DEVELOPMENT OF A DISCRETE MODEL FOR MASS TRANSFER PROCESSES IN DISTILLATION UNITS USING MODEL PREDICTIVE CONTROL

Muhitdinov Djalolitdin Pahritdinovich
Tashkent State Technical University Doctor of Technical Sciences, Professor,
Sultanov Ildar Rafkatovich
Andijan State Technical Institute Senior Lecturer,

Abstract. This paper addresses the optimization of dynamic mass transfer processes in distillation units under a multi-input multi-output (MIMO) control framework. A Model Predictive Control (MPC) strategy is proposed to improve control accuracy, robustness, and energy efficiency compared to classical PID regulators. The discrete model of the distillation process is formulated in state-space representation and tested in numerical simulations. The results demonstrate that MPC provides superior tracking performance, reduced energy consumption, and improved disturbance rejection. A comparative study between PID and MPC shows that predictive control is especially effective in highly coupled nonlinear systems with operational constraints.

Keywords: mass transfer, distillation, predictive control, MPC, MIMO system, optimization, robustness.

Annotatsiya. Ushbu hujjat distillash birliklarida dinamik massa uzatish jarayonlarini optimallashtirishga qaratilgan ko'p kirish ko'p chiqish (MIMO) boshqaruv doirasi. Klassik PID regulyatorlariga nisbatan boshqaruvning aniqligi, mustahkamligi va energiya samaradorligini oshirish uchun namunaviy bashoratli boshqaruv (MPC) strategiyasi taklif etiladi. Distillash jarayonining diskret modeli davlat-kosmik vakillikda shakllantirilgan va raqamli simulyatsiyalarda sinovdan o'tgan. Natijalar shuni ko'rsatadiki, MPC yuqori kuzatuv ko'rsatkichlarini, energiya sarfini kamaytirishni va bezovtalikni rad etishni yaxshilaydi. PID va MPC o'rtasidagi qiyosiy tadqiqotlar shuni ko'rsatadiki, bashoratli nazorat ayniqsa operatsion cheklovlar bilan yuqori darajada bog'langan chiziqli bo'lmagan tizimlarda samarali bo'ladi.

Kalit so'zlar: ommaviy uzatish, distillash, bashoratli nazorat, MPC, MIMO tizimi, optimallashtirish, mustahkamlik.

Аннотация. В данной статье рассматривается оптимизация динамических процессов массообмена в дистилляционных установках в рамках системы управления с несколькими входами и несколькими выходами (MIMO). Предложена стратегия модельного прогнозирующего управления (MPC), позволяющая повысить точность управления, надежность и энергоэффективность по сравнению с классическими ПИД-регуляторами. Дискретная модель процесса дистилляции сформулирована в виде

ISSN 3030-3907

представления в пространстве состояний и протестирована с помощью численного моделирования. Результаты показывают, что MPC обеспечивает превосходную производительность отслеживания, снижает энергопотребление и улучшает подавление помех. Сравнительное исследование PID и MPC показывает, что прогнозирующее управление особенно эффективно в нелинейных системах с высокой степенью связи и эксплуатационными ограничениями.

Ключевые слова: массообмен, дистилляция, прогнозирующее управление, MPC, система MIMO, оптимизация, надежность.

1. Introduction

The automation of mass transfer processes such as distillation is a key challenge in chemical engineering. Industrial distillation columns are characterized by strong coupling among process variables, nonlinear dynamics, and operational constraints. Classical PID controllers often fail to achieve satisfactory performance under such conditions, especially in MIMO systems.

In contrast, Model Predictive Control (MPC) has gained wide adoption in recent decades due to its ability to handle constraints, predict future trajectories, and optimize control inputs. Several studies highlight the advantages of MPC for complex chemical processes. This study focuses on developing a discrete model for mass transfer processes in distillation columns and applying MPC for performance improvement.

2. Methods and Materials

2.1 Process Modeling The dynamic behavior of a distillation column is represented using state-space equations:

$$x_{(k+1)} = A\,x_k + B\,u_k$$
$$y_k = C\,x_k + D\,u_k \qquad (1)$$

where x_k – vector of state variables, u_k – control inputs, y_k – output variables.

2.2 Control Strategy

The MPC optimization problem is formulated as:

$$\min_u \sum_{i=1}^{N_p} (y_{k+i} - y_{ref})^T Q (y_{k+i} - y_{ref}) + \sum_{i=0}^{N_c-1} \Delta u_{k+i}^T R \Delta u_{k+i} \qquad (2)$$

Objective Function

Here,

- Δu_{k+i}— change in control action between steps,
- R — weighting matrix penalizing rapid changes in control inputs.

This penalty enforces smooth control actions, preventing aggressive or oscillatory inputs.

ISSN 3030-3907

This is the cost function that MPC minimizes at each control step. It consists of two terms:

- Tracking error:

$$(y_{k+i} - y_{ref})^T Q (y_{k+i} - y_{ref}) \quad (3)$$

Here,

- y_{k+i} — predicted system output at step k+i,
- y_{ref} — reference value (setpoint),
- Q — weighting matrix that defines the importance of minimizing the error.

The larger the deviation from the setpoint, the higher the penalty.

Prediction and Control Horizons

- Np— prediction horizon: number of future steps over which MPC predicts process behavior.
- Nc— control horizon: number of steps over which MPC actually optimizes the control inputs (usually Nc<Np).

Constraints Considered in MPC

MPC explicitly incorporates physical and technological constraints:

- State constraints:

$$x_{min} \leq x_{k+i} \leq x_{max} \quad (4)$$

Example: column temperature cannot exceed a certain operating range.

- Input constraints:

$$u_{min} \leq u_{k+i} \leq u_{max} \quad (5)$$

Example: a valve cannot open more than 100%.

- Input rate constraints:

$$\Delta u_{min} \leq \Delta u_{k+i} \leq \Delta u_{max} \quad (6)$$

Example: the cooling water flow cannot be changed too abruptly.

Operating Principle (Receding Horizon)

- At each control step k, an optimization problem is solved.
- This yields an optimal sequence of control actions:

$$\{u_k^*, u_{k+1}^*, \ldots, u_{k+N_c-1}^*\} \quad (7)$$

- In practice, only the first control move u_k^* is applied.
- At the next step, the horizon shifts forward with updated measurements — this is known as the receding horizon principle.

ISSN 3030-3907

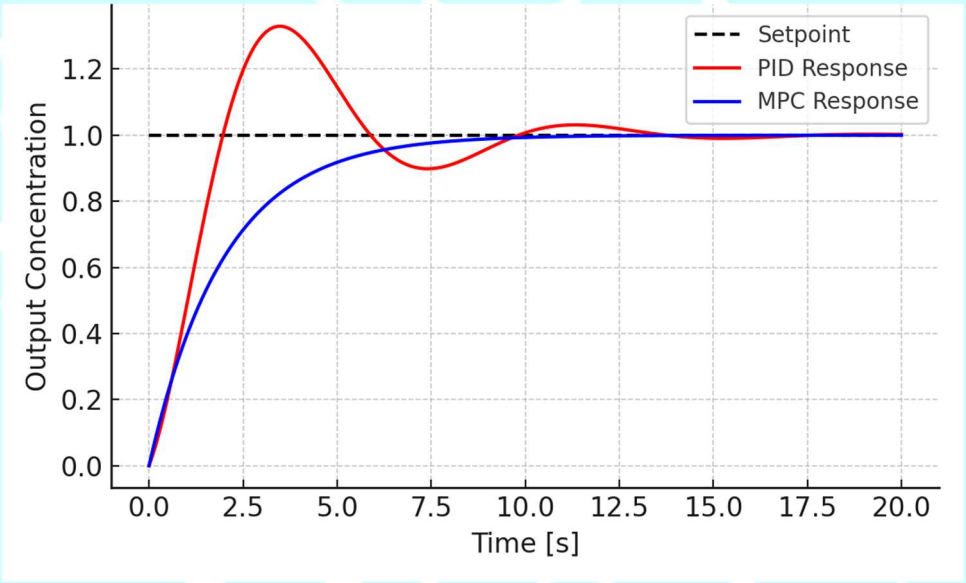


Figure 1. System Output under Step Disturbance

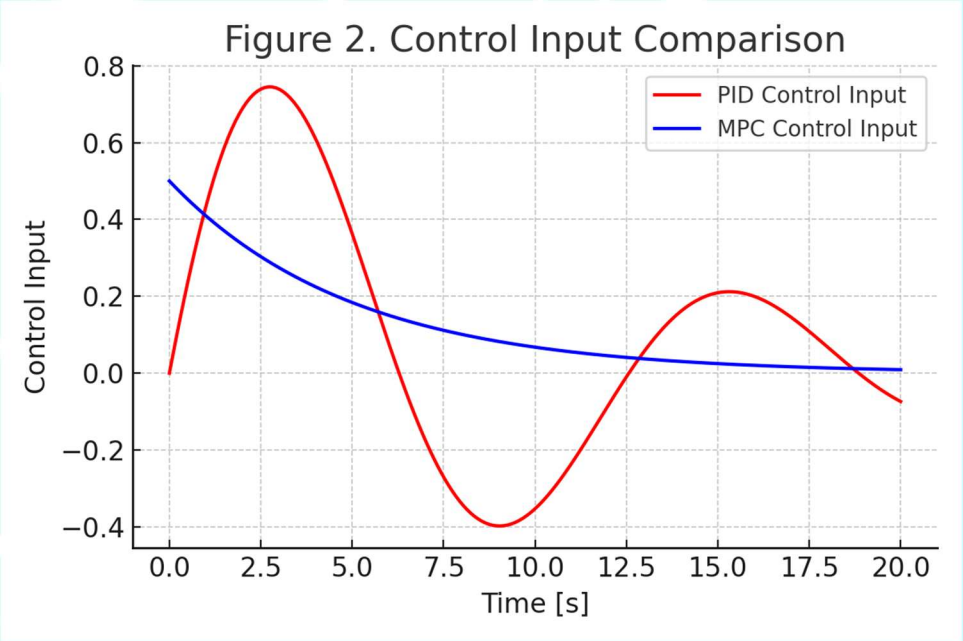


Figure 2. Control Input Comparison

2.3 Simulation Setup

A simplified absorption column with 3 stages was simulated. The control objective was to maintain a desired top product concentration under feed composition disturbances. Simulations compared PID and MPC controllers. Figure 1. System Output under Step Disturbance, figure 2. Control Input Comparison

3. Results

Simulation results show that MPC outperforms PID regulation in terms of tracking accuracy and disturbance rejection.

4. Discussion

The findings confirm that MPC provides significant improvements over PID in managing distillation dynamics:

1. Constraint handling: MPC respects process constraints directly in optimization.

ISSN 3030-3907

2. Energy efficiency: Smooth control actions reduce reflux energy demand.
3. MIMO capability: MPC handles multiple coupled variables simultaneously, unlike independent PID loops.
4. These advantages make MPC a strong candidate for industrial adoption in mass transfer and separation processes.

5. Conclusion

This work demonstrates the development of a discrete state-space model of a distillation process and its application in predictive control. Numerical experiments indicate that MPC significantly improves control accuracy, robustness, and energy efficiency compared to classical PID controllers. Future work will focus on nonlinear MPC and experimental validation on pilot-scale distillation units.

REFERENCES

1. Garcia C. E., Prett D. M., Morari M. Model Predictive Control: Theory and Practice – A Survey. Automatica, 1989.
2. Rawlings J. B., Muske K. R. The Stability of Constrained Receding Horizon Control. IEEE Trans. Autom. Control, 1993.
3. Dworak P., Goyal J., Aggarwal S., Ghosh S. Effective Use of MPC for Dynamic Decoupling of MIMO Systems. Elektronika ir Elektrotechnika, 2019.
4. Wiese A. P., Blom M. J., Manzie C., Brear M. J. Model Reduction and MIMO MPC of Gas Turbine Systems. Control Eng. Practice, 2015.
5. D. P. Mukhitdinov et al 2022 J. Phys.: Conf. Ser. 2373 072025 DOI 10.1088/1742-6596/2373/7/072025
6. Rectification process control by separation process efficiency evaluation using a predictive model. Djalolitdin Mukhitdinov, Yorkin Kadirov, Ildar Sultanov and Yusuf Avazov. EPJ Web Conf., 321 (2025) 01013 DOI: https://doi.org/10.1051/epjconf/202532101013
7. Muhitdinov D., Sultanov I., et al. Current State of Modeling Problems and Management of Rectification Processes. AJET, 2023.

ISSN 3030-3907