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Impact of Thermal Insulation on Vehicle Cabin Heat Loads and Energy Use

Hasnaa Oubnaki [1*], Charifa Haouraji [2], Ilham Mounir[3], Badia Mounir[4], Abdelmajid Farchi[5].

[1,2,5]IMMI Laboratory, Faculty of sciences and techniques, Hassan 1st University Settat, Morocco.
[3,4]LAPSSII Laboratory, Graduate School of Thechnology, Safi, Morocco.

E-*mail:* [1]h.oubnaki@uhp.ac.ma ,[2]haouraji.charifa@gmail.com ,[3]i.mounir@uca.ac.ma ,[4]b.mounir@uca.ac.ma , [5]abdelmajid.farchi1@gmail.com .

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KEYWORDS

Automobile cabin; CFD; Energy; Thermal insulation; Optimization.

ABSTRACT

A car's passenger cabin's heating, ventilation, and air conditioning system is the biggest auxiliary charge, other than the primary traction charge. It may cause a vehicle with a motor to increase its energy consumption by up to 25%. The main factor contributing to the passenger compartment's excessive warmth is the car's exposure to maximum sun radiation. The goal of this study is to predict the thermal loads of the studied vehicle. Indeed, energy-saving measures such as using various types of insulating and storing materials have been implemented in this paper to predict their impact on the vehicle's interior thermal loads.

The inside fluid domain of a cabin was modeled and simulated using CATIA and FLUENT to investigate the temperature drop in the car's cabin based on their thermal characteristics. Computational Fluid Dynamics (CFD) simulations were used Using a vehicle cabin CFD model that was verified by climatic measurements, simulation information covering the full range of boundary conditions that affect thermal loads was methodically generated. The results strongly supported the CFD study, highlighting its effectiveness in analyzing the key parameters impacting the internal thermal loads. They reveal that aerogel polymers are distinguished by a significantly superior insulating capacity, reducing energy consumption by up to 40% compared to existing materials. These findings pave the way for adopting highly economical and well-optimized vehicles.

*Corresponding author.

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أثر العزل الحراري على أحمال الحرارة في مقصورة المركبة واستهلاك الطاقة

حسناء أوبناكي , شريفة حوراجي , إلهام منير, بديعة منير, عبد المجيد الفارشي.

ملخص: يُعد نظام التدفئة والتهوية وتكييف الهواء في مقصورة ركاب السيارة أكبر شحنة مساعدة، بخلاف شحنة الجر الأساسية. وقد يتسبب ذلك في زيادة استهلاك السيارة ذات المحرك للطاقة بنسبة تصل إلى 25٪. والعامل الرئيسي الذي يساهم في ارتفاع درجة حرارة مقصورة الركاب هو تعرض السيارة لأقصى قدر من إشعاع الشمس. تهدف هذه الدراسة إلى التنبؤ بالأحمال الحرارية للمركبة المدروسة. في الواقع، تم تنفيذ تدابير توفير الطاقة مثل استخدام أنواع مختلفة من مواد العزل والتخزين في هذه الورقة للتنبؤ بتأثيرها على الأحمال الحرارية الداخلية للمركبة. تم نمذجة ومحاكاة المجال السائل الداخلي للمقصورة باستخدام CATIA وFLUENT للتحقيق في انخفاض درجة الحرارة في مقصورة السيارة بناءً على خصائصها الحرارية. تم استخدام عمليات محاكاة ديناميكا الموائع الحسابية (CFD) باستخدام نموذج ديناميكا الموائع الحسابية لمقصورة السيارة الذي تم التحقق منه من خلال القياسات المناخية، وتم توليد معلومات المحاكاة التي تغطي النطاق الكامل للظروف الحدودية التي تؤثر على الأحمال الحرارية بشكل منهجي. دعمت النتائج بقوة دراسة ديناميكا الموائع الحسابية، مسلطةً الضوء على فعاليتها في تحليل العوامل الرئيسية المؤثرة على الأحمال الحرارية الداخلية. وكشفت أن polymer Aerogels تتميز بقدرة عزل فائقة، مما يقلل استهلاك الطاقة بنسبة تصل إلى 40 % مقارنةً بالمواد الحالية. تُمهد هذه النتائج الطريق لاعتماد مركبات اقتصادية للغاية ومُحسّنة.

الكلمات المفتاحية – كابينة السيارة؛ ديناميكا الموائع الحسابية؛ الطاقة؛ العزل الحراري؛ التحسين.

1. INTRODUCTION

Since almost all cars now have air conditioning, it has become a necessary element of contemporary automobiles [1]. During hot summer months, 5–15% of the energy needed for vehicle propulsion may be used for air cooling [2]. Drivers need warmth rather than cooling in colder climates. The range of the electric vehicle may be greatly reduced if direct electrical heating through resistive parts is powered by battery power [3]. For instance, cold weather can reduce an EV's range by up to 50% due to the energy required to heat both the cabin and the batteries [4].

In order to maximize the efficiency of the heating system in automobiles, it is critical to recognize that solar radiation and ambient temperature are important heat sources that impact passenger vehicles comfort [5]. Hence, controlling the flow of heat via the car's external surfaces is essential [6]. Indeed, the windows and interior wall surfaces allow solar radiation to enter the vehicle compartment both directly and indirectly. Due to this, the cabin air temperature increases [7].

Several investigations have examined how to anticipate the interior temperature of a car using models or experimental testing to improve thermal comfort [8]. Additionally, many studies address the characteristics of car surfaces, such as the kind of windows and walls, as well as the vehicle's overall design. A heating technique was developed by R. B. Farrington et al. [9] to quantify the energy of solar radiation that solar-reflective glazing rejects. Additionally, they took measurements of soak temperatures in several car models with various glass configurations. They also forecasted how improved glass will affect the vehicle's occupants' thermal comfort. C. Croitoru et al. [10] investigated comfort and thermal environment models for vehicles by combining thermal psychological models with cabin CFD simulations. However, they had to use manikins, which took a lot of time and money, because of computational limitations. J. W. Lee Lee et al. [11] investigated how temperature and airflow in an automobile cabin are affected by spectrum sun radiation. They discovered through CFD simulations that the spectrum distribution of light caused the temperature to rise by 3°C, emphasizing how crucial it is to take this effect into account for precise thermal conditions and airflow forecast. W. Huo et al. [12] investigated a car's cabin's thermal comfort using CFD, and assessed how the field synergy angle affected heat distribution. They discovered that heat transmission performance is enhanced by a smaller synergy angle. H. Krishnaswamy et al. [13] investigate how vehicle structure affects air conditioning efficiency. They alter a small, low-cost Indian automobile by moving the air conditioner's outlet. I. Nastase et al. [14] investigate the thermal comfort of passengers in automobiles, with an emphasis on electric vehicles (EVs). They discuss current norms, ideas of thermal comfort, and the unique difficulties faced by EVs. They emphasize in their conclusion the necessity of modifying thermal comfort requirements to account for the particularities of EV cabins. Hariharan. C et al. [5] use CFD simulation to examine how a vehicle's HVAC system affects energy consumption. In order to lower cabin temperatures, they investigate the impact of window coverings and insulation. Based on HVAC settings, glazing characteristics, and climatic factors, A. Warey et al. [15] utilize CFD simulations to forecast thermal comfort in a car's cabin. Instead of depending on computationally costly simulations, they provide precise estimates of the Equivalent Homogeneous Temperature (EHT) and indicators like Predicted Mean Vote and Predicted Percentage of Dissatisfied. P. Bandi et al. [16] investigate how the temperature of a car cabin exposed to sunlight is affected by meteorological factors. They assess the driver position temperature and examine temperature cabin using CFD simulations.

Despite the large number of studies conducted on vehicle cabin thermal management, recent research still has a significant research lack, as the latest published study is that of Hariharan in 2022 [5], which lends our study a unique character and enhances its contribution to the corpus of current knowledge. As shown in figure 1, This study aims to determine the energy consumption for cabin temperature and examine the thermal performance of electric vehicle (EV) cabins. Evaluating the possible energy savings that could be attained by upgrading insulating materials is the goal. The findings of this study will aid in maximizing EV energy use, resulting in increased driving range and the sustainability of electric mobility as a whole. They will increase range, boost battery efficiency, and increase the sustainability of electric transportation in general.

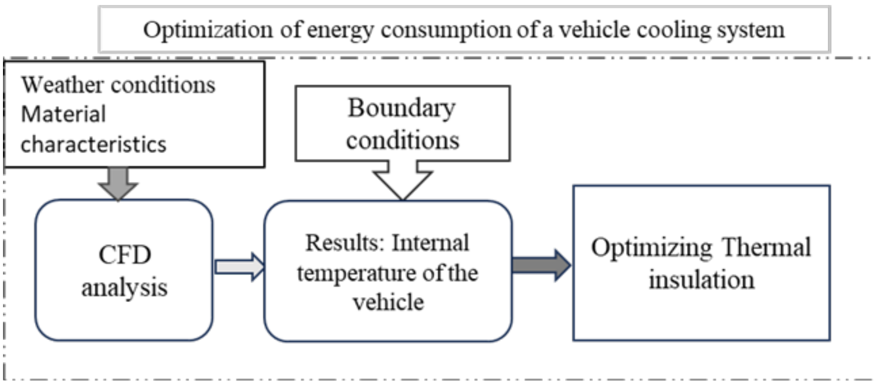

Figure 1. Overview of the temperature simulation method.

2. METHODOLOGY

2.1. Governing equations and boundary conditions

To study fluid behavior under different boundary conditions, including sun radiation, climate change, and ambient temperature, a CFD model of the fluid in the car cabin is constructed. Newton's second law and the conservation of mass, momentum, and energy equations are used to derive partial differential equations, and approximations are used to obtain numerical solutions. The Navier-Stokes equations, which are essential to CFD, explain the energy conservation of mass and momentum [17]:

Momentum Equation (1) (Conservation of Momentum):

$$\frac{\partial(pE)}{\partial t}+\nabla\cdot(\rho uu)=-\nabla\rho+\nabla\cdot\tau+f \quad (1)$$

where f stands for the external forces, p for the pressure, and τ for the stress tensor.
Continuity Equation (2) (Mass Conservation):

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho u)=0 \quad (2)$$

The velocity vector is represented by u, and the fluid's density is represented by ρ.

Energy Equation (3) (Conservation of Energy):

$$\frac{\partial(pE)}{\partial t}+\nabla\cdot(\rho Eu)=\nabla\cdot(k\nabla Tu)+\Phi \quad (3)$$

where viscous dissipation (Φ), thermal conductivity (E), temperature (T), and total energy (E). The CFD model receives time-dependent inputs from the models of solar radiation and ambient temperature. Two distinct thermal boundary conditions, convective and heat-flux were applied consistently throughout the analysis. The input parameters utilized in this study were selected in Morocco in order to ensure that the analysis represents relevant and realistic meteorological conditions [18]. The boundary conditions and surface material properties for the internal fluid flow were listed in Tables 1 and 2 [5].

Table 1. Vehicle Surface Boundary Conditions.

	Heat transfer coefficient ($W.m^{-2}.K^{-1}$)	**Internal Emissivity**	**Transmissivity**
Car wall	5	0.26	-
Glass	5	0.49	0.8

Table 2. Insulation material characteristics

Insulation Materials	**Thermal conductivity ($W.m^{-1}.K^{-1}$)**	**Density**	**Specific heat ($KJ.kg^{-1}K^{-1}$)(Kg/m^3)**
Polyurethane	0.19	1100	1.76
Thinsulate	0.030	240	1.3
Polymer Aerogels	0.040	300	1.2

2.2. Numerical methodology

An electric car's geometrical model was made for the analysis. The vehicle's pedals, storage spaces, nozzles, and other small components were left out. The vehicle's measurements (figure 2) are used to create the model in CATIA v5 software, which is then loaded.

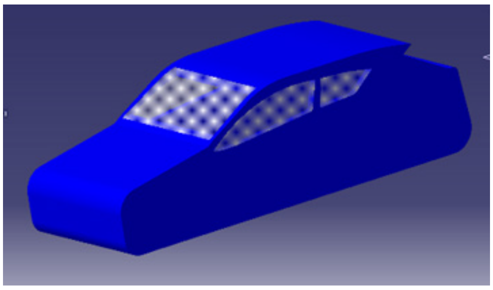

Figure 2. Car design in Catia v5.

The mesh test is also carried out. The spatial discretization method and convergence tolerances are examples of solver-specific parameters that have been chosen. These settings optimize calculation speeds while guaranteeing the simulations' correctness and stability.
Then the required simulations are run to look at the thermal loads in the passenger compartment. During mesh generation, the refining and sizing functions were used where necessary to provide a high-quality mesh and size ratio.
The analyzer used in this investigation has the following solver parameters: 3D; turbulent; incompressible; K-Epsilon turbulence model; solar heat addition modeled using the solar irradiation model. Below is an example of how to include a figure.
The CFD model uses wind speed, ambient temperature, and solar radiation as time-dependent inputs. It is necessary to specify the initial and boundary conditions in order to solve any computational fluid dynamics issue.
The mesh was created requiring several iterations for each of the transient simulation's 864-time steps (100 size) throughout a 24-hour period.
To validate the CFD simulations, the mesh quality was evaluated by checking skewness, aspect ratio and orthogonal quality parameters, in order to avoid numerical errors. Therefore, by reducing the residuals of the conservation equations, a convergence test was carried out. These tests verified that the mesh quality was at its best and that the outcomes were reliable.

2.3. Selection and Definition of the insulation materials studied and justification

This paragraph will discuss the criteria of insulating materials used in the automotive industry, highlighting their strengths and weaknesses. Table 2 provides a detailed overview of the thermal characteristics of these components, including parameters such as density, specific heat. and thermal conductivity, Polymer aerogel and Thinsulate are distinguished from Polyurethane by its extremely low thermal conductivity, providing optimum insulation and remarkable durability. On the other hand, although Thinsulate light weight, which results from its low density (240 Kg/m^3), is unquestionably advantageous, Polymer Aerogels stand out for having a little higher density (300 Kg/m^3), which guarantees stronger durability and long-lasting performance over time.
On the other hand, the use of this material insulant in vehicles has significant financial implications. The cost of aerogel families is estimated at between $40/m² and $80/m², while Thinsulate is generally more affordable. These initial investments can be offset by a significant reduction in energy consumption in the long term. In addition, aerogel and Thinsulate provide noticeably superior thermal performance than conventional insulation materials as rock wool or polyurethane foam (λ = 0.030-0.046 W.m-1.K-1) [5]. These materials offer extra advantages including durability and fire resistance together with more effective insulation that is thinner. The next section presents the results derived from the CFD study. These results highlight the efficacy of the suggested insulation materials by providing a thorough examination of their thermal performance.

3. RESULTS AND DISCUSSION

Figure 3 compares three insulating materials to illustrate how temperature changes inside a car cabin. Among these, polymers minimize temperature swings and have performant thermal insulation qualities and a remarkable ability to keep a steady internal temperature in spite of environmental fluctuations. It still has some vulnerability to heat peaks, though. In contrast, thinsulate stands out due to its thermal stability. Meanwhile, the third material shows the highest temperature fluctuations, highlighting its lower effectiveness compared to the other two materials.

The results indicate that the best insulation material tested in this study performed better than those reported by Hariharan [5].

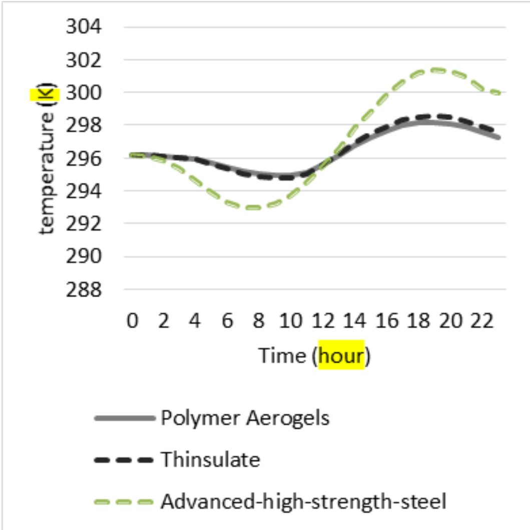

Figure 3. Temperature Variation Over Time for Different Insulation Materials.

The contrast between the highest temperatures attained in the car cabin for each type of insulation highlights the variations in their thermal performance. The highest temperature recorded for Polymer was 297.55 K, followed by Thinsulate at 298.006 K. These findings underscore the impact of insulation type on cabin temperature regulation and emphasize the importance of insulation selection for efficient thermal management in vehicles. These findings demonstrate how each kind of insulation impacts cabin thermal regulation and highlight the importance of insulation choices in vehicle thermal management.

Our primary goal is to maximize our car's energy usage, especially for the air conditioning system, which is one of the biggest energy users. Thus, our goal is to assess the chosen material's energy efficiency. In order to ascertain whether this insulation material actually lowers the vehicle's energy usage, we will use an electrical energy equation to model the air conditioning system:

$$E = P \cdot t \tag{4}$$

Where P is electric power and t is time.

Understanding the relationship between the air conditioner's electric power and coating is essential.

$$P = \frac{Q}{COP} \tag{5}$$

Where:

Q: Thermal power required (in joules or watts if divided by time).

COP is the performance coefficient of the air conditioner.

Table 3. Energy Simulation Results (MJ).

Material	Energy (MJ)
Polyurethane	142.64
Polymers	78.73
Thinsulate	86.65

Based on Table 3, Polyurethane uses 142.64 MJ of energy when the air conditioner is turned

"ON". The compressor's electrical power usage drops to 78.73 MJ when Polymers are included in the simulation. In the same way, the third material lowers power usage to 86.65 MJ.

The findings demonstrate the substantial influence that insulating material selections have on air conditioning system energy usage and vehicle interior thermal management. When compared to polyurethane (301.52 K) and Thinsulate (298.006 K), the incorporation of Polymers allows for a significant decrease in energy consumption while preserving a lower interior temperature (297.55 K).

It is observed that the increase in indoor temperature coincides with the heat peaks of the day, as does the intensity of solar radiation. Thus, the indoor temperature curve is directly linked to fluctuations in outdoor temperature and the intensity of solar radiation. Similarly, the insulating materials have great importance.

4. CONCLUSION

This study emphasizes how important thermal insulation materials are for lowering the energy consumption of a car's heating, ventilation, and air conditioning (HVAC) system, which under some circumstances can account for up to 25% of the vehicle's overall energy consumption and is one of the biggest auxiliary energy demands.

Examining the thermal efficiency of several insulating materials helped to reduce the excessive heat accumulation in the passenger compartment, which was mostly caused by solar radiation. The car cabin's thermal loads were modeled and evaluated using CFD simulations with realistic boundary conditions.

The most efficient material, according to the results, is Aerogel Polymers, which achieved the lowest maximum cabin temperature of 297.55 K and drastically reduced energy usage to 78.73 MJ. On the other hand, polyurethane and Thinsulate used more energy and produced warmer cabin temperatures, indicating less effective performance.

These results highlight the possibility of enhancing energy efficiency and thermal comfort in automobiles using cutting-edge insulation materials like aerogel polymers. The usefulness of CFD simulation as a reliable method for assessing and forecasting the effects of different parameters on a vehicle's internal thermal loads is further demonstrated by this study. The knowledge acquired here serves as a basis for developing thermal management techniques in automobiles and for creating HVAC systems that use less energy. On the other hand, increasing energy efficiency by adding the suggested insulators also has a good environmental impact and indirectly lowers greenhouse gas emissions.

Although the findings of this paper make significant contributions to the field, they also highlight the need for a thorough investigation into material integration strategies in certain vehicle zones. This topic is a promising avenue for future research that would allow for a closer examination of the findings and the provision of practical answers to technical problems related to their implementation in current vehicle concepts.

In addition, future studies should examine how well these materials function in complicated geometries or unusual vehicle layouts.

Building on this, a study of the practical steps allowing their large-scale adoption in the automotive industry can be carried out. This includes the realization of real prototypes to evaluate their performance, the standardization of manufacturing processes to optimize costs.

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