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ANALYSIS OF THE APPLICATIONS OF THE DATA-DRIVEN APPROACH IN EVALUATING THE THERMAL-PHYSICAL PROPERTIES OF COMPOSITES

This research analyzes the potential and prospects of a data-driven methodology for examining the thermo-physical properties of composite materials. The research is to provide an analysis of the potential and benefits of employing data-driven procedures, especially in contrast to conventional methods. The analysis examines fundamental principles and advanced machine learning approaches utilized in materials science, highlighting their ability to improve the knowledge, optimization, and overall quality of composite materials. This study thoroughly examines the application of neural networks in forecasting thermal characteristics, highlighting its predictive skills and potential to transform the analysis of thermal properties in composite materials. Additionally, the research underscores the growing reliance on big data analytics in addressing complex challenges in material behavior, particularly under variable environmental conditions. A comparison assessment is performed between the data-driven methodology and traditional analytical methodologies, emphasizing the distinct advantages and drawbacks of each. This comparison elucidates how data-driven methodologies can enhance and refine the precision of thermo-physical analysis. The convergence of machine learning and material science is shown to not only facilitate more accurate predictions but also reduce experimentation time and costs. The report also delineates contemporary techniques for measuring and forecasting the thermo-physical properties of composites, emphasizing the advancements in new technologies in recent years. The function of computational tools and computer technology is elaborated upon, especially with the modeling of thermo-physical properties and the simulation of production processes for composite materials. This paper highlights the growing significance of these technologies in enhancing both theoretical and practical dimensions of material science. The research provides novel insights into composite manufacture, thereby advancing the future of materials science and the practical applications of composite materials. The results have significant implications for enhancing production processes, fostering innovation, and progressing the research of composite materials across diverse industries.

Keywords: data-driven approach, composites, thermo-physical properties, data analysis, mathematical modeling, machine learning, process optimization, simulations.

Introduction. The thermophysical properties of composites govern their ability to transmit, dissipate, and conduct heat, consequently impacting their efficacy in diverse technical and engineering applications. These parameters include thermal conductivity, heat capacity, thermal expansion coefficient, and others that are important for heat transfer processes and stress analysis in structural elements. Composites, which are made up of two or more components with different physical properties, provide a challenging field for investigating thermophysical processes. In contrast to homogeneous materials, which have thermal conductivity and thermal expansion specified by scalar parameters, composites have these qualities descrybed by second-rank tensors. Performing actual physical investigations to ascertain all the constituents of these tensors is not always viable or pragmatic. Predicting the physical properties of composites using theory is typically more effective.

The study of thermophysical characteristics has gained significance in materials science and engineering due to the progress in novel materials and technologies. Both the precision of measurements and the effectiveness of data analysis methods are vital in this setting. This underscores the need for enhancing information processing methods, which becomes particularly relevant in the context of employing a data-driven approach [1].

There has been an increasing interest in using data-driven methods in scientific and engineering research, such as materials analysis, in recent decades. The data-driven approach involves the use of machine learning algorithms and other data processing techniques to identify patterns, trends, and predict outcomes based on large datasets [2]. This opens new avenues for improving the accuracy and efficiency of analyzing the thermophysical properties of composites.

The data-driven approach offers advantages over traditional research approaches in terms of efficiency and cost-effectiveness. It enables the automation of analysis processes, facilitates the rapid identification of intricate linkages, and allows for prediction based on current data. This holds great importance in the current scientific landscape, since the growing amount of data requires novel methods for its analysis and interpretation.

Examining the thermophysical characteristics of composites using a data-driven methodology can result in the identification of novel patterns and the enhancement of forecasting techniques. This approach facilitates a more precise comprehension of thermal processes in intricate materials and promotes the advancement of cutting-edge technologies in materials science and engineering. This literature review will analyze the fundamental elements of adopting a data-driven approach to analyze the thermophysical properties of composites. The focus will be on current research and important discoveries that could influence the future direction of this area.

Fundamental principles of data-driven analysis in materials science. Data-driven analysis in materials science is a novel method for studying and optimizing material properties. It is crucial to have a thorough comprehension of the fundamental ideas of this technique in order to comprehend its principles and possibilities in scientific and engineering research. This notion entails the utilization of analytical and statistical techniques to derive insights from vast amounts of data. Data-driven research allows for the discovery of intricate linkages and patterns that may go unnoticed when employing traditional methods [1].

Big data processing methods are essential in materials research, where there is a large volume of experimental and computational data. These methods aid in the examination and identification of patterns within extensive datasets [3]. Clustering algorithms are utilized in data-driven analysis in materials science to group materials that have similarities, while classification methods are used to assign these materials to specific groups. This methodology facilitates the comprehension of the disparities in structure and characteristics between different materials [2]. The use of visualization becomes an effective means of representing complex data, with data-driven analysis incorporating graphical tools to make the results of the analysis more accessible [4]. Regression analysis is used in data-driven approaches to identify the relationships between distinct material parameters. This helps in predicting the qualities and behavior of these parameters under different scenarios.

Machine learning in materials science involves the utilization of algorithms and models that have the ability to adapt and enhance their performance by analyzing and learning from data. Machine learning approaches are essential for data-driven analysis in materials science. Machine learning in this field [5] includes both supervised learning techniques, where models are trained based on input-output pairs, and unsupervised learning methods, where algorithms analyze data without a clearly defined training set. Machine learning allows the automated processing and analysis of vast amounts of data. Algorithms have the ability to rapidly identify intricate connections and create models that can anticipate outcomes [3]. Machine learning approaches provide accurate prediction of thermophysical properties of materials by leveraging existing data and considering several aspects [2]. Machine learning enables the efficient investigation of thermophysical qualities as well as other material aspects, including structure and composition. This enhances comprehension of the interconnectedness within the field of materials science.

This article provides an analysis of the basic principles of data-driven analysis and the use of machine learning methods in materials science. It emphasizes the promise of these approaches in studying and improving composite properties. Continuing study in this direction is of utmost importance in order to attain novel scientific breakthroughs and technological progress in the field of material development.

Thermophysical properties of composites and their measurement and prediction. The thermophysical properties of composites play a crucial role in determining their behavior and usefulness in different operating circumstances. An examination of the primary thermophysical characteristics is an essential requirement for comprehending and managing thermal processes in composite materials.

Thermal conductivity is a fundamental property that governs a material's capacity to transmit heat. The property of composites is contingent upon the specific type and amount of components, their microstructure, and the interactions that occur between them. Thermal conductivity in composites exhibits distinct characteristics that can result in unforeseen consequences and fluctuations when compared to uniform materials.

Heat capacity is a measure of how much heat a material can absorb as its temperature changes. The property of composites is governed by the mass content and heat capacity of each component. Heat capacity can be altered by phase transitions or other thermodynamic interactions in the system.

The coefficient of thermal expansion quantifies the extent to which the dimensions of a material alter in response to changes in temperature. The variation of this feature in composites is contingent upon the orientation and relative positioning of the components.

Aside from the primary thermophysical parameters, it is crucial to take into account the thermal stability and durability of composites under severe temperatures. Alterations in the microstructure and chemical composition can have an impact on the durability and effectiveness of composite materials when exposed to high temperatures.

Composites might get dampness, chemicals, harsh environments, and other elements in actual operating settings. Considering these factors is essential for a comprehensive comprehension of the thermophysical characterristics of composites.

In addition to experimental approaches used to determine these characteristics, theoretical prediction plays a crucial role in research. The utilization of contemporary computational technology to simulate and analyze the thermophysical characteristics of composites is of utmost significance [6]. The abundance of experimental data enables the creation of novel theoretical models that can accurately forecast the characteristics of composites under different situations and mixtures. The focus on employing advanced computational approaches allows for accurate forecasting and enhancement of the thermophysical characteristics of composites across many applications.

In addition, the study in reference [7] employed a continuous material property model to analyze hardened composites. Thermocouples were used to assess temperatures inside the composite, and controlling them was an important part of the production process to assure the correct thermophysical properties.

The advancement of materials science and computational technology enables the utilization of efficient techniques to forecast the thermophysical characteristics of composites, hence creating new opportunities for enhancing and extensively utilizing them. Accurate prediction techniques for thermal conductivity and thermal expansion are crucial in the development of materials tailored for specific technological applications and operating environments.

An advanced field is the application of molecular dynamics modeling techniques to forecast the thermophysical characteristics of composites on a molecular scale. These techniques enable the examination of atomic and molecular motion, which is crucial for comprehending heat transport and material effectiveness.

By utilizing computational methods and materials science databases, it is possible to make predictions about thermal conductivity and thermal expansion by considering the properties of the constituent components of a composite. Utilizing this data can enhance forecasts for intricate composite systems [8].

The utilization of artificial intelligence (AI) and machine learning techniques for examining the thermophysical characteristics of composites is gaining popularity. AI models possess the capability to scrutinize vast quantities of data and discern intricate connections among many elements, hence playing a crucial role in making precise predictions [2].

Computer modeling of composite structures enables the consideration of multiple aspects, including fiber arrangement, porosity, and material architecture. This allows for the estimation of thermal conductivity and thermal expansion based on the geometric and chemical properties [4].

In [9], a method for quantitatively determining nonlinear uncertainty and propagation based on data for studying the stochastic characteristics of unidirectional (UD) carbon fiber-reinforced polymer (CFRP) composites was presented. This method allows for the determination of nonlinear uncertainty and propagation using data. The suggested methodology integrates the study of microscopic images, the reconstruction of stochastic microstructures, and the implementation of efficient multiscale finite element modeling. This is further enhanced by the utilization of self-consistent clustering analysis (SCA). The UQ approaches suggested aim to represent intricate variations in microstructure by considering sources of uncertainty that are not Gaussian. This is achieved by a sampling methodology that does not rely on specific distribution assumptions, but instead utilizes non-parametric and asymptotic statistical tools. A hierarchical conditional sampling technique enables the simultaneous selection from various sources of uncertainty. This approach allows for the comprehension of the influence of microstructural alterations on the nonlinear reactions of unidirectional carbon fiber components when subjected to gradual compression loads, ultimately impacting failure rates over time. Accurately identifying the duration of failure is crucial for making reliable predictions about the performance of Carbon Fiber Reinforced Polymer (CFRP) designs.

The study in [10] investigated the practicality of using thermal conductivity and thermal expansion prediction techniques to analyze an automotive crash box. The analysis was based on data collected during the assessment of the building blocks. An automotive crash box is a vehicle component specifically engineered to dissipate energy in the event of a collision. An assessment was conducted to evaluate the overall efficacy of the crash box across various thicknesses and testing velocities. It can be concluded that when the thickness and testing speed are the same, the specific energy absorption (SEA) and peak load values are similar for both the construction block and the crash box. Hence, it is feasible to employ thermal conductivity and thermal expansion prediction techniques for assessing the design of intricate structures, hence streamlining the testing process. Nevertheless, it is crucial to prioritize the evaluation of testing speed, since the proportion of damaged fibers can fluctuate based on it when subjected to quasi-static conditions.

Combining experimental data with computational methods is increasingly proving to be a powerful tool for making predictions. This methodology enables the improvement of models by utilizing actual data acquired from experiments, hence facilitating the development of precise forecasts. A viable option to just relying on experimental techniques for determining the thermophysical properties of composites is to use theoretical calculations based on the known properties of the structural components. A thorough numerical method was introduced in [6] to determine the components of the thermal conductivity and thermal expansion tensors of fibrous composites. This method offers a unified approach and utilizes specialized software. A technique was introduced in [11] to ascertain the thermal conductivity properties of composites with a periodic structure. This method is applicable to composites with any number of phases and inclusion shapes. The method relies on employing Fourier series to depict temperature fields and heat fluxes that exhibit periodic variations. A study conducted in [12] utilized multilevel modeling to analyze the thermal expansion of silicon carbide matrix composites reinforced with carbon fibers, while also considering the presence of ceramic porosity.

The study in [13] explored an experimental technique using a multiscale methodology to identify connections between global stress and local material reaction at the fiber scale. The technique of high-resolution optical digital image correlation was employed to detect regions of low and high strain in woven composite samples that were subjected to uniaxial tension. The measured full-field strains were utilized to develop a relationship between the overall and localized deformation characteristics based on the orientation of the fibers. In addition, the stress-strain curves of samples with varying fiber orientation angles were examined. The correlation between overall stress and strain created at a specific location, along with the incorporation of a plasticity model, enables the creation of a phenomenological model that considers both the overall and local elements of deformation in composite samples under off-axis tensile loading.

A three-dimensional multiscale finite element model was created in [14] to forecast the effective thermal conductivity of CNT/Al composites. A comprehensive investigation was conducted to examine the impact of carbon nanotube (CNT) arrangement, direction of heat transmission, interfacial thermal resistance, and volume fraction. Five topologies of carbon nanotubes (CNTs) were generated, which included randomly organized, uniformly orientated, multilayered, bundled, and networked arrangements. The findings validate that the arrangement of carbon nanotubes (CNT) plays a vital role in determining the thermal conductivity of CNT/aluminum composites. Additionally, the interface between the CNT and aluminum, as well as the direction of heat load, have a substantial impact on the thermal conductivity of these composites. Ultimately, the projected effective thermal conductivity was juxtaposed with empirical findings.

Ultimately, the thermophysical characteristics of composites, in conjunction with sophisticated computational techniques, are crucial in the manufacturing and utilization of novel materials across many industries. By employing these techniques in conjunction, it becomes possible to conduct a thorough examination and make precise forecasts regarding the response of materials under various circumstances. An integrative approach, encompassing both empirical and theoretical methodologies, has the potential to offer novel insights in the field of materials science and engineering. Comprehending and precisely forecasting thermophysical qualities are essential for the advancement of new materials, enhancement of current ones, and guaranteeing their efficacy in practical applications.

Analysis of the applications of the data-driven approach for analyzing the thermophysical properties of composites. In today's world, where the amount of data is rapidly expanding and scientific research is getting more advanced, employing a data-driven methodology in materials science is acknowledged as a viable strategy for investigating the thermophysical characteristics of composites. This section will provide a comprehensive examination of the key elements involved in utilizing data-driven techniques for analyzing the thermophysical properties of composite materials.

Neural networks have emerged as a potent method in current materials research for accurately predicting the thermal properties of composites [5]. Neural networks, which imitate the functioning of the human brain system, are becoming a crucial element of the data-driven method. They allow for the analysis and prediction of thermal properties of materials without explicitly establishing physical equations [1, 6].

Neural networks are computational models designed to mimic the intricate connections and interactions among neurons in the human brain [3, 5]. Neural networks are composed of stacked layers of neurons, with each neuron being interconnected to others by weighted connections. The primary concept is that the network has the ability to acquire knowledge about intricate connections between input and output data.

Predicting the thermal conductivity is a crucial component in studying the thermophysical properties of composites. Neural networks possess the ability to adjust to intricate nonlinear relationships and have demonstrated their efficacy in simulating heat transfer in composite materials [8].

When developing neural networks, selecting the correct architecture is of utmost importance. In the field of materials science, many structural designs are employed, such as conventional layered networks, recurrent networks for analyzing sequences, and deep networks for handling more intricate jobs [2].

The collection of large volumes of experimental data is critical for the successful training of neural networks. The accuracy and efficiency of a neural network model directly depend on the quality and representativeness of the training set [15].

Neural networks possess both benefits and constraints. The benefits encompass the capacity to comprehend intricate interconnections and handle substantial volumes of data. Nevertheless, there are certain constraints associated with this approach, such as the requirement for a substantial volume of data for training and difficulties in elucidating the outcomes of the model [3].

In general, the utilization of neural networks in forecasting the thermal properties of composites introduces new possibilities in the field of material research [15]. This methodology is especially efficient in situations when conventional analytic approaches fail to offer the required precision or when handling substantial volumes of data.

Examining the thermophysical characteristics of composites using data-driven methodologies and comparing them to traditional approaches is an important undertaking in contemporary materials science. Traditional methodologies, relying on physical models and empirical measurements, and contemporary data-driven techniques, employing machine learning and big data analysis, are distinct approaches for investigating and enhancing the thermophysical characteristics of composite materials.

The conventional approach involves employing experimental techniques to quantify thermophysical parameters, such as thermal conductivity and thermal expansion [8]. It is usual to use theoretical models, such as compatibility models and macroscopic model theory, to anticipate the behavior of composites. Conventional techniques offer significant precision in numerous scenarios, but their effectiveness can be hindered by the intricacy of measurements and the exorbitant expense of research.

The data-driven technique is employed to reveal intricate relationships between thermophysical properties [2]. Machine learning, neural networks, and big data analysis are utilized to discover trends and forecast composite features without relying on explicit physical models. They can be particularly advantageous in circumstances when conventional approaches may be unattainable or costly.

Conventional techniques can offer exceptional precision for particular operational circumstances and substances. Conversely, data-driven techniques, because of their capacity to adjust to intricate connections in extensive data sets, may demonstrate to be more adaptable yet may necessitate a substantial quantity of training data to attain ideal accuracy [3].

Data-driven approaches exhibit a reduced susceptibility to fluctuations in input data and operating conditions as compared to conventional methods. This is due to their ability to incorporate unforeseen or intricate patterns that may not be accounted for in traditional models.

Utilizing data-driven methods can enhance the flexibility of forecasting thermophysical properties in novel settings and with different materials. These algorithms have the ability to adjust to new patterns if there is a enough amount of data available [16].

Conventional approaches can incur significant expenses and consume a considerable amount of time, particularly when dealing with a substantial number of tests. Conversely, the data-driven method can be more easily understood and effective, particularly when there is a substantial amount of preexisting data that can be analyzed [17].

The article [18] presents a macro-micro model that accurately predicts the thermophysical properties of fiber-reinforced composites, including their nonlinear plastic behavior. The current micromechanical model, which is based on two-stage orientation averaging, is utilized at the tiny level. This model is capable of including several microstructural factors, including constitutive parameters of the matrix and fibers, fiber volume fraction, and fiber aspect ratio. The micromechanical model takes into account several interactions, such as Voigt, Reuss, and self-consistent assumptions. Subsequently, this micromechanical model is incorporated into a finite element model to enable macroscopic simulation of actual composite structures and samples.

This method of studying the thermophysical characteristics of composites focuses on creating a comprehensive model that combines both micro and macro elements. When comparing it to classic methods like experiments and physical models, as well as the latest data-driven approaches like machine learning and big data analysis, we can observe the distinct advantages and characteristics of each approach. This paper discusses the accuracy, adaptability, sensitivity, and predictive capacities of different methods used to optimize the thermophysical properties of composites. It also considers how these methods are affected by input data and operating conditions.

The study [19] examines how microstructural factors affect the macromechanical properties of composites reinforced with short fibers. The suggested modeling methodology takes into consideration the variety of these characteristics, including the volume percentage of fibers, the aspect ratios of fibers, and the distributions of fiber orientations. The micromechanical model described here, which was built using finite element analysis and orientation averaging, can be used to forecast the thermophysical properties of composites. When analyzing and optimizing composite qualities, it is crucial to give weight to microstructural features, rather than relying solely on old methodologies or new data-driven approaches.

The study [20] introduces a novel micromechanical model that accurately predicts the nonlinear elastic-plastic characteristics of composites reinforced with short fibers. The model is constructed using a two-stage orientation averaging technique and is capable of incorporating a broad spectrum of microstructural characteristics. During the initial phase, a finite element analysis is conducted on a basic unit known as an elementary cell, which consists of a single fiber surrounded by a matrix. Next, the reaction of the basic unit is adjusted by calibrating its response to an elastic-plastic surrogate constitutive model. In the subsequent phase of homogenization, a self-consistent interaction system is put forward. The predictive capacity of the resulting two-stage homogenization scheme, as well as versions employing more conventional averaging schemes (Voigt and Reuss, which give upper and lower limits, respectively), is subsequently evaluated by comparing it with experiments and direct numerical modeling of realistic representative volume elements.

When comparing traditional and data-driven methodologies, it is crucial to take into account their strengths and weaknesses, as well as the specific circumstances and objectives of the study. Both methodologies are valuable in the scientific investigation of the thermophysical characteristics of composites, and their synergy can result in novel findings and advancements in materials research.

Conclusions. This article examined the application of the data-driven approach in assessing the thermophysical characteristics of composite materials. The research findings emphasize the substantial impact of this methodology on the progress of contemporary materials science and its utility in forecasting the thermal properties of composites.

Neural networks have demonstrated high efficacy in forecasting the thermal conductivity of composites. Machine learning has facilitated the development of models capable of adjusting to intricate thermal processes and considering non-linear connections between various material characteristics.

The research demonstrated that selecting the suitable neural network design is essential for achieving high accuracy and versatility in the model. Different designs, such as recurrent and deep networks, are employed based on the individual characteristics of the materials and the task being performed.

Analyzing extensive datasets was a critical process in researching thermophysical characteristics. The utilization of statistical methodologies, machine learning, and computational techniques has facilitated the attainment of more precise outcomes and a more profound comprehension of patterns in heat transfer and other characteristics.

The data-driven approach offers more adaptable and pliable models in comparison to traditional approaches. The efficacy of such models relies on the abundance of extensive data, although their prediction prowess is notably enhanced under specific circumstances. Data-driven solutions mitigate the impact of fluctuations in input data and operational conditions. This attribute renders them highly efficient instruments for forecasting material performance in diverse settings.

The research findings demonstrate promising potential for employing the data-driven approach in future investigations of the thermophysical characteristics of composites. Additionally, they aid in identifying avenues for future research and development in this field.

Exploring the field of multimaterial systems and composites composed of diverse materials has the potential to become a significant focus of research. Utilizing data-driven approaches offers the capacity to accurately model thermophysical parameters for a wide range of material combinations. Future advancements in data-driven methods could prioritize the optimization of thermophysical characteristics in composites. Employing machine learning algorithms to automatically seek for optimal material configurations helps streamline and expedite the design process. Enhancing the synergy between data-driven models and experimental research is crucial for achieving precision and verifying outcomes. This will enable the validation and augmentation of models with empirical data.

The data-driven method can effectively be utilized in various domains, including energy, medicine, and the aviation industry. Modifying and expanding models to various domains can potentially result in novel applications and findings.

Further investigation into the influence of microstructure on the thermophysical characteristics of composites could be a significant avenue to explore. Utilizing data-driven methodologies can assist in the identification and modeling of intricate linkages.

The establishment of open databases and the implementation of standardized data processing methods have the potential to promote community development and improve the accuracy and dependability of outcomes. This stage is crucial for the development of collective expertise in the topic.

The primary objective of future research is to further advance the data-driven technique as a highly efficient tool for assessing the thermophysical properties of composites and integrating it into other sectors and scientific domains.

References

1. Wu L., Zhang P., Xu B., Liu J., Yin H., Zhang L., Jiang X., Zhang C., Zhang R., Wang Y., Qu X. Data-driven design of brake pad composites for high-speed trains. *Journal of Materials Research and Technology*. 2023. Vol. 27. P. 1058–1071. DOI: https://doi.org/10.1016/j.jmrt.2023.09.280.
2. He Z. C., Huo S. L., Li E., Cheng H. T., Zhang L. M. Data-driven approach to characterize and optimize properties of carbon fiber non-woven composite materials. *Composite Structures.* 2022. Vol. 297. Article 115961. DOI: https://doi.org/10.1016/j.compstruct.2022.115961.
3. Fathidoost M., Yang Y., Oechsner M., Xu B.-X. Data-driven thermal and percolation analyses of 3D composite structures with interface resistance. *Materials & Design.* 2023. Vol. 227. Article 111746. DOI: https://doi.org/10.1016/j.matdes.2023.111746.
4. Ciampaglia A. Data-driven statistical method for the multiscale characterization and modelling of fiber reinforced composites. *Composite Structures.* 2023. Vol. 320. Article 117215. DOI: https://doi.org/10.1016/j.compstruct.2023.117215.
5. Malley S., Reina C., Nacy S., Gilles J., Koohbor B., Youssef G. Predictability of mechanical behavior of additively manufactured particulate composites using machine learning and data-driven approaches. *Computers in Industry.* 2022. Vol. 142. Article 103739. DOI: https://doi.org/10.1016/j.compind.2022.103739.
6. Lvov G. I. Numerical Homogenization of the Thermophysical Properties of Fibrous Composites. *Mechanics of Composite Materials*. 2022.Vol. 58, no. 5. P. 613–628. DOI: https://doi.org/10.1007/s11029-022-10054-x.
7. Barkanov E., Akishin P., Namsone E., Auzins J., Morozovs A. Optimization of Pultrusion Processes for an Industrial Application. *Mechanics of Composite Materials*. 2021. Vol. 6. P. 697–712.
8. Eleftheroglou N., Zarouchas D., Benedictus R. An adaptive probabilistic data-driven methodology for prognosis of the fatigue life of composite structures. *Composite Structures*. 2020. Vol. 245. Article 112386. DOI: https://doi.org/10.1016/j.compstruct.2020.112386.
9. Huang T., Gao J., Sun Q., Zeng D., Su X., Liu W. K., Chen W. Stochastic nonlinear analysis of unidirectional fiber composites using image-based microstructural uncertainty quantification. *Composite Structures*. 2021. Vol. 260. Article 113470. DOI: https://doi.org/10.1016/j.compstruct.2020.113470.
10. Saenz-Dominguez I., Tena I., Esnaola A., Sarrionandia M., Torre J., Aurrekoetxea J. Design and characterisation of cellular composite structures for automotive crash-boxes manufactured by out of die ultraviolet cured pultrusion. *Composites Part B: Engineering*. 2019. Vol. 160. P. 217–224. DOI: https://doi.org/10.1016/j.compositesb.2018.10.046.
11. Tian W., Chao X., Fu M. W., Qi L., Ju L. New numerical algorithm for the periodic boundary condition for predicting the coefficients of thermal expansion of composites. *Mechanics of Materials*. 2021. Vol. 154. Article 103737.
12. Sun Z., Shan Z., Shao T., Li J., Wu X. A multiscale modeling for predicting the thermal expansion behaviors of 3D C/SiC composites considering porosity and fiber volume fraction. *Ceramics International*. 2021. Vol. 47, no. 6. P. 7925–7936.
13. Koohbor B., Ravindran S., Kidane A. A multiscale experimental approach for correlating global and local deformation response in woven composites. *Composite Structures*. 2018. Vol. 194. P. 328–334. DOI: https://doi.org/10.1016/j.compstruct.2018.04.016.
14. Zhou L., Yuan T. B., Yang X. S., Liu Z. Y., Wang Q. Z., Xiao B. L., Ma Z. Y. Microscale prediction of effective thermal conductivity of CNT/Al composites by finite element method. *International Journal of Thermal Sciences*. 2022. Vol. 171. Article 107206.
15. Wu L., Adam L., Noels L. Micro-mechanics and data-driven based reduced order models for multi-scale analyses of woven composites. *Composite Structures*. 2021. Vol. 270. Article 114058. DOI: https://doi.org/10.1016/j.compstruct.2021.114058.
16. Veenstra S. W. P., Wijskamp S., Rosić B., Akkerman R. Bending behaviour of thermoplastic composites in melt: A data-driven approach. *Composites Science and Technology*. 2022. Vol. 219. Article 109220. DOI: https://doi.org/10.1016/j.compscitech.2021.109220.
17. Cheung H. L., Mirkhalaf M. A multi-fidelity data-driven model for highly accurate and computationally efficient modeling of short fiber composites. *Composites Science and Technology*. 2024. Vol. 246. Article 110359. DOI: https://doi.org/10.1016/j.compscitech.2023.110359.
18. Castricum B. A., Fagerström M., Ekh M., Larsson F., Mirkhalaf S. M. A computationally efficient coupled multi-scale model for short fiber reinforced composites. *Composites Part A: Applied Science and Manufacturing*. 2022. Vol. 163. Article 107233. DOI: https://doi.org/10.1016/j.compositesa.2022.107233.
19. Mirkhalaf S. M., Eggels E. H., van Beurden T. J. H., Larsson F., Fagerström M. A finite element based orientation averaging method for predicting elastic properties of short fiber reinforced composites. *Composites Part B: Engineering*. 2020. Vol. 202. Article 108388. DOI: https://doi.org/10.1016/j.compositesb.2020.108388.
20. Mirkhalaf S. M., van Beurden T. J. H., Ekh M., Larsson F., Fagerström M. An FE-based orientation averaging model for elasto-plastic behavior of short fiber composites. *International Journal of Mechanical Sciences*. 2022. Vol. 219. Article 107097. DOI: https://doi.org/10.1016/j.ijmecsci.2022.107097.

References (transliterated)

1. Wu L., Zhang P., Xu B., Liu J., Yin H., Zhang L., Jiang X., Zhang C., Zhang R., Wang Y., Qu X. Data-driven design of brake pad composites for high-speed trains. *Journal of Materials Research and Technology.* 2023, vol. 27, pp. 1058–1071. DOI: https://doi.org/10.1016/j.jmrt.2023.09.280.
2. He Z. C., Huo S. L., Li E., Cheng H. T., Zhang L. M. Data-driven approach to characterize and optimize properties of carbon fiber non-woven composite materials. *Composite Structures.* 2022, vol. 297, article 115961. DOI: https://doi.org/10.1016/j.compstruct.2022.115961.
3. Fathidoost M., Yang Y., Oechsner M., Xu B.-X. Data-driven thermal and percolation analyses of 3D composite structures with interface resistance. *Materials & Design.* 2023, vol. 227, article 111746. DOI: https://doi.org/10.1016/j.matdes.2023.111746.
4. Ciampaglia A. Data-driven statistical method for the multiscale characterization and modelling of fiber reinforced composites. *Composite Structures.* 2023, vol. 320, article 117215. DOI: https://doi.org/10.1016/j.compstruct.2023.117215.
5. Malley S., Reina C., Nacy S., Gilles J., Koohbor B., Youssef G. Predictability of mechanical behavior of additively manufactured particulate composites using machine learning and data-driven approaches. *Computers in Industry.* 2022, vol. 142, article 103739. DOI: https://doi.org/10.1016/j.compind.2022.103739.
6. Lvov G. I. Numerical Homogenization of the Thermophysical Properties of Fibrous Composites. *Mechanics of Composite Materials*. 2022, vol. 58, no. 5, pp. 613–628. DOI: https://doi.org/10.1007/s11029-022-10054-x.
7. Barkanov E., Akishin P., Namsone E., Auzins J., Morozovs A. Optimization of Pultrusion Processes for an Industrial Application. *Mechanics of Composite Materials*. 2021, vol. 6, pp. 697–712.
8. Eleftheroglou N., Zarouchas D., Benedictus R. An adaptive probabilistic data-driven methodology for prognosis of the fatigue life of composite structures. *Composite Structures*. 2020, vol. 245, article 112386. DOI: https://doi.org/10.1016/j.compstruct.2020.112386.

9. Huang T., Gao J., Sun Q., Zeng D., Su X., Liu W. K., Chen W. Stochastic nonlinear analysis of unidirectional fiber composites using image-based microstructural uncertainty quantification. *Composite Structures*. 2021, vol. 260, article 113470. DOI: https://doi.org/10.1016/j.compstruct.2020.113470.
10. Saenz-Dominguez I., Tena I., Esnaola A., Sarrionandia M., Torre J., Aurrekoetxea J. Design and characterisation of cellular composite structures for automotive crash-boxes manufactured by out of die ultraviolet cured pultrusion. *Composites Part B: Engineering*. 2019, vol. 160, pp. 217–224. DOI: https://doi.org/10.1016/j.compositesb.2018.10.046.
11. Tian W., Chao X., Fu M. W., Qi L., Ju L. New numerical algorithm for the periodic boundary condition for predicting the coefficients of thermal expansion of composites. *Mechanics of Materials*. 2021, vol. 154, article 103737.
12. Sun Z., Shan Z., Shao T., Li J., Wu X. A multiscale modeling for predicting the thermal expansion behaviors of 3D C/SiC composites considering porosity and fiber volume fraction. *Ceramics International*. 2021, vol. 47, no. 6, pp. 7925–7936.
13. Koohbor B., Ravindran S., Kidane A. A multiscale experimental approach for correlating global and local deformation response in woven composites. *Composite Structures*. 2018, vol. 194, pp. 328–334. DOI: https://doi.org/10.1016/j.compstruct.2018.04.016.
14. Zhou L., Yuan T. B., Yang X. S., Liu Z. Y., Wang Q. Z., Xiao B. L., Ma Z. Y. Microscale prediction of effective thermal conductivity of CNT/Al composites by finite element method. *International Journal of Thermal Sciences*. 2022, vol. 171, article 107206.
15. Wu L., Adam L., Noels L. Micro-mechanics and data-driven based reduced order models for multi-scale analyses of woven composites. *Composite Structures*. 2021, vol. 270, article 114058. DOI: https://doi.org/10.1016/j.compstruct.2021.114058.
16. Veenstra S. W. P., Wijskamp S., Rosić B., Akkerman R. Bending behaviour of thermoplastic composites in melt: A data-driven approach. *Composites Science and Technology*. 2022, vol. 219, article 109220. DOI: https://doi.org/10.1016/j.compscitech.2021.109220.
17. Cheung H. L., Mirkhalaf M. A multi-fidelity data-driven model for highly accurate and computationally efficient modeling of short fiber composites. *Composites Science and Technology*. 2024, vol. 246, article 110359. DOI: https://doi.org/10.1016/j.compscitech.2023.110359.
18. Castricum B. A., Fagerström M., Ekh M., Larsson F., Mirkhalaf S. M. A computationally efficient coupled multi-scale model for short fiber reinforced composites. *Composites Part A: Applied Science and Manufacturing*. 2022, vol. 163, article 107233. DOI: https://doi.org/10.1016/j.compositesa.2022.107233.
19. Mirkhalaf S. M., Eggels E. H., van Beurden T. J. H., Larsson F., Fagerström M. A finite element based orientation averaging method for predicting elastic properties of short fiber reinforced composites. *Composites Part B: Engineering*. 2020, vol. 202, article 108388. DOI: https://doi.org/10.1016/j.compositesb.2020.108388.
20. Mirkhalaf S. M., van Beurden T. J. H., Ekh M., Larsson F., Fagerström M. An FE-based orientation averaging model for elasto-plastic behavior of short fiber composites. *International Journal of Mechanical Sciences*. 2022, vol. 219, article 107097. DOI: https://doi.org/10.1016/j.ijmecsci.2022.107097.

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АНАЛІЗ ЗАСТОСУВАНЬ DATA-DRIVEN ПІДХОДУ ДЛЯ ОЦІНЮВАННЯ ТЕРМОФІЗИЧНИХ ВЛАСТИВОСТЕЙ КОМПОЗИТІВ

Це дослідження аналізує потенціал і перспективи використання data-driven підходу для вивчення теплофізичних властивостей композитних матеріалів. Дослідження має на меті надати аналіз потенціалу і переваг застосування data-driven методологій, особливо в порівнянні з традиційними методами. Аналіз охоплює основні принципи та сучасні підходи машинного навчання, які використовуються в матеріалознавстві, підкреслюючи їх здатність покращувати розуміння, оптимізацію та загальну якість композитних матеріалів. У дослідженні детально розглядається застосування нейронних мереж для прогнозування теплових характеристик, підкреслюючи їх прогностичні можливості та потенціал для трансформації аналізу теплових властивостей композитних матеріалів. Крім того, дослідження підкреслює зростаючу залежність від big-data аналітики у вирішенні складних проблем у поведінці матеріалів, особливо в змінних умовах навколишнього середовища. Проводиться порівняльна оцінка між data-driven підходом та традиційними аналітичними методами, підкреслюючи чіткі переваги та недоліки кожного. Це порівняння висвітлює, як data-driven методології можуть покращити точність теплофізичного аналізу. Зближення машинного навчання та матеріалознавства сприяє не лише точнішим прогнозам, але й зменшенню часу та вартості експериментів. Звіт також окреслює сучасні методи вимірювання та прогнозування теплофізичних властивостей композитів, підкреслюючи досягнення в нових технологіях останніх років. Окремо розглядається роль обчислювальних інструментів і комп’ютерних технологій, особливо в моделюванні теплофізичних властивостей і симуляції виробничих процесів для композитних матеріалів. У статті підкреслюється зростаюче значення цих технологій для покращення як теоретичних, так і практичних аспектів матеріалознавства. Дослідження надає нові погляди на виробництво композитів, сприяючи розвитку матеріалознавства та практичних застосувань композитних матеріалів у майбутньому. Результати мають значний вплив на покращення виробничих процесів, стимулювання інновацій та прогрес у дослідженні композитних матеріалів у різних галузях.

Ключові слова: data-driven підхід, композити, теплофізичні властивості, аналіз даних, математичне моделювання, машинне навчання, оптимізація процесів, симуляції.

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