Design of a fuzzy controller for a membrane gas separation process control system

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Abstract. The production of nitrogen from the air through membrane gas separation processes is widely used in many industries. The problem of controlling the gas separation process, it is connected with multi-loop control using the control of several variables. This article proposes an intelligent controller for matching fluctuations in pressure and airflow of the gas separator. The intelligent controller is based on a fuzzy logic algorithm. Applying fuzzy logic in the proposed solution allows you to increase the speed of the control system. The effectiveness of the proposed controller was evaluated in comparison with the PID controller. The proposed fuzzy controller can improve the accuracy of the control system of gas separation, reduce the process transient duration and increase the service life of technological equipment.

Keywords: fuzzy logic; PID control; gas separation; membrane technology; nitrogen; control system

1. Introduction

Air separation for the production of enriched nitrogen and oxygen is of great importance to the chemical industry [1].

For practical applying, whether in laboratories or at large industrial enterprises, nitrogen is obtained in three main ways. All of these ways are based on the decomposition of atmospheric air: by the cryogenic decomposition of air, using short-cycle heat-free adsorption, and by the method of membrane diffusion [2].

The gas separation process based on membrane technology has a preferred application compared to other methods, since it is economical, compact in size, has a modular configuration and can provide low unit energy consumption [3].

Existing gas separation plants are a multi-stage multi-connected construction with non-linear connections between their constituent elements [1,3]. When designing multi-loop control using multi-variable control, it is important correctly to determine controlled variables and their combinations. Most control systems of gas separation plants are based on a traditional PID controller system. The presence of only three tuning parameters in the PID controller, which are configured only at the stage of system design, in some cases is insufficient to obtain the specified control quality, especially for systems with unstable properties, high delay, and systems that require high quality tracking at the same time setting.
and high quality of attenuation of external disturbances in conditions when there is the incompleteness of information about these disturbances and object properties.

An effective way towards overcoming the limitations in the management of complex objects is the applying of fuzzy controllers that allow shaping the effects on the object by changes in the state variables of the control object, for example, error and speed of error. The approach to constructing control systems based on fuzzy logic applies to many existing systems since in many cases the improvement of existing algorithms can be done at minimal cost using the existing hardware and software [4–6].

In this paper, for the plant of gas separation, the use of a fuzzy controller instead of a PID controller is proposed. The use of a fuzzy controller for the plant of gas separation will improve the accuracy and speed of the gas separation process.

2. Membrane technology for gas separation

Membrane processes are one of the main technologies for gas separation applications, the purpose of which is the separation gas mixtures using semipermeable membranes [7].

In the chemical industry, membrane methods are used to separate helium and hydrogen from natural gases, nitrogen, and oxygen from the air, etc [3,8].

Also, membrane technology is becoming increasingly important for medical purposes, especially in the process of enriching the level of oxygen concentration (O₂). Enrichment of O₂ level from nitrogen (N₂) streams using membrane processes is more economical than conventional cryogenic air distillation, mainly due to its low energy consumption, which subsequently leads to minimization of operating costs [8].

Purification of hydrogen, processing of natural gas, extraction of volatile organic compounds, and drying of gas are increasingly used in various industries due to membrane plants, but the membrane separation of gases remains the main market for the production of nitrogen from the air [9,10].

The membrane process is continuous (without a regeneration stage), it does not include chemicals, does not generate waste, offers the possibility of intensification, it is modular (easy to scale) and does not involve complex operations.

Membrane plants consist of membrane air separation modules, which are cylindrical tanks. Inside these tanks in parallel are many fibers consisting of special polymer materials [11,12].

Compressed air is supplied to the inlet of the membrane module, from where it is evenly distributed between all the individual fibers, arriving at their inner side (Figure 1). The fiber walls are membranes with an asymmetric pore arrangement through which water, hydrogen, and helium molecules diffuse quickly and easily to the outside of the fibers. Molecules of oxygen, as well as carbon dioxide CO₂, penetrate through the walls at an average speed. Principally the molecules of nitrogen, as well as argon contained in the air, remain on the inner side of the membranes [13,14].

![Figure 1. Membrane module](image)
Depending on the requirements for nitrogen purity (usually from 90 to 99.9%), one-stage or multi-stage membrane process configurations are used.

The general structures of the synthesis of processes correspond to the structures shown in Fig. 2. The number of levels for various purity levels corresponds to the number and location of recirculation circuits for multi-stage processes.

![Diagram showing structures of membrane processes with different nitrogen purities](image)

Figure 2. Structures of membrane processes with different nitrogen purities

As a rule, the "purity/performance" ratio can be adjusted as simply as possible with the help of a single flow regulator installed at the outlet of the membranes. At the same time, fluctuations in pressure or flow rate are more likely and may well lead to a drop in the purity of the gas. In this case, there is a need to improve the accuracy of regulation of pressure and gas flow [3,12].

3. Model of the gas separator

The gas dynamics in the gas separator model is based on the material balance equation and the ideal gas equation. The material balance equation determines the number of moles of total gas, component A (nitrogen) and component B (oxygen) in a gas separator. The ideal gas equation determines the total pressure and partial pressures of components A and B in a gas separator.

The diagram of a gas separator is shown in Fig. 3.

The equation of material balance, pressure and mole fraction are described as follows.

Changes in the number of moles of all gases in the material part per unit time can be expressed by the following equation.

\[
\frac{dN_{tot}}{dt} = F - W - N_A \cdot Area - N_B \cdot Area,
\]

where \(tW\) is all gases in the material part,
\(N\) is the number of moles in the gas,
\(F\) is the amount of material entering the material part per unit time,
\(W\) is the amount of gas emitted from a portion of the material per unit time,
\(Area\) is the membrane area.
Changes in the number of moles of gas component A in the material part per unit time can be expressed by the following equation

\[
\frac{dN_{AW}}{dt} = F \cdot X_{AF} - W \cdot X_{AW} - N_A \cdot \text{Area},
\]  

(2)

where \( X_{AF} \) is the mole fraction of component A in \( F \), index \( AW \) denotes the gas component A in the material part. Given the integral from time 0 to \( t \), it can be expressed by the following equation. This is the number of moles in the material at time \( t \)

\[
N_{tW}|_{t=t} = \int_{0}^{t} (F - W - N_A \cdot \text{Area} - N_B \cdot \text{Area}) dt + N_{tW}|_{t=0}.
\]  

(3)

Figure 3. Diagram of the gas separator

Given the integral from time 0 to \( t \), it can be expressed by the following equation. This is the number of moles of the gas component A in the material at time \( t \)

\[
N_{AW}|_{t=t} = \int_{0}^{t} (F \cdot X_{AF} - W \cdot X_{AW} - N_A \cdot \text{Area}) dt + N_{AW}|_{t=0}.
\]  

(4)

The pressure of all gases in the material is determined by the equation

\[
P_{tW} = N_{tW} \cdot R \cdot T / V,
\]  

(5)

where \( P \) is the pressure; \( R \) is the gas constant; \( V \) - volume in the material part (permeable part).

The mole fraction in the material part is determined by the equation

\[
X_{AW} = \frac{X_{AW}}{N_{AW}}.
\]  

(6)

The change in the number of moles of all gases in the permeable part per unit time can be expressed by the following equation
\[
\frac{dN_{tQ}}{dt} = N_A \cdot Area + N_B \cdot Area - Q .
\]  

(7)

Given the integral from time 0 to t, it can be expressed by the following equation. This is the number of moles in the permeable part at time t.

\[
N_{tQ}|_{t=t} = \int_0^t (N_A \cdot Area + N_B \cdot Area - Q) dt + N_{tQ}|_{t=0} .
\]  

(8)

The equation of the material balance of the gas component A in the permeable part can be expressed by the following equation:

\[
\frac{dN_{AQ}}{dt} = N_A \cdot Area - Q \cdot Y_{AQ} ;
\]  

(9)

\[
N_{AQ}|_{t=t} = \int_0^t (N_A \cdot Area - Q \cdot Y_{AQ}) dt + N_{AQ}|_{t=0} .
\]  

(10)

The pressure of all gases in the permeation part

\[
P_{tQ} = N_{tQ} \cdot R \cdot T/V .
\]  

(11)

The mole fraction in the permeation part

\[
X_{AQ} = \frac{N_{AQ}}{N_W} .
\]  

(12)

4. Fuzzy control system

The structure of the fuzzy-logical part of the controller is shown in Fig. 4 [15]. It consists of fuzzification blocks, fuzzy rules (rule base), fuzzy inference and defuzzification.

The fuzzy model uses fuzzy rules, which are linguistic statements, including fuzzy sets, fuzzy logic, and fuzzy inference. A fuzzy rule plays a key role in representing expert control and experience in matching input variables of fuzzy controllers with output variables.

Figure 5 (left) shows the transitional characteristic of the object, divided into areas A – I.

The formation of linguistic rules can be demonstrated using the phase plane (Fig. 5, right), the horizontal axis of which represents the values of the derivative of the control error \( de/dt \), and the vertical axis represents the values of the control error e.

The action starts from area A. Area A is characterized by a large error value and an almost zero value of the derivative by error. Therefore, in linguistic rules, this will be expressed as PB (positive big) and PZ (positive zero), respectively. When moving from area A to area B, the value of the error and the derivative of the error will change from PB to PM and PZ to PM, respectively.

![Figure 4. Fuzzy controller structure](image-url)
Consider the period in which the output values increase from C to D areas, where the error and derivative by error change from NZ to NM and PB to PM, respectively. Considering transitions in all areas, it is possible to form a matrix of fuzzy statements presented in Table 1.

Using the five membership functions, fuzzified input and output variables are normalized between +1 and −1. To get the fuzzy conclusion to a precise value, the centroid method is used. Fuzzy inference using five membership functions requires 25 rules.

An increase in the number of membership functions to seven leads to an increase in the number of rules to 49. However, this increases the cost of computing resources but does not lead to a significant improvement in control efficiency.

On the other hand, with three membership functions and 9 rules, calculations are faster. But compared to a system with five membership functions and 25 rules, the control efficiency is low in terms of overshooting and increasing the transition time. When creating the rule base, a table of linguistic terms is created (Table 1), based on data obtained during modeling under various operating conditions when the reference signal (target) and disturbances change.

| e   | NB  | NS  | Z   | PS  | PB  |
|-----|-----|-----|-----|-----|-----|
| de  |     |     |     |     |     |
| NB  | NB  | NB  | NB  | NS  | Z   |
| NS  | NB  | NB  | NS  | Z   | PS  |
| Z   | NB  | NS  | Z   | PS  | PB  |
| PS  | NS  | Z   | PS  | PB  | PB  |
| PB  | Z   | PS  | PB  | PB  | PB  |

In table 1, the following notation is accepted: NB is negative big; NS is negative small; Z is zero; PS is positive small; PB is positive big.

5. Simulation Results
The object simulation was created based on a gas separator model using Matlab/Simulink. The separator model is a three-stage structure as shown in Figure 2.

As a control system for an object, PID control, and a fuzzy controller are compared. The simulation results are presented in figures 6 and 7.
Figure 6 shows that tracking the setpoint is best for a fuzzy controller in gas separator 3, followed by gas separators 2 and 1, respectively, which confirms the behavior of the model.

Figure 7, right, demonstrates that the process of gas separation with fuzzy control requires less time than using PID control. This provides lower energy consumption during the process of gas separation. Figure 7, left, shows that the control accuracy for fuzzy control is higher than with PID control.

Thus, the proposed gas separator control system with a fuzzy regulator allows you to obtain a given level of nitrogen concentration at a lower cost than when using PID control.

6. Conclusion
Today, the production of nitrogen-enriched air using membrane gas separation is the main method. In this work, the problem of constructing a control system for the process of obtaining nitrogen from the air in gas separator using a fuzzy controller is solved.

The object of control (a plant) is a gas separator. A simulation model is created based on a gas separator model using Matlab/Simulink. In the object control system, the PID controller and the fuzzy
controller are compared. The fuzzy control model in this example as a whole has better control characteristics compared to PID control and allows us to obtain a given level of nitrogen purity with a lower unit energy consumption.

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