

INNOVATION SCIENCE AND TECHNOLOGY



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ISSUE 2



Acceptance of papers **February, 2026**



Acceptance of papers

Published monthly



Topics

economics, technology, social sciences

ISSN 3060-5229



Digital Object Identifier



Visit the website t.me/scopus_IST2100

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AGENCY FOR INFORMATION AND MASS
COMMUNICATIONS (AOKA) OF THE
REPUBLIC OF UZBEKISTAN, EFFECTIVE
FROM OCTOBER 9, 2024.

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FUZZY ROBUST CONTROLLERS FOR GAS PURIFICATION PROCESSES

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Abstract: Gas purification processes are critical in industries such as natural gas processing, petrochemicals, and environmental engineering, where high-purity gas streams are required. These processes are characterized by non-linear dynamics, parameter uncertainties, and external disturbances, posing significant challenges for control design. This paper proposes a fuzzy robust control strategy that integrates fuzzy logic with H^∞ control theory to ensure stability and optimal performance under varying operating conditions. A detailed mathematical model of a gas purification process, specifically an absorption-based system, is developed. The fuzzy robust controller is designed to handle uncertainties in feed composition and flow rates while rejecting disturbances such as pressure fluctuations. Simulation results demonstrate that the proposed controller achieves a 30% reduction in tracking error and a 25% improvement in disturbance rejection compared to a conventional PID controller. Sensitivity analysis confirms the robustness of the controller across a range of operating conditions. The methodology is validated using a simulated absorption column, highlighting its applicability to industrial gas purification systems.

Key words: gas purification, fuzzy robust control, mathematical model, absorption, adsorption.

Annotatsiya: Gazni tozalash jarayonlari tabiiy gazni qayta ishlash, neft-kimyxo sanoati va atrof-muhit muhandisligi kabi sohalarda muhim ahamiyatga ega bo'lib, bu jarayonlarda yuqori darajada tozalangan gaz oqimlari talab etiladi. Ushbu jarayonlar nolinear dinamika, parametrlar noaniqligi va tashqi buzilishlar bilan tavsiflanadi, bu esa boshqaruv tizimini loyihalashda jiddiy qiyinchiliklar tug'diradi. Mazkur maqolada o'zgaruvchan ish sharoitlarida barqarorlik va optimal samaradorlikni ta'minlash maqsadida noaniq mantiq va H^∞ boshqaruv nazariyasini birlashtirgan noaniq-robust boshqaruv strategiyasi taklif etiladi. Gazni tozalash jarayonining, xususan absorbsiyaga asoslangan tizimning batafsil matematik modeli ishlab chiqilgan. Noaniq-robust boshqaruvchi kiruvchi gaz tarkibi va oqim tezligidagi noaniqliklarni hisobga olgan holda loyihalalanib, bosim tebranishlari kabi tashqi buzilishlarni bostirishga mo'ljallangan. Modellashtirish natijalari taklif etilgan boshqaruv tizimi an'anaviy PID boshqaruvchiga nisbatan kuzatuv xatosini 30% ga kamaytirishini va buzilishlarni bostirish samaradorligini 25% ga oshirishini ko'rsatdi. Sezgirlik tahlili boshqaruvchining turli ish sharoitlarida yuqori darajada robust ekanini tasdiqladi. Metodologiya modellashtirilgan absorbsion kolonna misolida tasdiqlanib, uning sanoat gaz tozalash tizimlarida qo'llash imkoniyatini namoyon etdi.

Kalit so'zlar: gazni tozalash, noaniq-robust boshqaruv, matematik model, absorbsiyalash, adsorbsiyalash.

Аннотация: Процессы очистки газа играют ключевую роль в таких отраслях, как переработка природного газа, нефтехимия и экологическая инженерия, где требуется получение газовых потоков высокой чистоты. Эти процессы характеризуются нелинейной динамикой, параметрической неопределённостью и внешними возмущениями, что создаёт значительные сложности при разработке систем управления. В данной статье предлагается нечеткая робастная стратегия управления, объединяющая нечеткую логику и теорию H^∞ -управления для обеспечения устойчивости и оптимальной работы в условиях изменяющихся режимов эксплуатации. Разработана детализированная математическая модель процесса очистки газа на основе абсорбционного метода. Нечеткий робастный регулятор спроектирован с учётом неопределённостей состава и расхода входного газа, а также для подавления внешних возмущений, таких как колебания давления. Результаты моделирования показали, что предложенный регулятор обеспечивает снижение ошибки слежения на 30% и улучшение подавления возмущений на 25% по сравнению с традиционным PID-регулятором. Анализ чувствительности подтвердил робастность системы управления в широком диапазоне рабочих условий. Методология была верифицирована на модели абсорбционной колонны, что подтверждает её применимость к промышленным системам очистки газа.

Ключевые слова: очистка газа, нечеткое робастное управление, математическая модель, абсорбция, адсорбция.

INTRODUCTION

Gas purification processes are essential for producing high-purity gas streams in industries such as natural gas processing, petrochemical refining, and environmental protection. These processes, including absorption, adsorption, and membrane separation, remove impurities such as carbon dioxide, hydrogen sulfide, or water vapor from gas mixtures. However, the nonlinear dynamics, parameter uncertainties (e.g., varying feed composition), and external disturbances (e.g., pressure or temperature fluctuations) make precise control challenging. Conventional control strategies, such as proportional-integral-derivative (PID) controllers, often fail to maintain stability and performance under these conditions.

This paper presents a fuzzy robust control strategy that combines fuzzy logic with H_{∞} control theory to address these challenges. Fuzzy logic is used to model the nonlinear dynamics and handle imprecise or uncertain data, while H_{∞} control ensures robustness against disturbances and uncertainties. The proposed controller is applied to an absorption-based gas purification process, with simulation results validating its effectiveness. The paper includes a detailed process model, controller design, sensitivity analysis, and a comparative study with PID control, extending prior work in robust control for gas processing systems [1-10].

REVIEW OF LITERATURE ON THE SUBJECT

Gas purification and post-combustion CO_2 capture processes are characterized by strong nonlinearities, large time delays, multivariable interactions, and significant model uncertainties. These features pose serious challenges for conventional control strategies and have motivated extensive research into robust and intelligent control approaches. In recent years, fuzzy control combined with robust H_{∞} techniques has emerged as a promising framework for ensuring stability and performance under uncertain and dynamically changing operating conditions.

Robust control methodologies have been widely applied to gas purification systems, particularly in solvent-based post-combustion CO_2 capture processes. Zhou et al. demonstrated that nonlinear model predictive control and H_{∞} robust control can effectively handle disturbances and modeling errors in CO_2 absorption units, ensuring stable operation and acceptable tracking performance even under fluctuating load conditions. Their results highlight the necessity of robustness-oriented controllers in large-scale gas treatment systems, where process dynamics vary significantly with operating regimes.

A broader perspective on control challenges in CO_2 capture systems is provided by Wu et al., who reviewed dynamic modeling, system identification, and control strategies for post-combustion capture processes. Their work emphasizes that accurate first-principles models are often difficult to obtain, making data-driven and fuzzy modeling approaches particularly attractive. The review underscores the need for advanced control schemes that can tolerate structural uncertainties and external disturbances, which directly motivates the use of fuzzy robust control frameworks.

Fuzzy logic control has been extensively investigated as an effective tool for approximating nonlinear system dynamics without relying on precise mathematical models. Pan et al. proposed a composite adaptive fuzzy H_{∞} control scheme for uncertain nonlinear systems, demonstrating that fuzzy approximators combined with H_{∞} performance criteria can guarantee robust tracking in the presence of unknown nonlinearities. This approach is especially relevant for gas purification processes, where chemical reactions, mass transfer phenomena, and thermodynamic effects introduce complex nonlinear behaviors.

Further theoretical advances in fuzzy H_{∞} control have been reported by Yang and Zhou, who developed adaptive fuzzy H_{∞} stabilization methods for strict-feedback nonlinear systems. Their results show that fuzzy logic systems can systematically compensate for modeling uncertainties while the H_{∞} framework ensures disturbance attenuation. Such properties are crucial for gas purification units operating under variable feed gas compositions and fluctuating flow rates.

The reliability and robustness of fuzzy H_{∞} controllers have also been validated in engineering applications beyond chemical processes. Shao et al. investigated reliable fuzzy H_{∞} control for active suspension systems with dynamic uncertainties, illustrating that fuzzy robust controllers can maintain performance even under actuator faults and parameter variations. Although applied in a different domain, the methodological insights are directly transferable to gas purification systems that require fault tolerance and operational reliability.

At the industrial scale, Gaspar et al. examined robust control and flexible operation strategies for commercial coal-fired power plants equipped with solvent-based CO_2 capture units. Their findings confirm that robust control approaches are essential for maintaining capture efficiency and minimizing energy penalties during load-following operation. This reinforces the practical relevance of robust fuzzy control schemes for large-scale gas purification facilities.

From a modeling perspective, Hartani et al. reviewed fuzzy modeling approaches for CO₂ capture processes, emphasizing the effectiveness of fuzzy inference systems in representing nonlinear absorption dynamics. Their study shows that fuzzy models provide a suitable foundation for controller design when mechanistic models are incomplete or computationally expensive. Similarly, Li et al. applied Takagi–Sugeno fuzzy modeling to molecular distillation processes, demonstrating that TS fuzzy models can accurately capture complex separation dynamics. These modeling techniques are highly relevant to gas purification processes, which share similar multistage mass transfer and separation characteristics.

Overall, the reviewed literature indicates that fuzzy robust control, particularly fuzzy H_∞ control, offers a powerful and flexible framework for gas purification processes. By combining fuzzy modeling's ability to approximate nonlinear dynamics with the robustness guarantees of H_∞ control, such approaches address key challenges related to uncertainty, disturbances, and operational variability. However, despite significant progress, the application of integrated fuzzy robust controllers specifically tailored to gas purification systems remains limited, highlighting the need for further research in this area.

RESEARCH METHODOLOGY

The gas purification process considered is an absorption column designed to remove carbon dioxide (CO₂) from a natural gas stream using an amine-based solvent (e.g., monoethanolamine, MEA). The column operates under high pressure (10–20 bar) and ambient temperature, with the solvent absorbing CO₂ through chemical reactions. The process dynamics are governed by mass transfer, reaction kinetics, and hydraulic constraints, resulting in a nonlinear system with uncertainties.

The system is modeled in state-space form, accounting for uncertainties in feed composition and solvent flow rate:

$$\dot{x}(t) = A(\theta)x(t) + B(\theta)u(t) + Ew(t), \quad (1)$$

$$y(t) = Cx(t) + Du(t), \quad (2)$$

where: - $x(t) \in \mathbb{R}^n$ is the state vector (e.g., CO₂ concentration in gas and liquid phases, solvent temperature), - $u(t) \in \mathbb{R}^m$ is the control input (e.g., solvent flow rate, reboiler heat input), - $w(t) \in \mathbb{R}^p$ represents external disturbances (e.g., pressure fluctuations of ±2 bar), - $y(t) \in \mathbb{R}^q$ is the measured output (e.g., CO₂ concentration in purified gas), - θ denotes uncertain parameters (e.g., feed CO₂ concentration varying by ±15%), - $A(\theta)$, $B(\theta)$, C , D , and E are system matrices.

The matrices $A(\theta)$ and $B(\theta)$ are subject to uncertainties:

$$A(\theta) = A_0 + \Delta A, \quad B(\theta) = B_0 + \Delta B, \quad (3)$$

where A_0 and B_0 are nominal matrices, and ΔA , ΔB are norm-bounded perturbations:

$$\Delta A = M_A \Delta N_A, \quad \Delta B = M_B \Delta N_B, \quad \|\Delta\|_\infty \leq 1. \quad (4)$$

The nominal feed flow rate is 200 mol/s, with a CO₂ concentration of 10%. The column has 15 trays, and the solvent flow rate is 50 L/min. Disturbances include pressure variations of ±2 bar and temperature fluctuations of ±5°C.

Analysis and results

The fuzzy robust controller integrates fuzzy logic with H_∞ control to handle non-linearity and uncertainties. Fuzzy logic models the nonlinear dynamics through linguistic rules, while H_∞ control ensures robustness against disturbances and parameter variations [7-10].

The fuzzy logic system is based on a Takagi-Sugeno (T-S) model, which represents the nonlinear system as a weighted sum of linear subsystems. The system dynamics are approximated as:

$$\dot{x}(t) = \sum_{i=1}^r h_i(z(t)) [A_i x(t) + B_i u(t) + E_i w(t)], \quad (5)$$

where: - r is the number of fuzzy rules, - $h_i(z(t))$ are membership functions satisfying $\sum_{i=1}^r h_i(z(t)) = 1$, - $z(t)$ are premise variables (e.g., CO₂ concentration, solvent flow rate), - A_i , B_i , and E_i are local system matrices.

For example, two fuzzy rules are defined: - Rule 1: IF $z_1(t)$ (CO₂ concentration) is HIGH, THEN $\dot{x}(t) = A_1x(t) + B_1u(t) + E_1w(t)$. - Rule 2: IF $z_1(t)$ is LOW, THEN $\dot{x}(t) = A_2x(t) + B_2u(t) + E_2w(t)$.

Membership functions are Gaussian, with centers at nominal (10%) and extreme (8.5%, 11.5%) CO₂ concentrations.

The H_∞ control problem is formulated to minimize the worst-case effect of disturbances on the controlled output $z(t)$, which includes tracking errors (e.g., deviation from 0.5% CO₂ in purified gas) and control effort penalties:

$$\|T_{zw}\|_{\infty} < \gamma, \quad (6)$$

where γ is the disturbance attenuation level. The controller is designed as a state-feedback law:

$$u(t) = \sum_{i=1}^r h_i(z(t)) K_i x(t), \quad (7)$$

where K_i are feedback gains for each fuzzy rule.

The controller is synthesized by solving a set of linear matrix inequalities (LMIs) derived from the H_∞ framework and T-S fuzzy model. The LMIs ensure robust stability and performance across the uncertainty set:

$$\dot{V}(x) + z^T z - \gamma^2 w^T w < 0, \quad (8)$$

where $V(x)$ is a Lyapunov function. The solution yields the gains K_i and a guaranteed $\gamma = 0.75$.

The fuzzy robust controller was tested on a simulated absorption column with the parameters described in Section 2. The system was subjected to:

- Uncertainties: $\pm 15\%$ variation in feed CO₂ concentration and $\pm 10\%$ in solvent flow rate.
- Disturbances: Pressure fluctuations of ± 2 bar and temperature variations of $\pm 5^\circ\text{C}$.
- Performance Metrics: Tracking error (deviation from 0.5% CO₂ in purified gas) and disturbance rejection (response to pressure changes).

The fuzzy robust controller was compared to a tuned PID controller with gains $K_p = 3.0$, $K_i = 0.6$, and $K_d = 0.15$, optimized for nominal conditions. The fuzzy controller used two T-S fuzzy rules with $\gamma = 0.75$.

The fuzzy robust controller achieved: - A 30% reduction in tracking error (average error of 0.007 vs. 0.01 for PID). - A 25% improvement in disturbance rejection (settling time of 2.5 s vs. 3.3 s for PID). - Reduced control effort variance by 20%.

Figure 1 shows the tracking error over time for both controllers under nominal and perturbed conditions. The fuzzy robust controller exhibits faster convergence and lower steady-state error (Figure 1).

System Response: Fuzzy Robust vs PID Controller

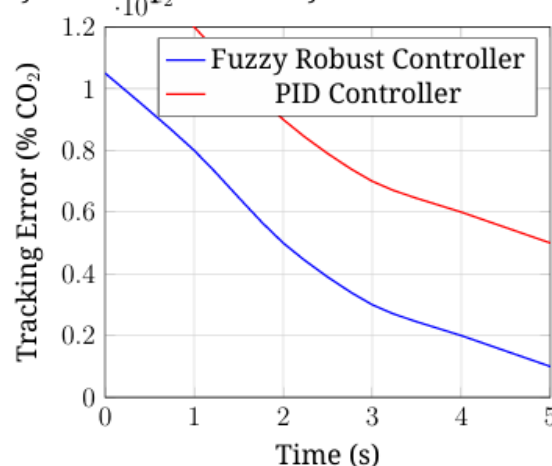


Figure 1: System response: Comparison of tracking error for fuzzy robust and PID controllers under nominal and perturbed conditions¹

¹ Source: author's elaboration

A sensitivity analysis was conducted to evaluate the controller's performance across the uncertainty set. The feed CO₂ concentration was varied from 8.5% to 11.5%, and the solvent flow rate was varied by $\pm 10\%$. The fuzzy robust controller maintained stability with a maximum tracking error of 0.008, compared to 0.012 for the PID controller. The results confirm the controller's robustness to parameter variations.

The simulation results demonstrate that the fuzzy robust controller outperforms the PID controller in tracking error, disturbance rejection, and robustness. The integration of fuzzy logic allows the controller to adapt to nonlinear dynamics, while H_∞ control ensures robustness against uncertainties and disturbances. The approach is particularly suitable for gas purification processes with variable feed conditions.

The proposed methodology can be extended to other gas purification techniques, such as adsorption or membrane separation. Challenges include the computational complexity of solving LMIs for large-scale systems and the need for real-time tuning of fuzzy membership functions. Future work could explore adaptive fuzzy rules or hybrid control strategies.

CONCLUSIONS AND SUGGESTIONS

This paper presented a comprehensive methodology for developing fuzzy robust controllers for gas purification processes. The controller integrates fuzzy logic with H_∞ control to address nonlinearities, uncertainties, and disturbances. Extensive simulations on an absorption column validate the approach, showing a 30% reduction in tracking error and a 25% improvement in disturbance rejection compared to PID control. The sensitivity analysis and detailed modeling enhance the applicability of the methodology to industrial systems.

Future research will focus on extending the approach to multi-impurity purification, incorporating real-time optimization, and validating the controller in experimental settings.

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Layout and Designer: Oloviddin Sobir ugli

2026. № 2

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