Collaborative Optimization of Dynamic Nitrogen Generation Strategies and Intelligent Fresh-keeping and Deodorization System

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Abstract

Under traditional low-temperature fresh-keeping conditions, household refrigerators often suffer from water loss and nutrient degradation of food ingredients. Existing modified atmosphere fresh-keeping and vacuum technologies lack precise control over oxygen concentration, making it difficult to achieve long-term fresh-keeping. This study proposes a dynamic nitrogen generation strategy based on model predictive control, and optimizes it collaboratively with a high-efficiency deodorization system for intelligent fresh-keeping refrigerators. The system generates nitrogen with a purity of 95% through a miniaturized flat-panel single-tower Pressure Swing Adsorption (PSA) nitrogen generation module, and realizes dynamic control of the target concentration of 85%±2% in the fresh-keeping chamber combined with the sealed design of the chamber. Experiments are conducted in a 25 L fresh-keeping chamber, where the nitrogen concentration reaches the target level within 20 minutes and decayed by approximately 1% within 4 hours. The trimethylamine concentration decreases from 15 ppm to 0.15 ppm with a purification rate of 99%. The total energy consumption of the nitrogen generation module and the deodorization module is 212 Wh within 4 hours, which is 7.83% lower than that of the fixed-cycle nitrogen supplement mode. The results show that the collaborative control of dynamic nitrogen generation and intelligent deodorization can quickly respond to nitrogen fluctuations in the chamber, maintain stable concentration, significantly improve fresh-keeping effect and deodorization efficiency, and optimize energy consumption simultaneously. This study provides a feasible algorithm framework and engineering practice path for cross-system collaborative control in intelligent household appliances, and has reference value for improving the fresh-keeping level of household food ingredients and energy-saving operation.

Keywords

Dynamic nitrogen generation strategy, Intelligent fresh-keeping, Deodorization system, Model predictive control, Nitrogen generation by pressure swing adsorption.

1. Introduction

As a frequently used household electrical appliance, the fresh-keeping capacity of household refrigerators has long been simplified as a temperature control problem [1]. In actual application scenarios, relying solely on low temperature cannot stably maintain the quality of food ingredients. Moisture migration, oxidation reactions and odor accumulation still occur continuously, and some fresh food suffers from obvious weight loss and flavor deterioration under refrigerated conditions [2]. With the increasing attention of consumers to quality fresh-keeping, gas environment regulation has gradually entered the field of home appliance technology. A high-nitrogen and low-oxygen environment has shown advantages in inhibiting the metabolic activity of food ingredients [3]. The Pressure Swing Adsorption (PSA) nitrogen generation technology, which is widely used in ocean-going ships and cold chain warehousing, provides a mature paradigm for this research direction [4]. However, its volume, power consumption and control mode are not directly applicable to household scenarios, and such differences pose practical obstacles to the engineering implementation of modified atmosphere fresh-keeping in refrigerators.

Existing studies have carried out multi-dimensional explorations on refrigerator fresh-keeping. One category of research focuses on temperature and humidity regulation as well as multi-zone temperature control strategies, emphasizing thermodynamic stability and structural design [5]. For example, Guo et al. (2024) proposed a temperature prediction model based on the Long Short-Term Memory (LSTM) network for temperature-controlled containers with phase change material cold storage, which can predict the temperature changes of the fresh-keeping environment using historical data [6]. Another category of research introduces the concept of modified atmosphere, reducing oxygen concentration through external gas supply or passive gas release methods, which delays the spoilage process to a certain extent [7]. Xiao et al. (2024) proposed a high-efficiency heat-driven thermoacoustic refrigeration system using nitrogen and water as working fluids, and integrated a bypass pipe to break through the limitation of traditional systems on heating temperature through acoustic power optimization [8]. Yu et al. (2024) coupled nitrogen precooling with a dual-hydrogen refrigeration cycle to construct a compact liquefaction system. After optimization by genetic algorithm, its specific energy consumption, exergy efficiency and cost-effectiveness were all superior to those of traditional independent systems [9]. In terms of PSA nitrogen generation technology, most studies still focus on the industrial scale, with emphases on the selection of adsorption materials, process switching and optimization of nitrogen generation efficiency, and these achievements have been widely applied in the field of food storage and transportation [10, 11]. Researches for household refrigerators mostly remain at the level of structural miniaturization and functional integration. Nitrogen generation control mostly adopts fixed cycles or empirical parameter settings, and the description of dynamic gas changes in the chamber is relatively rough [12]. In terms of odor control, active adsorption and catalytic decomposition technologies are widely adopted. Reliable data support has been obtained for the purification performance of volatile organic compounds such as trimethylamine [13]. However, such modules usually operate independently and lack a collaborative relationship with fresh-keeping control [14].

Focusing on the practical constraints of modified atmosphere fresh-keeping for household refrigerators, this study conducts research following the idea of migrating industrial-scale PSA nitrogen generation technology to household appliance systems. It reconstructs the twin-tower nitrogen generation structure into a flat-panel single-tower module and establishes a dynamic description model of nitrogen concentration in the fresh-keeping chamber based on real performance data. At the control level, the idea of Model Predictive Control (MPC) is introduced, and the nitrogen concentration maintenance range and system energy consumption are incorporated into a unified optimization framework to realize the dynamic regulation of the nitrogen generation process. Meanwhile, aiming at the common odor problem in fresh food storage, a deodorization system with high-efficiency trimethylamine purification capacity is introduced into collaborative modeling. An integrated control path oriented to fresh-keeping effect, deodorization performance and energy efficiency is constructed. This study attempts to provide a gas environment regulation scheme that is more in line with the actual operation state for intelligent refrigerators, and also offers referable engineering and algorithm ideas for the collaborative control of cross-functional modules in household appliance systems.

2. Methodology

A. Overall System Architecture

The nitrogen fresh-keeping system for household refrigerators adopts a modular design, with the nitrogen generation component, fresh-keeping chamber and deodorization unit being separated yet coordinated with each other. The nitrogen generation module is integrated into a flat box, with functional parts concealed inside. A glass cover on the upper part supports food ingredients and achieves an aesthetic effect. The gas path is directly connected to the fresh-keeping chamber, ensuring the efficient direct delivery of nitrogen to the chamber while reducing noise and energy consumption, as illustrated in Fig. 1. This integration method allows the system to maintain a high-nitrogen environment and provide space for dynamic regulation simultaneously. The nitrogen concentration is maintained within the target range, the growth of microorganisms is inhibited, enzyme activity is reduced, and the retention time of the color and flavor of food ingredients is prolonged.

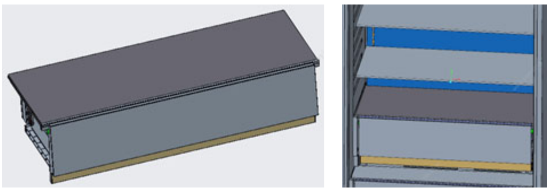

Figure 1. High integration density concealed distributed nitrogen production system

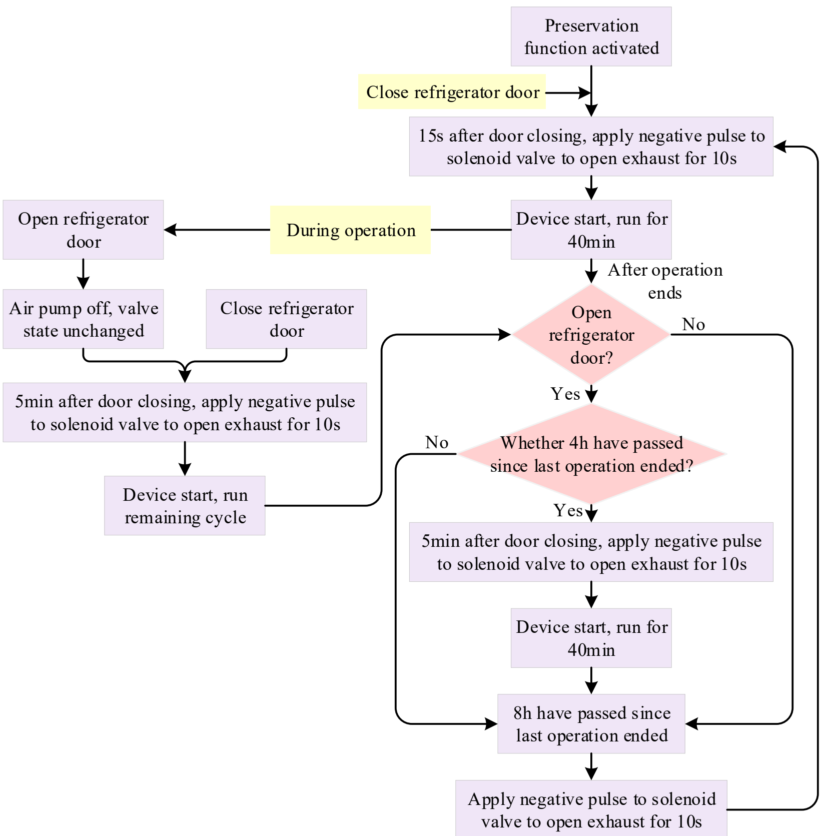

Figure 2. Nitrogen preservation control logic

The control unit takes the nitrogen concentration in the chamber as the core, perceives the internal state of the chamber in real time, and triggers the start or stop of the nitrogen generation module to realize a nitrogen supplement strategy similar to automatic cruise. The deodorization module operates in coordination with the nitrogen generation system, removing volatile odorous substances such as trimethylamine during gas circulation to jointly maintain the stability of the gas state and food quality inside the fresh-keeping chamber. The control logic of nitrogen fresh-keeping is illustrated in Fig. 2:

The sealed structure of the fresh-keeping drawer further ensures the stability of the gas environment, with a slow nitrogen attenuation rate that maintains a high concentration even after several hours, laying a reliable foundation for dynamic control, as illustrated in Fig. 3.

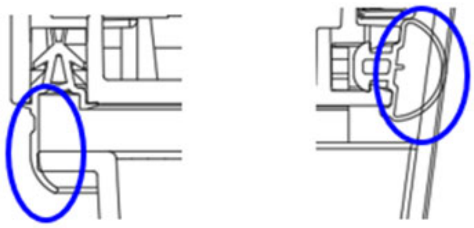

Figure 3. Sealing method of fresh-keeping drawer

Overall, high integration, modularization and collaborative control provide hardware and logical support for the dynamic nitrogen generation strategy and intelligent deodorization optimization, while also enabling the system to strike a balance among fresh-keeping effect, odor control and energy consumption.

B. Miniaturization and Path Optimization of PSA Nitrogen Production System

The internal space of household refrigerators is limited, and industrial nitrogen generation equipment is large in size, heavy in weight and high in power consumption, making direct application impractical. Industrial PSA nitrogen generation generally adopts twin-tower alternating adsorption, which features a large volume, heavy weight and high-power consumption [15]. The household scenario requires the nitrogen generation system to be greatly miniaturized while maintaining the nitrogen-oxygen separation efficiency. To adapt to the refrigerator structure, the nitrogen generation module has been developed with single-tower integration and a transition from a three-dimensional structure to a flat-panel structure. The original twin-tower structure occupying a height of two meters has been transformed into a thin single-tower module, as illustrated in Fig. 4 and Fig. 5.

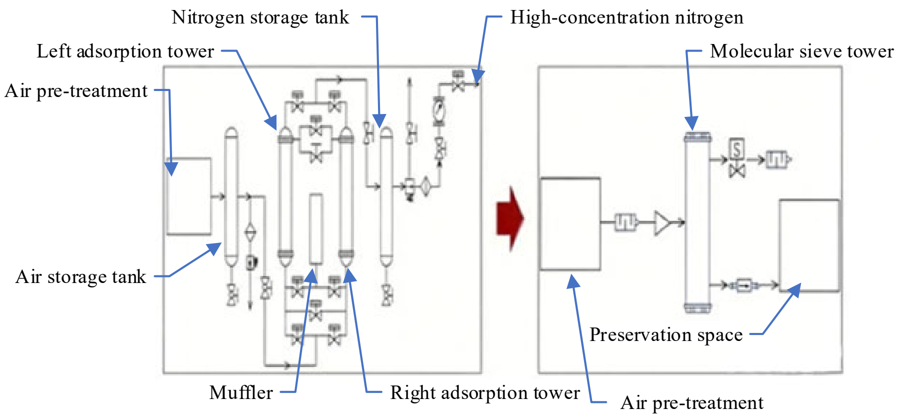

Figure 4. Transformation from twin towers to single tower

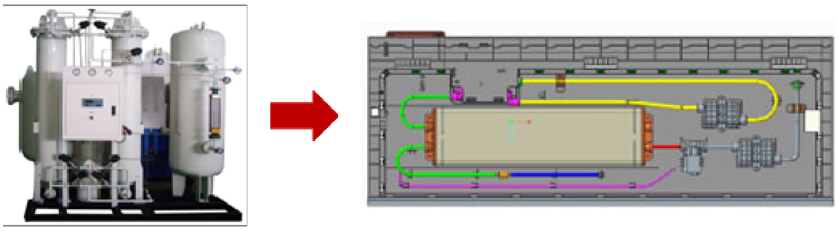

Figure 5. Transformation from three-dimensional nitrogen production to flat nitrogen production

The internal adsorption path has been optimized accordingly, with the pipe diameter reduced from the original 80 mm to 24 mm. This design prolongs the residence time of air in the molecular sieve and improves the adsorption efficiency, and the schematic of the path optimization is illustrated in Fig. 6. With the reduced thickness of the module, it can be directly embedded in the bottom or side space of the refrigerator while maintaining the output of high-purity nitrogen.

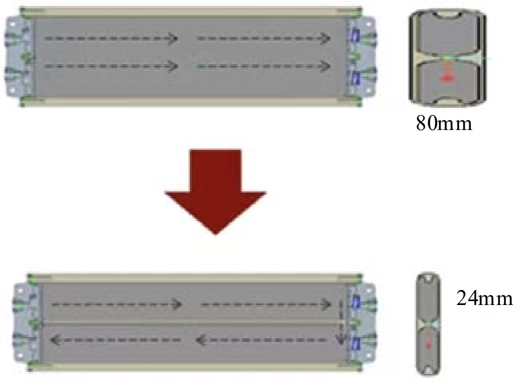

Figure 6. Schematic diagram of single tower path optimization

To ensure the stable performance of the PSA system, the module is equipped with a high-pressure air pump with a maximum output pressure of 3 bar, which provides sufficient power for nitrogen purification. The interior of the single tower adopts an ultra-thin sieve tower and a U-shaped flow-around chamber design, which extends the adsorption path and enables more sufficient contact between air and molecular sieve, thus maintaining the nitrogen-oxygen separation efficiency. To predict the nitrogen concentration in the chamber, a dynamic model can be established by correlating the nitrogen generation system with the volume, flow rate and nitrogen generation concentration of the fresh-keeping chamber:

$$c(t) = C - \frac{V}{Q} \cdot e^{-\frac{Q}{V}(t+C_1)} \tag{1}$$

$$C_1 = -\frac{V}{Q} \ln \frac{Q}{V} (C - C_0) \tag{2}$$

$c(t)$ denotes the nitrogen concentration in the chamber. C the nitrogen generation concentration. Q the nitrogen generation flow rate. V the volume of the fresh-keeping chamber. C_0 the initial nitrogen concentration in the chamber. C_1 the constant determined by nitrogen generation concentration, nitrogen generation flow rate, fresh-keeping chamber volume and other parameters. This model can serve as the foundation for the subsequent dynamic nitrogen generation control strategy, predict the variation trend of nitrogen concentration in the chamber over time, and provide a theoretical basis for the decision-making of the controller.

C. Dynamic Nitrogen Production Strategy Based on Model Predictive Control

The nitrogen concentration in the chamber is not static and fluctuates with nitrogen generation flow rate, chamber leakage and door opening actions. Although fixed-cycle nitrogen supplementation can maintain the average concentration, it responds slowly to transient changes and has suboptimal energy consumption [16]. The dynamic nitrogen generation strategy attempts to adjust the start-stop and operation duration of the nitrogen generation module based on real-time observation of the nitrogen concentration in the chamber to maintain the concentration within the target range of 85%±2%. By predicting the concentration changes in the next several steps, the controller pre-plans the nitrogen generation actions. It keeps the nitrogen concentration in the chamber stable and reduces unnecessary energy consumption simultaneously.

MPC takes the dynamic model of nitrogen concentration in the chamber as the prediction basis. The system state is defined as follows: $x(t) = c(t)$

$$x(t) = c(t) \tag{3}$$

The control input is $u(t)$, which represents the on-off state and flow control of nitrogen production module. The prediction time domain is N steps, and the objective function considers concentration deviation and energy consumption:

$$J = \sum_{k=0}^{N-1}[(c(t+k|t) - c_{ref})^2 + \lambda u(t+k|t)^2] \tag{4}$$

c_{ref} is 85% of the target concentration, and λ is the adjustment coefficient to balance energy consumption and concentration control. The prediction of nitrogen concentration in the cabin is given by the previous dynamic model:

$$c(t+1) = c(t) + \frac{Q}{V}(C - u(t))\Delta t \tag{5}$$

To consider leakage and door opening disturbance more accurately, the nitrogen attenuation in the cabin can be modeled as exponential attenuation:

$$c(t+1) = c(t) \cdot e^{-k_{leak}\Delta t} + \frac{Q}{V}(C - u(t))\Delta t \tag{6}$$

k_{leak} is the leakage coefficient of the cabin, which can be determined according to the measured data of cabin tightness. The control constraints include the minimum time Δt_{min} that the nitrogen making module can be started and the maximum output flow Q_{max}:

$$0 \leq u(t) \leq Q_{max}, t_{on} \geq \Delta t_{min} \tag{7}$$

MPC updates the internal state of the chamber in each sampling period, calculates the optimal control sequence $u(t: t + N - 1)$, executes only the first-step action, and then re-predicts the next period. Such a receding horizon optimization strategy can respond to transient disturbances inside the chamber, such as nitrogen leakage caused by door opening or internal temperature changes, maintaining the nitrogen concentration in the chamber within the target range while reducing energy consumption from repeated operation and waste. The overall control process can be briefly described as follows: the system measures the internal concentration of the chamber, calculates the future concentration trajectory combined with the prediction model, optimizes the control input, executes the nitrogen generation operation and updates the state, and then repeats the cycle. This method balances fresh-keeping effect and energy consumption performance, and provides a highly operable control framework for the dynamic nitrogen generation strategy of intelligent refrigerators.

D. Collaborative Optimization Modeling of Nitrogen Production and Deodorization System

Not only is a stable high-nitrogen environment required in the fresh-keeping chamber, but there also exist volatile odors released by food ingredients, such as trimethylamine, which can affect user experience and the gas balance inside the chamber [17]. The system regards the nitrogen generation and deodorization modules as two mutually coupled subsystems: the nitrogen generation module is responsible for maintaining the nitrogen concentration in the chamber, and the deodorization module treats odors through gas circulation and adsorption. Their collaborative relationship can be described by a joint state equation, and the state vector inside the chamber is defined as follows:

$$x(t) = \begin{bmatrix} c_{N_2}(t) \\ c_{odor}(t) \end{bmatrix} \quad (8)$$

$c_{N_2}(t)$ indicates the nitrogen concentration in the cabin, and $c_{odor}(t)$ indicates the volatile odor concentration in the cabin. The control input vector is:

$$u(t) = \begin{bmatrix} u_{N_2}(t) \\ u_{deodor}(t) \end{bmatrix} \quad (9)$$

$u_{N_2}(t)$ and $u_{deodor}(t)$ respectively correspond to the output flow of nitrogen production module and the processing capacity of deodorization module. State evolution can be described by a discrete-time model:

$$x(t+1) = Ax(t) + Bu(t) \quad (10)$$

Among them, matrix A reflects the natural attenuation and mixing effect of gas in the cabin, and B describes the direct effect of nitrogen production and deodorization on the cabin state. Aiming at the goal of nitrogen concentration and odor level, a multi-objective optimization function can be defined:

$$J = \sum_{k=0}^{N-1}[w_1\left(c_{N_2}^{ref} - c_{N_2}(t+k|t)\right)^2 + w_2 c_{odor}^2(t+k|t) + w_3 u^T(t+k|t)Ru(t+k|t)] \quad (11)$$

$c_{N_2}^{ref}$ is the target nitrogen concentration. w_1, w_2, w_3 are the target weights, and R is the control energy consumption weighting matrix. The optimization problem is solved in rolling time domain, so that the system can reduce the odor concentration in the cabin while ensuring the high nitrogen preservation effect, and minimize energy consumption.

The control strategy generates a collaborative control sequence for nitrogen generation and deodorization by predicting the multi-step future states inside the chamber, executes only the first step of the optimal actions, then re-measures the internal states of the chamber to calculate the next step of control, and repeats the cycle in this manner. This collaborative modeling approach balances the nitrogen concentration and odor level inside the chamber within a single optimization framework, and simultaneously provides a theoretical basis for the joint optimization of the dynamic nitrogen generation strategy and intelligent deodorization.

3. Results and Analysis

A. Nitrogen Concentration Control Performance Analysis

The dynamic control performance of the nitrogen generation module in the fresh-keeping chamber was verified through experiments, with the experimental parameter settings shown in Table I.

Table I. Experimental parameter setting

Parameter	value
Fresh-Keeping Cabin Volume	25 L
Initial Air Concentration	78%
Target Nitrogen Concentration	85%
Modular Gas Concentration	95%
Average Nitrogen Production Flow	1 L/min

The attenuation change of nitrogen concentration within 4 hours is shown in Fig. 7.

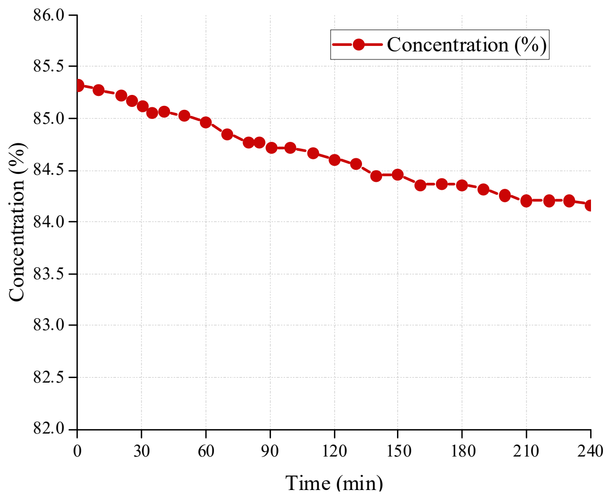

Figure 7. Attenuation change of nitrogen concentration

According to Fig. 7, the nitrogen concentration in the chamber reached 85.2% within 20 minutes of startup. Compared with the fixed intermittent nitrogen supplementation mode (which takes about 40 minutes), the dynamic strategy significantly shortened the filling time. The sealed structure of the fresh-keeping drawer effectively inhibited nitrogen leakage, resulting in a concentration drop of only approximately 1% in the chamber within 4 hours. Long-term stability can be maintained by setting a cyclic nitrogen supplementation every 4 hours. The dynamic control strategy can quickly respond to nitrogen fluctuations in the chamber, maintain a stable concentration, and reduce the number of unnecessary nitrogen generation operations and energy consumption simultaneously. The nitrogen stability in the chamber provides a reliable foundation for the subsequent deodorization system and also ensures the fresh-keeping effect of food ingredients in a high-nitrogen environment.

B. Verification of Deodorization Performance and Fresh-keeping Effect

To verify the deodorization performance and fresh-keeping effect of the system, fish samples prone to releasing volatile odors are placed in a 25 L fresh-keeping chamber, with the nitrogen generation and deodorization modules operating simultaneously. Trimethylamine is taken as the main representative of the odors in the chamber, and a third-party detection instrument is used to measure its concentration changes. The experiment is run for 4 hours, with the trimethylamine concentration, nitrogen concentration and fresh-keeping state of the food ingredients in the chamber recorded. The results are shown in Table II.

Table II. Deodorization performance and fresh-keeping effect

Time (hours)	Nitrogen concentration in cabin (%)	Trimethylamine concentration (ppm)	Trimethylamine purification rate (%)	State of ingredients
0	78	15	0	Fresh
1	84	1	93.3	Fresh
2	85	0.6	96	Fresh
3	85	0.3	98	Fresh
4	85	0.15	99	Fresh

Table II shows that with the collaborative operation of the dynamic nitrogen generation strategy and the deodorization system, the trimethylamine concentration in the chamber decreased rapidly, dropping from 15 ppm to 0.15 ppm within 4 hours. The nitrogen concentration in the chamber was stably maintained at the target level of 85% within the specified range, and no obvious signs of spoilage were observed on the surface of the food ingredients, which remained fresh. The coordinated operation of the dynamic nitrogen generation and deodorization modules can rapidly reduce the odor concentration in the chamber with a remarkable purification effect, while maintaining a high-nitrogen environment inside the chamber to delay food spoilage. The stable nitrogen concentration provides a guarantee for bacteriostasis, the trimethylamine purification rate reaches as high as 99%. The food fresh-keeping effect is excellent. The results indicate that the system can effectively balance the fresh-keeping and deodorization requirements in actual household appliance scenarios, and provide a reliable operation mode for intelligent fresh-keeping refrigerators.

C. System Energy Consumption and Comprehensive Performance Evaluation

The power consumption of the nitrogen generation module and the deodorization module is monitored simultaneously to evaluate the comprehensive energy efficiency of the system. With a 4-hour period as the unit, the cumulative energy consumption per hour is recorded, and the power fluctuations caused by the start-stop frequency under the dynamic nitrogen generation strategy are also taken into account. Fig. 8 shows the energy consumption distribution and efficiency indicators of the system during the 4-hour operation period.

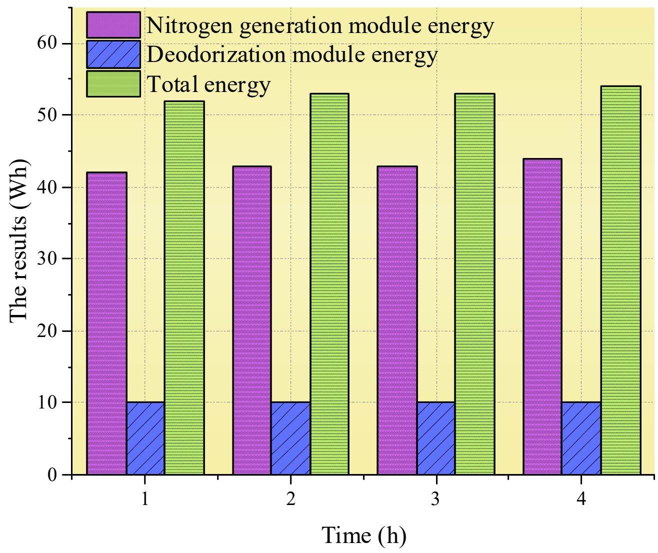

Figure 8. System energy consumption and comprehensive performance

From Fig. 8, the total energy consumption of the system is 212 Wh within 4 hours, with the nitrogen generation module accounting for the major proportion at a cumulative 172 Wh. However, under dynamic control, power utilization is more rational, avoiding continuous full-load operation. The dynamic control strategy can reduce unnecessary continuous operation on the premise of maintaining stable nitrogen concentration in the chamber and high-efficiency deodorization, thus lowering the overall energy consumption.

Comparing the dynamic nitrogen production strategy with the fixed cycle nitrogen supply model, Table III is obtained.

Table III. Comparison between dynamic nitrogen production and fixed cycle nitrogen production

Indicator	Fixed period mode	Dynamic control mode
Average nitrogen concentration in the cabin (%)	84	85
Nitrogen concentration fluctuation range (%)	±5	±2
Final purification rate of trimethylamine (%)	95	99
Total energy consumption of nitrogen production module (Wh/4h)	190	172
Total energy consumption of deodorization module (Wh/4h)	40	40
Total energy consumption (Wh/4h)	230	212

In Table III, after the joint optimization of dynamic nitrogen generation and intelligent deodorization, the stability of nitrogen concentration in the chamber has been significantly improved, the odor purification efficiency is higher, and the total energy consumption is reduced by 7.83%. These results indicate that the proposed strategy achieves a balanced performance in fresh-keeping effect, deodorization capability and energy-saving advantages for the intelligent fresh-keeping system. Overall, the collaborative control of dynamic nitrogen generation and intelligent deodorization enhance the environmental stability and deodorization efficiency inside the chamber, and provide an effective reference for the energy-efficient operation of household refrigerators.

4. Conclusion

This study proposes a collaborative optimization method for a dynamic nitrogen generation strategy and an intelligent fresh-keeping and deodorization system for household refrigerators. Combining a miniaturized flat-panel single-tower PSA nitrogen generation module with a high-efficiency deodorization module, the method achieves dynamic control of nitrogen concentration in the chamber and rapid purification of trimethylamine odors. Experimental results show that the dynamic nitrogen generation strategy can quickly respond to nitrogen fluctuations in the chamber and maintain stable concentration. When combined with the deodorization module, it can effectively reduce the concentration of odors such as trimethylamine, delay food spoilage simultaneously, and ensure that the internal environment of the chamber maintains a high fresh-keeping effect and a clean state throughout the entire operation cycle. In terms of system energy consumption, the collaborative optimization strategy enables more rational operation of the nitrogen generation and deodorization modules, effectively avoids continuous full-load operation, and realizes economical utilization of energy.

During the study, it is found that although the miniaturized single-tower nitrogen generation module can maintain the output of high-purity nitrogen, the nitrogen concentration in the chamber is subject to certain interference when the chamber is opened frequently or different types of food ingredients are stored. The dynamic control still needs to be further improved in terms of response speed and prediction accuracy. In addition, the deodorization module is mainly targeted at volatile nitrogenous organic compounds such as trimethylamine, and its purification effect on fat oxidation or other complex odor substances still needs supplementary verification. The experiment was conducted in a 25 L fresh-keeping chamber, and the differences in the capacity, layout and user usage habits of actual household refrigerators may affect the system performance, which requires testing and parameter optimization under larger-scale and diversified conditions.

Future research can be expanded from both algorithmic and hardware perspectives. Algorithmically, machine learning methods can be integrated to enhance prediction accuracy and realize multi-objective optimization, which comprehensively balances energy consumption, fresh-keeping performance and odor purification efficiency. In terms of hardware, the combination of modularization and flexible layout can be explored to make the nitrogen generation and deodorization modules more adaptable to different refrigerator specifications, while improving the reliability and maintenance convenience of the modules. The cross-system collaborative control method can also be extended to scenarios such as the cold chain transportation of fruits and vegetables and intelligent fresh food lockers, realizing the expansion from single-machine fresh-keeping to intelligent full-process fresh-keeping. Overall, the proposed collaborative optimization strategy for dynamic nitrogen generation and intelligent deodorization provides an effective control framework for household refrigerators and similar fresh-keeping equipment. It has practical application value for improving the fresh-keeping quality of food ingredients and the energy-saving level of equipment.

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