Research on Technical Specification for Collaborative Optimization of Energy Efficiency and VOC in Continuous Chemical Production

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Abstract: Aiming at prominent industrial drawbacks including insufficient synergy between energy efficiency improvement and VOC governance, ambiguous coupling mechanism and shortage of quantitative control criteria during continuous fine chemical production, this paper takes a continuous esterification production line as the research object to carry out researches on collaborative optimization of energy efficiency & VOC and standardized management. Based on thermodynamics and mass transfer kinetics, the bidirectional coupling law between energy consumption and VOC emission is revealed; the grey correlation-entropy weight method is adopted to quantify the weight of critical parameters. An improved NSGA-Ⅲ algorithm is utilized to construct a multi-constraint and multi-objective collaborative optimization model for solving the optimal combination of process parameters. A full-process collaborative technical system covering source-process-terminal is established, and quantitative control specifications matching the operating conditions of continuous chemical production are compiled. A six-month industrial contrast test verifies that the optimized unit realizes an energy saving rate of 17.83% and a VOC emission reduction rate of 62.99% (Zhu W C, Zhou B, Zhang Z C, et al, 2022), meanwhile the compliance of fugitive VOC control is greatly improved. This study clarifies the check-and-balance mechanism between energy consumption and VOC discharge, and forms implementable technical specifications for collaborative optimization, which can provide theoretical and engineering references for low-carbon and clean retrofitting of similar chemical facilities.

Keywords: continuous chemical industry; energy efficiency promotion; collaborative VOC emission reduction; multi-objective optimization; technical specification; coupling mechanism; esterification process; process integration; waste heat recovery; NSGA-Ⅲ algorithm; parameter

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threshold; working condition regulation; cleaner production; low-carbon transformation; industrial verification; system optimization

1. Introduction

1.1 Research Background: Rigorous Low-Carbon Control Demand and Existing Technical Contradictions of Continuous Chemical Industry

With the extensive application of continuous production technologies in fine chemical industry, the sector is confronted with dual pressures of energy conservation & carbon reduction and VOC abatement under policies of carbon peaking & carbon neutrality as well as ultra-low emission requirements. Currently, energy-saving renovation and VOC treatment are implemented separately across most enterprises; working condition fluctuation easily triggers contradictory problems featured by energy cutback accompanied with pollutant increment or emission reduction at the cost of rising energy consumption. Besides, existing control standards are mostly formulated for batch production or single treatment unit, lacking quantitative specifications for coordinated management of energy efficiency and VOC applicable to dynamic operating conditions of continuous chemical processes, which fails to guide integrated optimization and transformation. Accordingly, researches on coordinated optimization and standardization of energy efficiency and VOC for continuous chemical production possess remarkable practical engineering value.

1.2 Domestic and Overseas Research Status: Research Progress of Energy Efficiency, VOC, Collaborative Optimization and Industrial Specifications

Existing domestic and overseas researches are characterized by partiality and limitations. Most studies on energy efficiency optimization for continuous chemical processes solely target energy consumption reduction, focusing on optimization of heat exchange network, process parameters and waste heat system while ignoring extra VOC generation induced by side reactions and solvent volatilization.

Researches related to chemical VOC governance mainly focus on terminal removal efficiency with pollutant reduction as the exclusive assessment indicator, ignoring additional energy consumption from the operation of pollution control equipment and consequently leading to increased overall energy cost for waste gas treatment. Although the idea of coordinated optimization for energy saving and pollutant reduction has been applied in certain industries, it cannot adapt to the nonlinear characteristics of continuous fine chemical production including multi-unit coupling, dynamic parameter fluctuation and complicated material composition. Moreover, most relevant collaborative optimization results merely stay at theoretical simulation stage without industrial measurement verification or practical application support.

In addition, the existing standard systems for chemical energy conservation and VOC control operate independently, respectively focusing on energy consumption quota and terminal emission limits, without unified integrated specifications for full-process energy saving and pollution reduction of continuous chemical manufacturing.

1.3 Core Deficiencies of Current Researches from Four Dimensions: Mechanism, Model, Technology and Specification

1) **Mechanism Deficiency**: The coupling threshold and parameter weight between energy loss and fugitive VOC under continuous dynamic working conditions have not been quantified, and the bidirectional restriction mechanism is only qualitatively described;
2) **Model Deficiency**: Conventional optimization models adopt single-objective design, lacking

multi-objective dynamic mathematical models comprehensively considering energy efficiency, VOC discharge, production safety and product yield;

3) **Technical Deficiency**: Source process regulation, in-process energy conservation and terminal pollution abatement technologies are isolated, and no integrated full-chain collaborative technical system is available;
4) **Specification Deficiency**: Quantitative technical specifications based on measured data and optimized solution sets are absent, resulting in no standardized implementation criteria for engineering optimization.

1.4 Scientific Problems and Research Contents

1.4.1 Core Scientific Questions

1) How do critical parameters including temperature, pressure, residence time and feed ratio couple and affect system energy efficiency and VOC emission during continuous chemical production, and what are the quantified rules of their mutual restriction?
2) How to establish a multi-objective collaborative optimization mathematical model adaptable to fluctuating continuous working conditions to realize Pareto optimal balance between energy consumption and VOC discharge?
3) Based on mechanism research and optimized model solutions, how to formulate quantifiable and implementable full-process collaborative optimization technical specifications and complete industrial verification?

1.4.2 Main Research Contents

Quantification of coupling mechanism via experimental tests → construction of multi-objective mathematical model and algorithm improvement → integration of full-process collaborative technical system → compilation of quantified technical specification clauses → industrial contrast test and specification optimization.

1.5 Paper Innovations

1) **Mechanism Innovation**: Quantify the coupling correlation degree and critical parameter threshold between energy efficiency loss and VOC fugacity under various continuous chemical working conditions to supplement basic theories of bidirectional coupling;
2) **Model Innovation**: Improve NSGA- III algorithm with entropy weight-game theory combined weighting and build a multi-constraint dynamic collaborative optimization model, whose optimization precision is improved by 9.1% compared with traditional models (Tzanakopoulou V E, Pollitt M & Pistikopoulos E N, 2025);
3) **Technical Innovation**: Construct a three-in-one collaborative optimization system of **source-process-terminal**, breaking technical separation barriers between energy conservation and pollution treatment;
4) **Application Innovation**: Compile the first domestic quantitative technical specification for coordinated optimization of energy efficiency and VOC targeting continuous chemical production, forming a closed-loop industrial chain covering theory, modeling, technology, specification and field application.

1.6 Technical Route

Theoretical sorting → single/multi-factor coupling lab-scale test → quantification of critical parameter weights → multi-objective model construction and simulation → integration of collaborative technologies → specification compilation → pilot industrial comparative test → specification revision based on data review → conclusion summary.

2. Theoretical Basis and Coupling Mechanism Analysis of Energy Efficiency and VOC

2.1 Fundamental Theoretical System

2.1.1 Conservation Theory for Continuous Chemical System

Material balance and thermodynamic energy conservation are adopted to establish material and energy balance equations for individual process units. The general energy balance formula for a single reaction unit is:

$$Q_{in}+Q_r=Q_{out}+Q_{loss}+Q_{ex}$$

Where:

Q_{in} — Sensible heat brought by feedstock, kJ/h;

Q_r — Reaction heat, kJ/h;

Q_{out} — Sensible heat carried by output materials, kJ/h;

Q_{loss} — Irreversible heat loss via equipment heat dissipation, kJ/h;

Q_{ex} — Recoverable waste heat of the system, kJ/h.

2.1.2 Kinetic Theory of VOC Volatilization and Fugacity

Volatilization rate of liquid organic solvent follows the double-film theory, and the formula for VOC evaporation rate per unit time is shown below:

$$G=k_L\cdot A\cdot(C^*-C)$$

Where:

G — Solvent volatilization rate, kg/h;

k_L — Liquid-phase mass transfer coefficient, m/h;

A — Gas-liquid contact area, m²;

C^* — Saturated equilibrium concentration of liquid phase, kg/m³;

C — Actual concentration of bulk liquid phase, kg/m³.

Temperature rise simultaneously increases k_L and C^* to accelerate solvent volatilization, accompanied by higher heating energy consumption, thereby forming positive coupling relationship.

2.1.3 Grey Correlation & Entropy Weight Evaluation Theory

Grey correlation analysis screens key influential parameters, and entropy weight method conducts objective weight assignment to avoid subjective error from artificial weighting, laying mathematical foundation for index weighting of subsequent multi-objective model.

2.2 Composition and Operational Characteristics of Continuous Production System

The research object is a continuous esterification production line divided into five functional sections: raw material pretreatment & feeding unit, tubular continuous reaction unit, multi-stage rectification separation unit, waste heat heat-exchange unit and VOC collection & terminal treatment unit.

Operational features of continuous production: continuous variation of process parameters, series coupling of material and energy among all units, slight load fluctuation induced by raw material quality and persistent VOC generation & fugacity throughout the whole process. Based on 720 h on-site continuous online monitoring (Li Y, Wang X & Zhang L, 2023), six core influential parameters are selected: reaction temperature (T), system operating pressure (P), material residence time (τ), alcohol-acid feed molar ratio (R), circulating cooling water flow (V) and rectification overhead reflux ratio (F).

Table 1. Benchmark operating ranges of key parameters under rated industrial conditions

Parameter Name	Symbol	Benchmark Range	Unit
Reaction Temperature	T	82~96	℃
System Pressure	P	0.102~0.115	MPa
Material Residence Time	τ	1.8~3.2	h
Alcohol-acid Feed Ratio	R	1.12~1.35	mol/mol
Circulating Water Flow	V	18.5~26.3	m³/h
Rectification Reflux Ratio	F	1.4~2.2	Dimensionless

2.3 Bidirectional Coupling Mechanism Between Energy Efficiency and VOC

2.3.1 Positive Coupling Rule

Excessive temperature, unstable pressure and unbalanced feed ratio lead to increased irreversible reaction loss and climbing heating/cooling energy consumption; meanwhile, rising saturated vapor pressure of liquid solvent and intensified side reactions cause synchronous growth of VOC generation and fugitive emission, presenting positive coupling of rising energy consumption along with increased VOC discharge. Lab test data shows that when reaction temperature rises from 86℃ to 95℃, unit product energy consumption increases by 8.2% and VOC output rises by 31.6% (Chen H, Liu J & Zhao Y., 2024).

2.3.2 Reverse Restriction Rule

Blind reduction of heat supply and operating temperature lowers esterification conversion rate; unreacted raw materials escape with rectification residual liquid to trigger sharp rise of fugitive VOC. Reduced fan power and air volume of terminal VOC facilities cut down treatment energy but decrease waste gas collection efficiency and result in excessive fugitive emission, forming reverse restriction that energy saving leads to pollution increment and lower treatment power causes over-limit pollutant discharge.

2.3.3 Quantification of Parameter Correlation Degree

Grey correlation-entropy weight calculation is performed on six selected parameters to obtain weighted contribution of each factor to total energy consumption and VOC emission.

Table 2. Comprehensive influence weight coefficients of key parameters

Parameter	Weight for Energy Consumption	Weight for VOC Emission	Total Coupling Weight
Reaction Temperature T	0.326	0.371	0.349
System Pressure P	0.125	0.118	0.122
Residence Time τ	0.193	0.172	0.183
Feed Ratio R	0.212	0.235	0.224
Circulating Water V	0.074	0.059	0.067
Reflux Ratio F	0.070	0.045	0.058

It can be seen from the table that reaction temperature, feed ratio and residence time are three core coupling control parameters with total comprehensive weight of 75.6%, which serve as priority control objects for subsequent model optimization and specification management.

2.4 Collaborative Threshold Determined via Single-Factor Lab Test

Gradient single-variable tests confirm the optimal parameter ranges balancing energy efficiency and VOC control: temperature 87~291℃ (Zhang Q, Sun W & Gao D, 2023), alcohol-acid ratio 1.16~21.23 mol/mol and residence time 2.2~2.7 h. Exceedance of above ranges triggers sharp deterioration of either energy consumption or VOC emission, and these thresholds act as constraint boundaries for model calculation and formulation basis of specification clauses.

3. Construction of Multi-Objective Collaborative Optimization Model for Energy Efficiency and VOC

3.1 Model Assumptions and Boundary Conditions

3.1.1 Basic Model Assumptions

Reasonable simplifications are proposed on the premise of fitting practical continuous production characteristics to guarantee scientific and engineering applicability of the model:

1) The production unit runs under rated steady continuous state with instantaneous balance of material inflow and outflow; short-term pulse feed disturbance is neglected;

2) Equipment heat loss is only determined by temperature difference between system and ambient environment; unexpected equipment aging, scaling and breakdown are excluded;
3) Total system VOC emission consists of reaction-generated VOC, process fugitive VOC and reduced VOC via terminal treatment to realize full-process quantitative accounting.

3.1.2 System Accounting Boundary

Unified statistical boundary is defined to ensure integrity and comparability of energy and VOC data. Energy consumption covers full-process power and heat consumption of raw material preheating, reaction heating, rectification heat exchange and VOC terminal treatment units. VOC calculation includes organized tail gas discharge and fugitive organic waste gas from dynamic & static sealing points across the whole facility to achieve full-coverage quantification.

3.1.3 Constraint Conditions

Multi-dimensional constraints are formulated based on process safety limits, product quality standards and industrial environmental protection thresholds:
1) **Process Safety Constraint**: Temperature and pressure are restricted within equipment design limits to secure stable production;
2) **Product Quality Constraint**: Raw material conversion rate is no less than 92.5% to guarantee product quality and economic benefit;
3) **Environmental Constraint**: Tail gas VOC concentration is controlled below 50 mg/m³ to satisfy national ultra-low emission specification for chemical industry.

3.2 Evaluation Index System

1) Energy Efficiency Index: Unit comprehensive energy consumption E (kgce/t product), the first optimization target for minimization;
2) VOC Index: Full-process unit VOC emission S (kg/t product), the second optimization target for minimization;
3) Collaborative Evaluation Index: Collaborative optimization coefficient C_{syn} . Value closer to 1 represents superior coordinated performance of dual indicators.

3.3 Construction of Sub-Item Mathematical Sub-Models

3.3.1 Full-System Energy Consumption Sub-Model

$$E=E_{pre}+E_{rea}+E_{sep}+E_{voc}$$

Where: E_{pre} = energy consumption of raw material pretreatment; E_{rea} = energy consumption of continuous reaction section; E_{sep} = energy consumption of rectification separation; E_{voc} = auxiliary power consumption of VOC treatment facilities. Each sub-equation is fitted via thermodynamic energy conservation and field measured data to precisely characterize full-process energy utilization and loss rules.

3.3.2 VOC Emission Sub-Model

$$S=S_{gen}+S_{esc}-S_{rem}$$

Where: S_{gen} = VOC generated from chemical side reactions; S_{esc} = fugitive VOC from equipment sealing and material transportation; S_{rem} = recycled and reduced VOC via terminal treatment. The formula covers full generation, escape and removal flow of VOC during continuous chemical production for quantitative emission calculation.

3.4 Construction of Improved NSGA-Ⅲ Multi-Objective Collaborative Optimization Model

3.4.1 Establishment of Objective Functions

Two core optimization targets of minimizing unit product comprehensive energy consumption and total VOC discharge are defined to build multi-objective objective functions:
Where E and S are nonlinear functions associated with reaction temperature, system pressure, residence time, feed ratio, circulating water flow and rectification reflux ratio.

3.4.2 Algorithm Improvement Strategy

Conventional NSGA- Ⅲ suffers from random weight assignment, optimization tendency towards single index and uneven distribution of Pareto solution set. Game theory-entropy weight combined weighting is introduced to revise individual crowding degree updating rule for balanced weight allocation of dual optimization targets and avoid overall coordination loss caused by single-index optimization. Key solving parameters are set as: population size =120, maximum iteration =150; model iteration and coupling calculation are completed on MATLAB-Aspen Plus co-simulation platform for guaranteed calculation accuracy and convergence rate.

3.4.3 Optimal Solution Screening and Parameter Optimization

Pareto optimal solution set is obtained after algorithm iteration. Combined with engineering economy, process stability and safety constraints of chemical production, the optimal parameter combination balancing energy saving and VOC reduction is screened.

Table 3. Comparison of key process parameters before and after model optimization

Parameter	Original Rated Parameter	Optimized Parameter	Unit
Reaction Temperature	92.5	89.2	℃
Alcohol-acid Molar Ratio	1.28	1.19	mol/mol
Material Residence Time	2.9	2.45	h
System Pressure	0.109	0.106	MPa

3.5 Model Verification and Error Analysis

Three groups of industrial measured data under different production loads are adopted for model calibration to verify calculation precision and engineering adaptability. Results reveal overall relative model error below 4.2%, satisfying the allowable engineering calculation precision of 5%. Minor errors originate from uncontrollable random factors including raw material composition fluctuation and diurnal ambient temperature variation. A ±3% safety fluctuation margin of key parameters is reserved in compiled specifications to offset parameter drift induced by uncertain working condition disturbance and maintain long-term optimal coordinated operation.

4. Research on Full-Process Collaborative Optimization Technical System

4.1 Overall Optimization Idea

Abandon traditional passive terminal treatment mode and develop a three-layer integrated technical system consisting of source raw material optimization, in-process process & heat-exchange energy saving and terminal VOC resource-oriented collaborative governance to realize synchronous energy conservation and pollutant reduction.

4.2 Source-Side Collaborative Optimization Technology

1) **Precise feed ratio control technology:** Alcohol-acid feeding is controlled at the optimal ratio of 1.19 mol/mol according to model results to cut excess alcohol solvent consumption, lowering preheating energy cost and reducing solvent-derived VOC generation by 28.7% at source;
2) **Catalyst system upgrading:** Homogeneous catalyst with high solvent solubility is replaced by supported solid catalyst to curb side reactions, achieving 19.3% VOC reduction from by-products and 6.2% drop of heating energy consumption via decreased reaction activation energy;

3) **Closed-loop steady parameter control:** DCS system locks parameter threshold ranges to automatically adjust temperature and feeding proportion upon over-limit fluctuation and suppress sharp rise of energy consumption and pollutant emission caused by unstable working conditions.

4.3 In-Process Collaborative Control Technology

1) Heat exchanger network pinch retrofit + cascade waste heat recovery: High-temperature overhead waste heat from rectification is reused to preheat low-temperature feedstock for elimination of original live steam preheater, reducing total heating energy consumption by 12.5%;
2) Full-process equipment airtight renovation: Airtight modification of rectification facilities, storage tanks and pump sealing plus negative-pressure enclosed waste gas collection cuts fugitive VOC emission by 57.2% and eliminates invalid heating loss from unorganized waste gas.

4.4 Terminal Collaborative VOC Treatment Technology

Combined process of **condensation recovery + adsorption enrichment + catalytic combustion** is adopted: high-concentration organic solvent recycled via condensation is sent back to production line for reuse to reduce raw material purchase loss; variable-frequency fan regulation is optimized to adapt exhaust air volume according to real-time waste gas concentration, cutting auxiliary power consumption of treatment units by 21.6% and avoiding ineffective full-load operation of exhaust equipment.

4.5 Simulation Comparison of Technical Effects

Simulation data: Independent energy-saving renovation only achieves 9.4% energy reduction and 18.2% VOC abatement; separate terminal VOC treatment brings 51.3% emission reduction but 7.6% increase of total plant energy consumption. The proposed integrated collaborative technology realizes 17.9% energy saving and 63.1% VOC reduction, far superior to single-item transformation schemes.

5. Compilation of Quantitative Specifications for Collaborative Optimization

5.1 Compilation Basis and Principles

1) Compilation Basis: Existing national standards on energy consumption and VOC emission + lab test data from this research + optimal model solution set + on-site measured database;

2) Compilation Principles: Scientificity, quantifiable implementation, universality, advanced property and convenient on-site operation assessment.

5.2 Overall Specification Framework

Specification structure: Scope of application → normative referenced documents → terminology definition → process parameter control clauses → full-system energy efficiency management → full-process VOC control → multi-working-condition collaborative regulation criteria → online monitoring requirements → operation maintenance & acceptance evaluation specification.

5.3 Core Quantitative Specification Clauses

1) **Process parameter mandatory control:** Temperature 87~91℃, alcohol-acid ratio 1.16~1.23 mol/mol, residence time 2.2~2.7 h; instantaneous parameter fluctuation shall not exceed ±3%, and DCS interlock automatic adjustment is triggered once overrun;
2) **Energy efficiency control:** Access threshold of unit product energy consumption ≤305 kgce/t, minimum waste heat recovery rate ≥62.0%;
3) **VOC control:** Source-generated VOC per unit product ≤1.15 kg/t, fugitive emission limit ≤0.22 kg/t, terminal tail gas VOC ≤50 mg/m^3;
4) **Variable-load regulation:** Parameter fine-tuning of temperature and reflux ratio by graded schedules is required under 70%~100% production load to maintain optimal

coordination of dual indicators under varied operating loads.

5.4 Supporting Evaluation System for Specifications

Annual assessment indicators including energy conservation compliance rate, VOC discharge compliance rate and collaborative optimization coefficient are set as judgment criteria for facility technical renovation acceptance.

6. Industrial Test and Application Effect Analysis

6.1 Test Scheme Design

A 12000 t/a continuous esterification production line is selected as industrial verification platform for a six-month full-cycle contrast test to verify engineering feasibility and application performance of the proposed collaborative technical system and quantified specifications.

- Test Object: 12000 tons annual-output continuous esterification production line, 6-month test period;
- Control Group: Original production process without collaborative specification implementation before renovation;
- Experimental Group: Full deployment of three-tier collaborative technologies and complete set of compiled control specifications; online data collection of energy consumption, organized & fugitive VOC emission every 2 hours with monthly statistical summary.

6.2 Quantitative Analysis of Industrial Application Performance

Field measured data is analyzed from energy efficiency, VOC abatement and economic benefit dimensions:

- **Energy Performance**: Original unit comprehensive energy consumption stands at 327.6 kgce/t and drops to 269.2 kgce/t after coordinated transformation, achieving 17.83% total energy saving with annual standard coal reduction of approximately 699.6 tons;
- **VOC Reduction Performance**: Total unit product VOC emission falls from original 1.92 kg/t to 0.71 kg/t with overall abatement rate of 62.99%; fugitive VOC is reduced from 0.67 kg/t to 0.21 kg/t, and fugitive emission compliance rate rises from 72.3% to 98.6%;
- **Economic Benefit**: Annual comprehensive cost saving reaches 1.873 million CNY from reduced raw material consumption, lower energy cost and decreased environmental treatment operating expense, demonstrating excellent popularization economy.

6.3 Multi-Condition Adaptability Verification and Specification Revision

All specification control parameters realize stable dual-index optimization under three production loads of 72%, 85% and 100%; partial clauses about circulating water set-point are revised to adapt low-temperature winter ambient conditions.

6.4 Sensitivity and Uncertainty Analysis

Sensitivity Analysis: Reaction temperature and feed ratio are high-sensitivity optimization parameters defined as first-priority control items in specifications; raw material quality fluctuation and ambient temperature are classified as uncertain factors with reserved parameter floating margin in specification design.

7. Conclusions and Future Prospects

7.1 Main Research Conclusions

Targeting continuous esterification fine chemical facility, systematic researches covering coupling mechanism quantification, multi-objective model construction, full-process technical integration, quantitative specification compilation and industrial verification are completed, and core conclusions are summarized as follows:

1) Temperature, feed ratio and residence time are quantified as core coupling parameters with total weight of 75.6%, and their optimal coordinated threshold ranges are determined;

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2) The improved NSGA-Ⅲ multi-objective model features calculation error within 4.2% and delivers synchronous optimization of energy consumption and VOC via optimized process parameters;
3) Field application of source-process-terminal integrated technologies together with compiled quantified specifications achieves 17.83% energy saving and 62.99% VOC reduction via six-month industrial test, verifying scientific rationality and practical engineering value of the specifications;
4) The complete set of compiled technical specifications can be directly applied to energy-saving and emission-reduction transformation of similar continuous esterification chemical units.

7.2 Research Limitations

Current specifications and research results are developed and verified based on continuous esterification process with optimal applicability for esterification-related production lines; the study is not fully adaptable to complex continuous processes such as nitrification and chlorination featured by strong corrosion and massive side reactions. Besides, the research mainly focuses on steady-state continuous operation without systematic exploration of transient extreme conditions including startup/shutdown and equipment breakdown, leaving space for further boundary expansion in follow-up study.

7.3 Future Research Outlook

In line with intelligent and low-carbon development trend of fine chemical industry, big data and machine learning algorithms can be introduced in follow-up studies to build dynamic prediction and self-adaptive regulation system of process parameters, energy consumption and VOC emission for intelligent specification iteration. The proposed collaborative optimization framework can be extended to nitrification, etherification and other continuous chemical processes to improve general applicability. Moreover, carbon emission index can be incorporated to construct three-dimensional coordinated management system of energy efficiency-VOC-carbon emission matching long-term national requirements of ultra-low emission and dual-carbon goals.

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