Experimental and Numerical Investigation of Aerogel Based Insulation Material for Aerospace Applications

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It is extremely important to meet thermal insulation requirements in aircraft to ensure appropriate operational conditions, maintain structural integrity, and achieve energy savings and cost savings. In particular, it is critical to keep the external surface temperature of the pipelines through which hot gases or liquids pass at a certain level so that the aircraft operates under optimum temperature conditions. Silica-based aerogels, which are frequently used to provide this requirement, are high-performance thermal insulation materials. In this study, the operational performance and suitability for aviation of a composite insulation blanket containing aerogel was examined by using experimental and numerical methods.

Keywords: *Composites, Thermal insulation, Insulation material, Aerogel*

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1. INTRODUCTION

Thermal management in aerospace is crucial for aircraft design and operation, involving the regulation and management of heat within various aircraft equipment and systems. Effective thermal management ensures that all parts of an aircraft operate within their optimal temperature ranges, enhancing performance, reliability, and safety. This involves dissipating excess heat from hot areas, protecting sensitive parts from extreme temperatures, and maintaining uniform temperatures across different sections of the aircraft. Sensitive areas, such as avionics and electronic equipment, require materials that can maintain stable temperatures and protect against thermal fluctuations. With their low thermal conductivity and excellent insulating properties, Aerogel blankets, with their low thermal conductivity and exceptional insulating qualities, are well-suited for these applications, ensuring consistent and reliable performance [1–3].

Aerogel blankets represent a significant advancement in thermal insulation technology, offering substantial benefits for aviation applications. These materials are known for their remarkable thermal insulation properties, low density, high surface area, and versatility, making them highly suitable for various aerospace uses. Silica aerogels are typically synthesized by replacing the liquid in a gel with gas, resulting in a highly porous and low-density solid structure. Despite their outstanding thermal properties, the intrinsic fragility of silica aerogels presents challenges in their synthesis, scale-up, and direct application. To overcome these challenges, composite materials integrating aerogels, referred to as aerogel insulation blankets, have been developed by researchers [4]. These composite materials incorporate silica aerogels with substrates to improve mechanical properties while maintaining thermal insulation capabilities. This unique nanostructure allows aerogels to achieve low thermal conductivity, substantially better than conventional insulation materials like fiberglass and foam. Ceramic fiber blankets impregnated with silica aerogel provide a high-performance insulation solution for the aviation sector by fusing the mechanical strength of ceramic fibers with the extremely low heat conductivity of silica aerogels (0.015–0.020 W/m·K). These blankets are perfect for situations where weight reduction and thermal efficiency are crucial because of their outstanding thermal insulation, lightweight design, and strong durability. Aerogel blankets perform better in terms of fire safety and thermal resistance than other insulation materials including mineral wool, fiberglass and polyurethane foam as can be seen in Table 1. They offer modest acoustic insulation, are hydrophobic to stop moisture absorption, and can tolerate temperatures of up to 650°C. In contrast to mineral wool, which is excellent at dampening sound, the trade-offs are a slightly lower acoustic insulation and a higher cost. Traditional materials, such as fiberglass and polyurethane foam, are lighter and less expensive, but they don't have the moisture resistance and thermal stability needed in high-temperature aviation settings. Therefore, although silica aerogel blankets are more expensive, they are a smart investment for aircraft applications where weight reduction, thermal efficiency, and fire safety are more important than initial material costs [4–12].

Aerogel blankets are typically synthesized using dip-coating, immersing a substrate into a sol-gel solution and withdrawing it to form a coating. However, dip-coating has limitations, particularly in achieving uniform coatings on fibrous and porous materials, resulting in uneven or incomplete layers. The vacuum infusion method has been adopted for its benefits in infusing the fibrous matrix with the aerogel sol-gel solution, ensuring proper coating to the substrate and enhancing durability and efficiency [14,15].

Aerogel blankets have emerged as an innovative material in thermal management due to their exceptional insulating properties. High-temperature areas like engine and exhaust systems demand robust insulation to protect adjacent components and reduce heat loss. Aerogel blankets are well-suited for these applications due to their ability to withstand high temperatures while providing superior thermal resistance. Passenger cabins also benefit from aerogel blankets through improved thermal comfort, as these materials prevent heat and minimize heat loss in cold environments, enhancing passenger comfort and contributing to energy efficiency. Fuel systems require insulation to maintain consistent fuel temperatures, essential for efficiency and safety. Aerogel blankets provide thermal stability to prevent temperature-induced changes in fuel properties, ensuring optimal performance. The wings and fuselage of an aircraft are exposed to varying external temperatures during flight, making effective insulation crucial for maintaining integrity and performance. Due to their lightweight and durable nature, aerogel blankets protect against temperature variations and preserve structural efficiency and safety [1,16,17].

Table 1. Comparative analysis of insulation materials [7-13]

Attribute	**Aerogel Blankets**	**Fiberglass**	**Polyurethane foam**	**Mineral Wool**
Thermal conductivity	0.015 – 0.020 W/m.K	0.030 – 0.040 W/m.K	0.022 – 0.040 W/m.K	0.035 – 0.045 W/m.K
Density	0.15 – 0.20 g/cm^3	0.03 – 0.10 g/cm^3	0.03 – 0.06 g/cm^3	0.12 – 0.25 g/cm^3
Temperature Resistance	Up to 650 °C	Up to 500 °C	Up to 250 °C	Up to 700 °C
Mechanical Flexibility	Good (reinforced with fibers)	Good	Excellent	Moderate
Moisture Resistance	High(Hydrophobic treatment)	Moderate	Low	Moderate
Fire Resistance	High	Moderate	Low (unless treated)	High
Acoustic Insulation	Good	Good	Moderate	Excellent
Cost	High	Low	Low to moderate	Moderate

The application of aerogel blankets in aviation extends beyond thermal insulation. Their lightweight nature significantly contributes to overall weight reduction in aircraft, enhancing fuel efficiency and payload capacity. This advantage is crucial for commercial and military aviation sectors, where every weight saved leads to substantial cost savings and improved performance. Additionally, the flexibility and durability of aerogel blankets allow for easy installation and maintenance, even in complex or constrained spaces. This versatility makes them suitable for a wide range of applications within the aircraft, from engine compartments to passenger cabins. Fire safety is another critical benefit of aerogel blankets. Their excellent fire-resistant properties enhance aircraft safety by providing additional protection against potential fire hazards. This fire resistance ensures passenger and crew safety and protects valuable equipment and structural components. Moreover, aerogel blankets modified with hydrophobic properties resist moisture, making them suitable for high-humidity environments. This moisture resistance prevents corrosion of critical components, extending the lifespan and reliability of the aircraft [1,16].

Aerogel synthesis is a detailed chemical process, Methyltrimethoxysilane (MTMS) precursors are gaining interest in synthesizing aerogels as they shorten processing times, improve drying, and eliminate hydrophilization. Due to methyl group formation, MTMS-based methylsilsesquioxane (MSQ) aerogels resist capillary forces during drying. These aerogels can be synthesized in situ within ceramic blankets using the vacuum infusion sol-gel method (VASI). Ceramic fibers, suitable for aerospace applications, withstand temperatures up to 1800°C and offer superior thermal stability, insulation, and resistance to corrosion and chemicals compared to fiberglass. They also do not degrade or release toxic gases at high temperatures, making them ideal for demanding environments [18].

This study highlights aerogel blankets as a highly effective solution for heat management in aviation, offering superior thermal insulation, lightweight properties, flexibility, and durability. Their application across various thermal zones in aircraft enhances safety, efficiency, and performance, making them a vital component in modern aircraft design. As the demand for advanced materials in aerospace continues to grow, aerogel blankets are expected to play an increasingly important role, driving innovations and improvements in aircraft design and performance. Within the scope of this study, the thermal response, thermal conductivity variation with density, and temperature of MSQ aerogel blankets have been investigated. The thermal response of the blankets' outer surface was analyzed numerically and experimentally. This research aims to enhance the understanding of MSQ aerogel blankets' thermal properties for advanced insulation applications.

Regarding the incorporation of aerogel materials with flexible insulation blankets designed for particular aerospace applications, there is a notable gap in the literature. Developing a novel vacuum infusion technique to infuse ceramic fiber blankets with a silica aerogel solution is what makes our study novel. Through the method of directly generating the aerogel within the blanket fibers, a highly uniform dispersion of aerogel is achieved, leading to improved thermal insulation efficacy. In addition, our method enables the custom production of insulating materials that are precisely suited to the distinct geometries and specifications of aircraft components, in contrast to commercially available insulation materials that frequently need to be cut and joined to match complex geometries. This technique addresses important issues in the aerospace sector when traditional off-the-shelf products fail to meet complicated design and performance criteria. It not only increases insulation efficiency but also decreases material waste and installation time. Moreover, a test system specific to the part to be used in the aircraft, which is rarely seen in the literature, was developed and the produced aerogel blankets were tested on this device. Thus, the performance of the blankets was directly examined for the area of use without comparing them according to their thermal conductivity coefficients. In addition to the experimentally examined thermal performance, numerical studies were also carried out and the results were compared.

2. MATERIAL AND METHODS

2.1. Materials

Trimethoxymethylsilane (MTMS, 98%), hydrochloric acid (HCl, 37%), ammonia solution (NH_4OH 25%), and n-hexane were obtained from Sigma Aldrich. Absolute ethanol (EtOH, 99.9%) was obtained from Honeywell Riedel-De-Haën. The chemical substances were used as received, with no additional processing. Deionized water (DI) was utilized consistently in all experiments. The ceramic insulation blankets (BLANKET 1260) were obtained from ETS Endustriyel, Turkey.

2.2. Production of aerogel blankets

The MTMS sol was prepared using a two-step acid-base sol-gel process detailed in the literature [18]. A constant 2:1 EtOH-H_2O ratio was maintained as the solvent. Aerogels were prepared with MTMS in weight percentages of 10% and 30%. Hydrolysis of MTMS began in an acidic environment with a 0.05 M HCl catalyst, reaching a pH of 2, and was stirred for about 6 hours. The pH was then adjusted to 10 with a base catalyst and mixed for 20 minutes. The VASI method synthesized MSQ aerogel-blanket composites. This method is advantageous for large-scale production as it moderates gravitational effects by applying the coating fluid perpendicular to gravity, ensuring uniform sol distribution, and enhancing properties like thermal conductivity and mechanical strength. Gelation occurs over 12 hours, followed by flushing with ethanol to remove by-products and water. The aerogel blankets are aged in ethanol, immersed in n-hexane to remove residuals, and dried in an oven at 60°C for 8 hours and 140°C for 6 hours.

2.3. Thermal Performance Tests

To evaluate the insulation performance of the produced aerogel blanket system, a spiral coil resistance heating system was installed into a pipe which is produced from Inconel steel with a thickness of 2 mm. The resistance system has 1800 W power, and it is controlled by a PID system in which the temperature of the outer surface is measured via a k-type thermocouple. When the set temperature level is reached, the system controller keeps the temperature at a constant level throughout the experiment. The system has approximately ±10ºC accuracy. In addition, the temperature distribution on the pipe and blanket surface was measured via a thermal camera system, Flir T530. In Figure 1, the test and measurement system are depicted. The thermal camera system needs to be calibrated for the emissivity value of the samples. Therefore, the temperature level measured by a thermocouple is used to calibrate the thermal camera, and the emissivity value is determined as 0.72 for the tested aerogel blanket at 580ºC.

2.2 Finite Element Modelling of Insulated Pipe

Thermal analyses were carried out via Comsol Multiphysics software to estimate the thermal performance of an aerogel blanket covered around a stainless steel pipe and compared with experimental results. The model of blanket as 3D with a diameter of 64 mm and length of 200 mm was generated. Blanket was set as a solid material for simplicity. Meshes were created using Comsol Multiphysics and hexahedral element type was used. Then, heat transfer in solids was selected as physics of analysis. As a boundary conditions, 580°C inner surface temperature is set as thermal load and, convection and radiation which mimic the experimental setup were used to apply the simulations. The emissivity and heat transfer coefficients of exposed surfaces were taken as 0.7 and 10 W/(m^2.K) respectively. The required physical properties of the aerogel for the simulations such as thermal conductivity, density and specific heat, were determined from the related tests. Moreover, thermal conductivity variation with density and temperature is obtained from literature [19]. One of the essential points for the manufacturing of the aerogel materials is the density, which can affect the thermal conductivity. In Figure 2, the variation of the thermal conductivity with respect to the density for different temperature levels is given. As can be seen from the figure, the sensitivity of thermal conductivity of the aerogel materials is very high at higher temperature levels. However, this relation decreases at lower temperatures. In addition, the variation of the thermal conductivity with temperature was depicted in Figure 2, and it increases with the temperature increase. Since this variation is remarkable with the increased temperature, thermal conductivity of the blanket domain is defined as a function which is given in Eq.1 where *a* and *b* are the constants, and the values are taken as 0.0135 and 0.0024 respectively.

Figure 1. The thermal performance test device

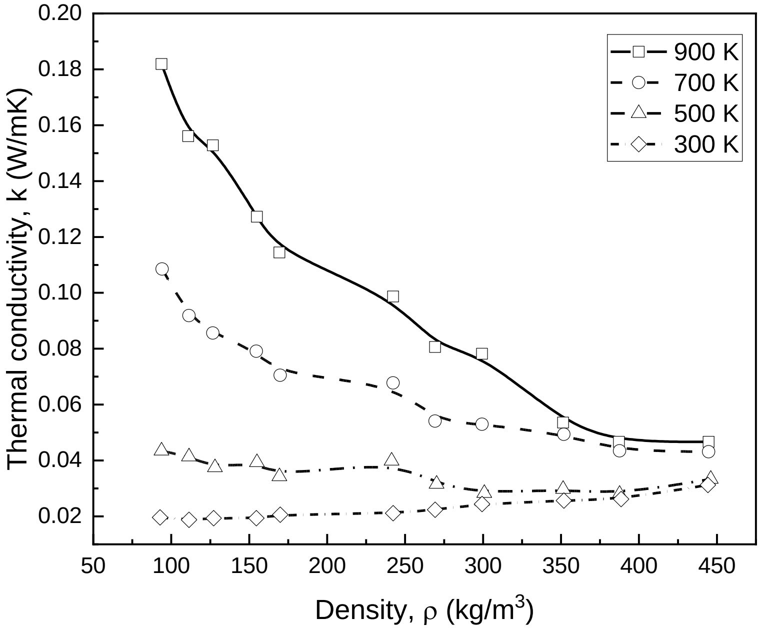

Figure 1. Thermal conductivity variation with density and temperature [19]

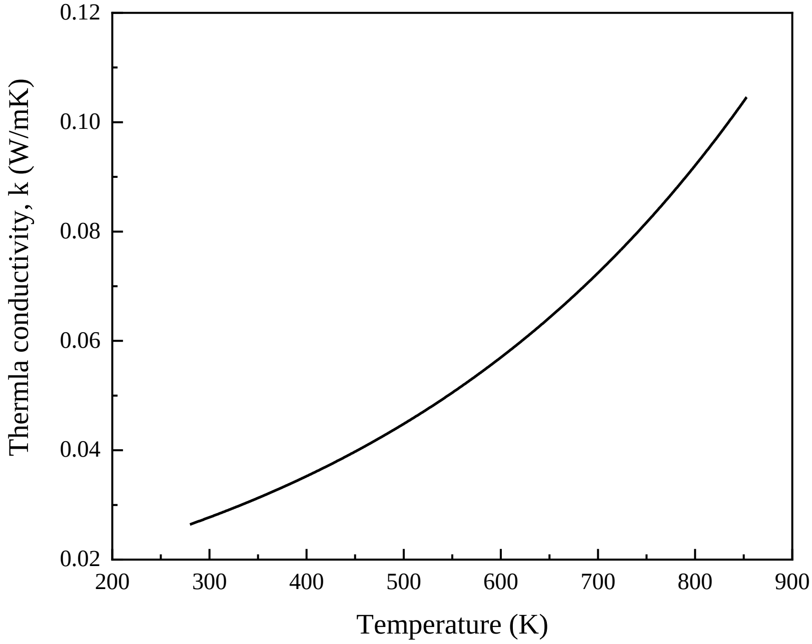

Figure 2. Thermal conductivity variation with temperature

$$k(T) = a * \exp(b * T) \tag{1}$$

Table 2. Material data

Material	10 MTMS
Density (kg/m^3)	310
Specific Heat (J/g.K)	1800

Similar to the experimental system which represents an aircraft pipeline, a cylindrical section was designed. Inconel 718 was selected as pipe material since it has common usage for such applications. To use the structural meshing technique, partition was applied to the pipe's and insulation blanket's vertical and horizontal sections which is illustrated in Figure 3. Meshed parts are shown in Figure 4. 20 elements are used along the quarter edge of pipe which means 80 elements totally for a circular edge of the pipe and blanket. Moreover, 3 elements are used through thickness direction and 50 elements throughout the length of both the blanket and metal pipe.

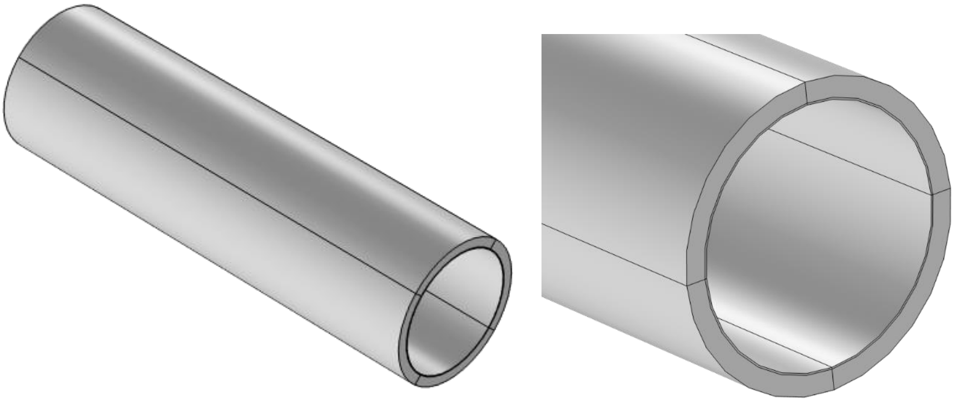

Figure 3. Geometry of metal pipe and aerogel blanket

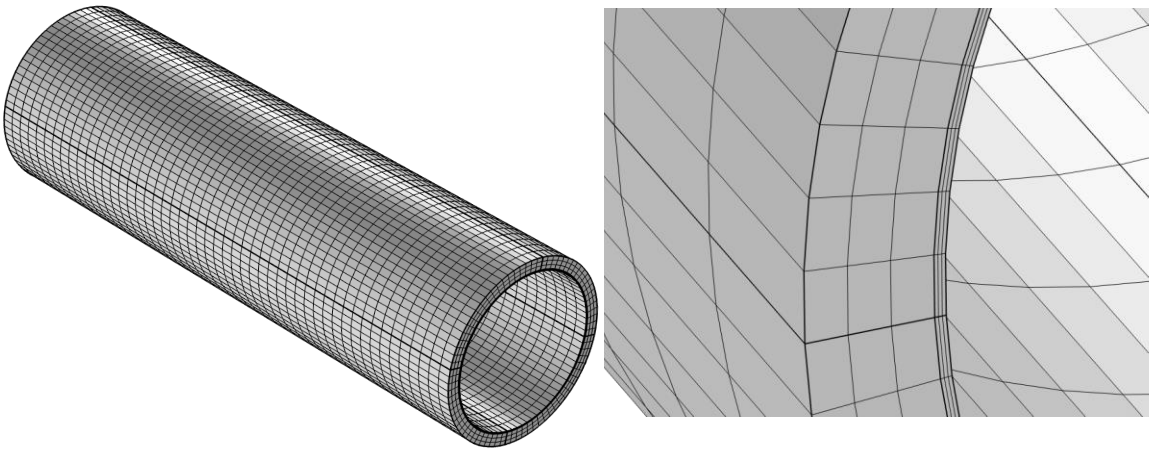

Figure 4. Model mesh structure.

3. Results and Discussion

3.1. Experimental results of insulated pipe

Thermal performance tests on the aerogel blanket insulation system were conducted at a high temperature of 580 °C. During these tests, temperatures on the surface of the aerogel blanket were monitored using a thermal camera and a K-type thermocouple system, both of which are widely used in high-temperature measurement applications due to their reliability and accuracy.

The maximum temperature recorded by the thermocouple on the outer surface of the blanket was 166 °C. This considerable difference between the inner surface temperature (580 °C) and outer surface temperature (166 °C) highlights the effectiveness of the aerogel blanket in insulating against difficult conditions since it has low thermal conductivity. Hence, it performed better than similar products in literature [20,21]

The porous structure of the aerogel blanket also means that minor peak temperatures could be detected on certain parts of the surface. These peaks likely result from variations in pore size and distribution, which can cause localized heat transfer on the surface. However, these peaks were not substantial enough to impact the overall thermal stability.

Temperature measurements were consistently taken over a 30-minute period. Throughout this time, no significant changes in the surface temperature were observed, suggesting that the aerogel blanket maintained a stable thermal barrier without degradation or fluctuations. This stability over time further reinforced the blanket's thermal insulation performance, demonstrating that it can reliably insulate against high temperatures for extended durations without losing effectiveness.

In summary, the results indicate that the aerogel blanket provides a satisfactory level of insulation, effectively protecting against high temperatures while maintaining surface stability. This characteristic makes it a promising candidate for applications requiring high thermal resistance like aerospace applications.

3.2. Numerical Results

In Figure 5, thermal response of the outer surface of 10% MTMS blanket is presented numerically. The temperature on the front face of the blanket was stabilized after 20 minutes and the outer face temperature was found as 173.04 °C numerically whereas 166 °C was experimentally recorded with a thermocouple. During the simulation there is fully thermal contact between aerogel blanket and pipe, was assumed. This assumption implies that there was no gap or air pocket between the blanket and the pipe, allowing direct heat transfer from the pipe to the blanket. By assuming full contact, any potential heat loss that might occur at the blanket-pipe interface is ignored, simplifying the simulation and focusing on the aerogel's intrinsic thermal insulation properties. Neglecting heat loss at the interface creates a more controlled model to analyze the blanket's response without needing to account for the influence of gaps or contact resistance. The 7.04 °C difference between the numerical and experimental values suggests that the simulation effectively represents the thermal behavior, with minor discrepancies possibly arising from real-world factors such as slight material inconsistencies or thermocouple precision and assumptions in the numerical model.

3.3. Discussion

The experimental and numerical results obtained in this study underscore the exceptional thermal performance of aerogel blanket insulation systems, particularly under high-temperature conditions. The significant temperature gradient observed (580 °C on the inner surface to 166 °C on the outer surface) highlights the aerogel blanket's ability to maintain effective thermal insulation. This aligns with the established literature on aerogels, which emphasizes their low thermal conductivity and high-temperature resistance, often attributed to their nanoporous structure. The minor surface temperature peaks detected during the experimental tests further corroborate the influence of microstructural heterogeneity, such as variations in pore size and distribution, on localized heat transfer. In order to overcome these peaks aerogel can be distributed on the blanket homogeneously. Moreover, the difference between numerical and experimental results can be eliminated by establishing the model closer to reality.

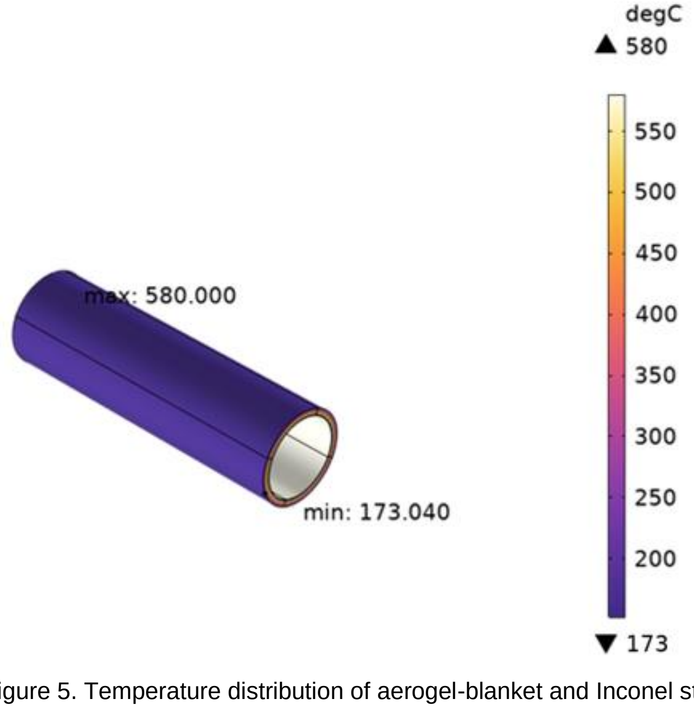

Figure 5. Temperature distribution of aerogel-blanket and Inconel steel.

4. CONCLUSION

In the study, insulation performance of the produced aerogel blanket was determined via covering a pipe made of Inconel stainless steel which mimics the exhaust system of aircrafts, experimentally and numerically. The simulation results showed good agreement with the experimental results and the maximum difference is about 4%. In addition, it is understood that the produced aerogel blanket can insulate such a hot pipe exhaust system according to requirements. Therefore, these aerogel blankets can be ideal candidates for multiple areas. For engine usage, they can effectively insulate the exhaust system, reducing heat transfer to surrounding components and improving engine thermal management. In the passenger cabin, aerogel blankets can help maintain a comfortable environment by minimizing heat intrusion from the surrounding heat sources, contributing to overall thermal comfort. Additionally, their excellent insulation properties can play a crucial role in preventing heat from avionics, shielding sensitive electronic equipment from excessive temperatures and ensuring reliable operation.

ÖZET

Hava araçlarında, uygun operasyonel koşulların sağlanması, yapısal bütünlüğün korunması, enerji tasarrufu ve maliyet konularında kazanım elde edilmesi için ısıl yalıtım isterlerinin yerine getirilmesi son derece önemlidir. Özellikle, sıcak gaz veya sıvıların geçtiği boru hatlarının dış yüzey sıcaklığının belirli bir seviyede tutulması ve böylece hava aracının optimum sıcaklık şartlarında faaliyet göstermesi kritiktir. Bu isteri sağlamak için sıklıkla kullanılan silika bazlı aerojeller yüksek performanslı ısı yalıtım malzemeleridir. Bu çalışmada, aerojel katkılandırma ile elde edilen kompozit bir yalıtım battaniyesinin deneysel ve nümerik olarak performansı incelenip havacılığa elverişliliği irdelenmiştir.

Anahtar Kelimeler: Kompozitler, Isıl yalıtım, Yalıtım malzemesi, Aerogel

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REFERENCES

1. Easa., Easy Access Rules for Large Rotorcraft (CS-29) Amendment 11, 2023. http://eur-lex.europa.eu/,.
2. N. Bheekhun, A.R. Abu Talib, M.R. Hassan., (2013) Aerogels in aerospace: An overview, Adv. Mater. Sci. Eng. 2013. https://doi.org/10.1155/2013/406065.
3. M.A. Hasan, R. Sangashetty, A.C.M. Esther, S.B. Patil, B.N. Sherikar, A. Dey., (2017) Prospect of Thermal Insulation by Silica Aerogel: A Brief Review, J. Inst. Eng. Ser. D. 98 297–304. https://doi.org/10.1007/s40033-017-0136-1.
4. M.A. Aegerter, N. Leventis, M.M. Koebel, S.A.I. Steiner., (2022) Handbook of Aerogels,.
5. Z. Sheng, Z. Liu, Y. Hou, H. Jiang, Y. Li, G. Li, X. Zhang., (2023) The Rising Aerogel Fibers: Status, Challenges, and Opportunities, Adv. Sci. 2205762 1–32. https://doi.org/10.1002/advs.202205762.
6. T. Xue, C. Zhu, X. Feng, Q. Wali, W. Fan, T. Liu., (2022) Polyimide Aerogel Fibers with Controllable Porous Microstructure for Super-Thermal Insulation Under Extreme Environments, Adv. Fiber Mater. 4 1118–1128. https://doi.org/10.1007/s42765-022-00145-8.
7. Hoseini A, Malekian A, Bahrami M., (2016) Deformation and thermal resistance study of aerogel blanket insulation material under uniaxial compression. Energy and Buildings. Oct 15;130:228-37.
8. Lakatos Á, Csík A, Csarnovics I. (2021) Experimental verification of thermal properties of the aerogel blanket. Case Studies in Thermal Engineering. Jun 1;25:100966.
9. Čubrić G, Salopek Čubrić I, Rogale D, Firšt Rogale S. (2021) Mechanical and thermal properties of polyurethane materials and inflated insulation chambers. Materials. Mar 21;14(6):1541.
10. Gama NV, Ferreira A, Barros-Timmons A. (2018) Polyurethane foams: Past, present, and future. Materials. Sep 27;11(10):1841.
11. Aditya L, Mahlia TI, Rismanchi B, Ng HM, Hasan MH, Metselaar HS, Muraza O, Aditiya HB. (2017) A review on insulation materials for energy conservation in buildings. Renewable and sustainable energy reviews. Jun 1;73:1352-65.
12. Pásztory Z. (2021) An overview of factors influencing thermal conductivity of building insulation materials. Journal of Building Engineering. Dec 1;44:102604.
13. N. Hebalkar, K.S. Kollipara, Y. Ananthan, M.K. Sudha, Nanoporous., (2019) Aerogels for Defense and Aerospace Applications,. https://doi.org/10.1007/978-3-319-73255-8_5-1.
14. X. Tang, X. Yan., (2017) Dip-coating for fibrous materials: mechanism, methods and applications, J. Sol-Gel Sci. Technol. 81 378–404. https://doi.org/10.1007/s10971-016-4197-7.
15. Y. Liu, C. Yuan, C. Liu, J. Pan, Q. Dong., (2019) Study on the resin infusion process based on automated fiber placement fabricated dry fiber preform, Sci. Rep. 1–11.

https://doi.org/10.1038/s41598-019-43982-1.
16. M. Ahlers., (2020) An Introduction to Aircraft Thermal Management,. https://doi.org/10.4271/9780768095524.
17. S.D. Sharma, L. Sowntharya, K.K. Kar., (2016) Polymer-based composite structures: Processing and applications. https://doi.org/10.1007/978-3-662-49514-8_1.
18. A. Tav, Y. Oz, · Halil, I. Akyildiz., (2023) Formation and thermo-physical properties of aerogel ceramic blanket composites synthesized via scalable atmospheric pressure process with methyltrimethoxysilane precursor, J. Porous Mater. 2023. 1 1–18. https://doi.org/10.1007/S10934-023-01521-4.
19. Qu, ZG., Fu, YD., Liu, Y., Zhou, L., (2018) "Approach for predicting effective thermal conductivity of aerogel materials through a modified lattice Boltzmann method", Applied Thermal Engineering, 132:730–9.
20. M. Ibrahim, P.H. Biwole, E. Wurts, P. Achard (2014)., A study on the thermal performance of exterior walls covered with a recently patented silica-aerogel-based insulating coating, Build. Environ. 81 112–122.
21. U. Berardi, R.H. Nosrati (2018)., Long-term thermal conductivity of aerogel-enhanced insulating materials under different laboratory aging conditions, Energy 147 1188–1202.