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Research and Application Progress of Insulation Materials in Cold Chain Logistics

Yuexia Dong[1, *], Xiaofeng Li[2], Di Liu[1], Lihua Zhu[3], Peisi Zhang[2]

[1]Hebei University of Science and Technology, Shijiazhuang, 050018, China
[2]Tianjin Key Laboratory of Refrigeration Technology, Tianjin University of Commerce, Tianjin, 300134, China
[3]Horizon (Tianjin) Energy Technology Co, Tianjin, 300400, China

[*] Corresponding author. E-mail address: d2047109@163.com

Abstract: In cold chain logistics equipment, the role of insulation materials is very important. With the continuous development of cold chain logistics, the requirements for insulation materials are getting higher and higher, and future insulation materials need to be more energy-saving and environmentally friendly. This paper introduces the development of cold chain logistics and the insulation materials commonly used in cold chain logistics, which include extruded polystyrene foam (XPS), polyurethane foam (PU), vacuum insulation panels (VIP), and aerogel materials. The performance of these insulation materials and their applications in cold chain logistics are also summarized. In addition, the future development direction of thermal insulation materials is envisioned to promote the sustainable development of the cold chain logistics industry.

Keywords: Cold chain logistics; Insulation materials; Vacuum insulation panels; Aerogel materials.

1. Introduction

In 2020, the country set a dual carbon target, aiming to peak CO_2 emissions by 2030 and achieve carbon neutrality by 2060 [1]. The proposal of this goal is not only conducive to improving the environment but also promotes the development of energy conservation and emission reduction in China. Currently, cold storage and refrigeration equipment in cold chain logistics consume a large amount of energy, accounting for about 30 % of China's total energy consumption, so it becomes particularly important to reduce the energy consumption of cold chain logistics in the process of carbon peaking and carbon neutrality. To reduce the energy consumption of cold chain logistics, we need to improve the insulation performance of cold chain equipment. When choosing insulation materials, in addition to considering the thermal conductivity of insulation materials, we should also give full consideration to their flame retardancy, stability, safety, and economy. This paper mainly summarizes the research and application status of cold chain logistics and the insulation materials therein and looks forward to the future development of the field.

2. Cold Chain Logistics

Cold chain logistics is a kind of systematic engineering that allows products to always maintain a prescribed low-temperature environment in storage, processing, transportation sales and other links. The main cold storage equipment used are cold storage, refrigerated vehicles, refrigerators, freezers, and so on[2] (as shown in Figure 1). Europe and the United States began to develop cold chain logistics in the 1930s. In comparison, China's cold chain logistics started in the 1950s, which has led to the relative backwardness of cold chain development and the limited scope of its use[3].In 2015, the cold chain transportation rate of meat, aquatic products, fruits and vegetables in foreign countries reached 80 %~90 %, while the cold chain transportation rate of fruits and vegetables in China was only 15 %, and that of meat and aquatic products was 30 % and 40 % respectively. Meanwhile, due to the insufficiency of infrastructure, a large number of products have the phenomenon of cold chain breakage, in which case the food depletion of fruits and vegetables in China reaches 15%, while that of developed countries is only 5%. The Central Document No. 1 of 2018 further proposes that various measures should be taken to develop the construction of cold-chain logistics vigorously. In 2021 the state issued the "14th Five-Year Plan Cold Chain Logistics Development Plan" made an all-round deployment for the high-quality development of cold chain logistics in China, proposing to continue to promote green development and improve cold chain infrastructure [4]. The plan proposes to continue to promote green development and improve cold chain infrastructure.

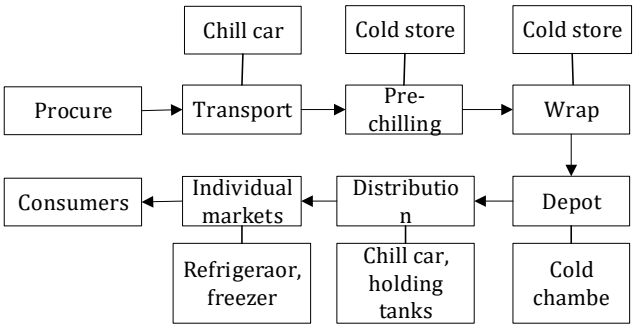

Figure 1. Cold chain logistics transportation diagram

2.1. Pre-chilling

Commodity pre-chilling is an important process, pre-cooled goods can better extend the freshness of time, but also reduce the energy consumption of the cold storage, increase the service life of the cold storage, and reduce the operating costs of the cold storage. General comprehensive cold storage, in addition to the main body of the cold storage as a cold storage, but also equipped with pre-cooling equipment, if the goods are not pre-cooling treatment, will lead to temperature

fluctuations in the original items in the cold storage, thus causing damage to the product. [5] [6] If the goods are not pre-cooled, it will lead to temperature fluctuation of the original items in the cold storage, thus causing damage to the products. Pre-cooling process of energy consumption is large, and the effective use of insulation materials can reduce the energy loss and temperature fluctuations in the pre-cooling process. [7] The effective use of insulation materials can reduce energy loss and temperature fluctuations in the pre-cooling process. Lin Qing et al. [8] In the pre-cooling and transportation process, respectively, the use of thermal insulation bubble film and fiber insulation cotton as thermal insulation materials, through simulation experiments concluded that the fiber material insulation performance is good, the thermal conductivity of 0.0304 W /(m·K), suitable for sugar-cored apples as a pre-chilling and transportation of thermal insulation materials.

2.2. Storage

2.2.1. Cold storage

Cold storage is a kind of warehouse with appropriate temperature and humidity, which can extend the storage time of products [9]. Since 2015, the annual growth rate of the national public-type food cold storage capacity has always remained between 10 % and 20 %, and by 2022, China's cold storage capacity will reach 83.65 million tons, with a year-on-year growth rate of 11.56 % [10].

With the increase in cold storage capacity, energy consumption in the process of cold storage operation has become a non-negligible problem, and it is necessary to adopt reasonable and effective energy-saving measures to reduce the energy consumption of cold storage. In recent years, researchers have proposed the application of cold storage technology and heat preservation materials to reduce the energy consumption of cold storage. [2][11] Zhao et al.[12] prepared a kind of high-efficiency phase change thermal insulation material and applied it to cold storage, and the results showed that the longest time for vaccines to keep cold from 2 ℃ to 8 ℃ in cold storage was about 52.36 h, and the average time for keeping cold was 46.04 h. Zhang et al [13] designed an ultra-low-temperature cold storage using polyurethane +vacuum insulation board as the insulation material. Theoretical calculations showed that the leakage heat loss of the wall surface of the cold storage was only 239.4 W, which had a good heat preservation effect.

2.2.2. Refrigerator

A refrigerator is an end device in cold chain logistics to ensure that food is kept in a low-temperature preservation environment during storage, and refrigerators consume large amounts of energy when in use. To implement the carbon neutral policy and realize energy saving and environmental protection in the field of refrigerators, China has set higher requirements for the energy efficiency standards of refrigerators, as shown in Table 1, and the energy consumption of the new level 1 refrigerator is 40 % lower than that of the old level 1 refrigerator. The improvement of the energy efficiency class standard depends largely on the performance improvement of the insulation material [14]. In 2019, the "Chinese domestic refrigerator industry technology roadmap" is proposed to focus on the research and development of refrigerator insulation materials, in the vacuum insulation board product performance improvement, the target thermal conductivity of 0.0015 W/(m-K) to be achieved in 2025. At present, the domestic low-end refrigerator insulation layer is mainly selected polyurethane foam, and vacuum insulation panel (VIP) is mainly used for energy efficiency, volume rate and price are relatively high in the high-end refrigerator [15] Vacuum insulation panel (VIP) is mainly used in high-end refrigerators with relatively high energy efficiency, volume rate and price.

Table 1. Grade energy efficiency index of new and old standard refrigerators ηs

Energy efficiency grade	GB 12021.2-2015	GB 12021.2-2008
1	$\eta_s \leq 25\%$	$\eta_s \leq 40\%$
2	$25\% \leq \eta_s \leq 35\%$	$40\% \leq \eta_s \leq 50\%$
3	$35\% \leq \eta_s \leq 50\%$	$50\% \leq \eta_s \leq 60\%$
4	$50\% \leq \eta_s \leq 60\%$	$60\% \leq \eta_s \leq 70\%$
5	$60\% \leq \eta_s \leq 70\%$	$70\% \leq \eta_s \leq 80\%$

2.3. Distribution

2.3.1. Refrigerated trucks

A refrigerated truck is a kind of vehicle specially used for the transportation of refrigerated goods, the compartment heat insulation performance directly affects the effect of cold storage, the use of poorly insulated compartments in refrigerated trucks will not only increase the energy consumption of refrigerated trucks, but also increase the temperature fluctuations within the compartment, so it is necessary to apply high-performance heat preservation materials to reduce energy consumption and temperature fluctuations [16]. Therefore, it is necessary to apply high-performance insulation materials to reduce energy consumption and temperature fluctuations. Lou et al [17] used numerical simulation to study the change of temperature field inside the refrigerator compartment using a vacuum insulation board and concluded that the overall heat dissipation of the refrigerator truck using high-performance insulation materials is 56.1 % of that of an ordinary refrigerator truck. Li Jun et al[18] used the vacuum insulation panel structure to make the refrigerated compartment. The temperature of the tuyere was set to-5 °C, and the heat flux density of the compartment with VIP coverage of different materials is shown in Table 2. When the VIP coverage is 0 (all using PU as insulation material), the maximum temperature in the compartment reaches 6 °C, and the regional temperature difference is 10 °C.When the VIP coverage is 87 %, the temperature in the compartment tends to be stable, the maximum regional temperature difference is 6 °C, and most of the temperature in the compartment is lower than -1 °C.

Table 2. Heat flux density of the wall of the box with different VIP coverage

VIP coverage/%	0 (full polyurethane)	48	57	66	74	87
Heat flow density ($W \cdot m^{-2}$)	10.68	9.68	9.26	8.87	8.31	7.31

2.3.2. Cold chain holding tanks

Cold chain heat preservation box is a kind of equipment dedicated to keep cold storage or frozen state in the process of cold chain logistics[19] , It has the characteristics of simple structure, flexible and easy to use, good thermal insulation, low production and maintenance cost, energy saving and environmental protection. Since there is no refrigeration system in the incubator, the key to its thermal insulation effect is the selection of thermal insulation materials.Pan et al[20] through simulation to study the thermal insulation performance of three different materials (XPS, PU, VIP) of the insulation box, the results show that for the three materials of the insulation box, the use of VIP insulation performance is the best, EPU and XPS thermal conductivity of the insulation box is 6.5 times and 9.0 times, respectively, of the VIP insulation box, and the VIP insulation box inside the various regions of the lowest temperature.

3. Insulation Materials

3.1. Extruded polystyrene (XPS)

Extruded polystyrene (XPS) is a kind of rigid foam plastic which is extruded by heating with polystyrene resin as the main component and adding a small amount of additives. XPS has the characteristics of low water absorption, strong compression resistance and low thermal conductivity.At low temperatures, the thermal conductivity of XPS decreases, the heat preservation performance is improved, and the thermal conductivity at -25 °C is 0.023 W/(m·K) [21] [22]. The thermal conductivity of XPS is 0.023 W/(m·K) at -25 ℃, but XPS has the problems of poor fireproofing performance, a large amount of smoke, easy to fall off, and difficult construction, etc. Wang et al[23] to improve the problem that XPS is easy to fall off and not easy to construct, XPS was modified by UV curing adhesive, and the results showed that the adhesive strength of XPS was increased to 0.21 Mpa after modification [24]. It was found that XPS could be modified by adding graphite, and the flame retardancy of XPS after modification was improved to B1 grade, and the thermal conductivity at room temperature was less than 0.026 W/(m·K).

3.2. Polyurethane materials (PU)

Polyurethane (PU) is generally a copolymer synthesized from thermoplastic polyisocyanate plastics and hydroxyl compounds by high-temperature heating polymerization crosslinking foaming [25] Compared with XPS, PU has a good thermal insulation effect, convenient construction, and excellent waterproof performance, see Table 3.

However, the combustibility of polyurethane restricts its application, and researchers at home and abroad have done a series of studies on the flame retardancy of PU, Han et al [27] the flame-retardant polyether polyol, flame-retardant polyester polyol, catalyst, blowing agent and hydrolysis-resistant flame retardant agent were used to prepare high flame-retardant and low-smoke sprayed rigid polyurethane thermal insulation material (RPUF), and the results showed that the flame retardant property of RPUF was excellent, and the oxygen index reached 30.3%. He Yun [28] the addition of phosphorus-containing modified polyether polyol, melamine, and ammonium polyphosphate in the preparation of rigid polyurethane achieved a phosphorus-nitrogen synergistic flame retardant effect, in which the vertical combustion rating of polyurethane materials could reach V-0. Gong et al[29] prepared a rigid polyurethane foam and a reactive hyperbranched flame retardant polyol (DOPO-MASi) containing three flame retardant elements, P, N, and Si to obtain a vegetable oil-based flame retardant RPUF with a multi-flame retardant system, which has excellent flame retardant properties with a vertical combustion energy level of V-0.

Table 3. Performance comparison between PU and XPS [26]

Performances	Polyurethane materials	Extruded polystyrene foam plastic board
Thermal conductivity W/(m·K) (25 °C)	≦0.024	≦0.028
Overall thermal insulation waterproof	fine	General
Slits between insulation boards	Nil	There are plate joints (transverse joints, vertical joints, plane high and low joints).
Special-shaped wall construction	Excellent	Construction difficulties
Chemical stability	Goodliness	General
Service temperature ℃	Long-term: -30~90 Short-term: 90 to 250	≦75 (Softens at 75 °C and melts at 90 ~ 100 °C.)

3.3. Vacuum insulation panels (VIP)

Vacuum insulation panel (VIP) is a kind of thermal insulation material, mainly composed of core material, absorbent, barrier film (as shown in Figure 2). It has excellent thermal insulation performance, in the case of achieving the same thermal insulation effect, the thickness of the use of VIP is one-tenth of other thermal insulation materials [30]. The current research on VIP is mainly to optimize the structure, select the appropriate core material to reduce the thermal conductivity of VIP, and extend the use of VIP time [31]. The current research on VIP is mainly to optimize the structure, choose suitable core material to reduce the thermal conductivity of VIP, and extend the service time of VIP. Shouxian Li et al [32] a structurally stable composite fiber mat vacuum insulation panel was prepared by using nano-silica and glass fiber composites as the core material, and the thermal conductivity was measured to be between 0.0046 and 0.0059 W/(m·K). Mao et al[33]established a theoretical model to study the effect of barrier film on vacuum insulation panels, and the results showed that the vacuum insulation panels with AF barrier film could keep the thermal conductivity lower than 0.008 W/(m·K) within 100 years.

Kan et al [34] showed that the thermal conductivity of vacuum insulation panels was as low as 0.0017 W/(m·K) at humidity levels from 30 %RH to 50 %RH and that the use time of the panels could reach 15 years at 50 %RH, and the larger the size of the vacuum insulation panels, the smaller the thermal conductivity.

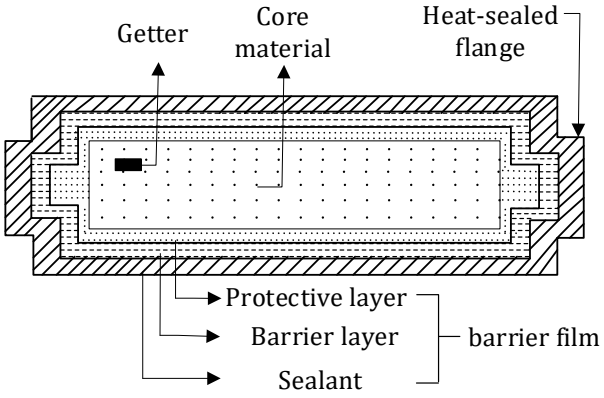

Figure 2. Structure diagram of VIPs

Existing problems with vacuum insulation panels are their high cost and the thermal bridging effect that occurs when they are used. Regarding the cost issue, Lorenzati et al [35] found that the reduced thickness of buildings using VIP panels saves space and can generate economic benefits to offset the higher investment costs. The thermal bridging effect is caused by the uneven heat transfer due to the excessive difference in thermal conductivity between the barrier film and the core material. Researchers at home and abroad have conducted a lot of studies to minimize thermal bridging .Yue Bai et al [36] confirmed that the linear thermal bridge affects the thermal conductivity of VIP, and found that the thermal bridge effect is not only related to the structure of VIP, but also related to the distance between the seams of the boards and the filler by deriving the formula of the linear thermal bridge, so the VIP boards of large sizes are chosen as much as possible to reduce the thermal bridge effect.liang et al [37] found that different barrier films have different effects on thermal bridging, metallized polymer barrier film (MF)produces less thermal bridging than aluminum polyester composite film (AF), in order to reduce the thermal bridging effect, as far as possible to take the thermal conductivity of the barrier film is small.

3.4. Aerogel

Aerogel materials are characterized by low thermal conductivity, low density, high porosity, good insulating properties, and large specific surface area[38] The thermal conductivity of aerogel material is between 0.013-0.038 W/(m·K) in the case of low temperature, and the thermal insulation performance is more excellent. In addition to being used as thermal insulation materials in pipelines, buildings, refrigerators, and thermal insulation boxes, aerogel can also be used in aerospace and catalytic adsorption and other fields.

Traditional thermal insulation materials are subject to water intrusion during use, resulting in poor insulation performance and shortened service life. Aerogel materials have waterproof properties due to their unique hydrophobicity, but they have the problems of high cost and brittleness, low compressive strength, and cannot be used alone. It has been found that its compressive properties can be improved, cost reduced and service life increased by modifying it. Rodan et al [39] Carbon fiber silica (CF/SiO_2) aerogel was prepared by atmospheric pressure drying with carbon fiber as the reinforcing phase, and the results showed that the compressive strength of CF/SiO2 aerogel reached 1.225 MPa at 60% strain, which is about twice the compressive strength of ordinary glass fiber silica aerogel. Liu et al [40] a silica aerogel material prepared from fly ash with a low thermal conductivity of 0.023 W/(m·K) and a superhydrophobic surface with a hydrophobicity angle of 146°, which resulted in stable performance and reduced preparation cost. Yan et al[41]used silica aerogel and expanded perlite to prepare a low-cost composite aerogel with stable mechanical properties, low thermal conductivity of 0.0212 W/(m·K), high porosity, and superhydrophobicity.

4. Application of Insulation Materials in Cold Chain Logistics

4.1. Application of Extruded Polystyrene in Cold Chain Logistics

Research has concluded that XPS is an ideal material for use in cold chain insulation projects. Using XPS in cold storage or holding tanks can increase the cold storage time of the equipment and keep the performance of the equipment stable[42].The use of XPS in cold storage or holding tanks can increase the cold storage time of the equipment and keep its performance stable. Bu Qinghao Bu[43]XPS was used as an insulation material in civil engineering cold storage and assembly cold storage. The results showed that the longitudinal connection of the cold storage using XPS boards was tight and did not run cold, the fire protection grade reached B1, and the energy consumption of the cold storage was reduced by 25-30 % compared with the traditional thermal insulation system. Song Hai et al[44] Developed a quick-frozen fresh corn insulation box, through the hotline method to study the PU, XPS insulation box insulation performance, the results show that at 23℃ the 40 mm thick XPS insulation box insulation effect is the best, keep cold time can reach 36 h or more.

4.2. Application of polyurethane materials in cold chain logistics

Polyurethane materials in rigid polyurethane foam are often used as thermal insulation materials in cold chain transportation and can play a thermal insulation effect, the use of the form of polyurethane sandwich insulation board and polyurethane foam on-site respectively [45] [46]. The use forms are polyurethane sandwich panels and polyurethane on-site foaming. Rigid polyurethane sandwich panels can be built in different sizes of cold storage, in the application more suitable as a cold storage wall and roof. To improve the insulation performance and reduce the construction cost of large-scale cold storage, polyurethane on-site foaming is mostly used. Gong et al [47] found that polyurethane sandwich panels used in cold storage have a simple construction process, do not need to do a moisture-proof layer, and have a shorter construction period. Zhi Lin et al [48] Optimized the traditional cold storage insulation structure, mainly using a polyurethane sandwich panel and polyurethane on-site filling (as shown in Figure 3), this structure can reduce the waste of materials, reducing the operation of the danger and fire hazard, and in the case of the insulation, the effect remains unchanged more beautiful. Wang et al [49] invented an insulation structure used in cold

storage, using pillars to install two iron plates on the cold storage wall, spraying polyurethane between the two plates, and utilizing the polyurethane's adhesion to bond closely with the plates, this structure makes the B1 grade flame retardant layer in the density does not become the case of the foam's resistance to compression increased by a factor of one.

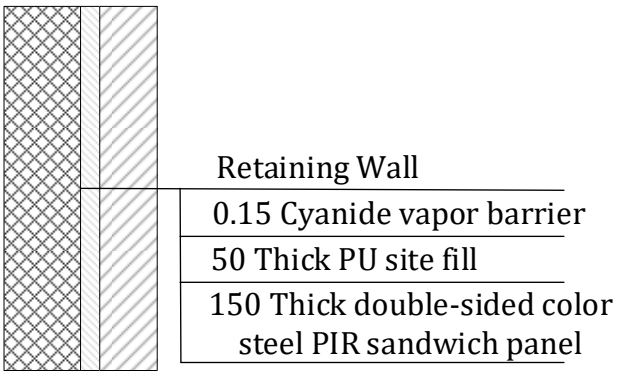

Figure 3. Typical nodes of cold storage insulation structure [48]

4.3. Application of vacuum insulation panels in cold chain logistics

Due to the double characteristics of energy saving and environmental protection, vacuum insulation panels are gradually used in cold chain logistics as thermal insulation materials, firstly in the refrigerator freezers[50].The first application is in refrigerator freezer. The cost of using VIP as insulation layer is relatively high compared with that of PU insulation layer, but the an insulation performance can be increased by about 50 %, and the volume rate can be increased by about 20 %, which has a high overall price-performance ratio. The study shows that the thickness of the insulation layer can be reduced from 8.5 cm to 3.5 cm and the effective volume of the refrigerator can be increased to 260 L by using the vacuum insulation panel on the refrigerator with the original volume of 242 L. The study also shows that the thickness of the insulation layer can be reduced from 8.5 cm to 3.5 cm.

In recent years, VIP boards have been used more often in insulated boxes, Pan Xinyi et al. [51] Constructed three different materials of the thermal insulation box, in which the use of VIP has the best heat barrier performance and the lowest temperature in all areas inside the VIP thermal insulation box. Enli Lv et al [52] Designed a cold storage heat preservation box with a vacuum insulation board as the insulation material, and verified by modeling and experiments, the heat preservation box maintained 0~8 ℃ for 106.14 h at a room temperature of 33.5 ℃. Kan et al[53] constructed three cold chain thermal insulation boxes to simulate the freshness of the goods (shown in Fig. 4), and through simulation, the attenuation factor of the VIP structure is 2.09, and the attenuation factor of the PU structure is 1.72, and the larger the attenuation factor is, the better the thermal stability and the better the insulation performance of the thermal insulation box is, so the thermal insulation box using the VIP board has a better thermal insulation effect.

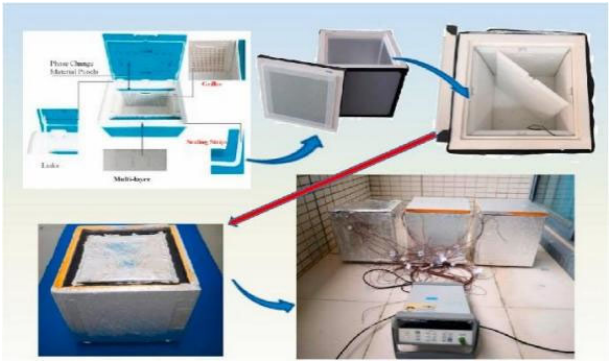

Figure 4. Cold chain chamber incubator in VIPs[53]

4.4. Application of aerogel materials in cold chain logistics

In cold chain logistics, organic materials such as PU and XPS have excellent heat insulation effects, but there are problems of non-environmental protection and poor flame retardant performance. As a new type of heat insulation material, aerogel material has the characteristics of good flame retardant performance, low thermal conductivity ,and strong waterproof ability, and the use of aerogel material to replace traditional material as heat insulation material of low -temperature cold chains can take into account both environmental protection and heat preservation [54] [55]. Luo et al [56] used glass fiber and washed cotton were composite with a silica aerogel composite system to obtain two kinds of composite materials, through the experimental study of two kinds of composite materials performance to meet the use of refrigerator requirements, and compared with the traditional polyurethane foam board, aerogel composite materials of the cold preservation effect is more superior, see table 4. Liu et al [57] in the insulation of ultra-low temperature refrigerators using aerogel, polyurethane foam formed composite materials, the use of composite materials of the refrigerator in the box when the average temperature reaches -93 ℃, the average cooling rate of the air inside the box 4.75 ℃ /h, able to meet the conditions of biological storage. Ren et al [58] the use of aerogel glass to produce refrigerated car compartments, the experimental results show that the average thickness of the compartment plate using aerogel materials can be reduced by 10-15 mm, and the volume of the compartment can be increased by a maximum of 2 m^2 .

Table 4. Comparison of refrigerator insulation panels [56]

Material	Traditional refrigerator polyurethane insulation board	Glass fiber gel composite materia	Washed cotton aerogel composite material	Vacuum foaming polyurethane insulation board	Vacuum Insulatio-n Panel
Thermal conductivity W/(m·k)	0.03~0.037	0.02375	0.02518	0.0187	0.0047~0.0070
Mechanical property	Meet the mechanical property requirements of refrigerator case				

5. Conclusion

It is one of the research hotspots in the field of cold chain logistics to select suitable high thermal insulation materials on cold storage equipment. XPS, PU, VIP, aerogel and other materials have their own characteristics, and there are differences in preparation and performance. Although PU materials and XPS materials are widely used in cold storage and refrigerators, their physical properties and thermal insulation properties still have room for improvement. In contrast, VIP and aerogel materials have better thermal insulation properties than PU and XPS, and the two materials are environmentally friendly. The use is relatively stable, but the problems of poor mechanical properties and high cost limit their application. Therefore, in the future, it is necessary to continuously strengthen the research on thermal insulation materials, improve the production process and improve the thermal insulation materials.

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