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REVIEW

Research trends of the application of aerogel materials in clothing

Ying Du[1,2] and Hee-Eun Kim[1*]

*Correspondence:
hekim@knu.ac.kr

[1] Department of Clothing & Textiles, College of Human Ecology, Kyungpook National University, 80 Daehak-ro, Buk-gu, Daegu 41566, South Korea
[2] Dept. of Fashion Design, Shandong University of Art & Design, Daxue Road, Changing District, Jinan 250307, Shandong Province, China

Abstract

This study investigated the application research of aerogel materials in clothing and analyzed the current research focus on aerogel clothing, the details of the development of aerogel materials, and the evaluation of the application effects of aerogel in clothing. Current research mainly focuses on the application of aerogel in firefighting clothing, space suits, wetsuits, and footwear products. The aerogel materials used in surveyed studies can be classified into aerogel fiber composite, aerogel foam composite, and aerogel coating fabric. Aerogel fiber composite is the most widely used aerogel material in the clothing industry. The thermal performance, mechanical properties, and comfort performance of aerogel clothing have been qualitatively discussed. This survey revealed that aerogel positively affects thermal performance of clothing. In addition, the mechanical properties such as the durability and strength of aerogel materials can meet the application requirements of clothing. However, the dust contamination hazard of aerogel particles limits the further application of aerogels in clothing. In addition, the experimental evaluation of the comfort performance of aerogel clothing through human- and manikin-wearing experiments is insufficient. The findings of this study reveal that it is essential to conduct further studies on the comfort performance of aerogel clothing to determine whether aerogel can have widespread application in clothing. Lastly, we provide suggestions on directions for future studies on the application of aerogels in clothing.

Keywords: Aerogel clothing, Aerogel material, Research trends, Application of aerogel, Application effect

Introduction

Aerogel was first reported in a paper submitted to Nature by Kistler (1931) as a low-density, porous solid gel derived from gel. Aerogel can be synthesized from a variety of organic and inorganic substances, such as silicon oxide, titanium oxide, aluminum oxide, and carbon (Venkataraman et al., 2016). Silica aerogel is a typical type of aerogel. It has drawn a lot of interest both in science and technology due to its low bulk density (up to 95% of its volume is air), hydrophobicity, low thermal conductivity, high surface area, and optical transparency (Gurav et al., 2010). This low-density lightweight structure has very good thermal insulation properties (Tang et al., 2006). However, from the viewpoint of applications, aerogels have the drawbacks of absorbing moisture from the atmosphere, being fragile, being difficult to handle, and being impossible to use to insulate complex shaped bodies (Katti et al., 2006). To make them flexible for wider applications, aerogels are usually used after being composited with other materials. However, while this improves the overall performance, the original performance of the aerogel will inevitably be weakened due to it mixing with other materials.

Aerogel blanket is a typical aerogel composite material. It is flexible, drapable, and is formed by depositing aerogel particles into fibrous substrates. Aerogel blanket has attracted attention in the clothing industry due to its unique properties, such as fire resistance, water resistance, heat resistance, and flexibility. Consequently, researchers have investigated the application of aerogel blanket in protective clothing used in thermal hazardous environments, such as high-heat, flame, electrical arc discharge, molten substance, and firefighting environments (Chakraborty et al., 2016). In addition, its application in winter clothing and footwear used in cold environments, such as alpine and polar regions, has been investigated. Du and Kim (2019) conducted market research on the application of aerogels in daily clothing and found that the application of aerogel blanket in daily clothing is becoming active and specialized.

However, the easy detachment and dispersion of aerogel particles attached to non-woven materials into the air have limited the further application of aerogel blanket. To address this problem, aerogel blanket is encapsulated before use; however, this negatively affects the flexibility and breathability of the material.

To address these problems, researchers are devoting efforts to develop new composites of aerogel and polymer materials. For example, NASA's Glenn Research Center developed polyimide aerogels, which exhibit approximately 500 times more compressive and tensile strength than silica aerogel and equivalent insulation ability. Polyimide aerogels are thin films with promising properties, such as high flexibility, light weight, and porosity (NASA's Technology Transfer Program, 2015). However, there are currently no studies on the application of this material to clothing. Another study employed a method known as "aerogel-infused closed cell polyfoam" to develop a composite material of aerogel and polymer. The researchers applied for a patent for this material under the name of SOLARCORE, claiming that it exhibits superior insulation properties to existing insulation materials and addresses the dispersion problem of aerogel particles in air. Particularly, they emphasized that the material exhibits good flexibility and breathability and enables direct cutting and sewing (Shiwanov, 2016).

However, despite several attempts, the application of aerogel materials in the clothing industry is still limited. Du and Kim (2019) conducted market research on aerogel clothing and found that that consumers' opinions on aerogel clothing products varied. For example, most consumers stated that aerogel clothing exhibits good insulation properties, particularly during strong wind. However, consumers also stated that it was difficult to clearly differentiate the performance of aerogel clothing from previous insulation clothing. In addition, the lack of breathability and flexibility of aerogel clothing have affected consumers' opinions of it.

From a human development perspective, with the increase in severe natural disasters caused by environmental destruction and the future exploration of severe cold area, the demand for clothing materials with strong protective properties for overcoming extreme environments will increase. Although several factors limit the effective application of aerogels to clothing, it is still highly anticipated due to aerogel's excellent irreplaceable properties. Therefore, it is important to conduct extensive research on the application of aerogel in the clothing industry.

To explore the application of aerogel in the clothing industry, it is essential to clarify the necessary direction of further research based on the current research stage and difficulties. Therefore, in this study, a literature survey of the application of aerogel in clothing was conducted to understand the current research focus on aerogel clothing, details on the development of aerogel materials, and effects of their application in clothing. Based on the analyses of the problems of aerogel application in clothing, we suggest further research directions on the application of aerogel in clothing.

Methods

This study retrieved and collected studies that have experimentally evaluated the application of aerogel in clothing and investigated them in three aspects: the focus of research on aerogel clothing, the development details of the aerogel materials used in the studies, and the evaluation of effect of aerogel applied to clothing.

The literature survey was conducted in five steps to retrieve and collect Korean, English, and Chinese studies published in domestic and foreign academic journals before December 28, 2020. First, related academic journal articles and proceedings were retrieved from the "Title" using keywords. The keywords used in this survey included words related to aerogel clothing, such as "aerogel clothing," "aerogel garment," "aerogel apparel," and "aerogel suit," and words related to aerogel clothing accessories, such as "aerogel footwear," "aerogel shoe," "aerogel boots," "aerogel insole," and "aerogel gloves." Studies in Korean were mainly retrieved from RISS; studies in English were retrieved from websites, such as Scopus, Springer, ScienceDirect, Web of Science, and Wiley Online Library; and studies in Chinese were mainly retrieved from CNKI.

The second step of the literature survey involved the exclusion of duplicated data that were retrieved from multiple sites, and the third step involved abstract screening of the retrieved studies to obtain highly relevant works. The fourth step involved obtaining additional data by conducting additional literature survey on the references included in the studies collected in the previous step. The fifth step involved the exclusion of studies that did not contain experimental evaluation contents. After the literature survey process, a total of 22 studies consisting of two studies in Chinese, three studies in Korean, and 17 studies in English were extracted. In terms of the research scope, 18 out of the 22 studies focused on aerogel clothing, while four focused on aerogel footwear.

The 22 extracted studies were investigated in three aspects: (i) research focus on aerogel clothing, (ii) development details of aerogel materials, and (iii) evaluation of the effect of aerogel applied to clothing. The research focus of aerogel clothing was examined using the keywords in the extracted studies, and the research focus was mainly analyzed in three aspects: (i) the aerogel clothing types, (ii) the aerogel material types, and (iii) the experimental measurement items. The development details of aerogel materials were examined by evaluating the methods used to fabricate the materials, and the development details of the three types of aerogel materials (i.e., aerogel fiber composite, aerogel foam composite, and aerogel coating fabric) were summarized. The effects of the application of aerogel in clothing were examined by summarizing the evaluation methodology of the performance of aerogel clothing and evaluating the experimental results and research conclusions, and the problems of the application of aerogel to clothing were analyzed. The research procedure of the application of aerogel in the clothing industry, including the research contents, is shown in Fig. 1.

Research focus on aerogel clothing

The research focus on aerogel clothing was examined using the keywords in the surveyed studies. For studies containing few or no keywords, nouns related to application purposes, aerogel materials, and measurement items were supplemented according to the titles and conclusions of the studies. A total of 105 keywords were collected from the 22 surveyed studies. To highlight the research focus of these studies, the same or similar keywords were combined, and the number of studies containing each keyword were indicated after the keywords. Subsequently, the collected keywords were divided into four categories: aerogel clothing types, aerogel material types, experimental measurement items, and other contents, as summarized in Table 1. The research focus of aerogel clothing was analyzed based on the four keywords categories, and they are discussed below.

Focus of aerogel clothing types

A total of 22 keywords were related to aerogel clothing types, with each study corresponding to a keyword. These keywords were divided into two categories: aerogel clothing and aerogel footwear. The aerogel clothing category consisted mainly of firefighter clothing, space suits, and wetsuits. Eleven keywords relating to firefighter clothing were

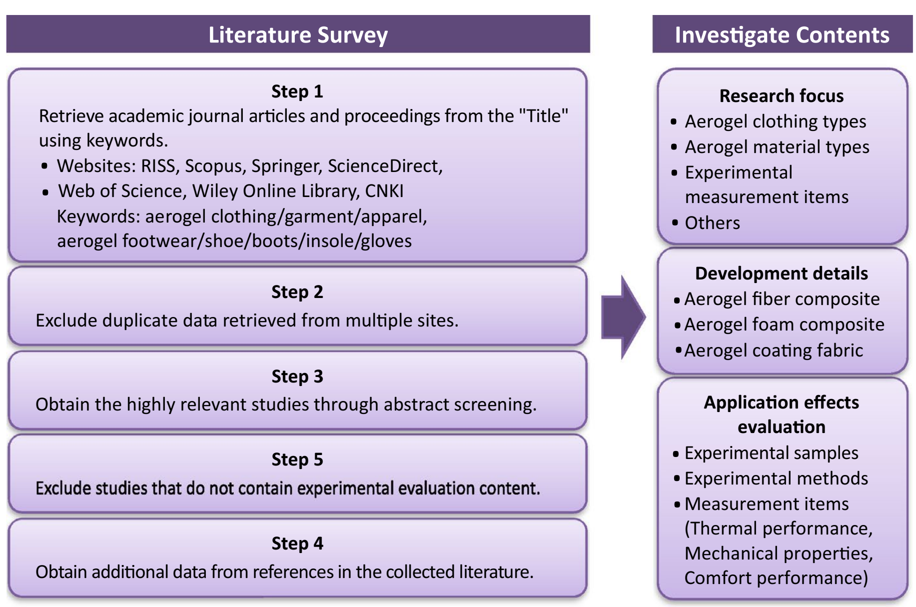

Fig. 1 Illustration of the research procedure

Table 1 Division of the 105 keywords into four categories

Categories	Sub-categories	Keyword list	No.	Subtotal	Total
1. Aerogel clothing types	Aerogel clothing	•Firefighter clothing	11	18 (81.8%)	22 (100%)
		•Space suits	4		
		•Wetsuits	3		
	Aerogel footwear	•Footwear	2	4 (18.2%)	
		•Insole	2		
2. Aerogel material types	Aerogel fiber composite	•Aerogel blanket	6	17 (77.2%)	22 (100%)
		•Aerogel*	5		
		•Fiber-reinforced silica aerogel composite	2		
		•Aerogel-infiltrated fabrics	2		
		•Aerogel interstitial void medium	1		
		•Laminated aerogel composite	1		
	Aerogel coating fabric	•Aerogel nanoparticle	3	3 (13.7%)	
	Aerogel foam composite	•Aerogel-syntactic foam hybrid insulation	1	2 (9.1%)	
		•Silica aerogel-reinforced polyurethane foams	1		
3. Experimental measurement items	Thermal performance	•Thermal protective	10	25 (67.6%)	37 (100%)
		•Thermal insulation	5		
		•Thermal conductivity	4		
		•Thermal resistance	2		
		•Thermal gravimetric analysis	1		
		•Fireproof	1		
		•Second-degree skin burn time	1		
		•Flame retardancy	1		
	Mechanical properties	•Durability	2	6 (16.2%)	
		•Mechanical properties	1		
		•Compressive mechanical properties	1		
		•Compression rate	1		
		•Shock attenuation performance	1		
	Comfort performance	•Subjectively comfort	1	6 (16.2%)	
		•Thermophysiological comfort	1		
		•Thermal comfort	1		
		•Water vapor permeability	1		
		•Moisture management	1		
		•Weight reduction	1		

Table 1 (continued)

Categories	Sub-categories	Keyword list	No.	Subtotal	Total
4. Other contents	Synergistic materials	•Phase change material (PCM)	3	11 (45.8%)	24 (100%)
		•Fibrous materials	1		
		•4DGTM fiber	1		
		•Foam neoprene	1		
		•Nonwoven fabric	1		
		•Pyrogel	1		
		•Textiles	1		
		•M400 Thinsulate liner	1		
		•Air layer	1		
	Problem and solution	•Simultaneous utilization	1	4 (16.7%)	
		•Encapsulation material	1		
		•Contamination hazard	1		
		•Thermal wrap	1		
	Experimental method	•Manned evaluation	1	6 (25.0%)	
		•Mechanical flex cycle	1		
		•Testing	1		
		•Instrumented manikin test	1		
		•Wood crib fire	1		
		•Foot temperature	1		
	Application field	•Moon and Mars exploration	1	3 (12.5%)	
		•Super-insulation	1		
		•Personal protective equipment	1		

* According to the description in the studies, it belongs to the "aerogel fiber composite" material type

observed, which indicates that firefighter clothing is the major type of aerogel clothing investigated in studies on aerogel clothing at present.

Focus of aerogel material types

Similarly, a total of 22 keywords were related to aerogel material types, with each study corresponding to a keyword. These keywords could be broadly classified into aerogel fiber composite, aerogel coating fabric, and aerogel foam composite. Aerogel fiber composite is commonly known as "aerogel blanket," and among the 22 keywords, there were 16 keywords relating to aerogel blanket, which indicates that it is the main type of aerogel material used in the clothing industry. The development details of these materials will be described later.

Focus of experimental measurement items

There were 36 keywords corresponding to the experimental measurement items. They could be broadly classified into thermal performance evaluation, mechanical properties evaluation, and comfort performance evaluation. Thermal performance here refers to the thermal conductivity and thermal protection performance of the fabric. Thermal conductivity (often denoted by k, λ, or κ) refers to a material's intrinsic ability to transfer or conduct heat, and the thermal protective performance (TPP) values are the product of the incident heat flux and the recorded tolerance time to second degree burn (cal/cm^2) (Stoll & Chianta, 1968). Keywords relating to thermal performance evaluation appeared in all surveyed studies, which implies that thermal performance is the most important factor to consider when applying aerogel to clothing.

Mechanical properties, according to the theme definition of Nature magazine, are physical properties that a material exhibits upon the application of forces. Examples of mechanical properties are the modulus of elasticity, tensile strength, elongation, hardness, and fatigue limit (Nature, n.d.). Keywords related to the measurement of mechanical properties in this study accounted for 16.7% of all keywords and were mainly related to research of durability and compressive properties. Because clothing requires repeated use, when aerogel materials are used in clothing, the enhancement of the mechanical properties of materials will inevitably become an important and even decisive factor.

Comfort performance is another important attribute of clothing. The comfort performance of this study included thermal comfort performance, but was not limited to thermal comfort. Thermal comfort is defined as the condition of mind that expresses satisfaction with the thermal environment (Choi & Loftness, 2012), and comfort is the result of many physical factors as well as the mental, subjective psychological reaction (De Looze et al., 2003). The content related to comfort performance in this study included subjectively comfort, thermophysiological comfort, water vapor permeability, and weight reduction. It is obvious that research on this aspect is lacking from the number and composition of keywords.

In addition to the above content, there were 25 other keywords, which were divided into four parts: "synergistic materials," "problems and solutions," "experimental methods," and "application areas." Through these keywords, the general content of previous research could be quickly understood.

Development details of aerogel materials

According to the analysis results in "Research focus on aerogel clothing," aerogel materials used in the surveyed studies were classified into three types: aerogel fiber composite, aerogel foam composite, and aerogel coating fabric. The details of their development are summarized and discussed based on the manufacturing process of experimental samples described in the surveyed studies, and are shown in Table 2.

Aerogel fiber composites

Early research on aerogel fiber composites mainly focused on optimizing material properties by controlling the type of fiber combined with aerogels and the ratio of the chemical reagents. For example, Tang et al. (2003) utilized five sets of fiber-reinforced silica aerogel composite with different fiber reinforcements and fiber additives as a space suit

Table 2 Development details of the three types of aerogel materials

Aerogel material types	Use purpose	Initial material	Development details
1. Aerogel fiber composite	Space suits Wetsuits	Silica aerogel blanket	• Optimize material properties by changing the compositions
	Firefighter clothing		• Direct utilization of commercially available aerogel fiber composites or their combination with other materials
	Footwear/insoles		• Encapsulate or laminate aerogel fiber composites before use
2. Aerogel foam composite	Wetsuits	Silica aerogel blanket	• Mix aerogel fabric composite and foam
	Footwear/insoles	Silica aerogel particle	• Mix aerogel particles and foam
3. Aerogel coating fabric	Firefighter clothing	Silica aerogel particle	• Aerogel coating
			• Hybrid coating of aerogel and phase change materials (PCMs)

insulation layer, and they evaluated the thermal performance and dust generation of the samples after repeated mechanical cycling. In addition, Paul and Diller (2003) numerically analyzed the thermal conductivity performance of three insulating fiber materials using aerogel as the interstitial void media in terms of various deniers (sizes), interstitial void fractions, and orientations to the applied temperature gradient to evaluate their applicability as a new type of insulation for Mars suits.

Recent research has focused on the direct utilization of commercially available aerogel fiber composites or the combination of aerogel fiber composites with other materials to fabricate experimental samples that can replace original thermal insulation materials. For example, Zhang et al. (2017) utilized the commercially available aerogel fiber composites and microencapsulated phase change materials (PCMs) as a thermal liner for firefighting suits, and they investigated the six-material composition schemes and their effects on the thermal protection performance of the firefighting suits. These commercially available aerogel fiber composites are mainly developed using Aspen Systems. Although all the evaluations of this application method affirm the thermal protection performance of aerogel and its synergistic materials, the detachment and dispersion of the aerogel particles attached to the fabric have restricted further application of this method. This is because the detachment of aerogel particles not only deteriorates the properties of the aerogel materials, but the inhalation of aerogel dust dispersed in air can also cause health problems.

To prevent the dispersion of aerogel particles into the air, aerogel fiber composites are usually encapsulated or laminated before use. For example, Nuckols et al. (2005) used a prototype aerogel liner fabricated using Aspen Aerogel AR5401 panels, and they encapsulated the liner with Pertex nylon Oxford covering to replace the commercial M400 Thinsulate coverall undergarment in cold-water diving garment ensembles. In addition, Zrim et al. (2015) described a two-sided lamination method for commercially produced aerogel fiber composites for the prevention of the dispersion of aerogel powder into the air and investigated its suitability for thermal insulation in protective footwear applications for severe cold and extreme high-altitude environments (Fig. 2).

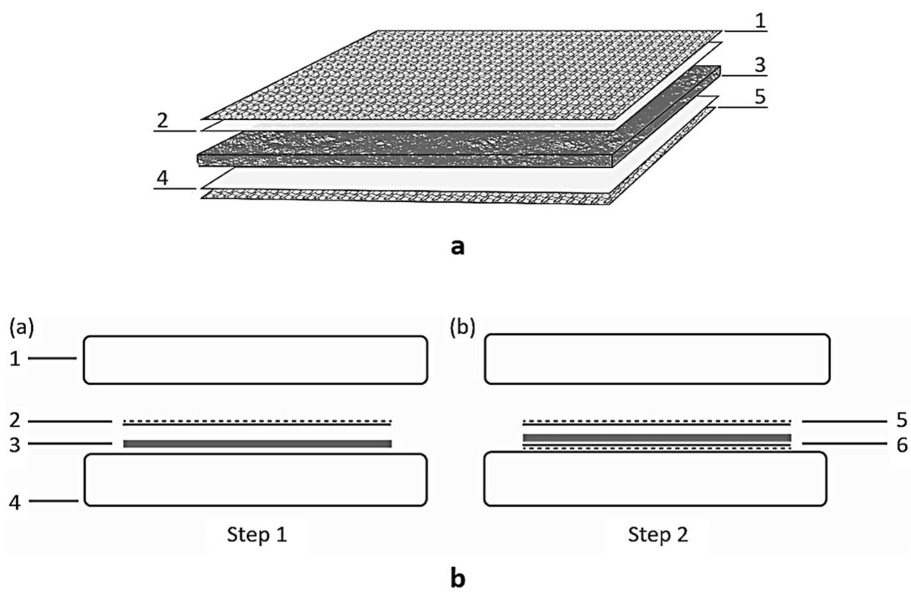

Fig. 2 A two-sided lamination method. **a** The scheme of the laminated aerogel composite. 1 and 5: wrap-knitted fabric; 2 and 4: membrane; 3: aerogel composite. **b** The scheme of the lamination process. 1: upper press-plate; 2: Sympatex 2093-3T (LM); 3: aerogel composite (AC); 4: lower press plate; 5: second layer of LM; 6: one-side laminated AC (Zrim et al., 2015)

Aerogel foam composites

The encapsulation or lamination of aerogel fiber composites prevents the dispersion of aerogel particles into the air; however, this reduces the flexibility and breathability of the material and restricts the cutting and sewing of the material. To solve these problems, researchers developed aerogel foam composite, which effectively locks aerogel particles in and increases the material's flexibility.

Aerogel foam composites are prepared by mixing aerogel fabric composites and foam or aerogel particles and foam. Bardy et al. (2006b) attempted to utilize a composite of aerogel fiber composite and foam in a wetsuit. To achieve this, the aerogel fiber composite was cut into circular discs and square shaped cut-outs, and these cut-outs were spaced apart in a set pattern, with the gaps between the cut-outs being filled with syntactic foam, as shown in Fig. 3. In addition, Yang et al. (2018) attempted to use a composite of aerogel particles and foam in footwear applications. To achieve this, they created a nanocellular structure within a polyurethane (PU) foam by incorporating silica aerogel particles in the PU foam.

Aerogel coating fabrics

Aerogel coating fabric was developed by Shaid et al. (Australia). They attempted to enhance the performance of firefighting suits using aerogel coating or hybrid coating of aerogel and PCM. Shaid et al. (2014) coated the 65/35 wool/Aramid blended fabric with different percentages (2%, 4%, and 8%) of NANOGEL (superhydrophobic aerogel nanoparticle from Cabot) using an acrylic binder. They analyzed the thermophysiological

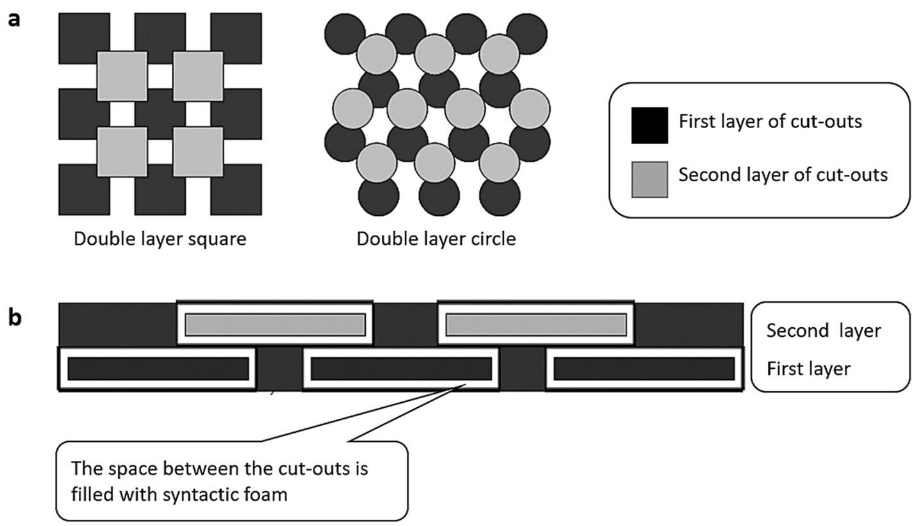

Fig. 3 A composite of aerogel fiber composite and foam in a wetsuit. **a** Cut-out arrangements considered for constructing the hybrid insulation. **b** Cross-section of double layer hybrid insulation (Bardy et al., 2006a)

comfort of the coating fabrics by determining air permeability, moisture management properties, and heat transfer properties, and they obtained positive results, thus identifying the potential use of aerogel in firefighter clothing. However, aerogel in firefighter clothing not only resists incoming heat fluxes, but also blocks outbound body heat, which increases the body temperature of the wearer. Shaid et al. (2016) tried to resolve this problem by using a hybrid coating of aerogel and PCM. They coated the ambient side of a thermal liner face cloth of traditional firefighting suits with silica aerogel particles and coated the skin side with PCM/aerogel composite powder. This successfully extended the time to reach pain threshold [human skin reaches around 44 °C (Stoll & Greene, 1959)] and increased the pain alarm time [the time gap between starting to feel pain and receiving second-degree burns (Rossi & Bolli, 2005)]. In addition, since most PCMs used in firefighter clothing are flammable, wearing protective clothing containing PCM presents a direct risk to the wearer. Shaid et al. (2018a) wanted to demonstrate that using aerogel along with PCM can improve the flame resistance of PCM-containing firefighter clothing. They added aerogel to the PCM-coated thermal liner, and then the coated thermal liner was used with an outer layer fabric and moisture barrier in a similar fashion as traditional firefighter clothing. They confirmed that aerogel coating on a PCM-coated thermal liner slowed down the spreading of flames in PCM-containing fabric. Of course, the coating increased the overall weight, but compared with PCM as the only coating material for firefighter clothing, the addition of aerogel reduced the weight.

Evaluation of the effect of aerogel applied to clothing

To understand the effects of the application of aerogel on clothing performance, the methodologies for the evaluation of the performance of aerogel clothing in the surveyed studies were summarized, and the application effect of aerogel to clothing were qualitatively analyzed using the experimental results and research conclusions. Finally, the main problems of the application of aerogels in clothing were discussed. The methodologies of the surveyed

Table 3 Methodology for the evaluation of the performance of aerogel clothing

Application purpose of aerogel	22 studies on aerogel clothing	Experimental samples		Experimental methods			Measurement items		
		Aerogel clothing	Aerogel fabric	Human-wearing	Manikin-wearing	Machine-measuring	Thermal performance	Mechanical properties	Comfort performance
Space suits	Paul and Diller (2003)	–	O (I)	–	–	O	O (+)	–	–
	Tang et al. (2003)	–	O (I)	–	–	O	O (+)	O (+)	–
	Tang et al. (2006)	–	O (I)	–	–	O	O (+)	O (+)	–
	Crowell et al. (2015)	–	O (I)	–	–	O	O (−)	O (+)	–
Wetsuits	Nuckols et al. (2005)	O[a] (I)	–	O (6)	–	–	O (+)	–	O (+)
	Nuckols et al. (2009)	O[a] (I)	–	O (1)	O	O	O (+)		–
	Bardy et al. (2006b)	O (II)	–	O (1)	–	–	O (−)	–	–
Firefighter clothing	Ren et al. (2011)	–	O (I)	–	–	O	O (+)	–	–
	Qi et al. (2013)	–	O (I)	–	–	O	O (+)	–	–
	Zhang et al. (2013)	–	O (I)	–	–	O	O (+)	–	–
	Jin et al. (2013)	O (I)	O (I)	–	O	O	O (+)	–	–
	Shaid et al. (2014)	–	O (III)	–	–	O	O (+)	–	O (+)
	Shaid et al. (2016)	–	O (III)	–	–	O	O (+)	–	O (+)
	Shaid et al. (2018a)	–	O (III)	–	–	O	O (+)	–	O (+)
	Shaid et al. (2018b)	–	O (I)	–	–	O	O (+)	–	–
	Huang and Guo (2017)	–	O (I)	–	–	O	O (+)	–	–
	Zhang et al. (2017)	–	O (I)	–	–	O	O (+)	–	–
	Kim et al. (2018)	–	O (I)	–	–	O	O (+)	–	O (+)
Footwear/insoles	Oh and Park (2009)	–	O (I)	–	–	O	O (+)	O (+)	–
	Zrim et al. (2015)	–	O (I)	–	–	O	O (+)	O (+)	–
	Lee et al. (2018)	–	O (I)	O (10)	–	–	O (+)	–	–
	Yang et al. (2018)	–	O (II)	–	–	O	O (+)	O (+)	–

Table 3 (continued)

Application purpose of aerogel	22 studies on aerogel clothing	Experimental samples		Experimental methods			Measurement items		
		Aerogel clothing	Aerogel fabric	Human-wearing	Manikin-wearing	Machine-measuring	Thermal performance	Mechanical properties	Comfort performance
Percentage of 22 studies		4 (18.2%)	19 (86.4%)	4 (18.2%)	2 (9.1%)	19 (86.4%)	22 (100%)	6 (27.3%)	5 (22.7%)

[a] Nuckols et al. (2005) and Nuckols et al. (2009) used the same aerogel clothing samples. (Number) indicates how many subjects participated in the human-wearing experiments. (I) means aerogel fiber composite, (II) means aerogel foam composite, and (III) means aerogel coating fabrics. (+)/(−) indicates if the evaluation result of the item is positive or negative

studies on the evaluation of the performance of aerogel clothing were summarized into experimental samples, experimental methods, and measurement items and are presented in Table 3. Studies in the table are classified by application purpose of aerogel and sorted by year within the classification, but studies by the same researcher are arranged together.

Experimental samples

The experimental samples in the surveyed studies could be broadly divided into clothing samples and fabric samples. Clothing samples are clothes fabricated by the application of aerogel, whereas the fabric samples are fabrics of clothes fabricated by the application of aerogel. The experimental samples used for aerogel footwear products were fabricated in the form of insoles, so all the experimental samples related to footwear were organized into the fabric samples category. As shown in Table 3, the experimental samples were mostly composed of aerogel fabric samples (86.4%), with aerogel clothing samples only occupying a small percentage (18.2%). How aerogel was used for fabric sample development has been described in "Development details of aerogel materials" section. The Arabic numbers in parentheses in the "Experimental samples" category in Table 3 indicate the types of aerogel materials developed. There were three cases of clothing samples that were made from aerogel fabrics in all surveyed studies, and they appeared in the studies of Nuckols et al. (2005, 2009), Bardy et al. (2006b), and Jin et al. (2013).

Both Nuckols et al. and Bardy et al. have developed wetsuits and used clothing samples to carry out human-wearing experiments. Nuckols et al. (2005) fabricated a prototype aerogel garment consisting of Aspen Aerogel AR5401 panels encapsulated with Pertex nylon Oxford covering, and they compared the thermal performance of this garment with the baseline Thinsulate worn under a commercial dry suit. The prototype aerogel garment was a one-piece coverall with two plies of AR5401 and only a single ply of AR5401 in the arms. Nuckols et al. (2009) used the same prototype aerogel garments to compare their thermal performance with those of commercial garments through infrared photography. Bardy et al. (2006b) designed and fabricated a hybrid wetsuit in collaboration with a wetsuit manufacturer. Since the hybrid insulation (Fig. 3) lacks the flexibility and stretching ability, portions of the hybrid wetsuit were made from syntactic foam at strategic stretch joints and along the seams.

While Jin et al. (2013) developed firefighter clothing and used a manikin to test the thermal protective performance of clothing samples by flame heat transmission test. They first used different concentrations of aerogel dispersed in acetone to treat the thermal barrier of the existing firefighting clothing, and they laminated it on both sides with

25-μm thick polytetrafluoroethylene (PTFE) membrane to prevent the dusting of the aerogel powder. Then, they made prototype firefighter clothing using aerogel-treated specimens as a thermal barrier.

Experimental methods

The experimental methods used in the surveyed studies could be classified into three types: human-wearing, manikin-wearing, and machine-measuring experiments. Machine-measuring experiments (86.4%) were the main experimental method used in the surveyed studies and were used to measure the aerogel fabric samples. In contrast, human- and manikin-wearing experiments (18.2% and 9.1%, respectively) used in the measurement of aerogel clothing samples were insufficient. Physiological data obtained through human-wearing experiments, as well as the evaluation of protective clothing in hazardous environments through manikin-wearing experiments, are crucial to the study of clothing performance. However, effective integration of aerogel materials into clothing is still challenging. The small number of available clothing samples has restricted the further application of these experimental methods. The numbers in parentheses in the "Experimental methods" category in Table 3 indicate how many subjects participated in the human-wearing experiments. Although the small number of test subjects reduced the statistical power of the study, in the Bardy et al.'s (2006b) study, only one subject was tested. They explained that the lack of flexibility of the wetsuit limited its use by many people. Considering the uniformity of thermal responses of normal subjects and the high cost of the hybrid wetsuit construction, they only tested one subject and assumed that the data would apply to the population in general. In comparison, Lee et al. (2018) tested the thermal insulation performance of aerogel insoles, which allowed for the participation of more subjects.

Measurement items

As shown in Table 3, the main measurement items evaluated in the surveyed studies included thermal performance, mechanical properties, and comfort performance. Thermal performance measurements (100%) were conducted in all the surveyed studies, and only few studies evaluated the mechanical properties (27.3%) and comfort performance (22.7%). The plus and minus symbols in parentheses in the "Measurement items" category indicate that the evaluation result of the item is positive or negative, respectively. In other words, based on the purpose and method of that research, they indicate whether the application effect of aerogel is good or insufficient.

Thermal performance

The 22 studies surveyed in this study investigated the thermal performance of the experimental samples containing aerogel. Among them, 20 studies reported that the samples exhibited excellent thermal performance; however, two studies reported negative poor thermal performance.

As an example of the positive conclusions, Nuckols et al. (2005) found that replacing the M400 Thinsulate liner in diving suits with a prototype aerogel garment not only increased the dive duration time in cold water by 38% but also enhanced the thermal protection of the garment for the fingers and toes. In addition, 11 out of the 22 surveyed studies investigated the application of aerogel to firefighter clothing. Their findings revealed that the thermal performance of aerogel materials is superior to that of conventional materials. For example, Kim et al. (2018) used an aerogel to replace the thermal liner of traditional firefighter clothing and tested the thermal properties of fabrics containing aerogel materials through flame, radiant heat, and a mixture of flame and radiation heat, and found that the application of aerogels enhanced the thermal protective performance of firefighter clothing. In addition, Jin et al. (2013) reported that the heat-insulating properties of aerogel-containing fabrics increased with an increase in the aerogel content, and the developed aerogel garment exhibited higher TPP than the existing firefighter clothing in the instrumented manikin test. Furthermore, Shaid et al. (2016) reported that the simultaneous use of PCM and aerogel can significantly enhance the thermal protection of such hybrid fabrics in terms of pain threshold and pain alarm time. In addition, all four studies that applied aerogel to footwear products reported the positive influence of aerogel on the thermal performance of footwear. For example, Oh and Park (2009) reported that aerogel fiber composite exhibited promising potential as an insole material for cold winter shoes requiring good thermal insulation protection. In addition, Yang et al. (2018) concluded that the loading of the aerogels into foams effectively improved the thermal insulation.

In contrast, two studies including Bardy et al. (2006b) and Crowell et al. (2015) reported negative effects of aerogel on thermal performance. Bardy et al. (2006a) prepared the aerogel-syntactic foam hybrid insulation (Fig. 3) for wetsuit, and measured the thermal resistance of the prepared material in a previous study. The results have showed that the aerogel-syntactic foam hybrid insulation has a thermal resistance significantly higher than those of both foam neoprene and underwater pipeline insulation at atmospheric and elevated hydrostatic pressures (1.2 MPa). However, when they used the developed aerogel-syntactic foam hybrid insulation to make a wetsuit, they reported that the aerogel-syntactic foam hybrid insulation wetsuit cannot provide more thermal protection than the foam neoprene wetsuit (Bardy et al., 2006b). According to their analysis, due to the lack of flexibility and stretchability of the hybrid insulation, the strategic stretch joints and the seams of the wetsuit were could only be made from syntactic foam. In addition, the aerogel-syntactic foam hybrid insulation does not fit the body very well due to its lack of flexibility, so the water flow over the skin and the formation of thermal bridges in the insulation could have been contributing factors for the decrease in performance. Therefore, the reason for the negative results of the aerogel-syntactic foam hybrid insulation wetsuit can be attributed to the unsatisfactory method of integrating aerogel materials with clothing. They believed that an aerogel-syntactic foam hybrid insulation wetsuit can provide more thermal protection when the presence of its surface depressions can be eliminated and alternative methods for a tighter fit can be achieved.

As another negative conclusion on thermal performance, Crowell et al. (2015) reported that stitching the aerogel non-woven composites was not a viable option for space suits due to the increase in thermal conductivity and the difficult manufacturing. They evaluated the thermal conductivity of stitched, windowed, and packeted aerogel non-woven composites through Hot Disk Testing and Forward-Looking Infrared Imaging methods. They found that the thermal conductivity of the stitched material was significantly increased at the stitches, while the aerogel non-woven composites that were windowed and packeted showed a reduction in thermal conductivity. However, according to their experimental results, the largest increase in thermal conductivity in all test cases was only 0.01693 W/m·K, meaning that the thermal conductivity of the material increased from 0.01920 to 0.03613 W/m·K after stitching. In other words, while stitching an outer layer to the aerogel materials was unsuitable for space suits, this does not mean that the degree of thermal conductivity increase was unacceptable for general thermal protective clothing.

Mechanical properties

From the distribution of the mechanical properties' measurement items in Table 3, the mechanical properties evaluation mainly focuses on space suits and footwear, with five cases of aerogel fabric composites and one case of aerogel foam composite. All six studies that examined the mechanical properties of aerogel clothing reported positive conclusions. For example, Tang et al. (2003, 2006) reported that some aerogel materials retained good insulation performance after approximately 250,000 mechanical flex cycles and had less than 1.3% relative weight loss. In addition, Yang et al. (2018) evaluated silica aerogel-reinforced polyurethane foams for footwear applications and found that the incorporation of aerogels enhanced the compressive modulus, compressive stress, and deformation recovery of the foams, while preserving their excellent flexibility. Crowell et al. (2015) evaluated the mechanical properties of the aerogel non-woven composite stitched with an outer layer through tension tests and revealed that stitching increased the strength of the aerogel non-woven composite, although it also increased the thermal conductivity. In fact, for insole applications, the mechanical properties of aerogel materials have already met the standards for commercial use. Shoe insoles made with aerogel fabric composite have been marketed and sold in the United States since 2005 (Tang et al., 2006).

Comfort performance

Comfort of the human body is very complicated and is affected by many factors, including the thermal and mechanical properties of clothing. Comfort can be thermal, physical, sensational or thermophysiological, thermophysiological comfort refers to the heat and moisture transport properties of clothing and the way that the clothing maintains the body's heat balance (Huang, 2006). In this study, the research results of comfort performance are summarized mainly based on the theme discussed by the authors. In 22 studies surveyed, five of them presented research conclusions on the comfort performance of aerogel clothing, including subjectively comfort, thermophysiological comfort, skin–clothing microclimate, and weight reduction, and these research conclusions were positive.

The research of Nuckols et al. (2005) is the only study of the effect of aerogel application through the quantification of physical and psychological characteristics. The researchers asked the subjects to wear a prototype aerogel garment or commercial wetsuit for 6 hours of diving, and they evaluated the thermal benefit and wearing comfort of the prototype aerogel garment using the thermal state data and psychological state data of the body during the period. The authors suggested that the significant increase in the thermal benefit of aerogel clothing brings more comfort, which is mainly reflected in the increased temperature of the hands and feet. In addition, two subjects expressed in their subjective comfort evaluations that the prototype aerogel garment was less flexible than the commercial wetsuit.

Aerogel can improve the thermal protection, but it reduces the water vapor transmission of the thermal barrier, which causes the internal temperature of the clothing to rise. In firefighter clothing applications, the benefits of the extraordinary flame protection and heat insulation properties of aerogel can only be effectively utilized when sufficient release of body heat can be assured. Shaid et al. (2014) investigated the thermophysiological comfort of the aerogel coating fabrics by analyzing the air permeability, moisture management properties, and heat transfer properties of the fabrics. They concluded that aerogel coating fabrics have the possibility to improve the thermophysiological comfort of firefighting clothing by selecting suitable coating thickener to reduce the hydrophobic characteristic of aerogel.

Shaid et al. (2016) subsequently presented another approach to use PCM with aerogel to achieve added thermal protection without sacrificing comfort. They coated aerogel particle as a thermal protection aid on the ambient-side of fabrics and an aerogel/PCM composite powder on the skin side to absorb metabolic heat to enhance thermal comfort. Their results show that this approach allows the temperature of the skin–clothing microclimate to remain in the comfort zone for a longer duration. They emphasized that the PCM/aerogel composite powder was stable than pure PCM at elevated temperature, and no dripping or form deterioration was observed when the composite powder was heated over a temperature three times above the melting temperature of the pure PCM.

In addition, some studies mentioned that utilizing the lighter specific gravity of aerogel materials can reduce the weight of existing firefighter clothing to improve the comfort of the clothing (Kim et al., 2018; Shaid et al., 2018a). In general, the current research on the comfort performance of aerogel clothing is very limited due to the infeasibility of human-wearing experiments of high-heat protective clothing in high-risk environments and the immaturity of the technical means of integrating aerogel into clothing.

Problems of the application of aerogel in clothing

Through the above sorting, it can be observed that the improvement of the thermal performance of clothing and fabrics by aerogel materials has been widely affirmed within the scope of the surveyed literature. At present, the main problem is with how to apply this kind of high-efficiency thermal insulation material to clothing in a harmless and sustainable manner without losing too much thermal performance. The main reason for this problem is the rigidity of monolithic silica aerogel and the dust pollution of aerogel particles. Monolithic silica aerogel cannot be bent and must be compounded with other materials to be flexible when used in clothing. The aerogel fabric composite used in most research tends to fracture, and aerogel particles loosen from the fiber reinforcement after repeated handling. Although the aerogel itself is harmless to the body, the aerogel particles that fall into the air and make contact with the skin or are inhaled by the human body produce a desiccant effect and cause irritation due to aerogel's excellent hydrophobicity. Tang et al. (2006) stated, "the answer to the contamination hazard generated by the decomposition of current 'fiber-reinforced silica aerogel composite fabric' matrix still remains elusive." From the "Development details of aerogel materials" section in this study, researchers have tried various methods to apply aerogel materials in clothing. However, the current applications are mainly limited to aerogel fabrics, and there is still a lack of verification of the effect of aerogel fabrics applied to clothing. Kim et al. (2018) found that both weight reduction and thermal protective performance were improved by the use of aerogels, while due to the fragile nature of aerogels, a method of fixing them at a constant thickness between layers of firefighters' protective clothing should be considered in the future.

Conclusions

To facilitate future investigation on the application of aerogel materials in the clothing industry, this study evaluated the current research stage and proposed useful insights for further research by summarizing the problems encountered in current studies. This study examined and analyzed the results of previous studies on the application of aerogel in the clothing industry through domestic and international literature surveys and summarized these studies in terms of the research focus on aerogel clothing, the development details of aerogel materials, and the evaluation of the effect of aerogel applied to clothing.

The analysis result revealed that the application of aerogel to clothing significantly enhanced the thermal performance of aerogel clothing. In addition, the mechanical properties such as the durability and strength of aerogel materials can meet the application requirements of clothing. However, the dust contamination hazard of aerogel particles was reported as the major problem in the application of aerogel to clothing. Consequently, several measures have been implemented to solve this problem; however, these measures reduce the thermal performance of the aerogel materials. Particularly, the encapsulation of aerogel composites reduces the flexibility of materials and negatively affects the feasibility of the manufacturing process. In addition, as there are few experimental aerogel clothing samples, the experimental evaluation of the comfort performance of aerogel clothing through human- and manikin-wearing experiments is insufficient, which limits the understanding of the comfort performance of aerogel clothing.

The findings of this study revealed that the application of aerogel in clothing is effective and should be researched further. In addition, the commercialization of aerogel clothing can be achieved by effectively controlling the dust generated by aerogel particles and improving the application method of aerogels in clothing. In addition, for the commercialization of aerogel clothing, it is very important to measure the thermal performance and comfort performance through human- and manikin-wearing experiments. Future research should focus on developing new methods to address the aerogel dust contamination of aerogel materials, such as the composite using of aerogel and foam materials, and the coating of fabrics with aerogel; evaluating the performance of aerogel clothing in terms of human physiology and psychology through wearing experiments; and researching the application effect of aerogel clothing in various environments, such as polar and cold-mountain environments.

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Author contributions
The authors contributed equally to all phases of this research (data collection, analyses, and the preparation of this manuscript). Both the authors have read and approved the final manuscript.

Authors' information
Ying Du is a PhD student at the Department of Clothing & Textiles, College of Human Ecology, Kyungpook National University, South Korea.
Hee-Eun Kim is a Professor at the Department of Clothing & Textiles, College of Human Ecology, Kyungpook National University, South Korea.

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