Performance Optimization of Cold Storage Insulation Materials Integrating Artificial Intelligence

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Keywords. Artificial Intelligence, Cold Storage Insulation Materials, Performance Optimization, Temperature.

Abstract: The optimization of energy efficiency of cold storage has always been a key topic in the field of cold chain logistics, especially in the context of energy shortage and increasing environmental pressure, improving the energy efficiency of cold storage and reducing energy consumption is the common goal of most enterprises. to solve the problems of insufficient performance of insulation materials, unstable temperature control and high energy consumption in the traditional cold storage design, this paper proposes an artificial intelligence-based performance optimization model for cold storage insulation materials. The design of this model mainly includes the optimization of heat conduction performance, heat capacity performance, material thickness, sealing performance and dynamic optimization, etc., which aims to comprehensively improve the thermal insulation performance of cold storage and reduce energy consumption. The experimental results show that the heat loss of the cold storage is reduced by 26.7%, the energy efficiency is increased by 16.7%, and the internal temperature fluctuation of the cold storage is reduced by 37.8% based on the performance optimization model of the cold storage integrated with artificial intelligence. In summary, the AI-based optimization model can effectively improve the energy efficiency of cold storage, reduce its energy consumption, and improve the temperature control stability of cold storage.

1 INTRODUCTION

Due to the intensification of the global energy crisis and the increasing severity of greenhouse gas emissions, the optimization of energy efficiency of cold storage, as a major energy consumer, has become a key issue in the field of cold chain logistics (Eberwein, Hajhariri, et al. 2024). The selection and configuration of cold storage insulation materials can directly affect energy efficiency. Traditional cold storage design often fails to take into account the interaction and interaction of multiple factors, resulting in problems such as low energy efficiency and serious cost increases(Jiang, Zhang, et al. 2024). Therefore, based on the selection of insulation materials and the improvement of the rationality of their configuration, the comprehensive optimization of heat conduction and temperature control of cold storage has become a direction of general concern in the industry. In this regard, some researchers have proposed solutions to reduce energy consumption by improving the thermal conductivity of insulation materials (Li, Yang, et al. 2023). Some researchers have also used materials with low thermal conductivity to optimize thermal insulation performance, in order to reduce the heat exchange between the inside and outside of the cold store (Liu, Liu, et al. 2023). Basically, the above methods ignore the role of the thickness of the insulation material and the sealing performance of the cold storage, so it can not achieve a good optimization effect. Some researchers have also proposed to optimize the heat capacity performance of cold storage by adjusting the thickness of the material to reduce temperature fluctuations and improve energy efficiency (Mahajan, Emmanuel, et al. 2023). This method fails to adapt to the thermal insulation needs under dynamic environmental changes, nor does it effectively consider the synergies between different modules (Mahajan, Emmanuel, et al. 2023), to achieve the goal of high efficiency and energy saving. In this paper, a performance optimization model of cold storage insulation materials integrating artificial intelligence is proposed, which is expected to achieve a comprehensive optimization of the performance of cold storage insulation materials, which is conducive to the application of insulation materials in all walks of life. This round mainly expounds the various

Li, D., Li, T., Xiao, D., Jiang, Y. and Li, J.
Performance Optimization of Cold Storage Insulation Materials Integrating Artificial Intelligence.
DOI: 10.5220/0013536300004664

In *Proceedings of the 3rd International Conference on Futuristic Technology (INCOFT 2025) - Volume 1*, pages 109-115
ISBN: 978-989-758-763-4

problems that need to be faced in the optimization process of cold storage insulation materials and combines the research practice of the academic community on the optimization of cold storage insulation materials, and puts forward the research plan of this paper, so as to better pave the way for subsequent research.

2 RELATED WORKS

2.1 Prediction and Optimization of Energy Efficiency of Cold Storage Based on Artificial Intelligence

The energy efficiency of cold storage is closely related to the selection and thickness of insulation materials, but the optimization of energy efficiency of cold storage also involves the operation efficiency of the temperature control system in the cold storage, humidity regulation (Pan, Yuan, et al. 2023), air circulation, etc. The integration of artificial intelligence can be based on real-time data monitoring, using the dynamic changes of the cold storage operating environment to achieve accurate prediction of energy efficiency fluctuations, and put forward accurate energy-saving optimization suggestions for users. In terms of intelligent sensing and data collection, based on the deployment of multiple sensors in the cold storage, including temperature sensors, humidity sensors, airflow sensors, etc. (Sartori, Ornaghi, et al. 2023), the real-time collection of environmental data inside the cold storage is achieved, and at the same time, it is uploaded to the artificial intelligence system for research. The construction of energy efficiency prediction models is also important. It is mainly based on historical operating data and environmental parameters, and uses AI technology to establish an energy efficiency prediction model. For example, an AI model can be used to predict the trend of energy efficiency changes in cold storage in different environments (Zhou, Zhao, et al. 2024). In addition, AI models or systems can automatically adjust the temperature setting and temperature control parameters in the cold storage based on the energy efficiency prediction results, and then optimize the overall energy efficiency of the cold storage to maximize energy savings.

2.2 AI-Assisted Material Design and Innovation

The optimization of traditional cold storage insulation materials is generally affected by the improvement of existing materials, and the introduction of artificial intelligence technology (AI) can promote the innovation of new insulation materials. The AI-generated model will effectively simulate the process by which multiple material combinations affect thermal insulation performance, and then screen for high-performance materials at the laboratory stage. Combined with computer-aided technology and artificial intelligence models (Zotova, Gendelis, et al. 2024), the mechanical properties and thermal properties of different materials can be effectively simulated, so as to design various new insulation materials. Artificial intelligence algorithms can be used to adjust the composition ratio of composites, resulting in better thermal conductivity and lower energy consumption. In addition, AI technology will help people develop intelligent adaptive materials that can automatically adjust their thermal conductivity in response to changes in ambient temperature and effectively improve the energy efficiency of cold storage.

3 RESEARCH ON THE MODEL AND SYSTEM OF COLD STORAGE INSULATION MATERIALS INTEGRATING ARTIFICIAL INTELLIGENCE

3.1 Architecture of Cold Storage Insulation Material System with Artificial Intelligence

The cold storage insulation material system designed in this paper with artificial intelligence mainly includes data acquisition and monitoring, data preprocessing and feature engineering, artificial intelligence optimization model, intelligent decision-making and control, simulation and verification, self-learning and adaptation, energy efficiency evaluation and feedback, etc. The data acquisition and monitoring module is responsible for obtaining various parameters inside and outside the cold storage in real time, including temperature, humidity, airflow, etc., based on sensors and infrared detectors, so as to provide powerful data information for the subsequent decision-making of the system. The data preprocessing module is responsible for completing the original data cleaning work, combined with feature extraction, to improve the data quality. The AI optimization model is used to optimize the configuration of insulation materials and the energy efficiency of cold storage. In addition, the intelligent decision-making module is responsible for adjusting the operating status of the equipment based on the optimization results, so as to ensure the stable operation of the equipment. The simulation module will use CFD simulation techniques and thermodynamic principles to verify the effectiveness of the optimization scheme. The self-learning module can automatically adjust the optimization strategy to respond to changes in the environment based on real-world operational feedback. The energy efficiency evaluation module is responsible for monitoring the operation of the cold store and providing energy efficiency reports. The User Interaction & Visualization module will provide a simple, easy-to-understand graphical interface through which data can be displayed, optimization suggestions, evaluation results, and remote control and fault diagnosis will be supported to help managers make timely decisions.

3.2 Design of Performance Optimization Model of Cold Storage Insulation Materials Integrating Artificial Intelligence

Thermal conductivity optimization is a key design focus of the performance optimization model of cold storage insulation materials. Its goal is to reduce the influence of various factors on its internal temperature by reducing heat, increasing the speed of insulation material transfer, and reducing the external temperature of cold storage, to reduce its energy loss. The performance optimization model of cold storage insulation materials integrated with artificial intelligence will effectively optimize the heat conductivity performance through a number of measures, such as selecting low thermal conductivity materials and adjusting the thickness of insulation materials. Formula for optimizing thermal conductivity, as shown in Eq. (1).

$$Q = E(m) + \frac{1}{abs\left(qd_n - 3\right)} \tag{1}$$

In equation (1), Q the smaller the value of the heat transferred per unit of time, the better the insulation effect of the material, and the higher the energy efficiency. a Represents the thermal conductivity of a material, which is mainly used to measure the ability of a material to conduct heat. A a low value indicates that heat transfer can be effectively prevented and the insulation of the cold room can be improved. b Represents the heat transfer area, which represents the surface area of the insulation material in contact with the external environment, and in general, it is necessary to reduce heat loss by reducing the contact area and using materials with low thermal conductivity. s On behalf of the temperature difference, that is, the temperature difference between the inside and outside of the cold storage, if the temperature difference is larger, the faster the heat transfer, so generally choose materials with better thermal insulation performance and more optimized thickness materials to reduce the heat loss caused by the temperature difference. d Represents the thickness of the insulation material. The thicker the material, the greater the resistance of heat based on the material transfer, which in turn reduces heat loss. When optimizing the design, AI can automatically adjust the thickness of the material based on external temperature differences and insulation needs. This section will allow one to quantify the heat transfer process in the cold room and find the important part of the heat loss. Artificial intelligence can play an important role in this process to optimize the thermal conductivity.

The optimization of heat capacity performance is to reduce temperature fluctuations based on improving the heat capacity of cold storage insulation materials,to reduce the operating burden of refrigeration equipment. By selecting materials with higher specific heat capacity and reasonably distributing materials with different heat capacities, the system can achieve the effect of buffering temperature changes, as shown in equation (2).

$$\omega'_{ij} = \omega_{ij} + \alpha\delta_2 \frac{df_1(E)}{dE} x_i \tag{2}$$

In equation (2), ω'_{ij} is the coefficient of heat change is described, which is used to describe the amount of heat change inside the cold store. If there is a change in temperature, then the heat absorbed and released by the insulation material in the cold storage can be determined by equation (2). α is The lower the value, the smaller the temperature fluctuation inside the cold storage and the higher the energy efficiency. E Represents the mass of the material, if the mass of the material is larger, then the material will have more capacity to store heat, which can better mitigate temperature fluctuations. High-quality materials can absorb more heat during the temperature change process and avoid problems such as excessive fluctuations in the temperature of the cold storage. δ is the specific heat capacity of the material. The specific heat capacity represents the unit mass of the material, the heat absorbed and released when the temperature changes, the δ higher the material, the more heat can be absorbed, and then the impact of temperature changes inside and outside the cold storage on the temperature control system can be slowed down, and at the same time, the number of starts of the refrigeration equipment and the energy consumption are reduced. This step clarifies how cold storage insulation can affect fluctuations in internal temperatures. In the process of practical application, the AI model can adjust the selection of materials based on real-time temperature data to maintain a stable temperature environment in the cold storage.

The thickness of the insulation material directly affects the heat conduction efficiency and overall energy efficiency of the cold storage. In order to ensure the insulation effect and reduce excessive material waste, the thickness optimization method can select the optimal thickness based on the relationship between the optimized material thickness and heat transfer. As shown in Equation (3)

$$w = w_{\max} - \frac{(w_{\max} - w_{\min})t}{t_{\max}} \tag{3}$$

In Eq. (3), w is the t maximum permissible heat transfer, which is the maximum heat loss value that can be accepted by the cold storage system. t is This allows the system to better determine the optimal material thickness and keep the heat transfer rate within a safe and economical range. This step helps managers to maximize the use of insulation materials on the basis of ensuring the temperature control effect of cold storage. By constantly adjusting the thickness of the material, the heat loss can be kept within a reasonable range, thereby reducing the waste and energy loss of the material, and can help people find the most economical thickness configuration by combining the cost and efficiency of the material.

Tightness is one of the important factors in the insulation effect of cold storage, especially at the doors, windows and joints of cold storage. Based on the optimization of the sealing material and heat transfer coefficient, the external heat intrusion of the cold storage can be reduced, and the overall thermal insulation performance of the cold storage can be improved, so the optimization of the sealing performance is extremely important, see Equation (4) for this step.

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{4}$$

In equation (4), x represents the heat loss of the sealing part, which is used to describe the heat loss caused by the heat transfer of the sealing part, the greater the heat loss, the worse the insulation effect of the cold storage, and the lower the energy efficiency. v Represents the heat transfer coefficient of the sealed part. Based on the selection of sealing materials with low thermal conductivity, heat loss will be effectively reduced. Equation (4) shows that under the premise of ensuring the rationality of the design of the sealing part, the artificial intelligence system can operate automatically and effectively, and reduce the heat loss of the cold storage. The artificial intelligence system can automatically monitor the sealing performance, and continuously adjust its optimization strategy based on the monitored situation, and then improve the insulation effect of the sealing part, so that the overall performance of the cold storage can be improved.

The artificial intelligence dynamic optimization module is the focus of the design of the cold storage insulation material performance optimization system, which uses deep learning algorithms, based on real-time monitoring and analysis of multi-directional data, will automatically adjust the configuration of thermal insulation materials in the cold storage, and then improve the energy-saving effect. Artificial intelligence dynamic optimization, see Eq. (5).

$$p_i = f_i / \sum_{i=1}^{s} f_i \tag{5}$$

In equation (5), f_i represents the energy consumption of cold storage, which contains various energy needs such as refrigeration and lighting, ventilation, etc. Based on real-time data and intelligent algorithms, the AI system will adjust the temperature and sensor parameters in the cold storage to maximize the energy efficiency of the cold storage and effectively reduce energy consumption. In this way, the performance optimization system of cold storage insulation materials applied by artificial intelligence technology will adjust the insulation level of materials, sealing strategies, and the operation mode of temperature control equipment based on the temperature data in the cold storage, so as to achieve the goal of maximizing energy saving and emission reduction.

4 RESULTS AND DISCUSSION

4.1 Background of the Application Case of the Performance Optimization System of Cold Storage Insulation Materials Integrating Artificial Intelligence

Enterprise H is a high-quality enterprise specializing in cold chain logistics and cold storage facility construction, which mainly provides practical temperature control solutions for food and medical industries. From 2019 to 2024, the impact of global climate change will increase the number of problems such as energy consumption and energy prices. Enterprises in all walks of life have now realized the importance and urgency of the energy efficiency problem of cold storage, and at the same time, affected, enterprise H is also facing many problems, especially the insufficient performance of insulation materials and excessive energy consumption, which seriously affects the effect of temperature control services for users and threatens the future development of enterprises. Based on this, the company decided to introduce this set of artificial intelligence cold storage insulation material performance optimization system to achieve a high level of performance optimization of insulation materials, and reduce heat loss, energy waste, high cost, poor effect and other problems. Enterprise H hopes that the introduction of the optimization system can provide high-quality solutions for the comprehensive improvement of the thermal insulation effect of cold storage by integrating heat conduction performance and heat capacity performance, material thickness, sealing performance, dynamic optimization, etc. Enterprise H has 30 different sets of cold storage insulation equipment, serving more than 20 countries, more than 100 high-quality enterprises, at present, enterprise H uses this set of cold storage insulation material performance optimization system to carry out cold storage temperature control work. Specifically, the thermal conductivity of the original insulation material of the cold storage is 0.033 W/m·K, the heat loss is 1500W, and the material thickness is 0.15, which seriously affects the quality of the cold storage. The distribution of cold storage insulation equipment of enterprise H is shown in Figure 1.

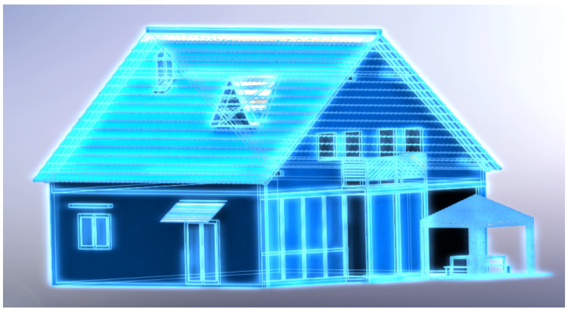

Figure 1: Distribution of cold storage insulation equipment of enterprise H

4.2 Comparative Analysis of Data Such as Heat Conduction Performance Before and After Optimization

After adopting the artificial intelligence cold storage insulation material performance optimization system designed this time, based on the selection of thermal insulation materials with relatively low thermal conductivity and adjusting the thickness of the materials, the heat loss of the cold storage has been reduced, the heat loss of the cold storage before optimization is 1500W, and the heat loss of the cold storage after optimization is 1100W, and the improvement range reaches 26.7, as shown in Table 1.

Table 1: Comparison of before and after optimization of thermal conductivity performance

Parameter medianM(P25，P75)			Kruskal-Wallis test statistic H value
Thermal conductivity（W/m·K）(n=1)	Thickness of the material（m）(n=1)	Heat loss (W) (n=1).	
0.033(0.0,0.0)	0.150(0.1,0.1)	1500.000(1500.0,1500.0)	2.000
0.022(0.0,0.0)	0.120(0.1,0.1)	1100.000(1100.0,1100.0)	2.000
0.333(0.3,0.3)	-0.200(-0.2,-0.2)	0.267(0.3,0.3)	2.000

According to Table 1, the artificial intelligence cold storage insulation material performance optimization system designed this time can adjust the selection and thickness of materials, and improve the thermal conductivity of materials and reduce the impact of external heat on the internal temperature of cold storage. The overall architecture of the artificial intelligence cold storage insulation material performance optimization system designed this time is shown in Figure 2.

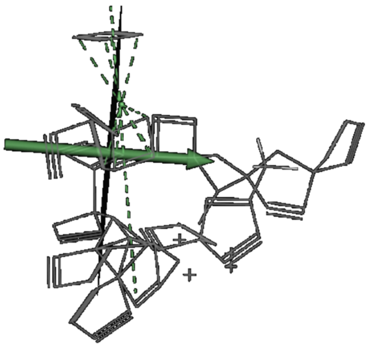

Figure 2: The overall architecture of the performance optimization system for artificial intelligence cold storage insulation materials

Through the performance optimization of artificial intelligence cold storage insulation materials, the specific heat capacity of cold storage materials has increased from 1300 J/kg· K increased to 1700 J/kg· K, an improvement of 30.8%. Moreover, the temperature fluctuation is significantly reduced, from 4.5 K to 2.8 K, an improvement of 37.8%. In terms of energy consumption, the optimization has been reduced from 1200 kWh to 1000 kWh, with an energy saving of 16.7%, as shown in Table 2.

Table 2: Comparison before and after heat capacity performance optimization

Parameters (Median)	Optimize the previous value	Optimized value	Extent of improvement
Specific heat capacity（J/kg· K）(n=1)	1300.000	1700.000	0.308
Temperature fluctuation (K) (n=1).	4.500	2.800	0.378
energy consumption(kWh)(n=1)	1200.000	1000.000	0.167
Kruskal-Wallis test statistic H value	2.000	2.000	2.000
p	0.368	0.368	0.368

* p<0.05 ** p<0.01

According to Table 2, it can be seen that through the application of the performance optimization system of cold storage insulation materials integrating artificial intelligence studied in this paper, the thermal performance of cold storage materials of enterprise H has been improved, its energy consumption has been reduced, and the optimization effect is remarkable. The design focus of this set of artificial intelligence cold storage insulation material performance optimization system is shown in Figure 3.

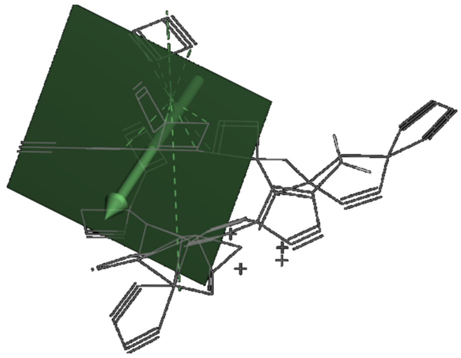

Figure. 3: Design focus of the performance optimization system for artificial intelligence cold storage insulation materials

4.3 Analysis of the Optimization Results of Sealing Performance

The optimization of sealing performance is one of the key points of the application of the performance optimization system of this set of cold storage insulation materials, and the sealing performance of the cold storage materials has been significantly optimized after the application of this optimization system by enterprise H. Among them, the sealing heat loss is reduced from 500W to 350W, a reduction of 30%. The sealing area has been reduced from 12 m² to 10 m², a reduction of 16.7%, and the sealing performance has been greatly improved. In terms of heat transfer coefficient, the coefficient of heat transfer increased from 0.035 W/m²· K to 0.025 W/m²· K, an increase of 28.6%, as shown in Table 3.

Table 3: Comparison of before and after sealing performance optimization

	Parameter median M(P25, P75)			Kruskal-Walli's test statistic H value	p
	Seal heat loss (W) (n=1).	Sealing area (m²) (n=1).	Heat transfer coefficient (W/m²· K) (n=1)		
Optimize the previous value	500.000(500.0, 500.0)	12.000(12.0, 12.0)	0.035(0.0, 0.0)	2.000	0.368
Optimized value	350.000(350.0, 350.0)	10.000(10.0, 10.0)	0.025(0.0, 0.0)	2.000	0.368
Extent of improvement	0.300(0.3,0.3)	-0.167(-0.2,-0.2)	0.286(0.3, 0.3)	2.000	0.368

According to Table 3, based on the improvement of the sealing of the doors and windows of the cold storage and the joints, the overall thermal insulation effect of the cold storage has been significantly improved, and the heat loss has been effectively controlled. Through the analysis of Table I, Table II and Table III, after the introduction of artificial intelligence optimization system, the company's cold storage has achieved many performance improvements. Based on the optimization of the insulation material, the thermal conductivity of the cold storage is increased by 33.3%, and because the thermal conductivity of the insulation material is improved, the intrusion of external heat can be avoided, and the energy loss can be reduced. At the same time, the optimization of the specific heat capacity and sealing performance of the material also increases the specific heat capacity of the cold storage by 30.8%, and greatly improves the sealing performance of the cold storage. In this way, the overall thermal insulation effect of the cold storage has been significantly improved, and the heat loss has been effectively controlled. It can be proved that after using the performance optimization system of cold storage insulation materials integrating artificial intelligence, the temperature control effect of enterprise H has been greatly improved, and it can provide effective temperature control solutions for many enterprise customers.

5 CONCLUSIONS

In this paper, an artificial intelligence-based performance optimization model and integrated system of cold storage insulation materials are designed to achieve a comprehensive optimization of the performance of cold storage insulation materials, and based on this, the temperature control effect of cold storage is improved. It has been proved that artificial intelligence can be fully utilized in the performance optimization of cold storage insulation materials, reduce the energy consumption of cold storage, improve its energy utilization efficiency, and improve the stability of cold storage temperature control. the application of artificial intelligence technology can also help enterprises greatly save material costs and enhance the reliability of cold storage operation. In the future, people can apply the cold storage temperature control technology fused by artificial intelligence to more fields, so as to provide green and efficient cold chain temperature control solutions for more enterprises. Although the research in this paper is as comprehensive as possible, there are still many shortcomings, which need to be further discovered and improved in the future.

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