\frac{\partial \theta_{DEG}}{\partial t}=v_{DEG}\frac{\partial \theta_{DEG}}{\partial z}+R_{\theta DEG}(\theta'_v-\theta_{DEG}),$$

where $C_{tc.v}$, $C_{tc.r}$, $C'_{tc.v}$, $C_{tc.DEG}$ – concentrations of the target component (TC) in the vapor and reflux of the enriching section, in the pair and DEG of fractionation section; $C_{tc.v}^{ec.c}(C_{tc.r})$, $C'^{ec.c}_{tc.v}(C_{tc.DEG})$ – equilibrium concentration of the target component in the vapor of the enriching section and in the equilibrium concentration of the target component in the vapor of the fractionation section; v_v, v_r, v'_v, v_{DEG} – are the velocities of vapor and reflux in the enriching section, vapor and DEG velocities in the fractionation section; θ_v, θ_r, θ'_v, θ_{DEG} – temperature of vapor and reflux in the enriching section, temperature of vapor and DEG in the fractionation section; R_v, R_r, $R_{\theta v}$, $R_{\theta r}$, R'_v, R_{DEG}, $R'_{\theta v}$, $R_{\theta DEG}$ – physical and technological coefficients, depending on the physical properties of the phases and geometry of the device; z – the spatial variable in height of the enriching and fractionation sections of the RC.

This model considers the effect of vapor temperature on its physical characteristics. The vapor velocity v_v, depends on the temperature θ_v.

The boundary conditions of MM:

$$C_{tc.v}(z,t)\big|_{z=0}=C_{tc.v}^{inlet}(t)\,;\ C_{tc.v}(z,t)\big|_{z=l_{es}}=C_{tc.v}^{outlet}(t)\,;$$
$$C_{tc.r}(z,t)\big|_{z=l_{es}}=C_{tc.r}^{inlet}(t)\,;\ C_{tc.r}(z,t)\big|_{z=0}=C_{tc.r}^{outlet}(t)\,;$$
$$\theta_v(z,t)\big|_{z=0}=\theta_v^{inlet}(z)\,;\ \theta_r(z,t)\big|_{z=l_{es}}=\theta_r^{inlet}(z)\,;$$
$$\theta_v(z,t)\big|_{z=l_{es}}=\theta_v^{outlet}(z)\,;\ \theta_r(z,t)\big|_{z=0}=\theta_r^{outlet}(z)\,;$$

$$C'_{tc.v}(z,t)\big|_{z=0}=C'^{inlet}_{tc.v}(t)\,;\ C'_{tc.v}(z,t)\big|_{z=l_{fs}}=C'^{outlet}_{tc.v}(t)\,;$$
$$C'_{tc.r}(z,t)\big|_{z=l_{fs}}=C'^{inlet}_{tc.r}(t)\,;\ C_{tc.DEG}(z,t)\big|_{z=0}=C_{tc.DEG}^{outlet}(t)\,;$$
$$\theta'_v(z,t)\big|_{z=0}=\theta'^{inlet}_v(z)\,;\ \theta_{DEG}(z,t)\big|_{z=l_{fs}}=\theta_{DEG}^{inlet}(z)\,;$$
$$\theta'_v(z,t)\big|_{z=l_{fs}}=\theta'^{outlet}_v(z)\,;\ \theta_{DEG}(z,t)\big|_{z=0}=\theta_{DEG}^{outlet}(z)\,,$$

where l_{es}, l_{fs} – height enriching and fractionation sections.

The initial conditions of MM:

$$C_{tc.v}(z,t)\big|_{t=0}=C_{tc.v}^{0}(z)\,;\ C_{tc.r}(z,t)\big|_{t=0}=C_{tc.r}^{0}(z)\,;$$
$$\theta_v(z,t)_{t=0}=\theta_v^{inlet}(z)\,;\ \theta_r(z,t)_{t=0}=\theta_r^{inlet}(z)\,;$$
$$C'_{tc.v}(z,t)\big|_{t=0}=C'^{0}_{tc.v}(z)\,;\ C_{tc.DEG}(z,t)\big|_{t=0}=C_{tc.DEG}^{0}(z)\,;$$
$$\theta'_v(z,t)_{t=0}=\theta'^{inlet}_v(z);\ \theta_{DEG}(z,t)_{t=0}=\theta_{DEG}^{inlet}(z).$$

B. A mathematical model of a controlled heat exchange process in an condenser

Dynamic non-linear MM of controlled heat-exchange processes of the subsystem "Air cooling" is characterized by the PDE system [2], [9]:

$$\frac{\partial \theta_{s.v}}{\partial t}=v_{s.v}(\bar{G}_{s.v},\theta_{s.v})\frac{\partial \theta_{s.v}}{\partial x}-R_{s.v}[\theta_{s.v}-\theta_{p.w}];$$
$$\frac{\partial \theta_{p.w}}{\partial t}=R_{p.w1}f(u)+R_{p.w2}\theta_{s.v}-R_{p.w}\theta_{p.w},$$

where $\theta_{s.v}$, $\theta_{p.w}$ is the operating temperature of the saturated vapor and the wall of the pipe bundle condenser; $v_{s.v}$ is the velocity of saturated vapor; $\bar{G}_{s.v}$ – saturated vapor flow rate; $R_{s.v}$, $R_{p.w}=R_{p.w1}+R_{p.w2}$ – physical and technological coefficients; x is the spatial variable along the length of the condenser; $f(u)$ is the function of controlling the ambient temperature.

The boundary conditions of MM:

$$\theta_{s.v}(x)\big|_{x=0}=\theta_{s.v}^{inlet}(t);\ \ \theta_{s.v}(x)\big|_{x=l_{condenser}}=\theta_{s.v}^{outlet}(t),$$

where $l_{condenser}$ is the length of the heat exchanger pipe.

The initial temperature distributions along the condenser pipe are given by the expressions:

$$\theta_{s.v}(x)\big|_{t=0}=\theta_{s.v}^{inlet}(x);\ \ \theta_{p.w}(x)\big|_{t=0}=\theta_{p.w}^{inlet}(x).$$

C. A mathematical model of a controlled heat exchange process in an evaporator

Dynamic non-linear MM of controlled heat-exchange processes of the subsystem "Evaporation" is represented by the PDE system [2], [10]:

$$\partial\theta_{flg}/\partial t=-f(u)(\partial\theta_{flg}/\partial x)-R_{flg}(\theta_{flg}-\theta_w);$$
$$\partial\theta_{DEG}/\partial t=v_{DEG}(\partial\theta_{DEG}/\partial x)+R_{DEG}(\theta_w-\theta_{DEG});$$
$$d\theta_w/dt=R_{flg\text{-}w}(\theta_{flg}-\theta_w)-R_{DEG\text{-}w}(\theta_w-\theta_{DEG}),$$

where θ_{flg}, θ_{DEG}, θ_w – temperatures of flue gases, liquid phase and wall; $f(u)$ function of controlling the velocity of flue gases; v_{DEG} – is the velocity of the liquid phase; R_{flg}, R_{DEG}, $R_{flg\text{-}w}$, $R_{DEG\text{-}w}$ – physical and technological coefficients, depending on physical properties of flue gases, liquid and wall material of the flame pipe.

The boundary conditions of MM:

$$\theta_{flg}(x)\Big|_{x=l} = \theta_{flg}^{in}(t);\ \ \theta_l(x)\Big|_{x=0} = \theta_l^{in}(t),$$

Initial distributions of coolant temperatures:

$$\theta_{flg0}(x) = \theta_{flg}(x,t)\Big|_{t=0};\ \ \theta_{l0}(x) = \theta_l(x,t)\Big|_{t=0}.$$

III. Selection of Parameters Influencing on the Process of Regeneration of DEG

To determine the strategy for automatic control of the TP of the regeneration of the DEG, it is necessary to determine its controllable and control parameters.

Controlled parameters of the TP of the regeneration of the DEG are the temperatures of the DEG in the evaporator and the vapor in the upper part of the enriching section of the RC, the level of the DEG in the evaporator, the pressure in the "Condenser – RC – Evaporator" system, the reflux temperature at the outlet of the condenser.

Control parameters are the DEG consumption at the evaporator outlet, the reflux at the inlet to the RC and the fuel gas (FG) at the inlet to the evaporator burner (or the ratio of the FG – air flow rates), the reflux temperature and the DEG at the entrance to the RC, the composition of the saturated DEG (SDEG) at the entrance to the RC.

It should be noted that the pressure in the "Condenser – RC – Evaporator" system should remain unchanged. As a rule, its magnitude is determined by the physical properties of the vapor phase and the design features of the RC. In this case, the regulation of the working pressure in the system is carried out by maintaining the heat balance in the condenser. The flow rate of the vapor phase in the RC is maintained by changing the evaporator's heat load according to the temperature of the DEG and vapor.

Define the parameters that exert perturbing effects on the flow of TP.

The insufficient or excessive *amount* of SDEG at the inlet to the RC leads to a change in pressure and temperature in it. Thus, for efficient work ensuring the quality of reflux and DEG, it is necessary to maintain a constant number of incoming SDEG.

Oscillations of the *SDEG composition* cause a decrease in TP efficiency and affect the quality of the RDEG. At the same time, the composition and temperatures of the liquid and vapor in the PC vary. Maintaining the quality characteristics of the TP is carried out by regulating the supply of FG (or the ratio of FG – air flow) at the inlet to the evaporator and reflux burner to the upper part of the enriching section RC.

Lowering the *SDEG temperature* at the inlet to the RC makes it difficult to control the pressure and causes descent of the quality of the RDEG at the outlet from the evaporator. To maintain the specified quality of the RDEG, it is necessary to increase the supply of the FG to the evaporator burner. This in turn reduces the economic efficiency and safety of the TP.

The efficiency and intensity of TP in the RC is affected by the *vapor velocity*. This parameter cannot be directly measured. In the packed RC, the more the vapor velocity, the slower the DEG will flow along the nozzle. Accordingly, the interaction of DEG and steam will be long, which increases the quality of the final products. It should be noted that maintaining a constant vapor velocity in the RC is advisable only when maintaining the unchanged composition of SDEG.

It was mentioned above that the *pressure* in the RC is constant. Thus, the qualitative indicators of TP (the composition of the DEG) depend only on the temperature in the "Condenser – RC – Evaporator" system. This means that to ensure the composition of the DEG at the outlet of the evaporator in such TP, it is necessary to regulate the system pressure and the boiling point of the DEG in the evaporator.

We note that changes in the *vapor velocity* and the *amount of reflux* in the enriching section of the RC lead to changes in the hydraulic resistance in it and in the condenser. This negatively affects the operation of the pressure regulator. Regulation of pressure in the RC is not difficult. Significant difficulties arise in the regulation of temperature, which is caused by the inertia of the processes of mass and heat transfer and a small range of temperature changes. While regulating these temperatures, fluctuations in the amount of SDEG, its temperature and composition, and pressure in the RC are considered as the disturbing factors.

IV. Analysis of the Strategies of Automatic Control of the Rectification Process

As already noted, the complexity of selecting a strategy for managing the TP of the regeneration of the DEG is determined by a vast number of interrelated parameters.

Analysis [1]–[3], [7], [11] provide possibility to identify a number of strategies for automatic control of the process of rectification.

A. Control strategy for pressure drop.

Regulation is effected by the influence on the supply of FG (or FG – air ratio) to the evaporator burner. Such a strategy allows to stabilize the heat and mass transfer processes at the calculated vapor velocity and to increase the productivity of the RC. The change in the pressure drop affects the mass of the liquid phase retained in the RC.

B. Level control strategy in the evaporator.

Level control in the evaporator leads to a change in the flow rate of the liquid phase at the output of the TP. Such a regulation strategy allows to stabilize the overall mass balance in the outbound part of the RC.

C. The strategy of controlling the consumption of DEG at the output of the system (or FG at the inlet to the evaporator)

With this strategy, a two-stage DEG flow control scheme is used at the system output. It is realized with correction for the temperature and composition of the DEG in the evaporator. At the same time, this scheme allows to regulate the flow rate of the FG at the feed to the burner with a level correction in the evaporator.

It should be noted that such parameters as the composition and consumption of SDEG are rarely selected as controls. They are usually treated as disturbing effects.

D. The strategy of controlling the temperature in the evaporator

This strategy allows to stabilize the temperature in the evaporator due to the change in the flow rate of the FG (or the ratio of FG – air) at the inlet to the burner with the correction for the FG temperature.

Also within the framework of this strategy, it is possible to implement a two-stage scheme where the FG flow control loop will be internal. The external circuit realizes the function of regulating the temperature in the evaporator and is corrective for the internal circuit.

V. FORMATION OF THE STRATEGY FOR AUTOMATIC CONTROL OF THE DEG REGENERATION PROCESS

The technological process of regeneration of DEG is characterized by changes in dynamic situations. They are caused by changes in both external factors (flow, temperature and pressure), and internal factors. Internal perturbing factors manifest themselves over time as structural changes in the installation (thinning of the walls of the apparatus, clogging of the pipeline cross-section, etc.). To maintain the set values over a wide range of changes in the effects, it is proposed to use the concept of multimode control [1].

In accordance with the principle of multimodal regulation, a local regulatory objective is established for each technological regime and local regulation law is selected (selected), taking into account previously developed recommendations and established standard solutions.

The use of the concept of multimode control in relation to process units is based on the provision of specified requirements to the current mode of operation by connecting local regulators (mode regulators, sub regulators) from the existing set of regulators in accordance with the dynamic situation that has developed at the moment. The change in the control law of a multimode regulator occurs when a certain set of informative characteristics is received, which are formed on the basis of measured values characterizing the current state of the installation and the state of the environment. Based on the information received, the multimode regulator, in accordance with the current process mode, generates the required control signal.

Thus, the concept of multimodal regulation can become the basis for developing a strategy for operating the TP of DEG regeneration.

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