Research Progress of Thermal Insulation Materials Used in Spacesuits

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Abstract

At present, multi-layer thermal insulation components are the most ideal materials for thermal insulation in high vacuum environments such as low earth orbit and the lunar surface, but further improvements are needed to improve the activity performance of spacesuits and the ability to adapt to the space environment. Fibrous materials have traditional advantages in spacesuit thermal insulation applications, but they fail to meet the thermal insulation goal of combining thermal conductivity and material thickness in deep space exploration for low vacuum environment represented by the mars mission. Aerogel materials have low thermal conductivity and good thermal insulation performance in low vacuum environment, but they cannot avoid dust pollution and mechanical durability problems on the surface of mars or the moon. The combination of fiber materials with appropriate scales and special void structures and organic aerogel materials with flexible and durable characteristics will become the main way to solve the thermal insulation problem of advanced spacesuits in the future. Therefore, this paper reviews the design requirements and related research of spacesuit thermal insulation materials based on the development status at home and abroad.

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1. Introduction

Spacesuits are important equipment to ensure the survival of astronauts in outer space, and are generally divided into intra-vehicular activity (IVA) spacesuits and extra-vehicular activity (EVA) spacesuits from practical purposes.¹⁻³ In the face of ultra-low temperature, strong radiation and high vacuum space environment, the design of extravehicular spacesuit is particularly important.⁴⁻⁵ According to the different space environment, the corresponding thermal environment is the main driving factor for the design of the thermal control system of the EVA spacesuits, which determines the design of the passive thermal control system in thermal protection, such as the selection of thermal insulation materials, infrared and solar radiation protection materials.⁶⁻⁷ At the same time, it also affects the design of the active thermal control system of the spacesuits, such as the sublimator, radiator, liquid cooling system, and the metabolic consumption of the crew during the extravehicular mission.⁸⁻⁹ As an important issue in the spacesuit thermal control system, the purpose of thermal insulation design is to make the inside of the spacesuit relatively isolated from the external environment from the point of view of heat transfer, so as to reduce the large amount of heat gain and heat dissipation caused by a variety of radiation heat sources and extreme temperature alternating environments in space.¹⁰⁻¹¹ If insulation is lacking, heat flow into or out of the suit from the outer space environment will increase significantly. Therefore, in order to maintain the body heat balance of astronauts, it is necessary to increase the design and research of the active thermal control system of spacesuits.¹¹⁻¹²

In future space missions, spacesuit insulation materials are required to have more comprehensive functions and better durability. Through continuous technical research, it is found
that a variety of non-woven materials, fiber materials, porous fabrics, aerogel composites, etc., are potential materials for advanced spacesuits to improve the heat insulation ability.5,12,13

With the development of international manned space missions and future manned moon landing programs, it is necessary to master the research status and development direction of spacesuit insulation material. This paper analyzes the design requirements of advanced spacesuit thermal insulation materials, sorts out the development direction of advanced spacesuit thermal insulation materials, and provides ideas for further research.

2. Thermal insulation technology requirements of spacesuits
In low earth orbit, radiation is the main form of heat transfer.14 According to the characteristics of this thermal environment, multi-layer insulation is widely used in the passive thermal protection system of satellites, spacecraft, space stations and launch vehicles.13,16 This type of insulation component is usually composed of alternating high reflectivity reflective screens and low thermal conductivity spacer layers, which utilize the layer by layer reflection of the screen surface to form a high thermal resistance to radiation heat.17 In addition, a reasonable and effective exhaust design forms a vacuum layer, effectively avoiding the conduction and convective heat transfer of interlayer gases, making the insulation component have good insulation performance in vacuum environments.19 Insulating components can isolate the internal temperature environment of spacecraft from the rapidly changing external thermal environment, ensuring that astronauts and instrument equipment work normally within the specified temperature range. In addition, multi-layer insulation materials are also widely used for insulation of low-temperature storage tanks and protection and insulation of re-entry aircraft.19

In addition, spacesuits should not only help astronauts achieve thermal insulation, but also enable them to wear them for physical activities (Fig. 1), therefore, materials that are too bulky are not suitable.20,21 Due to the consideration of clothing flexibility, a thick spacesuit will hinder astronauts from achieving limb movements in outer space, while a thin spacesuit may lead to reduced insulation performance. Therefore, we need to be cautious when choosing materials for spacesuits.

The demand for insulation materials varies in different thermal environments. In addition to experiments, it is also necessary to test the performance of insulation materials through practice. The temperature of the environment on the moon and mars is significantly different from that on earth, as both are in extreme environments of high and low temperatures. Therefore, the insulation materials applicable to these two planets are vastly different. We also need to make choices about aviation materials with different adaptability in these two different environments. The environmental temperature on the surface of the moon is extremely low, and its temperature between day and night is also different.22,23 Under the influence of solar radiation, the cold and hot temperature environments on the lunar surface can be described as rapidly alternating. Therefore, on the moon, we need spacesuits with thermal control systems to achieve a stable and suitable internal environment. For mars, its surface temperature changes have a seasonal cycle, with temperatures ranging from -83 °C to -33 °C in summer and stabilizing at -123 °C in winter.24 Therefore, it is necessary to maintain a relatively stable and suitable temperature environment through an effective thermal control system for spacesuits.

Compared to low earth orbit space, the lunar surface has special environmental conditions such as strong space radiation, high vacuum, low gravity, and extreme high and low temperature fluctuations.25 Although the temperature changes in the Martian environment with a thin atmosphere are relatively mild compared to the lunar environment, special protection is required at relatively low temperatures. In addition, the stardust environment on the planet's surface can also adversely affect the insulation material on the outer layer of the spacesuit.26 The Apollo lunar landing experience has shown that the adsorption of lunar dust on the clothing surface is difficult to remove, leading to changes in the thermal radiation performance of the contaminated insulation material surface.27 At the same time, the infiltration of lunar dust and the wear and tear on the material can also exacerbate the degradation of insulation material performance.28

3. Classification of thermal insulation materials for spacesuits
3.1 Fiber insulation materials
Fiber materials are classic low thermal conductive materials, which often have good thermal insulation performance in clothing cold and warm applications.29,30 At the same time, fiber materials have been widely used due to the diversity of
fiber structure, wide selection range of fiber materials, maturity of fiber industry technology, and research experience in fiber insulation applications.\textsuperscript{31,32}

The Nomex aramid nonwoven fabric was first studied in the application of advanced aerospace suit insulation materials.\textsuperscript{33} Due to factors such as the thermal conductivity of its substrate, the dielectric properties of fiber voids, and the internal structure of fibers, this fabric has a low thermal conductivity.\textsuperscript{34} The test results show that the thermal conductivity of Nomex can reach 15.7 mW/(m·K) in a Martian atmospheric pressure environment. However, this test only targets a single Nomex material and did not integrate it into thermal and microfluidic protective clothing, nor did it simulate the temperature environment on the Martian surface. This stage mainly explores the relationship between the thermal conductivity of fiber materials and different gas environments and gas pressures. The results show that the effective thermal conductivity of the material decreases with the decrease of gas pressure.\textsuperscript{35}

3.1.1 Polymer nanofibers

Polymer nanofibers have high porosity and good mechanical properties, making them widely used in the field of thermal insulation materials.\textsuperscript{36-38} Wu et al.\textsuperscript{39} successfully synthesized flexible aerogel composites with a size of 12 cm diameter and a low thermal conductivity via electrospinning and sol-gel processing. Three electrospun polyvinylidene fluoride (PVDF) webs with different microstructures (e.g., nanofibers, microparticles, and combined nanofibers and microparticles) were fabricated by regulating electrospinning parameters. The as-electrospun PVDF webs with various microstructures were impregnated into the silica sol to synthesize the PVDF/SiO\textsubscript{2} composites followed by solvent exchange, surface modification, and drying at ambient atmosphere. The morphologies of the PVDF/SiO\textsubscript{2} aerogel composites were characterized and the thermal and mechanical properties were measured. The effects of electrospun PVDF on the thermal and mechanical properties of the aerogel composites were evaluated. The aerogel composites reinforced with electrospun PVDF nanofibers showed intact monolith, improved strength, and perfect flexibility and hydrophobicity. Moreover, the aerogel composites reinforced with the electrospun PVDF nanofibers had the lowest thermal conductivity (0.028 W·m\textsuperscript{-1}·K\textsuperscript{-1}). It indicates that the electrospun PVDF nanofibers could greatly improve the mechanical strength and flexibility of the SiO\textsubscript{2} aerogels while maintaining a lower thermal conductivity, which provides increasing potential for thermal insulation applications.

Datsyuk et al.\textsuperscript{40} easily produced high-performance nanofiber-based insulation materials from recycled expanded polystyrene (EPS) by means of electrospinning. Nanofiber-based insulation materials from the recycled EPS show thermal conductivity values of 20 to 25 W·m\textsuperscript{-1}·K\textsuperscript{-1} (i.e., 20% to 30% below the thermal conductivity of the commercial EPS) (Fig. 2). The effect of integrating polystyrene nanofiber sheets into conventional wall-building materials is also investigated in terms of thermal insulation.

3.1.2 Carbon nanofiber

Carbon nanofibers have the advantages of large specific surface area, high porosity, good chemical stability, and high specific strength, and have broad application prospects in fields such as electronics, energy, and aerospace.\textsuperscript{41-43} Zhang et al.\textsuperscript{44} design a novel ultra-light graphene/carbon nanofibers/carbon nanotube aerogels (GCNAs) with excellent thermal insulating and hot oil adsorption ability. The results show the density of GCNAs is below 3.2 mg/cm\textsuperscript{3} and present a stable porous morphology at 300 °C. Notably, the GCNAs shows high adsorption ratio (> 27300%) toward hot engine oil (200 °C). The obtained GCNAs possess ultralight property, excellent hot oil adsorption performance, reusability and recoverability, matching well with the requirements for treating the hot oil spills pollution and presenting potential applications in fuel leakage and oil-flowing fire on aircrafts.

Wang et al.\textsuperscript{45} investigated and compared thermal properties of carbon nanofibers enhanced lightweight cementitious composite (CNF-LCC) with normal weight concrete (NWC) and lightweight aggregate concrete (LWAC). As a structural lightweight concrete, from Fig. 3, CNF-LCC showed the potential for fire resistance due to its good thermal insulation properties and low thermal strain under high temperature.

3.1.3 Ceramic nanofibers

Ceramic materials have the advantages of high temperature resistance, corrosion resistance, good insulation, etc., and have a wide range of applications in high temperature heat insulation, sound absorption, catalysis and other fields.\textsuperscript{46-48}
However, most of the existing ceramic nanofibers have high brittleness and poor mechanical properties, bending resistance and other defects, which limit its practical use value.\[49,50\]

Peng et al.\[51\] fabricated a yttria-stabilized zirconia mixed silica nanofibrous membrane (YSZ/SiO$_2$ NFM) by the electrospinning method. The lower density (12–35 mg/cm$^3$) and low thermal conductivity (0.0287–0.0469 W·m$^{-1}$·K$^{-1}$) maintained the thermal insulation properties (Fig. 4). The author anticipated that these excellent properties of YSZ/SiO$_2$ NFMs to have a wide range of technical impacts in the areas of high-temperature insulation, fire insulation, high-temperature filtration, flexible electronics, and energy. It also provided a general strategy for the further design and development of other high-temperature flexible, collapsible and wearable soft oxide nanofiber membranes.

Zhang et al.\[52\] have designed and prepared multi-phase SiZrOC (SiOxCy, SiO$_2$, ZrO$_2$, ZrSiO$_4$ and C) nanofiber (NF) according to the intrinsic factors of these phases with lower heat transfer effects (significant phonon scattering and infrared shielding) that contributes to the high-temperature thermal insulation performance in ceramic fibers. As shown in Fig. 5, the SiZrOC NFs displayed unique combination of remarkable properties, including high flexibility, excellent thermal stability (up to 1400 °C) and low thermal conductivity (~0.043 W·m$^{-1}$·K$^{-1}$ at 25 °C and ~0.233 W·m$^{-1}$·K$^{-1}$ at 1400 °C in Ar). The ultralow thermal conductivity is benefited from the reasonably designed multi-phase microstructure, which enhanced the phonon transfer barrier and effectively decreased the infrared radiation heat transfer. The excellent thermal stability is likely attributed to the formation of thermal stable Si-O-Zr structure.

### 3.2 Aerogel materials

At present, the most common aerogel material used in spacesuits is inorganic silicon aerogel.\[36,53,54\] Silica aerogel is a highly porous network of loosely connected small silica particles in the order of 1 to 10 nm in diameter.\[55\] The size of the pores is in the order of 20 nm. The pores or void space of the aerogel make up 90% or more of its volume. The density of the aerogel composites is in part determined by the pore size of the structure.\[56\] By reducing the pore size, the thermal conductivity of the aerogel could be reduced significantly, especially in a low vacuum environment.\[57\]

Zheng et al.\[58\] report the design and fabrication of robust flexible hybrid silica nanofiber (SNF)–SA membranes with super-insulating properties and improved mechanical properties by formation of an interpenetrating network of mesoporous silica within a flexible SNF scaffold. The hybrid SNF/SA membranes were obtained by impregnating electrospun SNF membranes with silica sol, then aging, solvent exchanging, surface modification, and drying at ambient atmosphere. The resultant highly porous (>90%) hybrid SNF/SA membranes exhibit meso- and macroporosity with average pore diameter less than free path of air molecules,
improved mechanical strength (224% increase in tensile strength), good flexibility (stiffness < 337.6 mN), hydrophobicity (water contact angle > 144.2°), while maintaining low thermal conductivity (0.021 W·m⁻¹·K⁻¹ under ambient conditions) (Fig. 6). Such a robust hybrid membrane with remarkable integrated performance will have great potential in special thermal management applications under harsh conditions, such as the aerospace field.

The main defects of aerogel synthetic fabric are its brittleness, dustiness, mechanical durability and packaging integration. The silica aerogel material is easy to break and come out from the fiber reinforced matrix after repeated use and treatment. In order to overcome the above shortcomings of silicon aerogels, various polymer aerogels have been prepared and studied abroad in recent years, such as phenolic, polyurethane, polyurea, polyimide aerogels, etc. Among them, research institutions represented by National Aeronautics and Space Administration (NASA) carried out systematic research on polyimide aerogel materials, and successfully developed polyimide aerogel products with excellent flame retardancy, insulation, high temperature resistance, thermal insulation and flexibility.
conductivity of this material at room temperature is $14 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, the density is equivalent to that of silicon aerogel, and it has higher modulus, and can form film like products.

4. Conclusions and perspectives
In the field of thermal protection for aerospace suits, although a series of important achievements and breakthroughs have been made in the research and application of insulation materials, there are still many challenges to be faced. The current difficulties and possible future development directions mainly focus on the following aspects:

(1) The insulation scheme based on multi-layer insulation structure is the result of long-term practice in the insulation design of orbital based spacesuits, and has also been successfully applied to Apollo lunar landing practice. In the lunar extravehicular activities, to ensure sufficient insulation performance, the use of thick multi-layer insulation structures in local areas will affect the efficiency of clothing activities. Therefore, in the future, it is necessary to continuously optimize its composition and structure to make it lighter, softer, and reduce obstacles to activities.

(2) Fiber materials have significant advantages in traditional insulation applications. A large number of experimental studies have been conducted on fiber materials for the development of advanced spacesuits abroad. Although most fiber porous insulation materials currently cannot meet the insulation goals required in Martian thermal environments, they can still be used as potential alternative materials. Non-woven fiber fabrics exhibit relatively excellent performance. The structural characteristics of fibers and their constituent fabrics play an important role in the heat transfer characteristics of materials. It is necessary to consider adjusting material structural parameters to control material voids and further improve their insulation performance. At the same time, with the development of material synthesis technology, it is necessary to explore new types of fibers with excellent insulation performance, and develop fiber materials with smaller fineness and higher void volume percentage structural characteristics, such as nanofiber materials.

(3) Compared with other thermal insulation materials, aerogel materials can better meet the thermal insulation performance requirements of spacesuits under high vacuum and low vacuum. Especially in low vacuum environments such as Mars exploration, aerogel based composites are currently the best materials for thermal insulation. Therefore, the aerogel thermal insulation technology has a good application prospect,
but its usability needs to be verified by the experimental test results of material mechanical properties, fatigue properties, etc. In the future, research on flexible aerogel based thermal insulation materials should focus on three aspects: on the basis of existing aerogel materials, solve the problems of integration of materials and spacesuits and dust sealing of materials. According to the local use characteristics of spacesuits, the appropriate aerogel based composite is selected; Seek other aerogels with good mechanical stability that can eliminate existing dust problems. Recent studies have shown that polyimide aerogels have good mechanical properties and have certain advantages in the thermal insulation application of future spacesuits, but their actual use performance needs further evaluation.

(4) For future multi planet exploration, the new generation of spacesuits should have good protective performance and efficient mobility, while also possessing lightweight, safe, and reliable characteristics. This poses more complex and systematic requirements for the insulation design of spacesuits; on the one hand, the protective performance and activity efficiency of spacesuits should be balanced; On the other hand, it is necessary to have strong comprehensive protective capabilities at the same time. For example, micro meteors and radiation protection during orbit exit, star dust protection during lunar and Mars exploration, and mechanical protection such as cutting and piercing when in contact with objects. Therefore, a single protective material is difficult to meet the requirements. It is necessary to explore a combination application scheme of different materials, give full play to the advantages of fiber materials such as firmness, durability, stability in space environment and low thermal conductivity of aerogel materials. To compensate for the defects of different materials and develop flexible protective structures suitable for future advanced spacesuits.

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Conflict of Interest
There is no conflict of interest.

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