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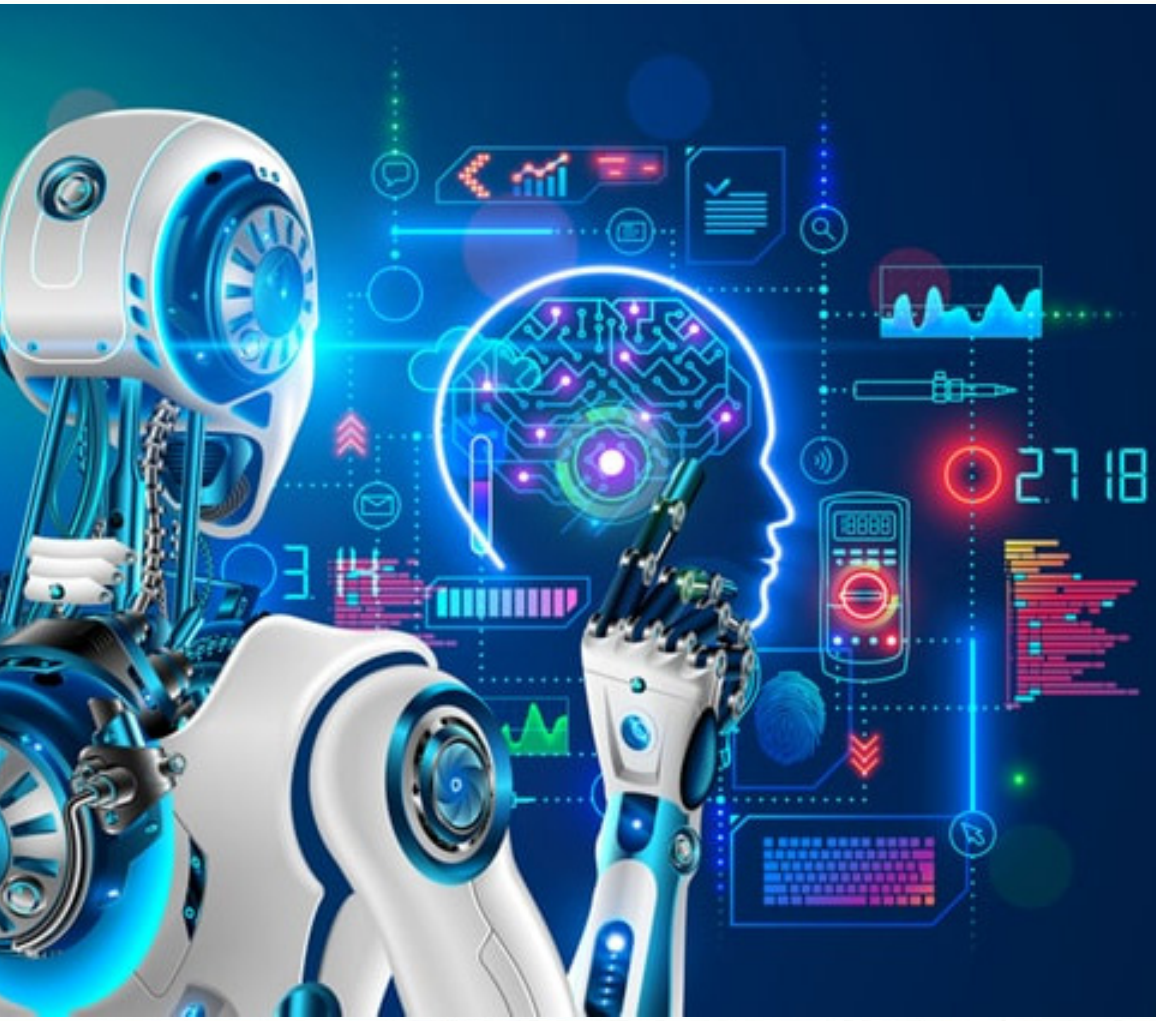

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DEVELOPING MATHEMATICAL MODELS TO SIMULATE THE DYNAMIC BEHAVIOR OF SEPARATION PROCESSES, CONSIDERING THE IMPACT OF EXTERNAL FACTORS

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Abstract: This study proposes a dynamic mathematical model for simulating separation processes in distillation columns under transient operating conditions. Due to the high inertia and structural complexity of column contact devices, experimental analysis of dynamic behavior is often limited. To overcome this challenge, the separation column is modeled as a distributed system composed of lumped-parameter elements, including trays, reboilers, condensers, and reflux accumulators. Each element is described using material and energy balance equations formulated as systems of ordinary differential equations.

The model accounts for time-dependent variations in flow rates, component concentrations, temperature, pressure, and phase equilibrium during process disturbances. A set of simplifying assumptions is applied to reduce computational complexity while preserving the essential physical characteristics of the separation process. Dynamic calculations are performed discretely over time, enabling the analysis of transient responses caused by control actions.

The model incorporates PID-based control strategies for key variables such as reboiler heat input, reflux rate, bottom product flow, and condenser cooling. The proposed approach can be effectively used for process optimization, control system design, and the development of digital twins and operator training simulators for industrial separation columns.

Key words: separation column, dynamic mathematical model, transient processes, automatic control, mass and energy balance, rectification, process optimization.

Annotatsiya: Ushbu tadqiqot o‘tkinchi ishlash sharoitlarida distillatsiya ustunlaridagi ajratish jarayonlarini modellashtirish uchun dinamik matematik modelni taklif etadi. Ustun kontakt qurilmalarining yuqori inertsiyasi va tuzilishining murakkabligi tufayli dinamik xatti-harakatlarni eksperimental tahlil qilish ko‘pincha cheklangan bo‘ladi. Ushbu muammoni hal qilish uchun ajratish ustuni tarelkalar, qayta qaynatgichlar, kondensatorlar va qaytarma oqim to‘plagichlarini o‘z ichiga olgan yig‘ilgan parametrli elementlardan iborat taqsimlangan tizim sifatida modellanadi. Har bir element oddiy differensial tenglamalar tizimi ko‘rinishida tuzilgan modda va energiya balansi tenglamalari yordamida tavsiflanadi.

Model jarayon buzilishlari paytida oqim tezligi, komponentlar konsentratsiyasi, harorat, bosim va faza muvozanatining vaqtga bog‘liq o‘zgarishlarini hisobga oladi. Ajratish jarayonining muhim fizik xususiyatlarini saqlagan holda hisoblash murakkabligini kamaytirish uchun soddalashtiruvchi farazlar majmui qo‘llaniladi. Dinamik hisob-kitoblar vaqt bo‘yicha diskret tarzda amalga oshiriladi, bu esa boshqaruv harakatlari natijasida yuzaga keladigan o‘tkinchi javoblarni tahlil qilish imkonini beradi.

Model qayta qaynatgichning issiqlik kirishi, qaytarma oqim tezligi, pastki mahsulot oqimi va kondensatorni sovutish kabi asosiy o‘zgaruvchilar uchun PID asosidagi boshqaruv strategiyalarini o‘z ichiga oladi. Taklif etilgan yondashuv jarayonlarni optimallashtirish, boshqaruv tizimlarini loyihalash, sanoat ajratish ustunlari uchun raqamli egizaklar hamda operatorlarni o‘qitish simulyatorlarini ishlab chiqishda samarali qo‘llanilishi mumkin.

Kalit so‘zlar: ajratish kolonnasi, dinamik matematik model, o‘tkinchi jarayonlar, avtomatik boshqaruv, modda va energiya balansi, rektifikatsiya, jarayonni optimallashtirish.

Аннотация: В данном исследовании предлагается динамическая математическая модель для моделирования процессов разделения в дистилляционных колоннах в нестационарных условиях эксплуатации. Из-за высокой инерционности и структурной сложности контактных устройств колонн экспериментальный анализ динамического поведения часто ограничен. Для преодоления этой проблемы разделительная колонна моделируется как распределенная система, состоящая из элементов с сосредоточенными параметрами, включая тарелки, кипятильники, конденсаторы и емкости орошения. Каждый элемент описывается с помощью уравнений материального и энергетического баланса, сформулированных в виде систем обыкновенных дифференциальных уравнений.

Модель учитывает зависящие от времени изменения расходов, концентраций компонентов, температуры, давления и фазового равновесия при возмущениях процесса. Применяется ряд упрощающих допущений для снижения вычислительной сложности при сохранении существенных физических характеристик процесса разделения. Динамические расчеты выполняются дискретно во времени, что позволяет анализировать переходные процессы, вызванные управляющими воздействиями.

Модель включает стратегии управления на основе ПИД-регуляторов для ключевых переменных, таких как тепловая нагрузка кипятильника, расход орошения, расход кубового продукта и охлаждение конденсатора. Предложенный подход может эффективно использоваться для оптимизации процессов, проектирования систем управления и разработки цифровых двойников и тренажеров для обучения операторов промышленных разделительных колонн.

Ключевые слова: разделительная колонна, динамическая математическая модель, переходные процессы, автоматическое управление, материальный и тепловой баланс, ректификация, оптимизация процесса.

INTRODUCTION

Separation columns play a pivotal role in modern chemical, petrochemical, and process industries, serving as core units for the purification and fractionation of multicomponent mixtures. The efficiency and economic viability of these processes largely depend on the stability and controllability of mass and heat transfer occurring within the column. As industrial separation systems grow in scale and complexity, the demand for high product purity, reduced energy consumption, and reliable operation under varying conditions has intensified. This places increased emphasis on understanding not only steady-state performance, but also the dynamic behavior of separation columns during transient and disturbed operating modes.

In practical operation, separation columns are subject to frequent disturbances caused by fluctuations in feed flow rate, composition, temperature, and pressure, as well as by changes in utility conditions and control actions. Due to the large number of contact devices—such as trays or packing elements—and the significant holdup of material within the column, these systems exhibit pronounced inertia. This inertia complicates experimental investigation of transient regimes and limits the applicability of purely empirical approaches for control system design. As a result, mathematical modeling has become an indispensable tool for analyzing column dynamics and supporting the development of effective automation and optimization strategies.

Dynamic modeling of separation columns is inherently challenging, as rigorous descriptions typically lead to systems of nonlinear partial differential equations with distributed parameters. While such models offer high accuracy, their computational complexity often makes them impractical for control-oriented studies and real-time applications. Therefore, there is a strong motivation to develop reduced-order dynamic models that balance physical fidelity with computational efficiency. Representing a separation column as a sequence of lumped-parameter elements with time delays provides a pragmatic framework for capturing essential dynamic interactions while remaining suitable for control analysis.

In this context, the present study focuses on the development of a dynamic mathematical model of a separation column that enables the analysis of transient processes and control behavior under non-steady-state conditions. The proposed approach is based on material and energy balances for individual contact devices, supplemented by phase equilibrium relationships and simplified hydrodynamic assumptions. By integrating dynamic control loops for key process variables, the model creates a foundation for evaluating controllability, stability, and optimization potential. Such a modeling framework is particularly relevant for the design of advanced automatic control systems, digital twins, and training simulators, where accurate yet computationally tractable representations of separation processes are essential.

REVIEW OF LITERATURE ON THE SUBJECT

Recent research on separation and rectification processes demonstrates a clear shift toward advanced modeling, optimization, and intelligent control methods aimed at improving efficiency, stability, and product

quality. Kozhakhmetova et al. (2024) analyze the operation of a distillation column in a catalytic cracking unit using fuzzy input information, showing that uncertainty-aware modeling improves decision-making under incomplete or imprecise process data. Their results confirm that fuzzy-based approaches are particularly effective for complex industrial columns where classical deterministic models may not fully capture operational variability.

Simulation-driven optimization remains a dominant research direction. Yang et al. (2024) investigate the rectification of tetrafluoroethylene through detailed process simulation and optimization, demonstrating how parametric adjustments can significantly enhance separation efficiency and reduce energy consumption. Their work highlights the importance of combining rigorous thermodynamic models with numerical optimization to identify optimal operating regimes. Similarly, Seferlis and Grievink (2001) propose collocation-based models for the optimal design and sensitivity analysis of reactive distillation units, emphasizing that dynamic interactions between reaction and separation must be considered at the design stage to ensure robust operation.

The influence of structural and operational parameters on rectification performance is addressed by Anokhina and Timoshenko (2023), who study the effect of side-draw quantity and level on extractive rectification agent consumption in systems with partially integrated heat and material flows. Their findings reveal strong nonlinear relationships between tray configuration, internal flows, and solvent demand, reinforcing the need for dynamic models capable of capturing transient and coupled effects in complex column systems.

Energy and enthalpy-based modeling approaches also play a significant role in separation process analysis. Cardoso and Salcedo (2010) introduce transformed enthalpy surfaces for multireactive systems, applying this concept to reactive distillation of MTBE. Their methodology provides valuable insight into heat–mass interaction mechanisms and supports the development of energy-efficient control and optimization strategies for integrated separation–reaction processes.

From a control perspective, the application of intelligent and fuzzy logic methods has gained increasing attention. Avazov and Abdullaeva (2024) demonstrate the practical implementation of fuzzy control for rectification processes, showing improved stability and adaptability compared to conventional control schemes. Their work confirms that fuzzy controllers are well suited for nonlinear, multivariable separation systems subject to disturbances and parameter uncertainty.

Although originating from computer science, the concept of separation and non-interference discussed by Karbyshev et al. (2018) provides a valuable theoretical perspective for complex systems modeling, emphasizing modularity and independence of subsystems. This idea aligns with modern approaches to representing separation columns as interconnected but locally describable elements, facilitating scalable dynamic modeling.

Overall, the reviewed studies confirm that effective analysis and control of separation columns require a combination of dynamic mathematical modeling, thermodynamic rigor, optimization techniques, and intelligent control strategies. These works collectively justify the development of integrated dynamic models that balance physical accuracy with computational feasibility and support advanced automation and optimization of industrial separation processes.

RESEARCH METHODOLOGY

The research methodology is based on the collection of input data from published scientific sources, process design documentation, and operational parameters of separation columns. Mathematical modeling is used to generate time-dependent datasets, which are analyzed through numerical simulation and sensitivity analysis to evaluate transient behavior, control responses, and the influence of key technological variables.

ANALYSIS AND RESULTS

For accurate separation of mixture components, columns requiring a substantial quantity of contact devices are indispensable. However, the inherent inertia of these devices presents a challenge for experimentally investigating their dynamic behaviors, a crucial step in selecting and designing automation systems. Addressing challenges related to optimal control and process optimization within separation processes necessitates the application of mathematical modeling techniques and their derived results.

Several mathematical models have been created to represent the separation process [1-3]. However, capturing the dynamic behavior of these processes within automatic control systems often results in intricate systems of nonlinear partial differential equations. To circumvent this complexity, researchers focus on either static optimization of the process or simplifying the model using reasonable assumptions.

A distributed separation column can be viewed as a system composed of individual components, each modeled as a lumped parameter system with inherent delays. These components include trays, boilers, condensers, and packing sections, each possessing a unique separation capacity for the fluids flowing through

them. Mathematical representations of these components are developed using systems of ordinary differential equations. These equations encompass balance relationships and nonlinear expressions that capture the dynamics of fluid flow, heat transfer, and mass transfer within each component.

Due to external disruptions, the separation process moves away from its state of dynamic balance. This shift causes alterations in the composition of both the liquid and vapor phases, along with changes in their flow rates, enthalpy, temperature, and pressure within each contacting device, the column base, and the reflux accumulator.

Technological artifacts, exemplified by separation columns, possess distinctive traits. These include multidimensionality, intricate interconnections between parameters, the spatial and temporal distribution of these parameters, and the prevalence of substantial disturbances. Modeling and computational analysis of such objects necessitate consideration of these inherent properties.

To streamline calculations and address the many variables influencing the separation process, which fluctuate over time, the dynamic model of the separation column employs the following assumptions:

Because the liquid on the trays combines immediately, we can treat the tray as a system with aggregated characteristics.

The impact of hydraulic delay on both liquid and vapor flow is disregarded in this analysis.

Thermal energy is not emitted by the device.

The liquid and vapor phases exist in a state of balance.

The operating characteristics of the separation column are intrinsically linked to the nature of the substances being separated within it.

The duration needed for hydrodynamic conditions and phase equilibrium to stabilize within the column is insignificant compared to the time necessary for concentration establishment.

Within the context of modeling, a separation column is viewed as a collection of basic components, each functioning similarly to a single tray, reboiler, condenser, or the reflux gathering point at the column's summit.

The diagram in Figure 1. provides a visual representation of the key material and thermal (heat) transfers occurring within the column's contact zone (Figure 1).

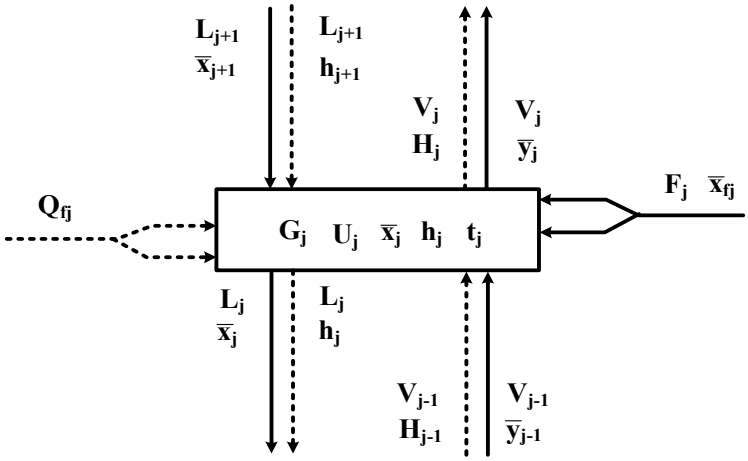

Figure 1. Visual representation of how materials and energy move through the separation column's contacting unit

The calculation of the transition process unfolds step-by-step at designated moments in time, with each point separated by a time difference denoted as Δτ:

$$\tau[k+1] = \tau[k] + \Delta\tau = (k+1) \cdot \Delta\tau;$$

where τ[0] = 0; k is an integer; k=0, 1, ..., m.

The key factors influencing this process, which are carefully regulated, include flow rate F_j, concentration f_j, feed temperature t_j, and pressure within the feed pipe P_j, all of which are time-dependent variables.

At a specific point in time, denoted as τ[k], the parameters of the contact device illustrated in Figure 1. are precisely defined. These parameter values are established either at the very beginning (τ[0]) through the use of a static model or by simulating the device's behavior during transient phases.

$$V_{j-1}[k+1]\bar{y}_{j-1}[k+1]H_{j-1}[k+1]L_{j+1}[k]\bar{x}_{j+1}[k]h_{j+1}[k]$$

The column's calculations progress in a single direction, moving upwards from the bottom. Consequently, at time τ[k+1], as the calculation reaches the j-th tray, the properties of the vapor exiting the contacting

device situated beneath are already determined. However, to determine the liquid flow entering the tray, the characteristics of the liquid at an earlier time, τ[k], must be employed.

$$\tau[k+1]:\ L_j[k+1],\ V_j[k+1],\ \overline{x}_j[k+1],\ \overline{y}_j[k+1],\ h_j[k+1],$$
$$H_j[k+1], G_j[k+1],\ t_j[k+1]$$

These calculations determine the features and attributes of the flows exiting the plate, along with the temperature and volume of liquid remaining within it at a later point.

Within the established mathematical model, every contact device is treated as a possible source plate, taking into consideration the influence of dynamic control maneuvers on the process:

$$\begin{cases} F_j = q \cdot F, & j = N_{f,1}, \\ F_j = (1-q) \cdot F, & j = N_{f,2}, \\ F_j = 0, & j \neq N_{f,1}, \neq N_{f,2}. \end{cases} \quad (1)$$

Every plate is supplied with liquid from the device situated above it and vapor from the section below. The liquid, determined by its composition, and the vapor, whose characteristics are influenced by the mass transfer efficiency within the device, leave the plate. The comprehensive material balance for the contact device can be summarized as:

$$\frac{dG_j}{d\tau} = L_{j+1} + V_{j-1} + F_j - L_j - V_j. \quad (2)$$

Material balance equation by components:

$$\frac{d(G_j \cdot x_{j,i})}{d_\tau} = L_{j+1} \cdot x_{j+1,i} + V_{j-1} \cdot y_{j-1,i} + F_j \cdot x_{f,j,i} - L_j \cdot x_{j,i} - V_j \cdot y_{j,i} \quad (3)$$

The left side of expression (3):

$$\frac{d(G_j \cdot x_{j,i})}{d\tau} = G_j \cdot \frac{dx_{ji}}{d\tau} + x_{j,i} \cdot \frac{dG_j}{d\tau}. \quad (4)$$

By inserting equations (4) and (2) into equation (3), we derive the formula for determining the concentration of the liquid-phase components.

$$G_j \cdot \frac{dx_{j,i}}{d\tau} = L_{j+1} \cdot (x_{j+1,i} - x_{j,i}) + V_{j-1} \cdot (y_{j-1,i} - x_{j,i}) + V_j \cdot (x_{j,i} - y_{j,i}) + F_j \cdot (x_{f,j,i} - x_{ji}).$$

(5)

The time constant for the column contact device is represented by the following expression:

$$T_j = \frac{G_j}{L_{j+1} + V_{j-1} - V_j + F_j} \quad (6)$$

The heat balance equation resembles equation (5), but instead of considering heat loss to the surroundings, it focuses on the heat stored within the liquid on the plate, specifically as a change in its enthalpy.

$$G_j \frac{dh_j}{d-} - L_{j-1} - (h_{j-1} - h_j) - V_{j1} - (H_{j1} - h_j) - V_j - (h_j - H_j) - F_j - (h_{f,j} - h_j).$$

(7)

The tray's structural configuration plays a crucial role in determining how much substance changes within the column's contact device during dynamic operation. When analyzing the feed tray of a separation column, it's generally accepted that the liquid level remains constant. Under these circumstances, the vapor phase contribution to the liquid can be disregarded, the liquid volume on the tray is steady, and the substance amount is:

$$G = \frac{\pi \cdot d^2 \cdot U \cdot \rho}{4 \cdot \mu}. \quad (8)$$

The determination of a liquid mixture's density and molar mass relies on the concept of additivity, along with the evaluation of individual component densities and molar masses. The relationship between the density of a pure component (i) and temperature (t) exhibits a linear trend, expressible as:

$$\rho_i = \rho_{i,1} \cdot t + \rho_{i,2} \quad (9)$$

Mixture density:

$$\rho = \frac{1}{\sum_{i=1}^{n}\left(\frac{x_i}{\rho_i}\right)} = \frac{1}{\sum_{i=1}^{n}\left(\frac{x_i}{\rho_{i,1}\cdot t+\rho_{i,2}}\right)} \quad (10)$$

The molar mass of a pure substance remains a fixed value. In contrast, the molar mass of a mixture:

$$\mu = \sum_{i=1}^{n}(\mu_i \cdot x_i). \quad (11)$$

Based on equations (10) and (11), the quantity of substance within the contact device can be represented by this equation:

$$G_j = \frac{\pi \cdot d_j^2 \cdot U_j}{4 \cdot \sum_{i=1}^{n}(\mu_i \cdot x_{j,i}) \cdot \sum_{i=1}^{n}\left(\frac{x_{j,i}}{\rho_{i,1}\cdot t_j+\rho_{i,2}}\right)}. \quad (12)$$

The quantity of substance present is determined based on the liquid phase composition at a specific point in time. The U_j values serve as tuning parameters within the dynamic model.

Our calculations rely on the vapor composition and the assumption that mass transfer coefficients remain constant in both the liquid $\beta_{x,j}$ and vapor $\beta_{y,j}$ phases.

$$m_j = \frac{\partial y_j^*(\overline{x})}{\partial x_j}, \quad (13)$$

$$K_{y,j} = \frac{S}{\frac{1}{\beta_{y,j}} + \frac{m_j}{\beta_{x,j}}}, \quad (14)$$

$$\eta_j = 1 - e^{-\frac{K_{y,j}}{V_{j-1}}}, \quad (15)$$

$$y_{j,i} = y_{j-1,i} + (y_{j,i}^* - y_{j-1,i}) \cdot \eta_{j,i} \quad (16)$$

$\overline{y}_j^*$ The makeup of the vapor phase at equilibrium is calculated using a phase equilibrium model [4], and can be represented as a generalized equation that depends on both the liquid phase composition and the pressure within the contacting equipment:

$$\overline{y}_j^* = f(\overline{x}_j, P_j) \quad (17)$$

We determine the temperature within the contact device concurrently with equation (17) through the application of iterative computational techniques.

$$t_j = f(\overline{x}_j, P_j) \quad (18)$$

Considering equation (18), we determine the enthalpy of both the liquid and vapor phases, analyzing how these values change based on their composition and the pressure exerted on the plate.

$$h_j = f(\overline{x}_j, P_j), \quad (19)$$

$$H_j = f(\overline{y}_j, P_j) \quad (20)$$

The column can receive feed in various phases: subcooled liquid, boiling liquid, a blend of vapor and liquid, condensing vapor, or superheated vapor. The specific phase of the feed directly influences the enthalpy of the incoming stream [5]:

$$h_{f,j} = f(\overline{x}_{f,j}, P_{f,j}, t_{f,j}) \quad (21)$$

The expressions provided, numbered (1) through (21), enable the calculation of dynamic modes for each individual contact device within the column. Based on these expressions, we outline the following algorithm to determine the required values:

$$h_{f,j}[k+1]$$

1) Before allowing the feed stream to enter the simulated plate, a specific criterion is evaluated. Upon fulfillment of this criterion, both the enthalpy of the feed (21) and the column's heat demand are determined.

2) The level of liquid within the contact device is measured (5);

$$x_{j,i}[k+1] = x_{j,i}[k] +$$

$$+\Delta\tau \cdot \frac{L_{j+1}[k] \cdot \left(x_{j+1,i}[k] - x_{j,i}[k]\right) + V_{j-1}[k] \cdot \left(y_{j-1,i}[k] - x_{j,i}[k]\right)}{G_j[k]} +$$

$$\Delta\tau \cdot \frac{V_j[k] \cdot \left(x_{j,i}[k] - y_{j,i}[k]\right) + F_j[k] \cdot \left(x_{f,j,i}[k] - x_{j,i}[k]\right)}{G_j[k]}.$$

3) By analyzing the composition and pressure within the contact device, one can ascertain the enthalpy of the liquid phase;

$$h_j[k+1], \qquad (2.19)$$

$$t_j[k+1]\overline{y}_j[k+1]$$

4) The parameters influencing the equilibrium state of the process are identified, including the equilibrium phase conditions, temperature, the effectiveness of the contact device for binary separations, and the composition of the vapor exiting each plate;

$$H_j[k+1]$$

5) The enthalpy of the vapor phase is directly influenced by its constituent components.

$$\overline{x}_j[k]t_j[k]\overline{x}_j[k+1]t_j[k+1]$$

6) Leveraging the provided molar masses (11) and density (10), the calculation of the liquid mixture's properties is performed;

7) The quantity of material within the contact device is controlled by ensuring the liquid level on the plate remains steady.

$$\Delta U_j = U_j;$$

8) Using the overall material balance equation (2), we can calculate the remaining unknown value: the rate at which liquid flows out of the plate.

$$L_j[k+1] = L_{j+1}[k] + V_{j-1}[k] + F_j[k] - V_j[k] - \frac{G_j[k+1] - G_j[k]}{\Delta\tau}.$$

Alternatively, considering equation (22), we can express it as:

$$L_j[k+1] = L_{j+1}[k] + V_{j-1}[k] + F_j[k] - V_j[k] - \frac{G_j[k] \cdot \left(\frac{\mu_j[k] \cdot \rho_j[k+1]}{\mu_j[k+1] \cdot \rho_j[k]} - 1\right)}{\Delta\tau}.$$

For each contact device, these calculations are performed step-by-step, starting at the base of the separation column and progressing upwards. Subsequently, the value of k is augmented by one, and the entire calculation sequence is replicated for the subsequent time point.

To determine the design parameters for a column reboiler, one must first ascertain the flow rate and properties of the streams exiting the bottom of the column. Additionally, the temperature, volume, and liquid level within the vessel at the subsequent time interval, τ[k+1], need to be established.

$$W[k+1], V_0[k+1], \overline{x}_0[k+1], y_0[k+1], h_0[k+1], H_0[k+1], G_0[k+1],$$
$$U_0[k+1],\ t_0[k+1]$$

.

$$Fl[k+1], D[k+1], \overline{x}_d[k+1], \overline{x}_{fl}[k+1], t_{fl}[k+1], h_d[k+1], h_{fl}[k+1],$$
$$F_{m3}[k+1], G_d[k+1], U_d[k+1].$$

During the reflux condenser calculation, key factors considered include the flow rate and properties of the streams leaving the reflux drum, the coolant flow rate feeding the condenser, and the quantity and level of the substance present in the reflux accumulator at the point in time denoted by τ[k+1].

Constructing the system of equations for the column reboiler and reflux condenser (equations 2-21) is a straightforward process, analogous to modeling the contact device, so a detailed explanation will be omitted.

The separation column's transition processes adhere to the fundamental principles of matter and energy

conservation. Any alteration in process parameters will shift the column from a stable, steady-state operation to a dynamic state. Achieving a new equilibrium state necessitates deliberate adjustments to the material and energy streams within the apparatus.

Therefore, managing the separation process necessitates both conventional control measures and dynamic actions. Dynamic actions are implemented at the column's extremities, and the dynamic models of the reboiler and reflux condenser require augmentation with models encompassing the relevant circuits designed to fine-tune process variables.

Crucially, the primary traditional control mechanisms for this process involve adjusting the heat input to the reboiler and the reflux rate fed into the column. These adjustments directly influence the column's liquid and vapor loading, its overall productivity, and the final cost of the produced product. Determining the ideal values for these influences involves employing a predictive mathematical model based on nonlinear statics, utilizing algorithms designed for optimizing the separation process [6-7].

Keeping the material balance stable at the column's base requires adjusting the reboiler vessel's liquid level by modifying the flow rate of the product exiting the bottom. The transfer function governing the Uw-W control loop exhibits characteristics of an integrating element:

$$W_0(s) = -\frac{1}{T_{w,o} \cdot s}. \quad (24)$$

We can represent this using a time constant:

$$T_{w,0} = \frac{\pi \cdot d_w^2 \cdot \rho_0}{4 \cdot \mu_0}.$$

Equation (24) employs a "minus" sign to show that the amount of product in the vessel is inversely proportional to the cubic product flow rate. The factor multiplying this relationship is not constant, since the molar mass and density of the cubic product fluctuate based on its makeup and temperature.

We express the allowable starting condition in the following manner:

$$\Delta U_0[k+1] = U_0[k+1] - U_{0,z} \quad (25)$$

Based on the given requirement, when employing a PID controller, the control action components are expressed as:

$$u_p[k+1] = K_p \cdot \Delta U_0[k+1], \quad (26)$$

$$u_i[k+1] = u_i[k] + K_p \frac{\Delta\tau}{T_i} \cdot \Delta U_0[k+1], \quad (27)$$

$$u_d[k+1] = K_p \frac{T_d}{\Delta\tau} \cdot (\Delta U_0[k+1] - \Delta U_0[k]). \quad (28)$$

Considering both the received negative feedback and the inherent negative transfer function, we can re-define the cubic product flow rate using the updated equation (24) as shown below:

$$W[k+1] = W[k] + u_p[k+1] + u_i[k+1] + u_d[k+1]. \quad (2.29)$$

The process of U_d involves dispensing the necessary volume of D distillate. The time constant, which defines the integrating element's reflux capability, is represented as follows:

$$T_{d,0} = \frac{\pi \cdot d_d^2 \cdot \rho_d}{4 \cdot \mu_d}$$

$F_{m3} Q_d$ Adjusting the cooling agent flow rate within the condenser controls the pressure at the top of the column. When the cooling agent flow increases, more heat is dissipated from the vapor product at the column's upper section, leading to increased condensation and a subsequent decrease in pressure within the system.

Elevated pressure within the column stems from the buildup of vapor within its spaces between the plates. We express the time constant as:

$$T_{P,0} = \frac{(N+1) \cdot S \cdot h_y \cdot (H_N - h_d)}{R \cdot T_N \cdot \Delta h_{m3}}. \quad (30)$$

$T_N P_N \overline{y}_N$ The value of T in equation (30) is determined by finding the condensation temperature of the vapor mixture, which has a composition of x, under the specified temperature T and pressure P.

$F_{m3}(\tau)$ To maintain control over the distillate level and pressure within the column's upper section, a

PID controller is employed. The determination of D (τ) and ω values is carried out using equations (25) to (29).

F_{m3} Based on the usage of the cooling agent, we calculate the rate at which steam condenses:

$$V_{N,cond}[k+1] = G_d[k] \cdot \frac{h_d[k+1]-h_d[k]}{\Delta\tau\cdot(H_N[k]-h_d[k])} + F_{m3}[k] \cdot \frac{h_{m3}[k]-h_{m4}[k]}{H_N[k]-h_d[k]}. \quad (31)$$

Equations (23) and (31), corresponding to the final column plate and the reflux condenser respectively, enable the calculation of the substance quantity variation within each inter-plate space of the column.

The pressure within each contact device is represented using the following formula during the computation process.

$$P_j[k+1] = P_j[k] + \frac{\Delta G_{y,j}[k+1] \cdot R \cdot T_j[k+1]}{S \cdot h_y}.$$

This dynamic model enables the investigation of how the column behaves during temporary changes brought about by control measures.

CONCLUSIONS AND SUGGESTIONS

In this study, a dynamic mathematical model of a separation column was developed to analyze transient operating modes and control behavior under non-steady-state conditions. The proposed modeling approach represents the separation column as a distributed system composed of lumped-parameter elements, including trays, a reboiler, a condenser, and a reflux accumulator. This structure makes it possible to adequately describe the dynamic interactions between material and energy flows within the column.

The model is based on rigorous material and energy balance equations that account for time-dependent changes in flow rates, component compositions, temperature, pressure, and phase equilibrium. The introduction of reasonable simplifying assumptions significantly reduces computational complexity while preserving the essential physical characteristics of the separation process. Step-by-step time discretization enables accurate simulation of transient responses caused by external disturbances and control actions.

The integration of PID control loops for key technological variables—such as reboiler heat input, reflux flow rate, bottom product withdrawal, and condenser cooling - allows the evaluation of controllability, stability, and process dynamics. The results demonstrate that dynamic control actions applied at the column boundaries play a decisive role in restoring steady-state operation and ensuring product quality.

The developed model provides a reliable basis for the design and optimization of automatic control systems, predictive analysis of separation efficiency, and energy consumption assessment. Moreover, it can be effectively applied in the creation of digital twins and computer-based training simulators for industrial separation processes, contributing to improved operator training and enhanced process safety and efficiency.

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